

An Investigation into the Aspiration Efficiency of Building Ventilation System Inlets for Reducing Energy Consumption in Air Filtration Systems

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By

Brian Considine

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Supervisors: Prof Aonghus McNabola & Dr John Gallagher & Prof Prashant Kumar

Department of Civil, Structural and Environmental Engineering,

University of Dublin,

Trinity College, Dublin.

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EXECUTIVE SUMMARY

The built environment is one of the largest sectors for energy consumption worldwide with a significant portion attributed to heating, ventilation and air conditioning (HVAC) services. To mitigate against climate change and improve the operating efficiency of buildings, novel solutions are required to combat the effects of environmental pollution on building operating efficiency. In particular, natural and anthropogenic sources of particulate matter (PM) have a detrimental impact on energy consumption and indoor air quality (IAQ) in buildings. The transfer of PM from the ambient environment to a mechanically ventilated building using an air handling unit (AHU) is poorly understood. Typically, two-stage filtration is used to maintain an acceptable IAQ at the expense of increased energy consumption as the filters are loaded with PM. The systems resistance rises and as a consequence, increases the fan load in order to maintain the required ventilation flow rates.

This research was focused on developing sustainable low carbon and low cost PM control technology known as aspiration efficiency reducers (AERs) to reduce the ambient PM concentration entering an AHU, and minimise filter loading. Novel AER technology was designed and evaluated using aspiration efficiency (AE) theory which measures the ratio of the ambient concentration to the in-AHU concentration. Conventional AE studies were conducted for aerosol samplers with the goal of measuring 100% of the ambient environment, in contrast AERs were designed by reverse-engineering AE to approach 0%. To determine the effectiveness of AER technology as a form of PM control, the results must be compared with the AE of the current AHU inlet attachments, rainhoods. Establishing the AE of existing AHU inlet designs, the dynamics of PM concentrations passing from the ambient environment to indoor spaces can be used in the creation of novel AERs. We also aimed to establish the baseline AE of existing rainhoods, which have not been designed with PM control in mind, but nevertheless possess an AE. Localised vehicular fine particulate matter ($PM_{2.5}$) emissions in an urban street canyon can also influence the energy performance and IAQ of a building ventilation system at roof level. A study was conducted on the rooftop positioning and $PM_{2.5}$ dispersion across the building rooftop. By examining the energy demands of air filtration through an AHU located in different positions and orientations, best practice guidelines for building service installation can be developed with the intention of improving the building operating efficiency.

The project aims required numerical modelling due to time constraints associated with field monitoring for a parametric investigation of the building and environmental variables that impact AE. This study modelled two commercial AHU rainhoods across a range of PM diameters, flow rates, wind speeds and directions. A 20-50% difference in particle concentrations between ambient air and the in-AHU concentration was observed between forward and rear-facing AHUs, with respect to ambient wind direction. Furthermore, a decrease in the ventilation flow rates resulted in a significant reduction in PM concentrations entering the rear-facing AHU. The follow-up AER investigation focused on technology designed to prevent the occurrence of a forward-facing AHU which had incurred the highest AE for commercial rainhoods. The study found that the engineering of wind flow around the AHU and its inlet resulted in lower PM concentrations across a range of particle diameters. The difference in AE for particles within the PM₁₀ range for the passive AER prototypes in comparison to a commercial rainhood ranged from 5-35% for various inlet designs. This translated into increased energy savings of 15.2-20.6% and extended fabric filter lifespan of up to an additional 100 hundred days until saturation.

The last numerical study examined the influence of AE on the filter loading rates as the distance from the source increases, and for varying wind speed, and AHU orientation relative to the ambient wind direction. The investigation found the ventilation PM_{2.5} concentration was equal to the ambient when positioned near the windward wall of the target building. A decrease of 33 % and 60 % in the filter loading rate at a wind speed of 7.5 m/s and 2.5 m/s was found at the leeward wall. Therefore, there were no energy savings when the AHU is positioned on the windward side of the target building but savings in energy consumption of 9.8 % at the building centre and 19.4 % at the leeward side. Comparing the effect of the wind orientation for identical AHU positions on the rooftop centre resulted in a 26-35 % reduction in AE when the AHU inlet is not facing into the particle laden wind and led to the largest energy savings of 25.8 %.

Finally, post numerical investigations, field studies were performed in an urban environment comparing the developed AER technology with commercial rainhoods and their filter performances were measured over several months. The study showed that AERs reduced energy consumption leading to minimal waste generation and presented cost savings whilst improving IAQ, through a reduction in maintenance activities and the number of filter replacements. This novel technology requires low-capital investment to deliver environmental, energy and economic savings in this sector.

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1 INTRODUCTION

The generation of air pollutants through the use of fossil fuels is a major anthropogenic cause of global warming and also has a significant effect on human health. The rapid expansion in populations and industrialisation over the past century has led to a large increase in the use of fossil fuels, especially in urban centres. The rate of global emissions has been increasing at an exponential rate, and the current trends are unsustainable. Further research and investment is required to increase the use of renewable technology for energy generation and innovative pollution control technology [1]. This fact has led to modern society identifying and creating mechanisms that ensure countries are taking a pro-active and legally binding approach to the reduction of their carbon footprint, and to human health protection. This is enshrined in the Paris 2020 accord. In response to the Paris 2020 accord, building energy consumption has been identified as one of the leading contributors in the total global emissions; particularly the heating, ventilation and air conditioning (HVAC) systems components of a building.

Therefore, this project is concerned with the development of innovative technologies and guidelines that target and strive towards the goal of mass-produced zero energy buildings. The filtration systems which are associated with all aspects of a buildings HVAC system are loaded with particulate matter (PM) and induce significant energy losses as particle accumulation increases. The filters act as a barrier, whereby these particles are trapped and prevented from entering the ventilation system. This method is used to maintain an acceptable level of indoor air quality (IAQ) in a building but as a consequence, the ventilation system requires more energy to overcome the filter resistance. This project is concerned with the development of sustainable energy efficient technology that will deflect and/or restrict a significant proportion of ambient PM away from the fresh air inlets of the ventilation system, thus increasing the life span of the filter and reducing fan motor loading. This research is based upon the principles of aspiration efficiency (AE) reverse engineered in order to reduce PM concentrations entering the ventilation system from the ambient environment.

AE theory was originally used in the performance assessment of air pollution sampling devices where various environmental and design characteristics were examined to improve AE toward 100% [2,3] and thus increase air sampling accuracy. AE is defined as the sampled

fraction of particles relative to the total concentration of particles dispersed in ambient air [2]. It was later applied to human mouth and nose aspiration studies [4,5] and most recently adapted for building ventilation intakes. McNabola et al. [6] first addressed building ventilation pollution control technology by applying an AE index to a ventilation system intake in order to develop novel PM control technology that reduces filter loading. Where air pollution samplers are designed to sample 100% of the concentrations within the ambient air, in contrast for a large ventilation system, an AE approaching 0% is most desirable. Hence the development of HVAC PM control technology known as aspiration efficiency reducers (AER) using AE theories.

AERs are sustainable technology designed to reduce the ventilation systems PM concentrations relative to the ambient concentration upstream of the air filtration system contained within a building air handling unit (AHU) and therefore act as a prefilter. AER technology to date, has been designed with an array of cylindrical orifices that have large orifice surfaces areas to induce low ventilation velocities. Current traditional HVAC infrastructure at the inlet upstream of the filtration system incorporate rainhoods whose sole function is to prevent the ingress of rain droplets into the ventilation system and subsequent deposition on the filters. Rainhoods are not designed to restrict PM particles from entering the AHU or lower the PM concentration entering the AHU. Moreover, the replacement of rainhoods with AERs as an AHU inlet attachment are advantageous as they will lead to (a) a reduction in the PM concentrations drawn into the ventilation system (b) lower a building energy consumption (c) lower maintenance cost due to increased filter life (d) improve IAQ (e) lower capital costs (f) be easily retrofitted and (g) rely on low carbon technology. Finally, AE concepts can also be adapted to assess and modify urban planning guidelines and stipulate best practices for AHU installations by aiming to reduce AE. Considering the surrounding urban environment, the AHU is situated in and assessing how AE changes from the local source, location of the AHU in the PM transportation path and filter loading (i.e., receptor) could also lead to the improvement outlined from a-g for AERs. The project is therefore concerned with the creation of sustainable energy infrastructure for HVAC industry in the form of AERs and improving future urban development strategies that improve the operations of buildings.

1.1 AIMS AND OBJECTIVES

The overall aim of this project is to develop passive PM control technology that can be installed onto new and existing building ventilation system inlets. The project is focused on examining the effects of an AER device on PM of various aerodynamic diameters and its effectiveness at reducing PM concentrations within an air handling unit (AHU). The variables that affect the process are poorly understood, and identifying the dominant building and environmental variables will inform the optimisation and design of said device. The project also aims to establish the optimum position of the AHU inlet upon a rooftop and the inlet orientation relative to the oncoming wind, to minimise energy consumption and improve IAQ. Combining innovative technology and urban planning considerations by placing the AHU in low concentration zones should drastically reduce AE and as a consequence, the incoming PM concentration. This will provide an energy efficient solution to reducing the built environments energy demands, lowering operating costs and improving IAQ. To achieve the aim of developing a fully functioning prototype the following objectives were proposed to increase the depth of knowledge:

1. Review of current PM and AE literature.
2. Advance our knowledge of AE for the purpose of air pollution control in an AHU.
3. Determine the effect of varying meteorological and building operating conditions on AE of existing commercial AHU rainhoods.
4. Analyse the effect on AE, IAQ and energy consumption of altering the orientation of the AHU intake relative to the wind direction.
5. Analysis of the relationship between AE and Stokes number (St) for large ventilation systems.
6. Development and optimisation of numerous AER prototypes which includes various configurations of circular orifices in an array, and strategically placed baffle plates/deflectors.
7. Determine the effect of pollutant dispersion to roof-top level on an AHU filtration system in an urban environment with a ground level vehicular pollution emission source
8. Analysis of the corresponding energy consumption of HVAC systems within an urban street canyon configuration, and assess the optimum location and orientation for placement of the AHU upon the rooftop.
9. Full scale field test of the final optimised AER prototypes and AHU with a commercial rainhood filter loading in an urban environment.

1.2 RESEARCH STRATEGY

The development of a strategy for improving knowledge in the area of PM control technology in large ventilation systems requires a numerical and experimental approach. A large number of variables were identified that could influence the AE of a building AHU. Therefore, parametric studies were required using computational fluid dynamics (CFD) methods to build upon the literature behind AE as a form of PM control. This was the only realistic approach to increasing the breadth of knowledge of how PM is drawn in through the building fresh air supply, in a timely fashion. To achieve this, the numerical approach was split into three main components that upon completion would provide a clearer picture of the processes that increase an AHUs filter loading. The following three numerical studies and a field test were considered for this research thesis:

- i. Development of baseline AE values for existing commercial rain hood technology, currently used in the European market, and based on designs acquired from an Irish HVAC equipment manufacturer. A detailed analysis of the particle laden wind flow around an AHU is required to develop passive control technology in the form of next generation AERs. The past literature has so far focused on numerical modelling of a small-scale AER and field test of a full-scale prototype. Refining the technology will require a baseline for comparison and also a thorough understanding of the environmental variables and building operations that increase AE across a range of particle diameters.
- ii. The following study will be informed by the former and will also use a similar numerical methodology in order to examine novel inlet geometries that will improve the ventilation systems energy efficiency. The AERs will be designed to consider the wind conditions, particle inertia and mechanisms of particle impedance. Previous research examining AER prototypes were excessively large compared to the AHU body. This study will develop prototype AERs at an equivalent scale and size as the AHU and induce velocities at the inlet orifices comparable to the commercial rainhoods.
- iii. In addition to examining novel inlet geometries that could impact AE, the location and orientation in a full-scale environment must also be considered. The building geometry and topography will alter the PM flow paths and trajectories and reduced AE could be achieved by a parametric study of a polluted urban environment such as a street canyon. A successful demonstration of the importance of an AHU installation's position could reduce the energy consumption of a building.

- iv. The final study of this project will consist of AHU field tests of the various AER prototypes developed. These will be compared with a commercial rainhood on a building rooftop in Dublin City Centre. The numerical models are tested under set boundary conditions that are representative of specific environmental conditions. The field tests are required to verify the veracity of the AER numerical models and demonstrate the viability of the technology in reducing the concentration of PM entering through the fresh air supply in real-world conditions.

1.3 RESEARCH CONTRIBUTIONS

The purpose of this research is to enhance the theoretical and practical knowledge of the built environment and air pollution. The theoretical contributions will be in the form of international journal and conference publications. The practical contributions will stem from the development of new technology and generation of IP that will be disseminated to improve the design practices of HVAC systems. The process has been divided into four journal papers and two conference publications that will systematically target each objective of the project. Typically, the scope of each academic contribution will involve the following research topics: building energy, air pollution, urban environment, building simulations, PM control technology and mechanical ventilation.

Journal paper 1: *Numerical investigation on the ingress of particulate matter from ambient air into the inlet of a building air handling unit.*

Journal: Published with Indoor Air, 2021.

This paper has been published and is concerned with developing an understanding of the AE of existing commercial AHU rainhood designs and to establish the dynamics of PM concentrations passing from the ambient environment to indoor spaces. Various meteorological and building operating conditions were examined to determine which variables influenced the aspiration of a ventilation system. The results from this paper provide a benchmark for comparison with the novel AER designs that will be tested for reducing AE in journal paper 2.

Journal paper 2: *A numerical analysis of particulate matter control technology integrated with HVAC system inlet design and implications on energy consumption.*

Journal: Published with Building and Environment, 2022.

This paper has also been published and was focused on developing novel sustainable energy technology in the form of AERs for PM control of an AHU. The results from numerical model of the traditional rainhoods used in the HVAC industry were used to develop novel AERs with the goal of replacement of the former. Furthermore, in addition to an AE comparison between rainhoods and AERs, the energy consumption and monetary costs of each system were analysed.

Journal paper 3: *The impact of street level particulate emissions on the energy performance of roof level building ventilation systems.*

Journal: Under review with Wind Engineering and Industrial Aerodynamics, 2022.

This paper is currently under review and was focused on creating urban planning guidelines for PM control of an AHU by considering the AHU inlet proximity to local PM sources and orientation relative to the wind direction. The results demonstrated the influence of urban environmental conditions and impact of pollution on an AHU by considering AE, energy consumption and monetary costs.

Journal paper 4: *Aspiration efficiency: A review of the application and evolution of air pollution monitoring, health assessment and control technology.*

Journal: Planned publication with Journal of Aerosol Science.

This paper is a planned publication and will incorporate aspects on AE theory related to aerosol sampling, human nose and mouth studies and large ventilation systems. The paper will address the various studies and how AE evolved to analyse areas other than aerosol sampling. Additionally, the paper will outline the future directions and other potential applications for AE.

Conference paper/presentations:

1. International Conference on Urban Air Quality Management, Environment and Technology (ICUAQMET) (September, 2020), Title: A Study on the Effectiveness of Alternative Commercial Ventilation Inlets That Improve Energy Efficiency of

Building Ventilation Systems. Awarded the International Research Conference Certificate of Best Presentation award.

2. Environ 2022 'Unlocking Sustainability', 32nd Irish Environmental Researchers Colloquium Jointly hosted by ESAI & Ulster University, 20th-22nd June 2022. Title: Reducing Energy Consumption in Air Filtration Systems.

1.4 THESIS OUTLINE

The thesis was structured systemically in order to achieve the aims and objective to the project beginning with a literature review in Chapter 2. The literature review identified the key areas of this project to be addressed in order to achieve a successful outcome. These include: an evaluation of sustainable infrastructure and their potential role in mitigating the effects of climate change; development of sustainable technology and infrastructure is required to address the current inefficiencies within the built environment and energy consumptions related to building design and operations incurred by HVAC systems; natural and anthropogenic sources of air pollution and their formation and distribution worldwide; impact of air pollution on health and wellbeing of building occupants; methods for improving IAQ in indoor environments such as filtration of PM; summary of particle dynamics and their influence on AE; wind dynamics in the built environment and details of past studies; a summary of the previous experimental and numerical studies conducted on using AE as a form of PM control for large ventilation systems.

Chapter 3 details the theories and application of computational fluid dynamic (CFD) methodology that will be used throughout the thesis. This chapter is concerned with ensuring quality control of the numerical models by incorporating best practices into model development and subsequent solutions. Chapter 4 is concerned with the verification of the grids used for each numerical study and that grid independence has been achieved. Moreover the validation is framed to compare analogous experimental studies considering AE and pollutant dispersion in urban environments with the numerical models in order to ensure the physical representation is captured.

Chapter 5 and 6 describe the modelling and results of an AHU with different inlet attachments. AE of both commercial rain hoods and new AER design are considered respectively. In addition, the energy consumption of each attachment is assessed using their corresponding AE and their associated flow patterns around the AHU body. The next

numerical study outlined in Chapter 7 examined an AHU in a full urban environment and used $\text{PM}_{2.5}$ distributions from a local traffic source in an urban environment under varying wind conditions, rooftop AHU locations and orientations. Chapter 8 outlines the experimental field research conducted in this project and compares the experimental prototypes from Chapter 6 with a commercial rainhood from Chapter 5, through field testing (i.e., in the real urban environment). Finally, Chapter 9 presents the conclusions from the overall research project, summary of the significant findings and the scope for future research on AE as a form of PM control.

2 LITERATURE REVIEW

2.1 SUSTAINABLE ENERGY INFRASTRUCTURE AND CLIMATE CHANGE

Sustainable energy is defined as the global human energy usage that meets demand without compromising future generations abilities to meet their own demand. The energy source must not be depleted and capable of continuing sustainable usage. The worlds current energy infrastructure has been classified into three categories, renewable energy, nuclear power and fossil fuels. The use of fossil fuels which are carbon based currently accounts for the largest source of energy generation but to the detriment of the planet's ecosystems, biosphere and atmosphere. A by-product of the use of fossil fuels is the generation of air pollutants and greenhouse gases, in particular CO₂. These greenhouse gases have been identified as the leading cause in the phenomenon known as global warming. As global energy consumption rises with increasing population, macroeconomic growth and industrialisation, this effect will become more profound on the world's climate and resources [7].

Global warming will alter current climates around the world, raise sea levels through the ice caps melting, contribute to biodiversity loss and extreme weather phenomena [8]. The Paris 2020 agreement was created to ensure all signatory countries adapted their energy infrastructure. This is to be achieved through energy efficient technology and an increase in renewable energy supplying their respective energy grids. The goal is to limit the average global surface temperature rise to below 1.5-2°C by 2050 [9]. A reduction in every nation's energy consumption and development of mitigation designed to limit the anthropogenic effects of civilisation from radically altering the world climate system. For example, the Sustainable Energy Authority of Ireland (SEAI) reported that the total energy requirement fell by an average of 0.8% per annum from 2005-2017 due to climate change mitigation measures. The breakdown of fuels that are used for primary energy generation is shown in Figure 1, and the graph shows a reduction in energy consumption within this period. A significant increase in the supply and usage of renewable energy was also observed over the same time frame indicating a shift from the over reliance in fossil fuels [10]. The decline in energy produced by fossil fuels appears to be attributed to the reduction in oil usage, which appears to be compensated by an increase in the energy generated from renewable sources.

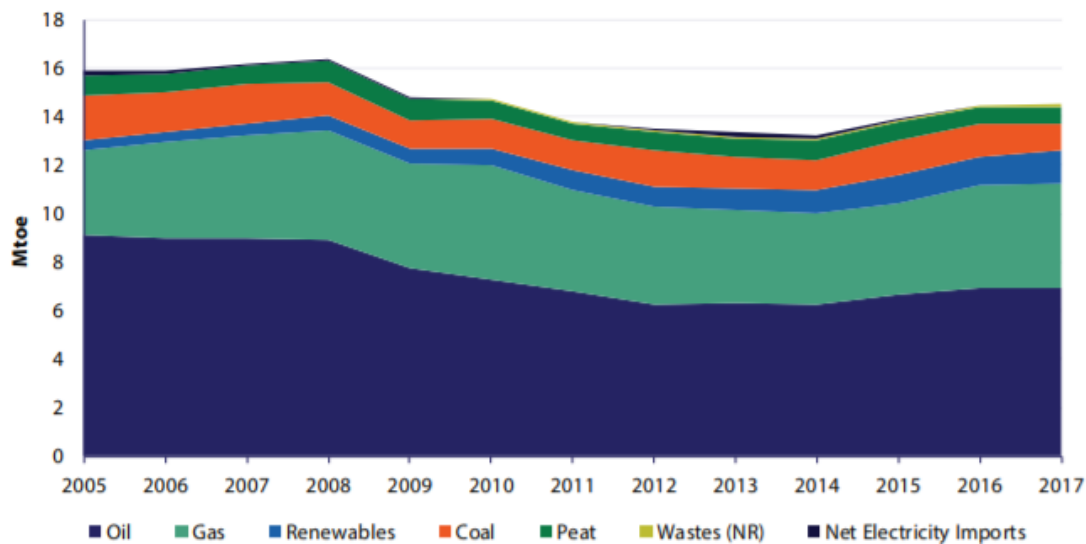


Figure 1. Ireland total primary energy requirement [10].

2.1.1 Energy Consumption in HVAC Systems for Commercial and Industrial Buildings

The EU directive on the energy performance of buildings identified building energy consumption as accounting for 40% of the total energy consumption within the EU [11] and globally [12]. HVAC systems in particular have been identified as a vital target area where significant reductions in energy consumption can be achieved. The 2020 climate and energy package legislated its member states towards three key targets of 20% reduction in greenhouse gas emissions, 20% of EU energy from renewables and 20% improvement in energy efficiency [13].

As the building sector currently accounts for 40% of the world's energy demand and 30% of greenhouse gas emissions; the drive towards zero energy buildings and retrofitting of new innovative energy efficient technology [14] is key to the vision of sustainable cities. The retrofitting of new energy efficient technology is key to environmental sustainability. Although significant challenges remain in identifying the key areas of energy consumption in not just a single building but with a holistic approach for every commercial and industrial building [15,16]. A disaggregation of a building's energy consumers in Figure 2 demonstrates that HVAC systems are shown to account for between 40-50% of the energy consumption among non-domestic buildings [17]. Moreover, the electricity usage associated with various motorised equipment is a significant contributor to HVAC energy consumption.

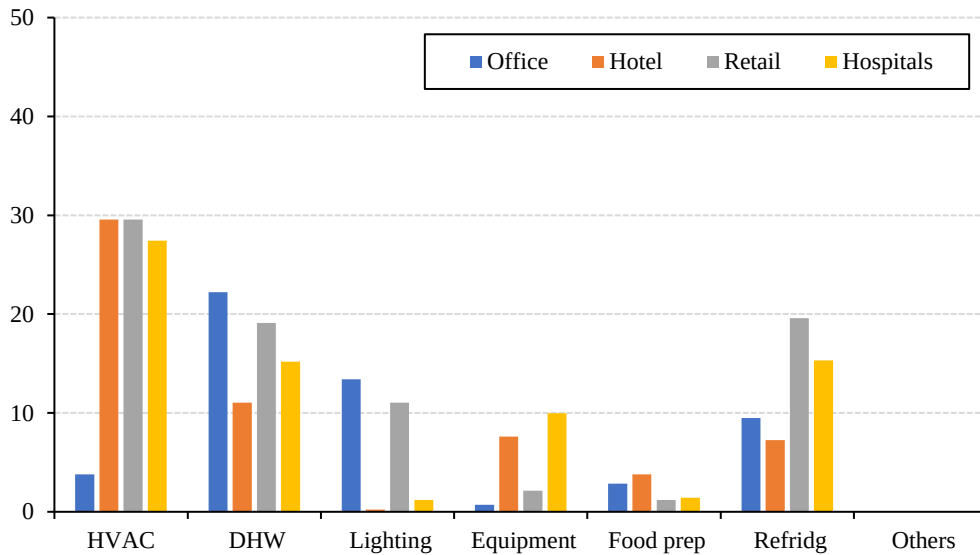


Figure 2. Energy consumption % for various commercial buildings [17].

In particular ventilation fans consume energy due to air exchanges between the fresh air and indoor air. The magnitude of the air exchange is dependent on the pressure drop which determines the system resistance associated with the index circuit of a ventilation system and its components. This criterion determines the energy consumed to achieve the optimum flow rates [18]. The fans infrastructure for the fresh air inlet to a building must be designed with consideration given to the effect of PM air pollution upon HVAC system efficiency.

An air filtration system is used to trap PM and prevent the occupants of the building breathing in large concentrations of air pollutants. A consequence of the filtration system is PM loading upon the filters, and since the pressure drop is related to the energy consumption of the fan, this has an adverse effect on building energy efficiency [19]. Particle loading increases the system resistance due to an increased pressure drop on filters and places an ever-increasing load upon the ventilation fans motors when maintaining the desired flow rates. This problem has been identified as a major issue within ventilation system operating costs and requires innovative technology to reduce the particle loading. The development of pollution control strategies and technology to mitigate the PM loading would be advantageous on several levels; in particular the synergy between the economic and environmental impact [20].

2.2 HEATING, VENTILATION AND AIR CONDITIONING SYSTEMS

Heating, ventilation and air conditioning are installed within a building with the purpose of controlling the indoor environment, this involves supplying air of an acceptable quality and maintaining the thermal comfort for the building occupants. HVAC systems are installed in residential, commercial and industrial buildings. The type of building and its corresponding requirements will dictate the quality of air, flow rates and its heating and cooling requirements. HVAC systems are a multi component system that provide conditioned air by a variable air volume (VAV) system which meets the fluctuating demand or a constant air volume (CAV) system, achieved through the use of an AHU. The type of system is determined based on the fan as VAV systems incorporates a variable speed drive motor and the CAV has a fixed speed motor.

The operation and monitoring of all the HVAC plant and equipment is achieved through strategically placed sensors that relay information back to a building management system (BMS) [21–23]. Reena et al. [21] found that the HVAC optimisation and control of VAV systems using historical data to inform real time operations based upon temperature readings provided significant energy savings. The BMS monitors humidity, CO₂, flow rates, temperature and pressure to maintain optimal conditions by controlling the HVAC plant. Mathematical modelling strategies are becoming more prevalent in conjunction with BMS data for optimisation of built environment models. Mustafaraj et al. [23] used this approach to demonstrate more efficient HVAC system control strategies in an office dwelling in London.

The AHU contains heating and cooling coils shown in Figure 3 that are supplied from centralised plants known as boilers and chillers respectively. The heating coils receives low pressure hot water from the boiler to increase the temperature of the air but depending on the outside environmental conditions, cooling may be required [24,25]. The cooling is achieved through the supply of chilled water to the cooling coil. Water is cooled from devices known as chillers that generally operate on a refrigeration cycle [24,25]. The environment also plays a key role in the design of an AHU and the humidity levels must be maintained at a level comfortable for the occupants. The Chartered Institution of Building Services Engineers (CIBSE) stipulates relative humidity levels of between 40-70% in moderate climates [26], this is achieved by the addition of a humidifier/dehumidifier depending on the time of year and relative humidity of the fresh air supply [27].

To lower the energy requirements from the heating and cooling demand, the incoming fresh air is mixed with the return air to increase the temperature of the supply air to the building. The flow rates are controlled by means of an automated damper at the inlet, exhaust and re-circulation loop. The selection of the fan type to be installed within the AHU is set according to the system's pressure drop on the index circuit. The index circuit is the main ventilation ducted pathway with the largest pressure drop that is generated when accounting for the secondary and primary pressure losses through the ductwork such as rainhoods, grilles, ducts and fittings. Within the AHU, the coils and filters will generate resistance to airflow, in particular the filter loading with PM will increase the pressure drop over time effecting the specific fan power for a given fan [19]. Currently only rainhoods are used to prevent the ingress of rain droplets entering the ventilation system and impacting the air filtration system.

HVAC-related energy consumption is attributed to system specific mechanical parameters such as fan speed control, fan curve, system curve and fan motor type, with previous research responsible for optimising the operating efficiency of these ventilation systems [28]. What remains is that the energy efficiency of HVAC systems is greatly impacted by increasing pressure drops across the filter [29]. As air pollutants and biological containments are removed from both the fresh and return air supply streams, the pressure drop increases with an accumulation of particles on the filter which amplifies the energy demands of the system. Leavey et al. [30] also found that operating HVAC systems with on/off cycles causes spikes in PM concentrations recorded due to particle deposition during the off stage which is then recycled through the mixed air.

With regards to the ventilation system design, there are several different types of fans that can be used, axial, radial, mixed and crossflow fans. Each fan has its own unique characteristics and is chosen based on the application. The axial fan is highly efficient with large flow rates under low pressure [31], and crossflow fans are also very efficient and have high pressure coefficients [32]. Similarly, forward curved radial fans generate medium pressures and low flow rates with low resistance [33] in comparison with the backward curved radial fans that incur medium/high pressure and flow rates regardless of static pressure [34]. The mixed flow fan is a combination of the axial and centrifugal fan with an intermediate fan performance curve between the two [34]. Typically, the backward curved centrifugal fan is used with a HVAC system's AHU.

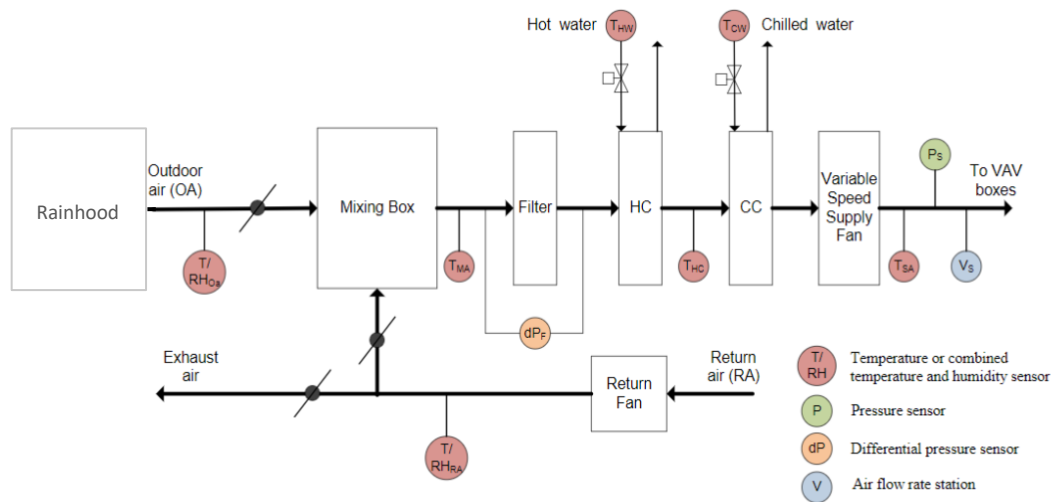


Figure 3. Typical Commercial AHU diagram [35].

2.3 AIR POLLUTION

2.3.1 History of Air Pollution

The origin of life is intermittently linked to the reduction in carbon dioxide and increase of oxygen, before man walked the earth, when natural pollutants were present in the atmosphere. These occurred from wind strewn deserts, volcanoes spewing ash, breakdown of the early biological lifeforms and various other natural disasters and processes. As people began to walk the earth lighting fires, constructing buildings and developing agriculture practices, anthropogenic sources of air pollution have steadily begun to dominate through the centuries. There have been various recordings of air pollution posing significant problems in earlier civilisations; Seneca reported heavy air from the stink of smoky Roman chimneys, famous Greek literature the Odyssey describes thick smoke from Troy and excessive air pollution levels were recorded numerous times during the middle ages [36].

It should be noted that the effect of air pollution was poorly understood and considered part of urban life. It was not until the 18th century and the industrial revolution that the British Government in London acted, where several serious outbreaks of smog had occurred throughout the centuries. The use of coal became the predominant method for heating and energy but with the consequence of producing heavy black sooty smoke. Other pollutants from the glass industry produced hydrochloric acid which now is understood as the prime mechanism in acid rain which led to the Alkali act in the hopes of controlling this issue [36]. The London Smog of 1952 shown in Figure 4 which killed 4000 people and left countless

more suffering from respiratory illnesses generated a reaction which cumulated in the so-called Clean Air Act in 1956 [37]. Similar legislation had been created in the United States the previous year as several smog episodes occurred in urban areas, in particular a serious smog event occurred in Donora Pennsylvania [38]. Various other acts had been developed throughout history but failed due to ambivalent attitudes. These acts were the starting point and recognition that air pollution was a significant problem to both human health and the urban environment. Both acts emphasised the reduction through control measures in the use of fossil fuels, namely coal and oil.



Figure 4. (a) London Great Smog, Trafalgar Square, 1952 (b) Photochemical smog.

Although coal and oil were the primary contributor, photochemical smog was observed in the industrialised world in the 1940's, this was generated from nitrogen oxide emissions and hydrocarbons reacting when exposed to sunlight. Countries with heavy traffic volumes produced a smog, brown in colour, that also effected vegetation, buildings and various aspects of human health [36]. Heavy traffic volumes also produced another significant effect in urban areas through lead usage in fossil fuels, predominantly in petrol and caused a serious increase in lead concentration levels within the atmosphere. The lead was also particularly damaging to the passive pollutant control technology known as catalytic converters. Industrialised countries have phased out lead and had replaced this with Benzene [36]. Although Benzene has now been classified as carcinogenic and has been superseded with a more environmentally friendly replacement, hydrocarbons. It should be noted that leaded petrol is still an issue to this day due to its use in developing countries. Other extremely harmful pollutants, dioxins and chlorofluorocarbons (CFCs) while small in concentration

were also identified as harmful to people and CFCs were found to be depleting the Ozone layer leaving holes in the gas layer [37].

Throughout the 1970's and 1980's various individual legislative acts were created to control, reduce and monitor all forms of air pollution in the developed and developing world. The Environmental Protection Agency (EPA), World Health Organisation (WHO) and numerous country specific environmental departments tightened concentration limits, rules and emissions standards. This also led to the Kyoto protocol in 1998 which committed state bodies to reduce their emissions on average to below 1990 levels through a series of emission related milestones [39] and has now been effectively replaced by the Paris 2020 agreement [40]. The various mechanisms and pathway towards greener economies identified the elimination of fossil fuels and/or methods for extracting fuels. The principles of all the agreements and conference of parties (COP) aims to clean up polluted air through control strategies and renewable technology. Each signatory to these agreements have pledged to limit the effect of global warming and hopefully reverse the damage already inflicted upon the environment. It is possibly the single greatest threat to the global community's way of life and standard of living.

2.3.2 Classification of Air Pollutants

Air pollution is defined as the release of contaminants consisting of particles, biological matter or gases into the air that is detrimental to the earth's atmosphere and biological lifeforms. The U.S Environmental Protection Agency (EPA) originally set specific concentration levels through the U.S National Ambient Air Quality Standards (NAAQS) for the so-called criteria air pollutants; lead (Pb), particulate matter (PM), ozone (O₃), carbon monoxide (CO), sulphur dioxide (SO₂) and nitrogen dioxide (NO₂) [41,42].

The EPA has classified geographical and urban areas that exceeds the concentration limits for any of the criteria pollutants as non-attainment areas and pollutant concentrations that fall within the standard as attainment areas [43]. There are numerous non-criteria air pollutants whose concentration levels are low within the atmosphere and as such are not considered a priority such as asbestos, chlorofluorocarbons (CFCs), various gases and volatile organic compounds (VOCs). However, pollution control measures must be implemented where the presence of the non-criteria pollutants are expected. The Criteria pollutants were the original pollutants that were identified as hazardous to biological

lifeforms and the environment when exceeding the WHO concentrations limits. The classification of the six criteria pollutants has not changed but legislative policies have been updated to set concentration limits for various other pollutants. These pollutants include benzene, polycyclic aromatic hydrocarbons (PAHs), arsenic, nickel, volatile organic compounds (VOCs), cadmium and mercury. In particular Benzo (a) pyrene (BaP) is monitored which belongs to the PAH family and is used as an indicator for PAH pollution levels [44].

The European Union (EU) set legislative limits on these pollutants as well as the six criteria pollutants through four daughter directives within its air quality framework directive (CAFE) [45,46]. Member states of the EU are required to adopt the CAFE directive into their constitution which specifies concentration limits, monitoring methodology and responsibilities of the government. The Irish government adopted the CAFE directive into law through the air quality standards regulation 2011 [47] and the arsenic, cadmium, mercury, nickel, and PAHs in ambient air regulation 2009 [48].

2.3.3 Air Pollution Concepts

The various pollutants present within the earth's atmosphere occur through both natural and anthropogenic sources (i.e., stationary, mobile and area). They are created through combustion processes of burning multiple fuel types, manufacturing processes, landfills, agriculture, grinding processes, and fumes.

- Naturally sourced pollution is generated from sea aerosols, volcanic activity, dust, resuspension, living matter decay and forest fires [49].
- Industrialised areas which contain manufacturing facilities and power plants are described as stationary sources.
- Mobile sources account for any moving vehicle that generates pollutants through combustion and disturbing the environment.
- Area sources describe agriculture areas, fossil fuel burning fireplaces, residential and commercial areas.

The air pollution that is transported and dispersed into the atmosphere from the sources described above are removed from the air by sinks. The rate of removal is based upon the individual pollutant half-life (i.e., time taken for half the quantity of the pollutant to be

removed by a sink) [50,51]. There are various natural and artificial sinks involved in this process including: vegetation, soil, water and structures to name a few. Although not all of the pollutants are processed by sinks, a receptor also takes in pollutants, which is a person or living organism that is adversely affected by air pollution [52].

Air pollutants that are emitted directly from sources are known as primary pollutants, the primary pollutants in combination with the natural constituents in the atmosphere through chemical reactions form secondary pollutants [53–55]. Monk [55] found that additional ozone (O_3) levels in specific areas could potentially be attributed to the increase in primary pollutants from man-made activity. Secondary PM is also formed from various types of nitrates and sulphates through ion induced or free radical oxidation [56], this also contributes to photochemical smog/haze. The sulphate and nitric chemicals and matter can be absorbed or intercepted by rainfall whereby this combination leads to acidic rain. Niu et al. [57] and various other studies found that flue gas desulphurisation in China had reduced sulphuric acid in rain but was replaced by nitric acid rain from increased motor traffic with a combination of mixed acid rain also present depending on dispersion [58–60]. Acid rain has been found to cause significant damage and health issues where applicable to vegetation, people, animals, water sources and buildings.

2.3.4 Particulate Matter Formation

Among the criteria pollutants PM is of special interest as it has been noted worldwide as one of the main contributors to premature death and morbidity among the population, and has been shown to be at levels in the urban environment well in excess of limit values in many locations in Europe and elsewhere [61]. PM as stated previously is formed through both direct (primary) and indirect (secondary) processes. Primary particles are emitted directly from sources into the atmosphere and the secondary particles are formed through a process known as nucleation. The initial stage of secondary PM formation generates ultra-fine particles in nucleation mode, this consists of various chemical reactions which form particles smaller than $0.01\ \mu\text{m}$ [62]. As the particles are transported in the atmosphere, condensation from secondary sources increases the particle size. The particles transition from the nucleation stage to the Aitken mode where sizes are between $0.01\text{--}0.1\ \mu\text{m}$ as shown in Figure 5. The number of particles present in the atmosphere in these stages far exceed larger particle diameter sizes.

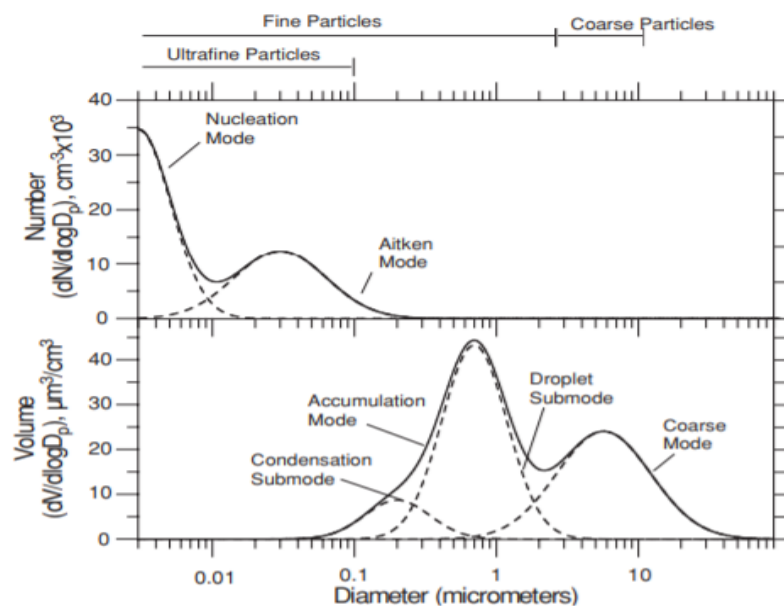


Figure 5. Typical PM size distribution curves and frequencies [62].

Through various transport mechanisms (e.g., convection, turbulence, diffusion, Brownian motion), particle sizes are increased. As the particles become larger, Brownian motion does not occur and where the particles are not too large for sedimentation, a bimodal distribution can be seen for particles greater than 0.1 μm . The initial increase is attributed to coagulation by collisions and vapour condensation [63]. Bimodal distribution occurs when examining the volume or mass distribution of the larger particles in both the fine and coarse regions. Hering et al. [63] confirmed that the accumulation mode appears to be bimodal and suggests the presence of a droplet and condensation sub mode. The first maxima to occur is under the droplet sub mode and the second in the condensation sub mode. Within the accumulation mode region, as the particle sizes increase, the droplet sub mode becomes dominant. Meng and Seinfeld [64] found that water accretion alone was not sufficient to account for the particle growth in the droplet sub mode. It was proposed that the condensation mode particles formed clouds which led to aqueous-phase sulphate formation and fog evaporation. Generally, larger coarse particles are not considered to be part of the nucleation or accumulation transformation but attributed to natural sources.

2.3.5 Particulate Matter Distribution and Chemical Composition

Baglaeva et al. [65] examined the frequency distribution of particle sizes in Ekaterinburg which is a large city characterised by a large industrial centre and contrasted with Belyy island as this is an area that has no industrial or modern settlements in Figure 6a and Figure

6b. Similar distribution curves occurred between samples taken in Ekaterinburg and research conducted by Yue et al. [66] in Shanghai, albeit with different maxima as shown in Figure 6c. The Belyy islands distribution curve examined particles from land and seas breezes and found only natural PM to be present. This is a significantly different composition to the urban centre's distribution curve due to the abundance of anthropogenic activity. Therefore, PM size and frequency are highly dependent on the natural and anthropogenic sources that are dispersed into the local atmosphere.

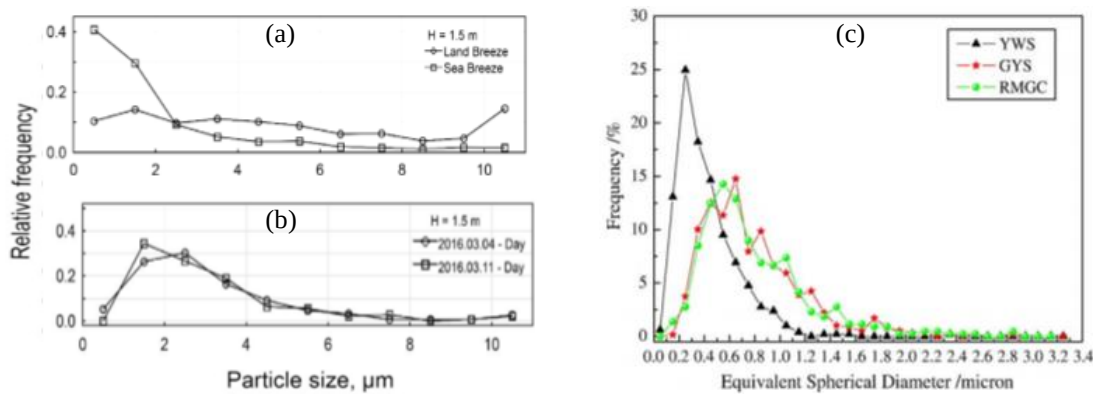


Figure 6. Particle size distribution vs frequency (a) Belyy island (b) Ekaterinburg [65] (c) Shanghai [66].

Various studies have been conducted on the effect seasonal changes have upon the concentration and size distribution of PM. Duan et al. [67] found that the bimodal distribution was prevalent and independent of the seasonal changes but the accumulation mode is higher relative to the winter and autumn. The mass percentage of particle size also varied, and the results suggested this occurred due to lower wet deposition rates, again in the Winter and Autumn as shown in Figure 7. Dedele and Miskinyte [68] found that the concentration of PM₁₀ within Kaunas city in Lithuania was significantly different from season to season, this study took a holistic approach and modelled a combination of industrial, traffic and home heating PM emissions. McNabola et al. [69] found that PM_{2.5} concentrations emitted through traffic air pollution in Dublin City were higher in the Summer compared to Winter.

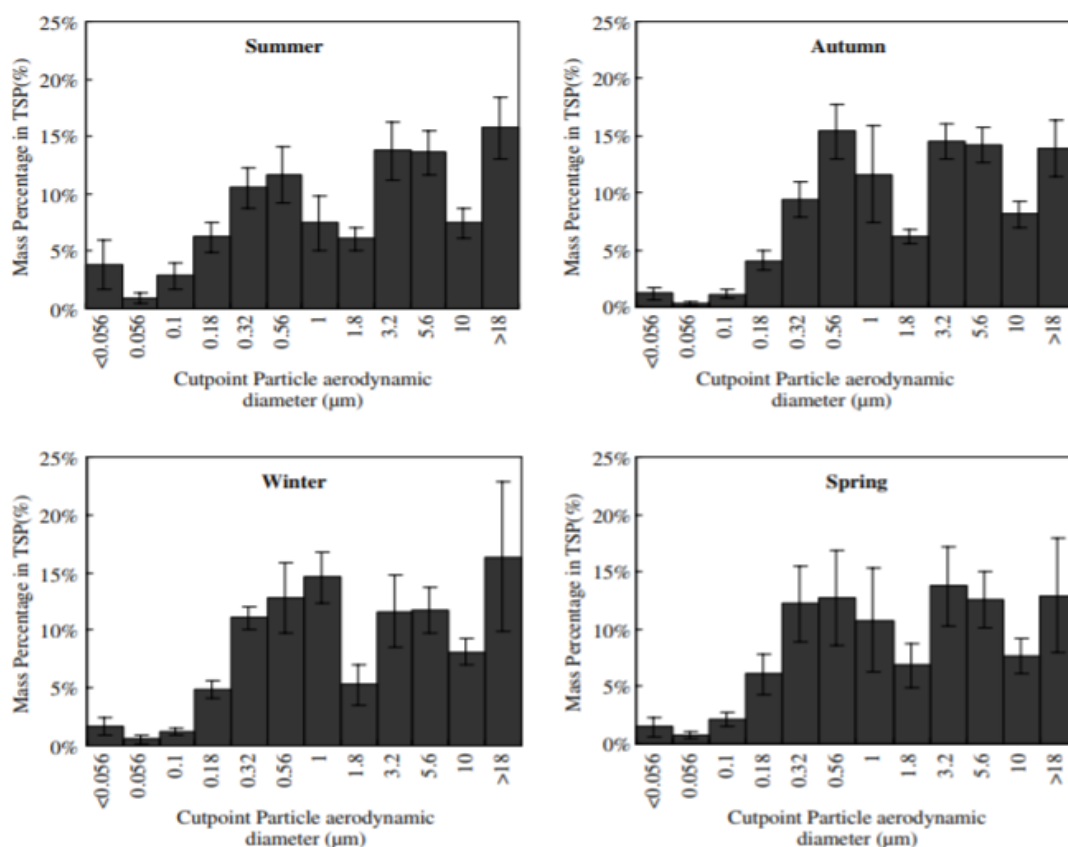


Figure 7. Seasonal PM mass distribution Guangzhou city [67].

Gonzalez et al. [70] examined four distinctly different areas in Mexico based upon their level of industrial activity, transport, residential population and mining. As expected, the specific concentration of elements present in the atmosphere differed but of interest was the concentration also varied not just at their location but seasonally. Parolovo et al. [71] also found similar results which was recorded during the Amazon region wet and dry season; a significant difference in the chemical composition of the PM occurred and was attributed to seasonal variations. A study conducted by Jennings et al. [72] for the Irish EPA found that the concentration levels based upon seasonal change at an urban roadside in Dublin (site A) and within the Dublin City Centre (site B) were also significantly different. In comparison with research conducted by Xu et al. [73], the concentrations and chemical compositions of PM_{2.5} in China are vastly different to the results presented in Table 1.

Table 1. Seasonal mean concentrations ($\mu\text{g}/\text{m}^3$) of measured chemical components at two sites in Ireland [72].

			Cl^-	Na^+	Mg^{2+}	K^+	Ca^{2+}	NH_4^+	SO_4^{2-}	NO_3^-	CH_3SO_3^-	EC
Site A	Fine	Autumn	0.46	0.35	0.05	0.10	0.16	0.95	1.70	1.06	0.01	7.65
		Winter	0.88	0.50	0.08	0.08	0.18	0.92	1.96	1.28	-	7.81
		Spring	0.32	0.45	0.06	0.05	0.12	1.39	1.85	2.00	0.05	6.54
		Summer	0.16	0.23	0.04	0.06	0.18	0.65	1.58	0.47	0.10	7.10
	Coarse	Autumn	1.34	0.87	0.15	0.06	1.32	0.03	0.41	0.66	-	0.71
		Winter	2.16	1.32	0.22	0.05	1.31	0.01	0.59	0.56	-	0.62
		Spring	1.65	1.27	0.19	0.03	1.22	0.03	0.42	0.78	0.01	0.48
		Summer	0.82	0.60	0.12	0.07	1.58	0.01	0.36	0.47	0.02	0.53
Site B	Fine	Autumn	0.30	0.30	0.04	0.08	0.15	0.81	1.66	0.74	0.01	3.37
		Winter	0.77	0.45	0.07	0.08	0.15	0.91	1.83	1.30	-	3.79
		Spring	0.28	0.46	0.06	0.05	0.11	1.21	1.83	1.69	0.05	2.56
		Summer	0.14	0.22	0.03	0.04	0.09	0.57	1.47	0.28	0.10	2.31
	Coarse	Autumn	1.45	0.99	0.15	0.06	1.09	0.04	0.39	0.76	-	-
		Winter	2.14	1.34	0.22	0.05	0.93	0.02	0.56	0.61	-	0.19
		Spring	1.55	1.32	0.18	0.03	1.01	0.02	0.37	0.79	0.01	-
		Summer	0.78	0.58	0.11	0.05	0.84	0.02	0.28	0.47	0.02	-

The literature suggests that the chemical composition of PM varies depending on location which in turn is dependent on the type of anthropogenic and natural sources within the local vicinity, climate and seasonal changes.

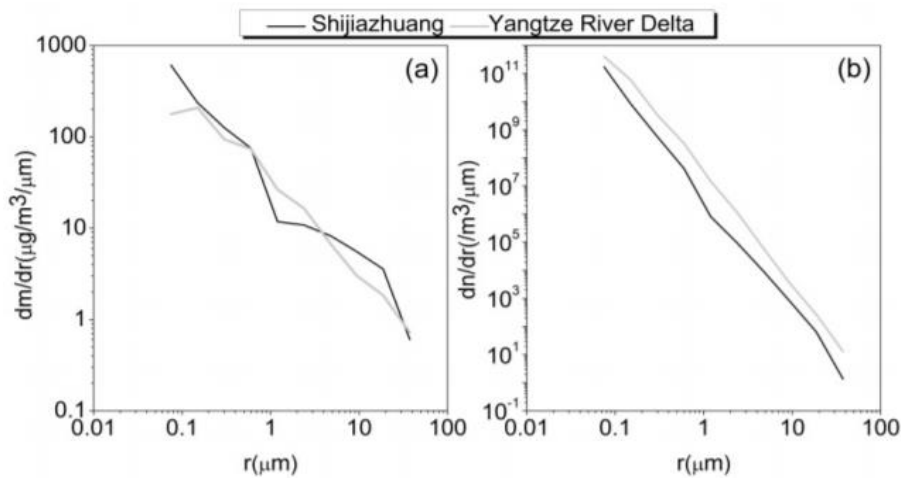


Figure 8. (a) Average mass density spectrum of aerosols (b) average number density spectrum of aerosols [74].

As elements have different atomic weights, this can lead to particles with similar diameters but different densities and this will affect the dynamics of the particle in air due to its inertia. A recent study examined PM concentrations within Shijiazhuang and Linan as shown in Figure 8, with the former being classified as severely polluted. Results showed that the average number density in Shijiazhuang was less but the average mass density was greater indicating variations due to differing chemical compositions [74].

2.4 GREEN BUILDING CERTIFICATION, INDOOR AIR QUALITY AND HEALTH

The effects of air pollution on human health are well documented and is the leading environmental risk to human health. The WHO attribute air pollution as the cause of one in nine deaths annually [75]. The various constituents of air pollution have significant negative effects on different aspects of human health. Both ambient and indoor air pollution contain bioaerosols such as bacteria and viruses, sulphur dioxide, nitrogen dioxide and PM which effect the wellbeing of humans. PM has been identified as the major health effect on humans according to the WHO, in particular on cardiovascular and respiratory health [76]. The monitoring of the IAQ is vital to wellbeing, work efficiency and health of building occupants. Improving IAQ eradicates or reduces the effect of sick building syndrome (SBS).

SBS is defined as a building with poor air quality through various environmental and mechanical factors such as volatile organic compounds, moisture content, pollutant gases, PM and inadequate ventilation which gives rise to high CO₂ levels [77–79]. Sun et al. [78] investigated the effects of NO₂, SO₂ and PM₁₀ which were significant contributors to SBS and Colton et al. [79] found that green certified buildings occupants experienced 47% fewer SBS symptoms.

The emergence of rating systems and classifications of the sustainability of the building was primarily introduced as both an energy saving measure and to combat SBS. Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEM) are the current voluntary green certification methods for analysing the quality of the building design, improving the health of the building's occupants and improved IAQ [80,81]. They are primarily concerned with the measuring and monitoring of the various aspects that contribute to sick building syndrome. This is taken into consideration during the design stages and the operation and maintenance of the building to ensure acceptable IAQ [82]. The following criteria must be addressed

when examining the building's indoor environment: materials, ventilation outlets and inlets locations, adequate supply of air to rooms, HVAC plant, occupant movement and ambient air quality [83].

2.4.1 Effects of Air Pollution on Human Health

The various constituents of air pollution described above effect human health in various ways, as each constituent depending on exposure will affect a specific area of the human health system. Long term exposure to air pollution can cause cancer, chronic and acute respiratory illness such as asthma and decreased lung function [84,85]. While short term exposure generates headaches and effects can irritate ears, nose and throat in addition to cardiovascular and respiratory diseases [86,87]. This project is concerned with the diversion of PM from the fresh air supply, and reducing incoming concentration to buildings, depending on the aerodynamic particle size this will dictate the penetration levels into the human body in indoor microenvironments.

Epidemiological studies have shown that fine particulate matter (PM_{2.5}) in particular has an adverse effect upon both the respiratory and cardiovascular systems. Yang et al. [83] examined the various elements and compounds of PM_{2.5} and found that a significant increase in morbidity and mortality with high concentrations of organic carbon and black carbon are present. Deng et al. [88] reported that particles larger than 2.5 µm were deposited by impaction in the tracheobronchial region of the lungs and particles less than 2.5 µm penetrated to the pulmonary region through the oxygen-blood barrier by sedimentation and diffusion at the alveoli or deposition on the alveoli [89]. Particles can potentially be transferred further into the circulatory system and lead to inflammation within the lungs and the cardiovascular system [90]. This effect has also been attributed to being the leading cause of acute exacerbation of chronic obstructive pulmonary disease (AECOPD) [91].

2.5 POLLUTION CONTROL STRATEGIES

The pollutions levels within the world's atmosphere have been steadily increasing for decades. Various governments and organisations have advocated for tighter controls, emissions standards and policies. Four areas of modern society have been identified as key in achieving a cleaner and less polluted atmosphere: legal, social, economic and technological [92]. Governments have set legal standards on the type and concentration of

air pollutants produced within their country's environment and implemented monitoring standards for both urban and industrial areas. Socially, the individual citizen and communities are responsible for implementing pollution control measures provided by their government such as recycling and energy conservation practices. The economic aspect and technology are somewhat interlinked. Advances in technological equipment must also be economically viable or companies/individuals will not pursue their implementation. Various studies have been conducted on the effects of air pollution from a socio-economic perspective. Briggs et al. [93] found a correlation between areas that are socially and economically deprived and increased air pollution in England. Goodman et al. [94] showed similar results in Ireland, meaning air pollution was greater for areas and individuals with a lower socio-economic position.

Currently there is no legal universal standard for pollution control limits and various governments depending on the region have published different concentration limits. The European Environment Agency (EEA) as set by the EU ambient air quality directive states that PM_{10} and $PM_{2.5}$ established annual average limits are $40 \mu\text{g}/\text{m}^3$ and $25 \mu\text{g}/\text{m}^3$ respectively, while the WHO revised guidelines have also resulted in a further reduction in the acceptable long term exposure limits of $PM_{2.5}$ and PM_{10} concentrations to $5 \mu\text{g}/\text{m}^3$ and $15 \mu\text{g}/\text{m}^3$ respectively [95]. The European Union clean air policy set three goals to be implemented by member states; achieve ambient air quality standards to protect human health, compliance on national emissions reduction targets, and emission and energy efficiency standards for key sources of pollution [96].

Creating mitigation strategies to reduce our reliance on fossil fuels requires an understanding of the processes that produce PM and greenhouse gases. This is achieved through the source-pathway-receptor model which is a holistic approach to defining the problem. Sources of harmful emissions can be described based upon their emission rates over time/distance (g/s or g/km) and their total emissions (g). The next step is to analyse the pathways the emissions will take, and the concentrations (g/m^3) involved both in transportation and receptor exposure [97]. The pathways the air pollutants follow can vary from several metres to hundreds of kilometres. Creating a mitigation strategy requires an understanding of the emission source, how and where the pollutant concentrations will travel and the effects of the exposure on a receptor [97]. This is shown in Figure 9 where various transport pathways can be seen including wind, water and vegetation.

The Irish government recently published their Climate Action Plan in 2021 detailing the paths towards decarbonisation and a carbon neutral economy. Five vital sectors have been identified for reformation and are key to achieving a carbon neutral economy; agriculture, electricity, built environment, transport and waste management [98]. Mitigation strategies are generally tailored around the specific sector involved, although certain measures are common to all or several sectors. Specifically, the built environment and transport are of particular interest due to higher PM concentrations that adversely affect HVAC systems within urban centres.

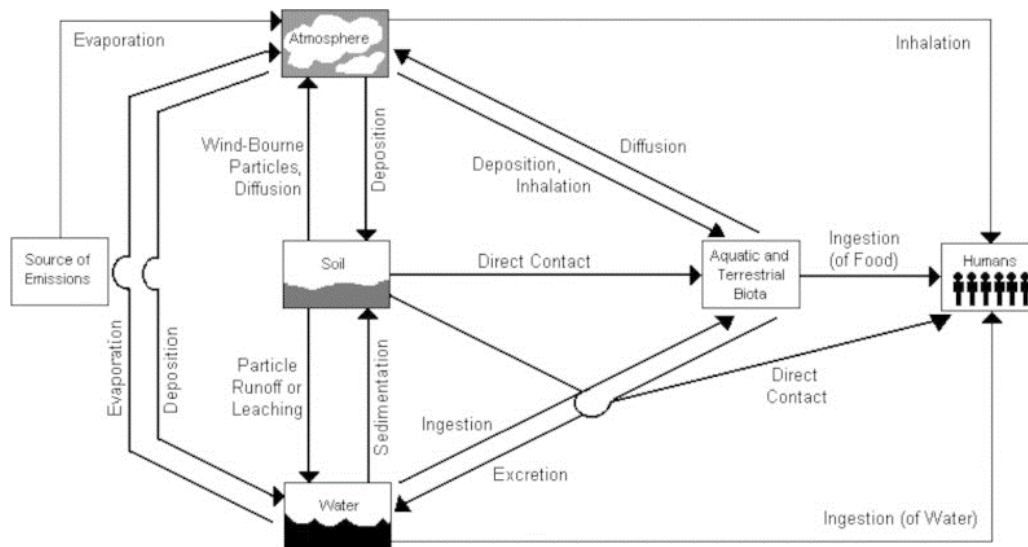


Figure 9. Source-pathway-receptor model example [97].

The mitigation of PM present in the built environment will require new control measures through devices to remove all or part of PM pollutants in the atmosphere and/or reduce emissions from sources. Government grants must be provided to switch to innovative greener technology to encourage businesses and people to adapt new technology [50]. There is a legal obligation by signatory nations of the Paris 2020 agreement to reduce their emissions. The SEAI has been providing grants to homeowners and business owners to retrofit their premises with more energy efficient technology and materials currently on the market [99,100]. This must be expanded through research programmes and enhanced funding as it is currently limited towards specific applications and technology.

2.5.1 Particulate Matter Control Technologies

This research is primarily focused on control technologies for PM. Various methods of dealing with PM pollutants have been developed depending on the application. As discussed previously the reduction in concentration of PM within the built environment and industrial processes would have a significant effect on improving the health of human beings and reducing the carbon footprint of the built environment. Filtration systems are the most prevalent method in industry for the removal of PM, but these effect the energy consumption of both fans and pumps and is discussed further in the next section.

Electrostatic precipitators (ESP) are another method which produces high particle collection efficiencies. In particular this method is very effective with particles smaller than $< 10 \mu\text{m}$. ESP devices charge particles with ions that are collected by media during transport through an electrical field as the particles are attracted by a charge differential within the media [101]. There are two methods for charging the particles, diffusion and field charging. Field charging employs an external electrical field that increases motion of the ions and subsequently increasing the rate of collisions which transfer the charge to the particles. Diffusion charging is independent of the electrical field and particles become charged due to random collisions caused by Brownian motion [101,102].

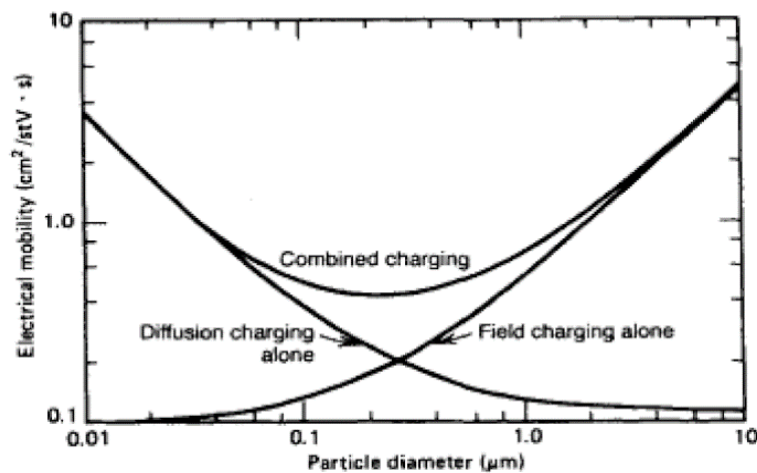


Figure 10. Electrical Mobility vs particle charging methods [92].

Sharma et al. [101] found that the ESP collection efficiency range for particles between 30 nm and $2.5 \mu\text{m}$ was between 25-75% and a maximum of 60-70% for a sub-particle range of 0.2-0.8 μm . Field charging is extremely efficient at removing PM $> 1 \mu\text{m}$ [103] while diffusion charging is dominant for PM $< 0.2 \mu\text{m}$ with a combination filtering the range in

between [104], as shown in Figure 10. This method produces a universally low pressure drop independent of collection time, low electrical consumption, high removal efficiencies and collection of high particle concentrations [101–103]. These devices suffer from particle re-entrainment due to shocking, high capital costs and space requirements [105].

Inertial collectors remove PM based upon gravitational, inertial and centrifugal forces. Dust is removed from the flue gas using the particles inertia [106], centrifugal forces trap the dust against the wall and it falls into a dust hopper by gravity. The removal efficiency of this process reduces with decreasing particle size [107]. Wet collector's (Scrubbers) are also used to remove PM from gas streams. The gas stream passes through liquid droplets which removes the PM by inertial impaction, Brownian diffusion, hygroscopic growth of the particles, and direct interception which are then removed from a wet collection surface [108]. Another collector variation is the dry scrubber's which are also used to remove harmful substances by spraying a dry reagent into gas stream to remove PM [109].

2.6 AIR FILTRATION

Air filtration as stated has a significant effect on a typical buildings energy consumption and the type of filter installed influences the level of consumption; finer filters consume more energy due to greater pressure drops [110,111]. Depending on the type of building and stipulated air cleanliness, various filter classifications exist relative to the size of the PM to be removed. There are several standards for filter classification but ISO 16890 is the current European standard [112] and ASHRAE 52.2 its American equivalent [113]. Due to the increase in efficiencies among finer filters, ISO 16890 was developed to supersede EN 779:2012. Filters were originally classified under EN779:2012 in Europe as coarse, medium and fine with similar ranges to ASHRAE 52.2. The new ISO system analyses the filter efficiencies under four classes; coarse, ePM₁₀, ePM_{2.5} and ePM₁. The filters are defined based upon the diameter range of the PM and their corresponding efficiency rates at removing said particles as shown in Table 2 [112]:

- ePM₁ ($0.3 \leq x \leq 1 \mu\text{m}$)
- ePM_{2.5} ($0.3 \leq x \leq 2.5 \mu\text{m}$)
- ePM₁₀ ($0.3 \leq x \leq 10 \mu\text{m}$)
- Coarse ($x > 10 \mu\text{m}$)

Filtration technology in HVAC systems often adopts a two-stage approach to improve IAQ by using a coarse panel filter and a fine bag fabric filter that removes particles with diameters greater than 10 μm and less than 10 μm , respectively [114]. Typically, coarse filters tend to be panel pleat prefilters with ePM₁₀ in use as either a panel prefilter or a bag filter. The ePM_{2.5} and ePM₁ range are fabric bag or various types of HEPA and ULPA filters. HEPA and ULPA filters tend to be used by pharmaceuticals, hospitals, and chip manufacturers within the fresh air delivery into a clean room. The HEPA filters have filtration efficiencies of 99.97% for airborne PM when measured at minimum particle size of 0.3 μm and for bioaerosols [115,116]. Fabric filtration incurs an initial pressure drop, and when the pressure increases by 300 pascals (Pa), a saturation point of particle loading occurs and the filter requires immediate replacement [117]. Typically, manufacturers guidelines recommend replacement before the saturation limit is reached due to the exponential relationship between the pressure drop and filter loading.

Table 2. Filter groups classifications [112].

Group	Requirement			Relevant value
	ePM ₁ , min	ePM _{2.5} , min	ePM ₁₀	
ISO Coarse	-	-	$\geq 50\%$	Initial grav arrestance
ISO ePM ₁₀	-	-	$\geq 50\%$	ePM ₁₀
ISO ePM _{2.5}	-	$\geq 50\%$	-	ePM _{2.5}
ISO ePM ₁	$\geq 50\%$	-	-	ePM ₁

2.6.1 Particulate Matter Filtration Mechanisms

The various methods discussed for removing particles from gas streams were; filtration, scrubbers, cyclones and electrostatics, but fibre filtration media is most commonly used in HVAC systems. The filtration method uses fibre patterns that are arranged so that the pores between the fibres are significantly larger than the targeted particle size. Riefler et al. [118] found that the condition of the filter (i.e., loaded, unloaded and aged) had a serious effect on the filtration efficiencies as the pore surface area is reduced and/or degraded. The filter efficiency, also known as the dust spot filter efficiency as shown in Table 2 relates to the minimum removal percentage of the specified particle diameter range [119]. Arrestance which is measured in weight and used to analyse the overall dust removal from the atmosphere. Larger diameter particles weigh more (i.e., assuming equivalent densities) and prefilters are used for removal of particle $>10 \mu\text{m}$ and fabric filters for $<10 \mu\text{m}$ [112].

Depending on the particle size, various mechanisms exist which causes a particle to strike the filters fibres. Larger particles that are $>10\text{ }\mu\text{m}$ are dominated by gravitational, direct impaction and interception. A particles probability of hitting the fibre is higher as the aerodynamic diameter size increases. For direct impaction the particle size is greater than the pore size and smaller for interception conditions [120]. Inertial impaction is dominant from $0.5\text{--}10\text{ }\mu\text{m}$ where higher density particles cannot follow the curved airflows within the filter and is deposited on the fibre [121] as shown in Figure 11b. The filtration efficiency for both the inertial and interception mechanisms reduce with decreasing particle sizes and increasing velocities. Conversely diffusion filtration efficiencies increase with decreasing particle sizes and velocity [122,123]. This occurs from the phenomena known as Brownian motion, the particles oscillate due to irregular motions from thermal movement.

The most penetrating particles size (MPPS) occur between $0.1\text{--}0.3\text{ }\mu\text{m}$ when analysing all the mechanisms holistically as shown in Figure 11a. No mechanisms dominate within this range [121] and the overall filter removal efficiency tends to be at its minimum. The MPPS range and its maxima can change depending on the current state of the filters. Jung et al. [124] demonstrated that MPPS decreases as flow increases and is strongly affected by the quantity of particles deposited over time. Consequently this also increased the minimum collection efficiency due to a reduction in pore size [124]. The final mechanism involves electrostatic interaction where positively charged filter media are used to polarise the particles to attract them to the filter media. This is an induced mechanism and does not occur naturally in filters in comparison to the other mechanisms described [19].

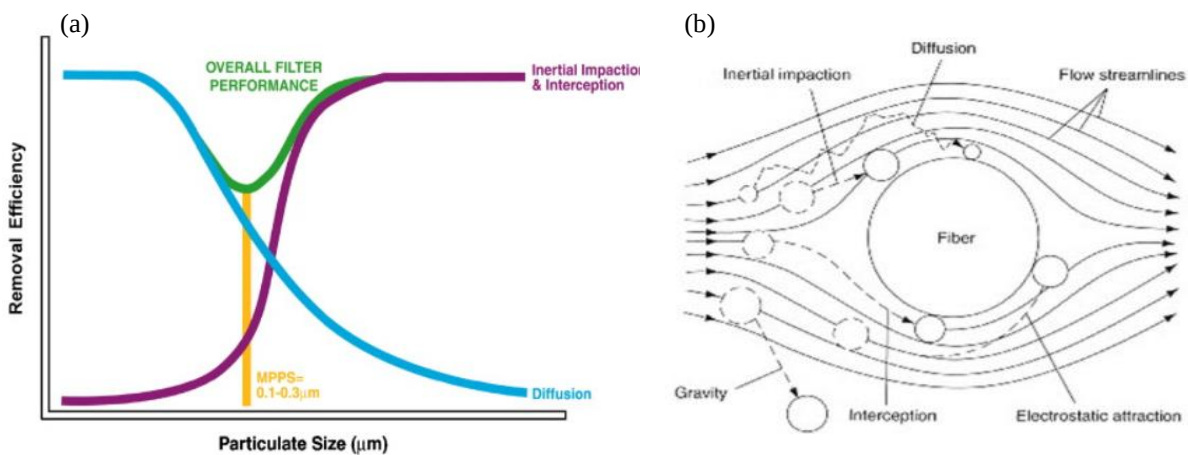


Figure 11. (a) Particle capture methods efficiencies [121] (b) Particle separation physics diagram [125].

2.6.2 Energy Consumption of a Filter

Depending on the filter used, the pressure drop will be relative to the type of filter and the filtration efficiency. Generally, air quality requirements will typically dictate the filter type and consequently effect the operating efficiency of the HVAC systems. Fabric bag filters which are the prevalent method for filtering fine particles from the ambient air and are sized based upon the diameter of the PM that is required to be controlled in the ventilation system in order to achieve the desired IAQ. Various factors in the ventilation system effect efficiencies including ventilation flow rates, fan motor efficiency, filter type, and increasing pressure drop due to filter particle saturation as shown in Figure 12 [126,127].

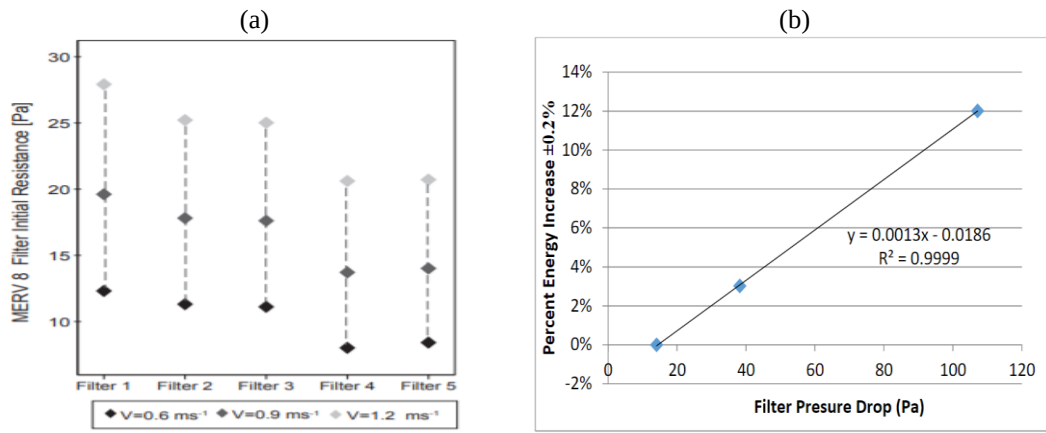


Figure 12. (a) Initial resistance vs filter face velocities [114] (b) Instantaneous energy increase across a fouled filter [126].

Thomas et al. [127] also found increasing the PM accumulation on the filter caused the pressure drop to rise and the filter fibres went through a process known as caking. Montgomery et al. [128] calculated the cost associated with increasing the pressure drop over time until saturation occurs and found a significant increase in operational costs over time. The filters pressure drop relationship with the yearly energy consumption (W) is associated with the increased loading and W is evaluated as a function of the volume flow rate (q_v), operation time (t), fan efficiency (η) and the average pressure drop $\overline{\Delta p}$ across the filter. This is expressed in Eq. (1) as:

$$W = \frac{(q_v)(\overline{\Delta p})(t)}{(\eta)1000} \quad (1)$$

The average pressure drop is determined by analysing the pressure drop at various intervals until saturation of the filter is achieved [129]. The mathematical method that generates 4th order polynomial expression is used to evaluate the pressure drop but depending on the curve other mathematical methods may be applied:

$$\Delta p = a.m^4 + b.m^3 + c.m^2 + d.m + \Delta p_i \quad (2)$$

Where a, b, c and d are the curve fit coefficients and Δp_i is the initial pressure drop before dust loading occurs. The average pressure drop ($\overline{\Delta p}$) is evaluated by the integration of Eq. (2) that was generated from the curve fit data and is expressed as:

$$\overline{\Delta p} = \frac{1}{m_x} \int_0^{m_x} \Delta p(m).dm = \frac{1}{5}a.m_x^4 + \frac{1}{4}b.m_x^3 + \frac{1}{3}c.m_x^2 + \frac{1}{2}d.m_x + \Delta p_i \quad (3)$$

Where m_x is equal to the amount of dust required to replicate the effects of annual loading on the filter, this quantity varies depending on the type of filter used. The ventilated air velocity of the system also has a significant impact on the pressure drop, as shown in Figure 12a. Zaatari et al. [114] found a rise in the filter face velocity increases the resistance regardless of the filter efficiency and Li et al. [130] also demonstrated a linear relationship between the face velocity and the pressure drop. There are various filter design variables that effect the pressure drop and collection efficiency such as the fibre diameter, arrangement, filter thickness, porosity, air permeability and packing density [131].

Significant changes in the pressure drop associated with the filters will impact the fan operating efficiency which is dictated by its characteristic curve and duty point. Lanzerstorfer [132] investigated the effects of pressure drop variations and conducted a comparative cost analysis between design and operating configurations which is influenced by the fans operating efficiency. It was found that control of the pressure drop and using variable speed drives provided significant savings. Varying the pressure drop for an uncontrolled system caused the efficiency of the fan to change as it was not operating on its optimum corresponding design performance curve [132]. The various issues associated with the method of filtration and their maintenance demonstrates the need for a new approach regarding HVAC pollution control devices.

2.7 ASPIRATION EFFICIENCY THEORY

Aspiration efficiency is the measure of the ratio of concentration of the particles in the cross sectional area of the inlet of an orifice C to the concentration present in the undisturbed ambient air upstream C_0 [133]. This ratio determines the efficiency with which particles are transported from the ambient environment into an orifice inlet. Inertial forces acting upon the particles prevent the particles from following the fluid streamlines which can prevent an AE of 100% which is most desirable for PM measurement devices. The ratio is expressed as:

$$AE = \frac{C}{C_0} \times 100 \quad (4)$$

Numerous studies have been conducted on the factors that influence the aspiration efficiency of PM sampling devices, both for thin and thick-walled probes. While thin and thick-walled probes were investigated initially, the same theory has been applied to analysing the aspiration associated with the human head. A velocity ratio, R , can be used to analyse the effects upon aspiration efficiency [134]. Sampling velocity U_S and freestream velocity U_0 effects are examined through a ratio that is given as:

$$R = \frac{U_0}{U_S} \quad (5)$$

Belyaev and Levin [134] investigated the effects of thick and thin walled cylinders on isokinetic sampling where isokinetic sampling has the following conditions: $U_0 = U_S$ and the angle between the nozzle inlet and the freestream air vectors is zero. The thickness of the walls have a significant effect on the sampling efficiency with thin walled probes preferable, thick walled probes are more sensitive to secondary aspiration [134–136]. Particles that are directly transported into an air pollution samplers or human nose and mouth without wall contact is known as primary aspiration. Whereas secondary aspiration occurs as the particles rebound off the surface and becomes re-entrained in the particle flow and/or through deposition [135]. Particles accumulate around the mouth and nose which become more populated as the wind speed increases [5,135]. Similarly, the air pollution samplers suffer from secondary aspiration depending upon the geometric design of the inlet face and body and especially under anisokinetic conditions [137]. Anisokinetic conditions are determined through R and the orientation of the inlet relative to the wind direction. Only when $R \neq 1$ and $\alpha \neq 0^\circ$ can the conditions be considered anisokinetic [137].

The thickness of the blunt nose can contribute to decreases in AE due to sampling losses. The larger the blunt body inlet surface area, the more particles that will rebound and not be sampled. Re-entrainment can also occur which will lead to errors in the sampling process. This implies that thick walled probes will be dominated by St and sampling accuracy compromised, while this effect is not as profound with thin walled probes [138]. The particles will also be deposited on the cylinder walls and face, decreasing the efficiency of the sampler due to the nozzle diameter and thickness which is influential on the process.

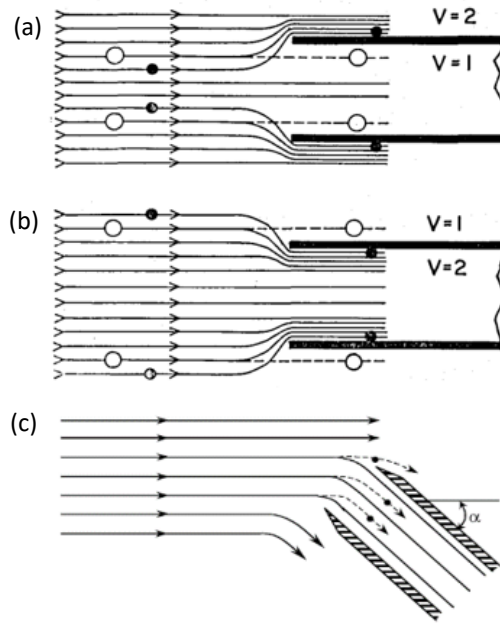


Figure 13. (a) Supersokinetic [139] (b) Subisokinetic [139] (c) Misalignment [140].

Performing isokinetic sampling is an extremely difficult condition to achieve due to the variability associated with both the freestream velocity and angle of attack relative to the nozzle entrance. As isokinetic sampling is generally unattainable, the samples are measured based upon anisokinetic conditions. The anisokinetic sampling criteria as shown in Figure 13 are misalignment of the sampler ($\alpha \neq 0^\circ$), supersokinetic ($U_s > U_0$) and subisokinetic ($U_0 > U_s$) states. Supersokinetic conditions generate AE efficiencies less than unity as the sampling velocity is higher than the freestream velocity which causes the flow to converge into the nozzle, particles with larger inertias will be lost [139]. Conversely subisokinetic conditions have sampling velocities less than the freestream velocities generating efficiencies greater than unity as the particles can be impacted into the nozzle leading to greater enrichment [139]. These conditions are governed by several factors: orifice velocity,

ambient wind speed, St , inertia impaction, nozzle geometry, ambient wind direction and gravitational settling [2,136,140–143].

The magnitude of the ambient and orifice sampling velocities has a significant effect on the AE. Furthermore, the angle of the ambient wind to the orifice inlet plane otherwise known as the yaw angle (α) can cause AE to increase or decrease depending on R . The literature shows larger yaw angles tends to decrease the AE with a constant R . AE was also found to increase at yaw angles of $0^\circ - 60^\circ$, as R increases. Conversely as R decreases at $\alpha \geq 90^\circ$, AE increases [2,3,141,142,144]. This can be seen for each yaw angle in Figure 14 for a thin walled probe. The sampling velocity was found to increase the acceleration near the orifice inlet which draws in a greater concentration of particles for rear facing probes. Further consideration of the ambient wind velocity shows that the proportionality with both St and Reynolds number (Re) impacts AE. This suggests that particles at higher velocities as a consequence have greater inertias and thinner boundary layers around the sampler. Wen and Ingham [142] demonstrated that a rear-facing (RF, $\alpha=180^\circ$) thin walled sampling probe under those conditions caused a reduction in particles sampled with increasing ambient speed. Tsai et al. [141] investigated the effect of orientation-averaged conditions and found that the AE remained relatively high with a coaxial forward-facing (FF, $\alpha=0^\circ$) conditions configuration but approached zero with perpendicular side facing orifice (SF, $\alpha=90^\circ$) and RF sampling [141,142].

The size of the particle also has a significant effect on the aspiration efficiency for a constant flow rate and nozzle size. Kenny et al. [145,146] investigated the effect of the AE with regards to the aerodynamic sample size through wind tunnel testing. The results demonstrated a reduction in AE with increasing aerodynamic diameter for various aerosol sampling instruments. Analogous to the air pollution sampler, Tao et al. [5] found that AE ranged from 110-170% for a moving manikin and as both the particle diameter and walking speed/freestream velocity increased, AE rose. Erdal and Esmen [4] found varying AE ranging from 5-110% for coarse particles measured in 25 μm intervals up to 200 μm for a human nose and mouth with varying freestream velocities at $\alpha=0^\circ$. Armbruster and Breuer [147] found variations in AE within the mouth and nose to be between 10% and 200% depending on orientation.

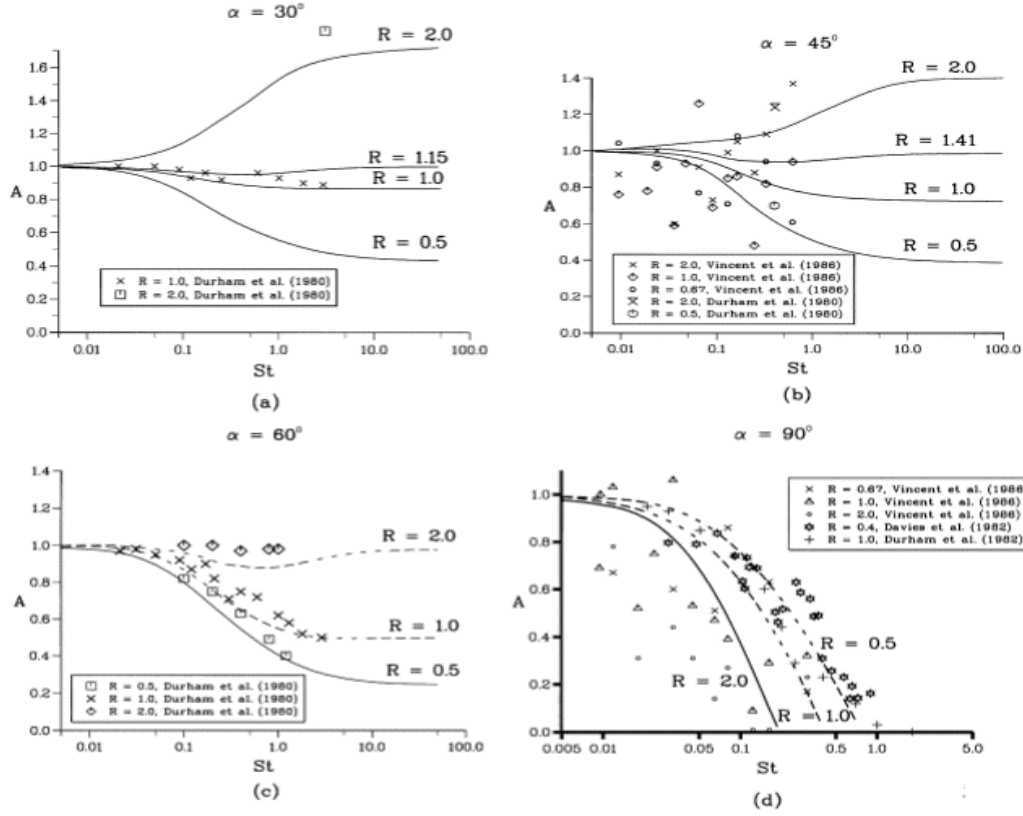


Figure 14. Variation of AE as a function of Stokes number and Velocity ratio at angles (a) 30° (b) 45° (c) 60° (d) 90° .

The aerodynamic diameter has a squared function relationship with St which means that small values (i.e., $St \ll 1$) have quick response times to the fluid flow and will follow the fluid streamlines. This is the basic principle of particle image velocimetry (PIV) where dye is injected into a fluid and acts as a passive scalar [148]. Conversely when $St \gg 1$, the effects of the turbulent fluctuations become negligible, and the particle inertia dominates. Wen and Ingham [3] also suggested that the St , R and α are intrinsically linked. Larger St have greater inertias which delay the particle reaction for converging flow, especially at greater yaw angles. AE was found to be a monotonic function of the St where AE increased when $R > 1/\cos \alpha$ and inversely the AE decreased for $R < 1/\cos \alpha$ as St increased. Although the AE decreases from unity when $R \cong 1/\cos \alpha$ but recovers after the St increases past unity [3]. Hangal and Willeke [144] found similar results for forward-facing (FF) sampling with regards to the effect on AE by R and St [144]. Both studies showed that as the St approached zero, AE approached 100% and for optimum sampling conditions the R required were highly dependent on the yaw angle for larger St . AE was found to deviate from unity at a greater rate with increasing yaw angles, at $\alpha=90^\circ$ increasing the St and R decreased the AE.

Dunnett and Vincent [138] found that the effect of gravity was negligible for the majority of conditions and should only be considered for low wind speeds of ≤ 0.1 m/s or particles greater than 50 μ m. The results showed that where the sampler was facing directly into the wind (FF), an AE of over 200% occurred as the St number increased. Although AE was found to decrease significantly as the angle between the inlet and ambient wind increased and the St number increased [138]. Furthermore, Grinshpun et al. [149] showed results which suggested that gravity had a similar effect on thin walled probes but with larger magnitudes of aspiration efficiencies. The thin walled probe also was compared directly with various blunt probes by Eddy et al. [150] and found decreasing AE efficiencies for increasing blunt probe wall thicknesses and decreasing the samplers inlet diameters.

2.8 HVAC ASPIRATION EFFICIENCY REDUCERS (AER)

It was proposed by McNabola et al. [6] that the aforementioned AE index could be used to reverse engineer a passive control device for a HVAC system. This device would be optimised to achieve AE that approached zero, in contrast to the desired 100% required of thin walled aerosol probes [6]. PM sampling probes and HVAC systems have inherent similarities but vastly differing scales. Both contain an inlet, transmission lines, a filter for PM collection, and forced ventilation. Two prototypes were developed on the basis of designing a device capable of restricting the ingress of PM concentrations into the ventilation system inlet. The initial AER prototype developed by McNabola et al. [6] was a 1:4 scaled prototype. This design incorporated an array of 58 blunt nose cylindrical orifices with a 25 mm diameter and monitored by a PM sampling probe using high flow pumps as shown in Figure 15a. The unit was supplied by a constant flow rate of approximately 1300 m³/hr which placed limitations on the quantity of inlets and the velocity within the blunt nosed inlets which was between 1 m/s [6].

This add on device to an AHU reduced the PM_{2.5} concentrations by approximately 50% and could result in significant energy savings. Notwithstanding, there are various configurations of add on rain hoods for AHU's installed in existing buildings but there has been no research published on the AE of such devices for comparison. The rainhoods mentioned previously were designed to prevent the ingress of rain droplets and therefore have not accounted for PM control using AE concepts. The suction velocity incurred by the rainhoods cross sectional orifice area and geometry design could have a profound impact on PM transport into a building ventilation system. Further comparative studies on novel AERs and

commercial rainhoods is required to determine the formers effectiveness at reducing PM concentrations within the ventilation system compared to the latter.

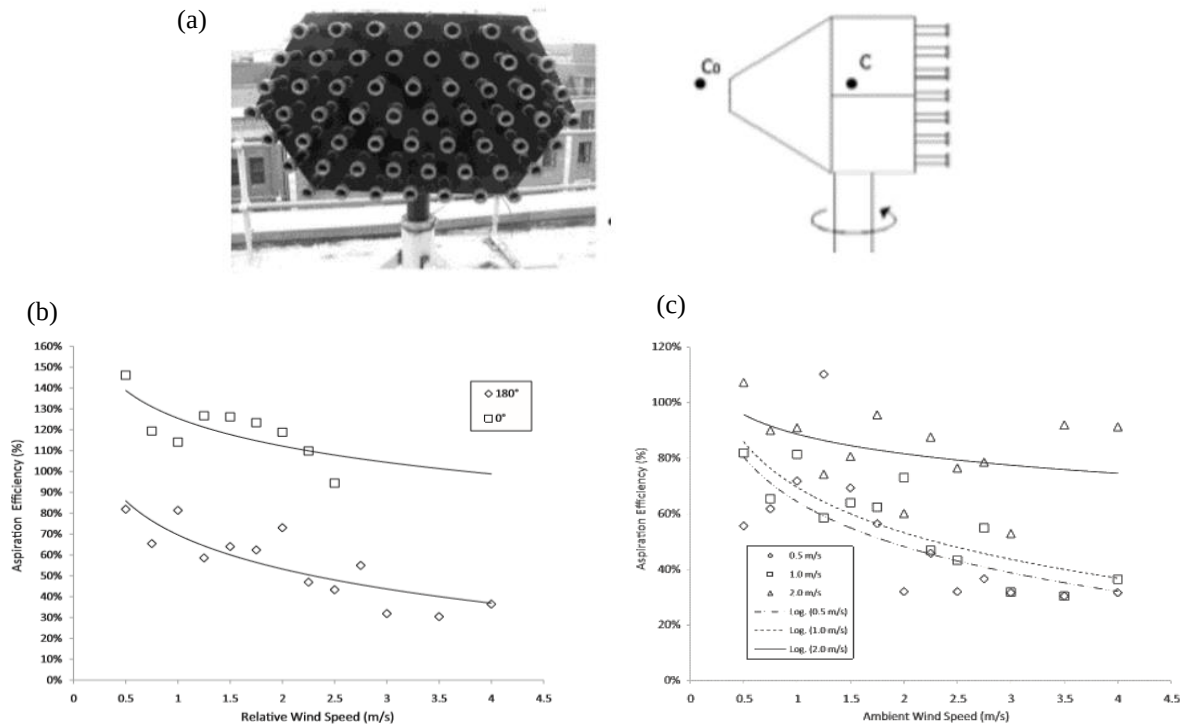


Figure 15. (a) Original 1:4 scale AER prototype with rotating frame [127] (b) Comparison of AE at opposite wind angles relative to the inlet (c) effect of ventilation velocity on AE [6].

The scaled AER inlet was designed to maintain an inlet orientation that was always opposite to the ambient airflow ($\alpha=180^\circ$) leading to lower AE. The relationship between the air pollution sampler probe's and orientation was discussed previously with 0° to achieve optimum AE conditions for a sampling device [141,142]. Therefore, this orientation and design would force the particles to reverse direction, and as particles with large inertias in theory would follow their initial streamline, these would be less likely to be diverted into the AHU inlet. The study confirmed, AE at 180° demonstrated a significant decrease in comparison to a 0° orientation for HVAC systems, and that the AE concept translated directly to this much larger physical scale. AE also decreased for both angles as the wind speed increased as shown in Figure 15b [6]. AE was also found to decrease with a reduction in ventilation velocity as shown in Figure 15c for a RF configuration. The results would suggest that an AER device would benefit from lower inlet ventilation velocities in the blunt nose section. Although it should be noted that research experiments have the advantage of positioning the units to the desired orientation. Commercially this may not be practically

achievable and further investigation into the effects on AE due to varying wind direction must be conducted.

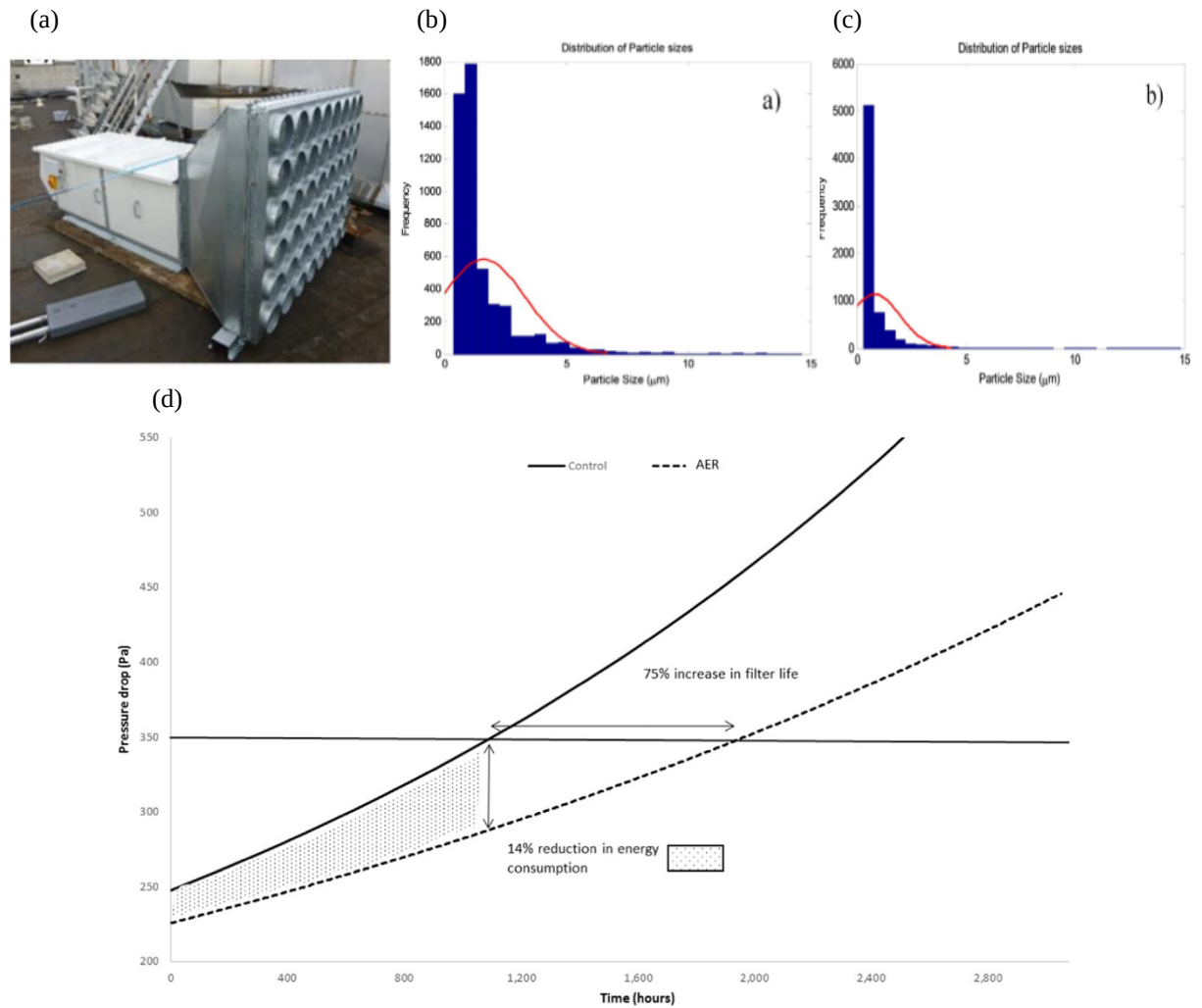


Figure 16. (a) Full-scale AER AHU (b) Control AHU particle size distributions (c) AHU with AER particle size distributions (d) Δp comparison between a control AHU with a commercial rainhood and an AER-AHU [162].

The second generation AER prototype was developed by Morgan et al. [151] as a full scale attachment for an AHU tested in the field as shown Figure 16a and incorporated 48 x 160 mm diameter orifices. This prototype was designed to limit the ventilation velocity at the orifice inlets to $< 1 \text{ m/s}$ at the maximum flow rate of $3400 \text{ m}^3/\text{hr}$. The original scaled device incorporated a rotating frame to maintain the 180° orientation with respect to the orientation of the ambient airflow. This was not incorporated into the full-scale design due to impracticality, and deviations from this angle could occur depending on the variable nature

of the wind direction, although there was no major deviation in the prevailing wind direction during testing [151].

Morgan et al. [151] also examined the particle distribution sizes of a control AHU and an identical AHU fitted with the full-scale AER device as shown in Figure 16b-c respectively. Results from the field test in Dublin City Centre showed the scaled and full-scale AER prototype both found that AER device was more effective at preventing larger particles from entering the device [6,151]. A similar trend was observed for the distribution curve of both AHUs but with different maxima and frequencies of particle diameters. Although the frequency of smaller particles typically found within the PM_{2.5} range for the control AHU far exceeded the AER configuration and there was also a greater abundance of larger diameter particles in the control AHU [151].

This indicates the AER device is effective at high St and will reduce the clogging effect on the filters, albeit depending on the type of filter installed. Where finer filters are used, the pressure drop is higher and optimisation of the AER device to also remove smaller particles would provide enhanced benefits, both financially and to human health. The results showed that the filter's used in this study achieved energy savings of between 14-20% and a 75% increase in the filter life as shown in Figure 16d [151]. The energy savings were achieved using a very low-cost passive intervention. The savings in electricity cost and CO₂ emissions the world over that could result from savings of this size are very large relative to the investment needed.

The experiment had some limitations in that the inlets were positioned facing into opposite directions, and only the ventilation system pressure was monitored instead of the individual filters. Hence the increase in pressure could be attributed to PM filter loading of either a fabric bag filter or the coarse panel filter or an equal combination of both. Another limitation occurs when considering differing flow rates which are dependent on the building ventilation demands. This prototype represents a small AHU and typically much larger flow rates, and AHU's, will be found in commercial buildings and therefore a further increase in the cross sectional area of the AER when maintaining the < 1 m/s design stipulation would be required. Even considering the small AHU in Morgan et al. [151], the AER prototype size was excessively large in comparison to the original AHU inlet due to achieving said velocities [151]. The physical scale of the AER device for larger AHU's would be an impracticable configuration in its current format. Therefore, future research should focus on

developing a prototype that is approximately of similar dimensions to the AHU's inlet in order to increase its practical feasibility while maintaining performance standards and the 14-20% energy savings.

The above literature on AER's describes areas and gaps relating to ventilation velocities in the AER device, issues pertaining to AER design, physical scale, wind speed and direction. The orifice geometry shape, size, quantity and interference between multiple inlets is poorly understood and their relationship with AE also requires further analysis. Further investigation must be conducted into limiting both larger and smaller particles ingress into the system. Moreover, the key variables within this process are poorly understood and determination of which factors are dominant must be ascertained in order to design a functioning PM control attachment for AHU's. Using a holistic approach to AER design could produce an attachment for PM control that will supersede the commercial rainhoods currently used throughout the world for HVAC systems.

2.9 WIND DYNAMICS AND TURBULENT FLOWS AROUND STRUCTURES

The previous section was concerned with the development of PM control technology for attachment to an AHU inlet but does not consider the dynamics of the surrounding environment and their effect on AE. The potential for further reduction in an AHUs filter loading rates can be achieved by optimum placement and orientation of an AHUs inlet on a building rooftop. Further investigations are required and must examine how building topographies, proximity to local sources and consideration of how the wind dynamics around a building impact AE. This section details previous studies on air flow around buildings, wind distribution, wind profiles, urban boundary layer and pollutant dispersion in both urban street canyons and building arrays. Contributing to the development of a wind-pollutant index for urban planning guidelines could result in lower building energy consumptions and improved IAQ when accounting for AE.

2.9.1 Wind Distribution and Profiles

Wind speed is highly variable both temporally and across geographical locations and also varies significantly depending on the seasons. Although the annual variations are difficult to model or predict, a Weibull distribution is generally used to model the variations in hourly wind speed per annum [152]. Sunderland et al. [153] investigated the wind energy potential

at accessible heights within Dublin city centre. In Figure 17a the research showed that an average wind speed of 3.64 m/s which was similar to a suburban analysis within Dublin but less than the average wind speed of 5.2 m/s at Dublin airport [153]. The Weibull distribution of each location had similar distributions but different maxima. It should also be noted the average wind speed increased to 4.31 m/s when comparing wind speeds in the prevailing wind direction (120-300°) which accounted for >80% of the data in Figure 17a.

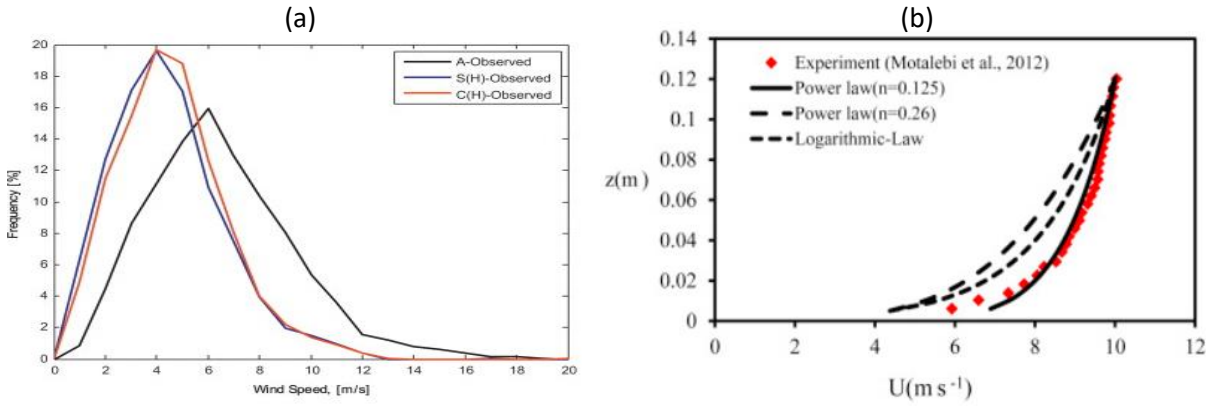


Figure 17. (a) Dublin City Centre Weibull distribution [153] (b) Comparison between velocity profiles. Note $n=\alpha_S$.

The variations in wind speed can be accounted for by analysing the surface topology and is characterised by surface length coefficients (Z_0). The coefficients for boundary layer analysis over various terrains and surface roughness are described in full by Davenport et al. [154]. The roughness lengths provide coefficients based on the shearing effect between the wind and surface irregularities that can be applied to obtain the logarithmic wind profile and subsequently calculate wind speeds at specific heights. The log wind profile can be determined using the following formula:

$$\bar{U}(Z) = \frac{u_*}{k_{vk}} \ln \left(\frac{Z-Z_d}{Z_0} \right) \quad (6)$$

Where u_* is the friction velocity which is obtained from empirical methods, k_{vk} is von Karman's constant (0.41), Z and Z_d are the height above ground and displacement height. The displacement height is the location where $U(Z)$ goes to zero [152,153]. Two simplified versions of Eq. (6) exist for calculating wind speeds at various heights and their profiles are shown in Figure 17 (b). The graph shows excellent agreement between the power law for $n = 0.125$ and the experimental results but both configurations are for smooth surfaces, hence

the close agreement [155,156]. The logarithmic-law and power law where $n = 0.26$ deviated from the experimental results due to both profiling methods being modelled relative to an urban environment and consequently a rougher surface [156]. The power law shown in Eq. (7) where α_s is an exponent that is empirically derived based upon surface topology. For neutral atmospheric conditions the log profile can be extrapolated using a simplified approach for Eq. (6) and is shown below in Eq. (8):

$$\bar{U}(Z) = U_{ref} \left(\frac{Z}{Z_{ref}} \right)^{\alpha_s} \quad (7)$$

$$\bar{U}(Z) = U_{ref} \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{ref}}{Z_0}\right)} \quad (8)$$

The turbulence kinetic energy (k) and dissipation (ε) profiles are also required to properly capture the wind effects in a large physical environment and are expressed as:

$$k_{in}(y) = (U_{in}(y) \times I_{in})^2 \quad (9)$$

$$\varepsilon_{in}(y) = \frac{C_u^{3/4} k_i^{3/2}}{k_{vk} y} \quad (10)$$

Where the (U_{ref}) is the reference velocity, I_{in} is the turbulence intensity and C_u is a constant whose values are 0.1 and 0.09 respectively.

2.9.2 Urban Boundary Layer

Various methods for modelling planetary boundary layers are important when analysing fluid flow around structures as the velocity profile will have a major influence on the building flow dynamics. The boundary layer can be described within an urban environment on three scales: the microscale, local scale and mesoscale. The microscale describes turbulent effects within the urban canopy layer (UCL) and roughness sublayer, this accounts for the buildings, trees roads, urban canyons etc. [157]. The local scale extends beyond the microscale and ignores the microscale effects and measures several kilometres from the ground. The local surface, its roughness and inertial boundary layer can be examined at this

scale [157]. The Mesoscale is used to analyse entire cities and incorporates both the planetary boundary layer and the urban boundary layer [157].

This study is concerned with the turbulent effects on the microscale as HVAC systems are generally located on the roof of a building and the wind dynamics will have an effect upon the operation of the AHU. Numerous studies have been conducted on fluid flow around buildings and particle deposition rates [156,158–161]. Oke [162] suggested three different flow patterns defined by their critical length spacing that dictate the microclimate; isolated roughness flow, wake interference flow and skimming flow.

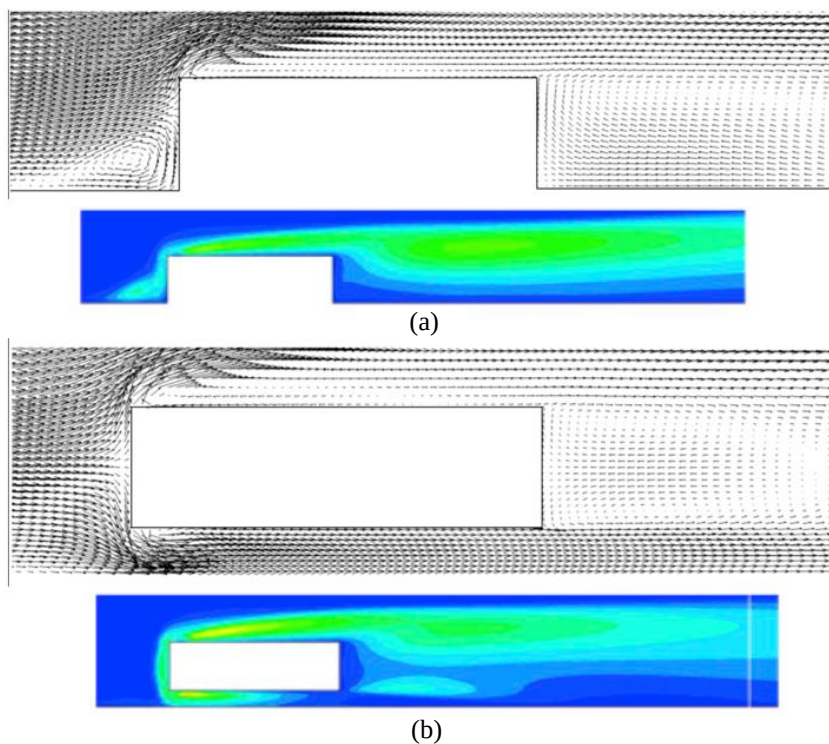


Figure 18. Fluid velocity vectors and TKE (a) Standard building (b) supported building [156].

Hunter et al. [163] suggested that as the flow transitioned from skimming to wake interference, double vortices on the leeside corners of the building occurred due to full formation and an increase in the fluid flow in the cross canyon direction. Hunter et al. [164] also suggested in a previous study that from a 2D elevation perspective, the skimming flow will contain a single vortex, while wake interference will have reversed flow in the lower canyon and parallel flow in the upper section. Isolated roughness flow has been shown in Figure 18 where an eddy forms in the wake but flow reattachment and forward flow occur. The above studies found eddies forming on the roofs and in the wake buildings, but the

dynamics of an urban canyon must also consider the spacing between the buildings for pollutant dispersion. Haghighifard et al. [156] investigated the effect of wind flow and particle dispersion around two inline buildings and a single isolated building. The study showed large eddies forming behind the buildings and is in agreement with a similar study of a single building by Liu and Ahmadi (2006) [160].

Both studies also showed that near the front of the building roof, smaller eddy formation was observed due to flow separation and resulted in significant particle build up, particularly for larger diameter particles. Xia and Leung [165] found large eddies forming in urban canopies behind each building with a 2D inline configuration of multiple buildings, and this significantly affected the pollution deposition rates upon the downstream buildings. An increase in mid to high-rise buildings and greater concentrations of fine particulate matter emissions from vehicular sources has worsened air quality conditions in urban settings [166]. Understanding air flow and pollutant dispersion in urban street canyons can help support the development of mitigation measures to protect urban populations. Research studies have improved our understanding of flow patterns within urban street canyons, and how this influences pollutant dispersion in urban environments [167–170].

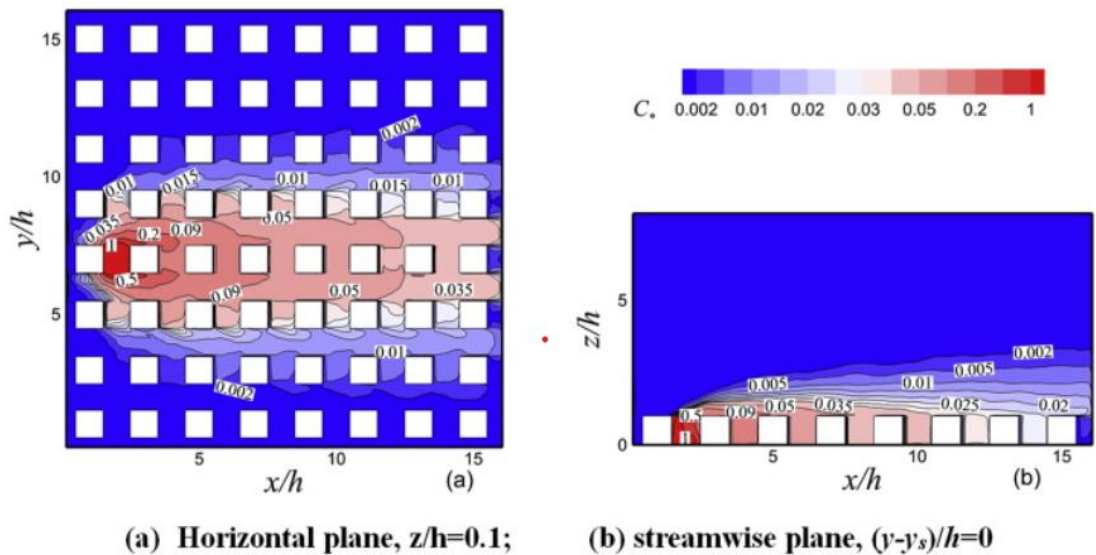


Figure 19. Distribution of pollutant concentration of skimming flow in non-staggered layout. [171].

Meroney et al. [168] expanded on the influence of the aspect ratio and their associated flow patterns by analysing how the pollutant is dispersed at street and roof levels, with Liu et al.

[172] identifying the highest level of pollutant removal occurring on the windward face from the urban canyon. This was due to boundary layer separation occurring at the roof/wall corner intersection of a street canyon directly increasing pollution levels on the windward building rooftop [172]. Expanding the domain from a single street canyon to a building array, Shen et al. [171] demonstrated a significant decrease in downwind pollutant concentrations occurs when increasing distance from the target pollutant source as shown in Figure 19. The closest downwind building to the pollution source experienced concentration levels a tenth of the street canyon on the rooftop at a non-dimensional value of 0.09 where continued pollutant dispersion further downstream at rooftop level results in concentration levels of 0.02. This understanding has led to researchers like Fan et al. [173] developing a street-air index based on wind velocity and pollutant concentrations that informs urban planners on how to maintain optimal air quality and wind comfort within street canyon environments. Therefore, an investigation into the location of a ventilation inlet on a rooftop is required in order to determine the most efficient guidelines for AHU installation based on the surrounding urban environment.

2.9.3 Passive Ventilation

Passive ventilation is a method of supplying and removing air for indoor environments without the use of a mechanical system such as HVAC technology. Two systems have been developed to provide acceptable IAQ and comfortable thermal conditions for the building occupants, wind driven and buoyancy ventilation. The former is based on pressure differences observed on the windward wall compared to the leeward wall and is the main factor for driving airflow within the building [174]. The latter method uses the difference in temperature between the indoor and outdoor environment and the so called stack effect to induce buoyancy driven airflow [175]. Numerous studies have focused on developing passive ventilation methods such as single sided [176], cross ventilation [177], stack [178] and windcatchers [179] as shown in Figure 20 in order to remove the necessity of a HVAC system. Furthermore, the application of each passive ventilation can be achieved through a myriad of designs founded on window design, louvre designs, traditional and double skinned façade wind towers, exhaust cowls, wing walls and atria/courtyards. However, HVAC systems are preferred in mid to high-rise buildings as passive methods are not effective in these densely populated urban city settings. Passive methods only work effectively as a hybrid solution, and thus HVAC systems are still widely used for ventilating buildings [178].

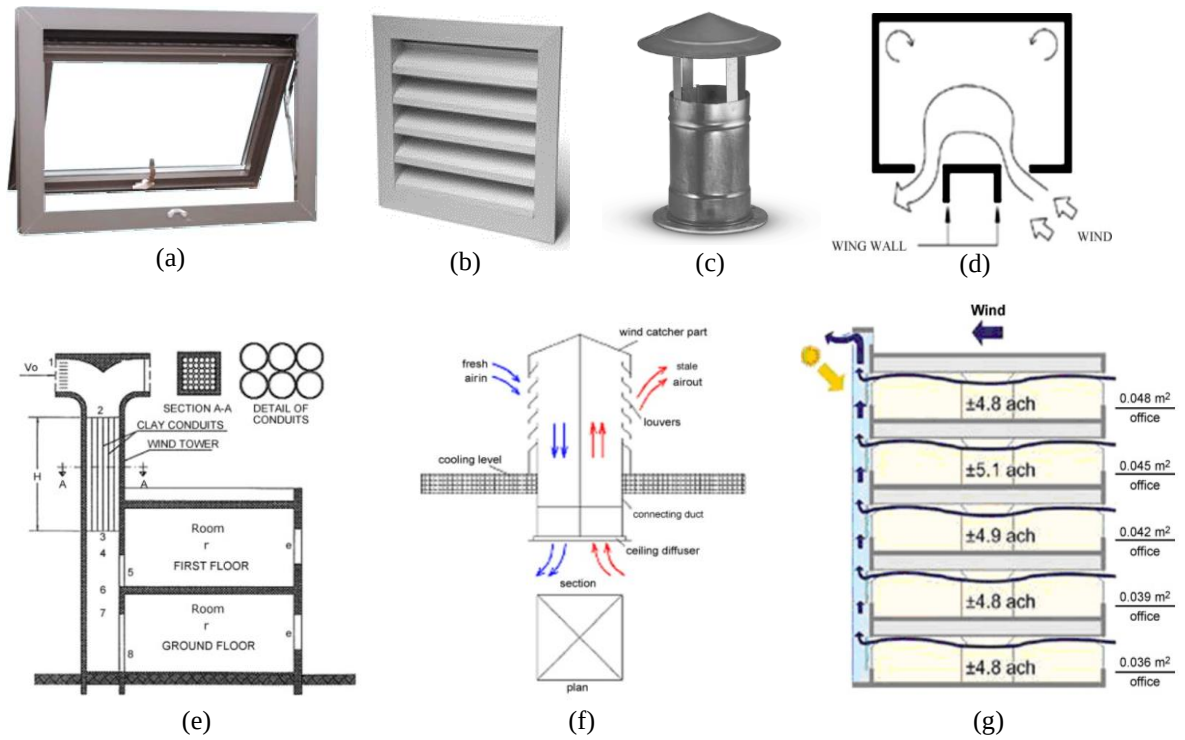


Figure 20. (a) Conventional window (b) louver vent (c) exhaust cowl (d) wing walls (e) wind tower (f) wind catcher (g) double skinned façade wind towers [174].

2.10 SUMMARY

The literature that was examined demonstrated the issues that are currently facing modern society and their potential solutions. Air quality was shown to be of particular importance to both the environment and human health. As the building sector has been shown to be one of the largest consumers of energy, it is vital that the development of innovative greener technology is pursued with the goal of developing net zero energy buildings. HVAC systems were identified as the leading contributor to emissions and energy consumption within the built environment. The various components for improving IAQ generate a resistance to the air flow, increasing the ventilation systems energy consumption. Specifically, the filtration system becomes clogged with PM over time and leads to an increase in the energy consumption of the AHU fan for a VAV system or reduced air flow rates for a CAV system. Building management systems monitor the condition of the building during real time and a reduction in CO₂ and PM in the indoor micro-environment is necessary to protect the occupant's health. New commercial and industrial buildings are generally applying for green certification awards that demonstrate the carbon footprint of the building and its eco-friendliness.

Various PM control technologies are available on the market, but filtration systems are the most prevalent method in the HVAC industry. The filter classification systems are based upon the removal of PM of a specific size range, albeit the cleanliness of the air required will dictate the magnitude of the pressure drop and consequently the energy consumption. The PM loading upon the filter also affects the fans operating efficiency due to changes in the system pressure. A fan is designed to work at a specific flow rate and operating pressure that maximises the efficiency of a fan, deviations from this duty point will affect the efficiency of the system.

The prevention of the PM reaching the filter is the key research output of this project. Previous studies have been conducted on producing a device that works on the reverse engineering of ventilation inlets AE based on prior knowledge from personal air pollution sampling devices. Personal air pollution sampling devices aim to achieve an AE of 100% and this signifies that the concentration sampled in the device is equivalent to the PM in the ambient air. However, this is not practically achievable in real world sampling. Numerous studies have been conducted on examining the effect of the sampling devices flow rates, wind speeds, wind direction, orifice designs and gravitational effects with the hopes of developing the most efficient sampling device possible. Previous research papers have suggested that the AER device is influenced by the same design and environmental variables as the air pollution sampling devices but is designed to work in a converse manner. Only two studies have been published on AER devices and found the following gaps in the literature which concerns the motivations for this project:

- AHUs have been used for decades as a means for delivering large volumes of either cooled or heated air to a building's occupants. In recent times more attention is being drawn to the IAQ due to the identified health impacts of air pollution and energy cost of treating the ambient air at the fresh air intake. There has been no research conducted on typical AHU inlets commercial rainhoods with regards to their AE as all inlets have a specific AE even when not considered in their design. Quantification of the efficiency of these devices is required to establish the baseline AE of existing HVAC systems against which improvements could be achieved (i.e., lowering their AE using an AER).
- This project will also focus on expanding the literature on the variables that may affect AER device design in the HVAC domain and use this to subsequently design novel AER's. Previous studies on AER devices maintained a 180-degree orientation

relative to the wind direction but achieving this with existing AHU's that will be retrofitted with the AER device is impractical. CFD provides an excellent platform for the alteration of the AHU inlet and the effect this will have on AE. Previous studies examined the effects of wind speed and found increasing the wind velocity decreased the AE for the RF AER. Although the original prototype developed by McNabola et al. [6] was mounted off the ground and the design has changed significantly in the follow up paper by Morgan et al. [151]. The ambient particle laden air was capable of flowing both under and over the device of the former, but this is unlikely to occur with a large full-scale AHU on a building rooftop. This will change the flow dynamics at the AHU inlet due to flow separation and modelling the flow patterns is essential to understanding the process and flow patterns at the interface between the ambient environment and the indoor microenvironment. Additionally, the impact of the added influence of the ventilation system inlet intake and its effect on the boundary layer around the AHU requires analysis.

- There is also a lack of information when examining the inlet hoods and AER device in its current configuration efficiency at removing particle of different sizes. Further investigation must also be conducted into the effect of St upon the AE and in particular a holistic approach when considering the particle diameter, ventilation velocity and AER design as they are inherently linked to particle inertia and St . There also appears to be a dearth of knowledge regarding the design variables and varying St associated with an AER device. There could also be an interdependency on particle distributions and the design variables which effects AE. Areas to be studied include the size of the orifices, array configuration, number of orifices and the orientation of the device relative to the ground and wind.
- Section 2.9 detailed the wind dynamics associated with building geometry and urban environment flow patterns and pollutant dispersion. There are currently no studies conducted on the effect of boundary layer separation of the particle laden ambient wind on a building rooftop and the impact on AE with changing orientation and/or location of the AHU upon the roof. This could have a major effect on AE and is a significant gap in knowledge with regards to HVAC systems. Previous sub-sections described the varying particle distributions depending on geographical locations due to their environment and climate. The effects of different particle distributions in the form of $PM_{2.5}$ are poorly understood and have not been addressed in previous AER studies.

- The pressure drop across both a fabric bag filter and a panel filter in a two-stage HVAC filtration system requires monitoring and comparison between AERs and rainhoods in a field test environment. The past study on the full-scale AHU only monitored the system pressure and further quantification on which filter drove the system change in pressure is required. Moreover, analysing both filters and their importance will inform future AER designs as this will allude to the particle diameters that are dominate in the driving up the energy consumption. That is to say, if the panel filter has a much larger increase in Δp than the bag, it could be inferred based on their manufactured filtration efficiency, which sized particle should be considered when designing AERs.
- Air pollution is a worldwide problem, but the formation of PM and chemical composition varies from region to region. The literature review detailed the potential issues that need to be considered when designing a passive PM control device. The varying chemical compositions due to regional variations can affect the density, shape, distribution and aerodynamic size of the particles. Understanding the geometry, weather patterns, seasonal changes and the types of sources near polluted areas is vital when assessing validity of the devices efficiency at removing PM. Furthermore, this suggests that field tests will need to be conducted in multiple locations with varying PM distribution curves, climates and their associated environments. For example, a desert region with regular sandstorms such as Egypt or areas prone to wildfires including California or Australia.
- Finally, the literature review identified the means and scope to expand knowledge on low carbon and cost PM control technology for HVAC systems in buildings. The project will seek to achieve prior or better of the aforementioned prior AER performance results while reducing the scale of the AER device and consequently the attachments footprint. Additionally combining novel AER technology with best practice installation for optimum AHU placement on building rooftops in heavily polluted areas will produce a solution that could be rolled out on a practical level to achieve large impacts in building energy and CO₂ savings. Thus, contributing to the development of greener existing and new builds throughout the world using AE concepts.

3 METHODOLOGY

3.1 RESEARCH METHODOLOGY

A plan was constructed post literature review to develop the overall methodologies required for achieving a reduction in a building HVAC system's energy consumption and development of low carbon PM control technology. The research methodology was designed to enhance AE and building science literature through a number of work components using market analysis, technological assessments for AHU infrastructure, parametric methods for prototype testing, numerical modelling, real world demonstrations and energy and economic evaluations. A guide to the project's workflow is presented below in Figure 21 and outlines the step-by-step process describing sub tasks and work involved for each stage.

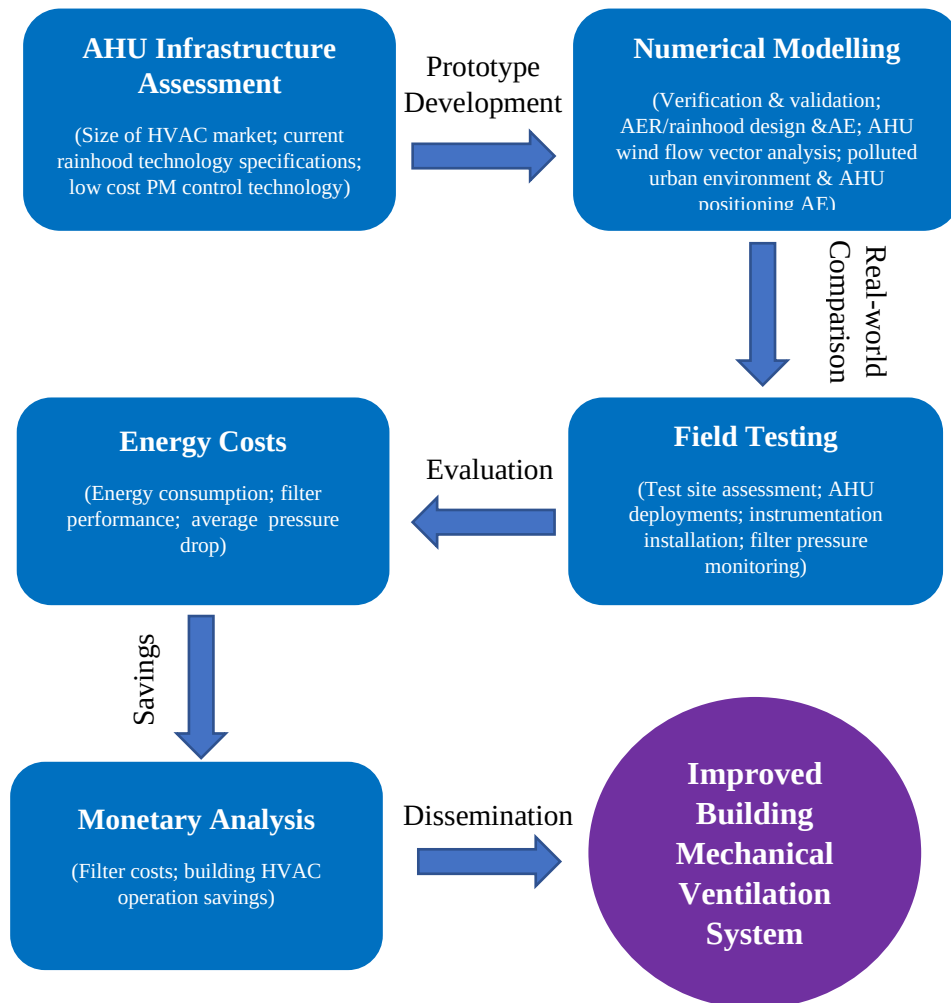


Figure 21. Workflow chart for development of low carbon PM control technology for building ventilation systems.

3.1.1 AHU Infrastructure Assessment

A market assessment for the HVAC industry in Ireland was undertaken at the project start. The purpose of the assessment was to quantify the potential market for low cost and carbon PM control technology for AHUs and requirements for disruptive technology that could improve a buildings carbon footprint. The market survey used to collect information on the market size and evaluation of current rainhood technology can be seen in the Appendix. A survey was performed with targeted questions on annual AHU sales and AHU design specifications in order to meet the target market's demands. In addition, AHU rainhoods designs were acquired from a prominent Irish HVAC equipment manufacturer and provider during site visits and used for the initial numerical modelling.

3.1.2 Numerical modelling

Initially, the numerical models used in the CFD process require validation against experimental results to confirm the model's accuracy at capturing the conditions and processes of a physical environment. Following this, commonly used AHU rainhoods were replicated using CAD software and modelled with CFD software as field experiments are time consuming and provide no information on the wind flow dynamics. Particle laden wind flow was simulated around an AHU in order to determine their AE regardless of the fact rainhoods were designed without considering AE concepts. Baseline AE trends were developed by exploring the variation in AE with changing ventilation flow rates, wind speeds, wind direction and particle diameter. Following this modelling stage, CAD prototypes of AERs were created for a similar parametric CFD analysis. The prototypes were designed to prevent particle laden wind flowing directly into the AER orifices and compared and contrasted with the numerical rainhood model's results. Finally, the previous studies focused on design characteristics and reduction in an AERs AE relative to the rainhoods AE at essentially a design scale. Further numerical models were developed of a full urban environment and the influence of local PM sources have upon an AHUs proximity and orientation to the prevailing wind direction. The numerical modelling required a step-by-step approach that first quantified the state of the industry through an AE of analysis of rainhoods and then focussed on the developing low carbon PM control technology alternatives, followed by a full urban environment analysis.

3.1.3 Field Testing

A site survey was conducted for AHU deployments for testing. The Simon Perry building was chosen for ease of access and proximity to Pearse Street which is subjected to heavy traffic volumes in an urban area. Two AHUs were installed on the building's rooftop, a control AHU and an AHU with the novel AER prototypes developed during the numerical modelling. Fabric bag filters and coarse panel filters were placed within the AHUs and a differential pressure sensor was used to measure the differences in pressure increases due to filter loading. The pressure trends were analysed over a set period of time coinciding with filter saturation. Results between the AERs and the rainhoods filters were determined and compared to assess the viability of the former as a low carbon PM control attachment for an AHU.

3.1.4 Energy and Economic analysis

Finally, energy and the economic costs were evaluated to ascertain the efficiency of each AER compared to rainhoods. The energy consumption of each AHU inlet attachment was calculated based on ambient PM concentrations adjusted using their respective AE. A characteristic curve based on the relationship between the pressure drop and PM loading rate from a filter manufacture was used to analyse potential energy savings and quantified based on the standard rate of electricity usage in Ireland.

3.2 COMPUTATIONAL FLUID DYNAMICS

3.2.1 History and evolution of CFD practices

In the late 19th and early 20th century extensive research was conducted into creating mathematical formulations that describe fluid flow, boundary layer theory, conservation laws and turbulence modelling. The first tests conducted used simple structured grids that employed a discretisation technique for partial differential equations known as finite difference method (FDM). This method examines the difference between variables in a defined region within the model. Models had been developed for the testing of weather patterns using FDM but were incapable of being solved due to the large-scale computational requirements that did not exist in the mid-20th century. The earliest success occurred with a numerical model of flow over a cylinder and subsequently confirmed with the use of a mechanical calculator for flow over a cylinder by Kawaguti [180]. It wasn't until NASA

started development of numerical codes in their Los Alamos laboratory through the 60's that CFD as a concept and tool really began to form.

CFD was expanded and developed in its current format for the purpose of analysing fluid flow problems related to the aviation industry in the early 1970's. Imperial College London pioneered the k - ϵ turbulence model and the SIMPLE algorithm. The numerical models were developed using Navier-Stokes equations which describe single phase fluid flow for a gas or liquid. Typically, the first numerical models were 2D to allow simplifications of the Navier-Stokes equations. Further simplification involved neglecting the viscosity terms to yield the Euler equations, followed by removal of vorticity terms which lead to non-linear full potential equations [181]. As CFD is intrinsically linked to the computational resources, advances in CFD techniques have typically occurred with increasing computational power. 3D modelling of the Euler equations occurred in 1980's and the scientific community then focused on the development of numerous turbulence models of differing complexity and accuracy, albeit requiring ever increasing computational resources [181]. Due to the geometric complexity of the models now being tested, further advancements in the grid generation methods were required. This led first to the development of multiblock approaches for more complex geometry and subsequently the creation of the finite volume method (FVM) where the variables are assessed in their discretised integral forms over a predefined space and is essentially based on conservation laws [181].

From the development of the various turbulence models, discretisation techniques and grid generation and advancements in computational power, CFD has become critical in the design and analysis of numerous engineering advancements over the past 40 years. Initially Reynolds averaged Navier-Stokes (RANS) turbulence model were prevalent in the 90's and 00's but both Large Eddy Simulation (LES) and Direct numerical Simulation (DNS) has become more prominent in the last decade. Also, various models have been developed for the modelling of solid particles in a Lagrangian reference frame while coupled to a fluid Eulerian model. Both species and multiphase model have also been developed in a Eulerian-Eulerian reference frames where several gases and/or fluids can be modelled depending on the nature of the problem.

3.2.2 Turbulence modelling

Turbulence is a phenomenon that has random fluctuations within the mean flow caused by excessive kinetic energy. The viscous effects that dominate laminar flow are reduced and the effect of inertia becomes more dominant generating vortices and inherent randomness in the system. The Re formula in Eq. (30) describes this effect in dimensionless form through the ratio of inertial forces to viscous forces. The mean velocity and pressure at a single fixed point within turbulent flow does not remain constant but fluctuates and is by nature, transient [182]. Large eddies are dominated by inertial forces and the effect of viscous forces are negligible as their characteristics are dictated by the geometry and mean flow. Therefore angular momentum is conserved as the large eddy can be considered inviscid during vortex shredding [182,183]. The shearing flow within the fluid domain will cause the eddies to distort but due to the inviscid property assumption, the eddy rotation rate and radius will increase and decrease respectively.

This causes the phenomenon known as energy cascading shown in Figure 22 whereby the stretching of the larger eddies influences the stretching of the smaller eddies causing kinetic energy transfer. As the eddies get progressively smaller, Kolmogorov theorised that the large eddies which are anisotropic will become isotropic as they reduce in size.

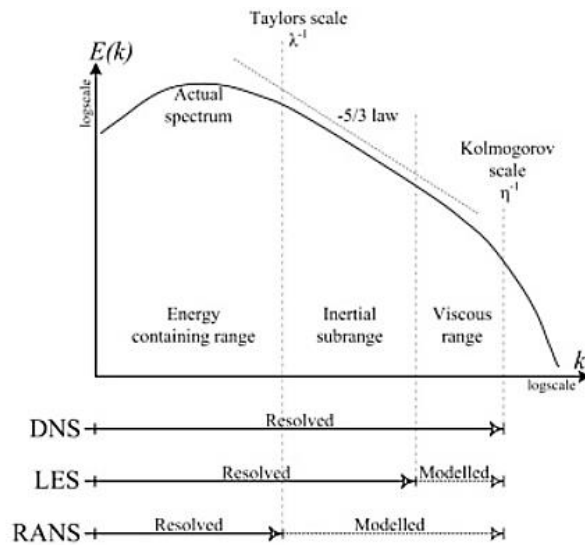


Figure 22. Energy cascade of turbulent flow [184].

Therefore, at this scale, eddies are only dependent on the kinetic energy and dissipation rates. This is known the Kolmogorov microscales where the turbulence is homogenous and viscous forces through dissipation converts the small eddies from kinetic energy to heat energy

[185,186]. The eddies of a specific size contained between the large eddies are dominated by the integral scales and the smaller isotropic eddies dissipating are known as the inertial subrange. The rate of energy transfer from kinetic energy of the larger eddies to the smaller dissipating eddies in the inertial sub range remains constant, hence they are in equilibrium with a constant slope of $-5/3$ [198].

The choice of turbulence model for numerical simulations is problem specific and will largely depend upon the application, amount of available time, fluid flow properties and the available computational resources. Various methods have been designed to resolve and/or model the energy cascade shown in Figure 22. The fluid flow does not technically require a turbulence model and can be resolved by DNS. The Navier-Stokes equations are fully resolved for large eddies and at the Taylor and Kolmogorov scale. This method is not generally used as it requires very fine grids as the Kolmogorov scales are resolved, large computational resources due to the grid density, small time steps and is limited by the magnitude of Re [184]. The issues with DNS simulations are well understood and turbulence models have been designed based upon counteracting the issues involved with DNS.

This has led to the development of two families of turbulence models; the aforementioned RANS and LES. Hybrid methods have also been developed combining both families on a single grid. Hybrid models and the LES model can be further classified as scale resolving simulations (SRS). The following list contains several variations of both families that are currently available on ANSYS FLUENT:

- Spalart-Allmaras model - RANS
- $k-\epsilon$ model - RANS
- $k-\omega$ model - RANS
- Transition- $k-k_l-\omega$ - RANS
- Transition SST - RANS
- Reynolds stress - RANS
- Scale adaptive simulation (SAS) – hybrid RANS/LES
- Detached eddy simulation (DES) – hybrid RANS/LES
- Large Eddy simulation (LES)

In each of the above models, variations of the standard models have been created such as $k-\omega$ shear stress transport (SST) model and the $k-\varepsilon$ Re-Normalisation Group (RNG). The constants employed change and how each model treats fluid flow near a wall surface differs. RANS family turbulence models simulate/model the boundary layer formed by the fluid wall interaction through the law of the wall principles. Whereby the average velocity is calculated using proportionality with the logarithmic distance to the wall from a specific point location [187]. In the case of the $k-\omega$ shear stress transport (SST) turbulence model, the viscous and log layers are automatically identified, and the correct functions applied. However the standard wall function must be enabled to model the boundary layer and the first cell is located in the log-law region of the boundary layer [187].

3.3 CFD PROCESS

Developing actual representations of engineering projects and the physical environment requires a systematic approach to model creation as shown in Figure 23. Pre-processing is concerned with CAD model development, boundary model limits and subsequent meshing activities. Solver set up essentially assigns values to known variables and imposes physical boundary conditions representative of the physical environment modelled. The solution component is the preparation of monitors for data collection, computational resource allotments and methods of calculating the everchanging variables across the grid cells. The models are now required to be measured against experimental data analogous to the model geometries and boundary conditions for validation. Grid independence must also be checked using numerical verification techniques. In addition, the solution is monitored for steady state conditions and convergence limits set. Finally, upon completion of the four previous stages, post processing of the data can begin, and the models analysed for useful novel information pertaining to performance enhancing endeavours related to the project.

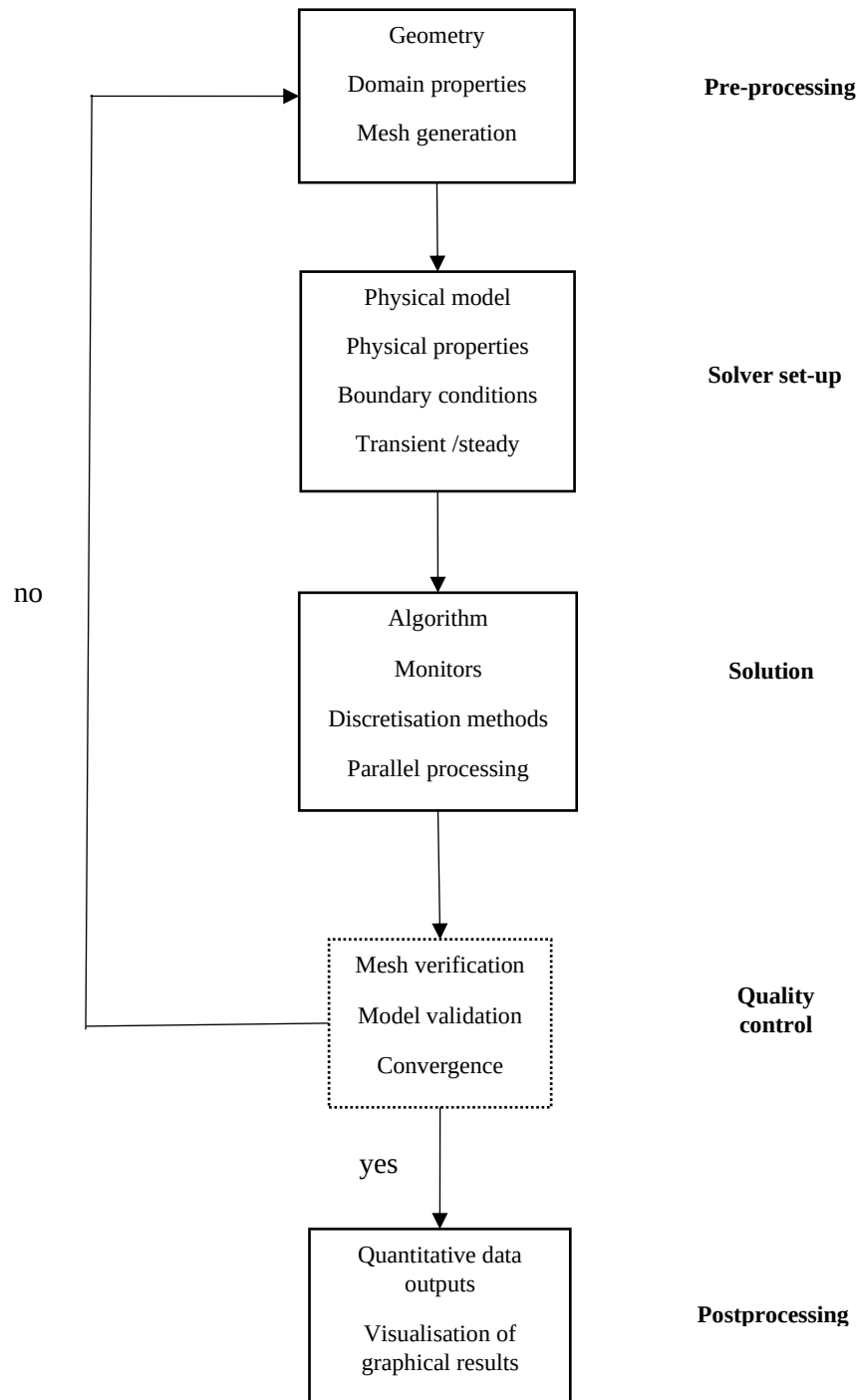


Figure 23. CFD process flow chart for an optimised model and adheres to quality control standards.

3.4 PRE-PROCESSING

3.4.1 Geometry

2D geometries were constructed using a planar surface in design modeller on ANSYS 18.1 and 3D models with SOLIDWORKS 2018. Several commercial inlets and an AER-AHU prototype with a deflector system were developed in the initial stages of the project with 2D methods. Following the completion of the 2D parametric study, certain performance characteristics were identified as crucial to the development of a novel AER. Numerous 3D models followed with the purpose of manipulating the airflow around the AHU inlet and base models for comparison. This was achieved using a Boolean operation between two separate geometries to create the final model for CFD analysis. A square block which represents the fluid domain was created first and the dimensions are based upon recommendations for airflow around a building [188,189]. The AHUs with commercial rainhoods and AERs were constructed as a separate part and a Boolean subtraction was performed between both the former and latter parts. That is, the AHU was positioned to ensure a blockage ratio less than 3%, placed upstream at 5H (H being the AHU height) from the freestream inlet and the pressure outlet was placed downstream at a distance of 10H from the AHU which is based on best practices taken from analogous studies on buildings [188,189]. The design scale dimensions for the AHU inlet testing domain can be viewed in Chapter 5 Figure 36 and Chapter 6 Figure 48. For the full-scale urban canyon model, the AHU scale to the environment scale is large and the above recommendations are easily met. The domain layout and dimensions for the AHU study in the urban canyon is illustrated in Chapter 7 Figure 62.

3.4.2 Mesh Generation

Different meshing approaches were employed depending on the model. 2D and 3D models have two and five different cell types that can be used respectively. The quadrilateral method is generally preferred, especially on structured grids, but can become distorted depending on geometry. The quadrilateral cells were deployed correctly align more efficiently with flows and the cell count is reduced in comparison to triangular cells of similar size. Triangle cells are used where an unstructured grid is used and the geometry is complex [190]. Similar characteristics can be inferred for 3D cell types depending on the geometry complexity and flow conforming to the geometry shape. Hexahedral cells are preferred to a tetrahedron, pyramid, polyhedron or prismatic cells but are more reliant on less complex geometries in order to maintain cell quality. Hexahedral cells were predominantly used for the 3D model

meshing, and tetrahedron cells were chosen for complex geometries such as near wall meshing around the commercial rainhoods and AERs.

3.5 SOLVER SET-UP

3.5.1 Physical Models

The choice of turbulence model is dependent on the application and the complexity of the geometry and environmental conditions. Therefore, two turbulence models from the RANS family were used within this project, the first, the more accurate $k-\omega$ (SST) turbulence was chosen for modelling particle laden wind flow over an AHU at a rooftop (design) scale. The second used the $k-\epsilon$ (RNG) turbulence model and analysed an AHU in a full-scale urban environment. The governing equations for both models are presented below.

3.5.1.1 Conservation of Mass and Momentum for Fluids

The air flow in the open urban environment was assumed to be incompressible, transient, and turbulent. Therefore, RANS models were used to simulate the time-averaged equations of motion for fluid flow. Where a 2D model is employed, a RANS model must be used as the turbulent viscosity is isotropic, with the exception being the Reynolds stress model and the use of an LES model would be redundant [191]. The RANS turbulence model uses time-averaged conditions to model the fluid flow instead of the instantaneous quantities in the Navier-Stokes equations:

$$u_i = \bar{u}_i + u'_i \quad (11)$$

This is achieved using a mean ($\bar{u}_i$) and fluctuating component (u'_i), where the fluctuating components are modelled as stresses. The following set of equations are known as the RANS equations. The time-averaged equations for continuity and momentum are expressed in tensor notation as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (12)$$

$$\rho \frac{\partial \bar{u}_i}{\partial t} + \rho \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u'_i u'_j} \right) + \rho F_i \quad (13)$$

Where x_i and F_i is the direction and external forces in the i^{th} direction respectively. $\bar{u}_j$ and x_j are the mean flow and direction in the j^{th} direction. While $\bar{P}$, ρ and t are the mean pressure, density and time components respectively. The term incorporating the velocity fluctuations ($\overline{u'_i u'_j}$) is more commonly known as the Reynolds stress tensor. The Reynolds stress tensor is resolved based upon the Boussinesq's eddy-viscosity hypothesis and is expressed as:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (14)$$

Here μ_t is the turbulence eddy viscosity, k is the turbulent kinetic energy and ε the energy dissipation rate. The turbulent fluctuations inherent within the fluid flow were modelled as stresses through:

$$\mu_t = C_u \frac{k^2}{\varepsilon} \quad (15)$$

3.5.1.2 k-ε Renormalisation Group (RNG) Turbulence Model

Closure was achieved with the Renormalization Group (RNG) k-ε turbulence model in an Eulerian reference frame [192] through the transport equations of k and ε in Eq. (16) and (17)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon \quad (16)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \rho \quad (17)$$

The main difference with the RNG model from the standard k-ε turbulence model arises from the development of Eq. (18) by Yakhot et al. [192] in order capture smaller length scales for low Re flow conditions:

$$C_{\varepsilon 2} = \tilde{C}_{\varepsilon 2} + \frac{C_u \eta^3 (1 - \eta / \eta_o)}{1 + \beta \eta^3} \quad (18)$$

Where σ_k , σ_ε , $C_{\varepsilon 1}$, $\tilde{C}_{\varepsilon 2}$, C_u , η_o and β are constants valued at 0.7194, 0.7194, 1.42, 1.68, 4.38 and 0.012 respectively, and μ is the fluid viscosity. While P_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, S the mean rate-of-strain tensor and η is the mean strain time scale.

$$P_k = \mu_t S^2 \quad (19)$$

$$S = \sqrt{2S_{i,j}S_{i,j}} ; S_{i,j} = \frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (20)$$

This turbulence model has been used extensively for modelling urban canyon flows and/or pollutant dispersion in an urban environment [193–196].

3.5.1.3 *k- ω Shear Stress Transport (SST) Turbulence Model*

The k- ω SST model is also a semi-empirical two equation RANS system created to model turbulence. The k- ω SST model was chosen as it is superior to the k- ε models in near wall flow and produces similar results within freestream flow regions for particle deposition [197] and ventilation of buildings [198]. The original k- ω model was developed to model low Reynolds number flow in the near wall region but performed poorly in freestream flow and the outer wake regions of the boundary layer. The k- ε model was superior in this regard, but Menter [199] overcame this issue by the use of blending functions in the k- ω SST. The blending functions allow the turbulence model to gradually differentiate between near wall flows and free stream flows. The model would change between the original k- ω which is activated at the near wall and standard k- ε which works in the free stream areas.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho \bar{u}_j k)}{\partial x_j} = \bar{P}_k - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (21)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \bar{u}_j \omega)}{\partial x_j} = \alpha S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \frac{\rho \sigma_\omega 2}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (22)$$

Where ω is the specific dissipation rate and the production of turbulence kinetic energy for this turbulence model for $\bar{P}_k$ is expressed as:

$$\bar{P}_k = \text{MIN}(P_k, 10\rho\beta^*k\omega) \quad (23)$$

The turbulent eddy viscosity in Eq. (15) is expressed in the SST model as:

$$\mu_t = \frac{\alpha_1 k}{\text{MAX}(\alpha_1 \omega, SF_2)} \quad (24)$$

Where the blending functions F_1 and F_2 are found by:

$$F_1 = \tanh\left\{\left\{\text{MIN}\left[\text{MAX}\left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\mu}{y^2 \omega}\right)\right], \frac{4\sigma_{\omega,2}k}{CD_{k\omega}y^2}\right\}^4\right\} \quad (25)$$

$$F_2 = \tanh\left\{\left[\text{MAX}\left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\mu}{y^2 \omega}\right)\right]^2\right\} \quad (26)$$

$$CD_{k\omega} = \text{MAX}\left(2\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, 10^{-10}\right) \quad (27)$$

The constant ϕ for the k- ω SST model are determined based upon the blending function and the distance from the wall y. The constants in Table 3 are used and $k = 0.41$ and $\beta^* = 0.09$ is common to both models. When the function F_1 is equal to one, the near wall model (original) is activated and changes to the freestream model (transformed) when zero.

$$\phi = F_1\phi_1 + (1 - F_1)\phi_2 \quad (28)$$

Table 3 Constants for the k- ω SST model [200].

Original k- ω model (ϕ_1)				Transformed k- ε model (ϕ_2)			
$\sigma_{k,1}$	$\sigma_{\omega,1}$	β_1	α_1	$\sigma_{k,2}$	$\sigma_{\omega,2}$	β_2	α_2
0.85	0.5	0.075	0.556	1	0.856	0.0828	0.44

3.5.1.4 Particle Dynamics

3.5.1.4.1 Spherical Particles

The below formulae deal with the variation between Re and their effects on the slip velocities and consequently the drag force exerted upon the particle. Various methods for the diameters (i.e., Stokes, aerodynamic, equivalent diameter) depending on size can be used to model PM transport. Each method operates based on the assumption that the flow around the sphere is a perfect sphere, but the actual particle shape and drag can vary leading to differing particle trajectories and movements. Re is a non-dimensional number used to ascertain the ratio of inertial forces to viscous forces in a fluid flow. Laminar flow occurs at low Re where inertial forces are dominated by viscous and transitions to turbulent flow at high Re as inertia now dominates. Various Re can be evaluated for particle laden fluid flow where Eq. (29) and (30) states the particle and freestream Re respectively [201]:

$$Re_p = \frac{\rho_f(\vec{v}_f - \vec{v}_p)d_p}{\mu} = \frac{\rho_f(v_{ts})d_p}{\mu} \quad (29)$$

$$Re_0 = \frac{\rho_f(\vec{v}_f)d_p}{\mu} \quad (30)$$

Where $\vec{v}_f$ is the fluid velocity, $\vec{v}_p$ is the particle velocity in an inviscid fluid, v_{ts} is the terminal velocity, ρ_f is the fluid density, μ is the fluid dynamic viscosity and d_p is the particle diameter. The movement of particles within a fluid medium was first described using a mathematical expression by George Gabriel Stokes. This expression followed several assumptions including laminar flow, no slip condition, smooth spherical particles and no particle-particle/wall interactions [202]. The Stokes law concerns itself with the drag force exerted upon a small spherical particle by the medium's viscous forces for $Re < 1$ and in the continuum regime, this is expressed as:

$$F_D = 3\pi d_p \mu (\vec{v}_g - \vec{v}_p) \quad (31)$$

Where d_p is the diameter of the sphere/particle. As the particle Reynolds number approaches the transitional regime and the continuum is affected by a slip factor, Eq. (32) and (33) must be used [187,203]:

$$F_D = \frac{18\mu}{d_p^2 \rho_p C_c} \quad (32)$$

$$C_c = 1 + \alpha Kn = 1 + \alpha \frac{\lambda}{r}$$

Or

$$C_c = 1 + \frac{2\lambda}{d_p} \left(1.257 + 0.4e^{-\left(\frac{1.1d_p}{2\lambda}\right)} \right) \quad (33)$$

Where C_c is the Cunningham correction factor for slip conditions, Kn is the Knudsen number, α is the slip correction constant and λ is the mean free path of the molecule [187,203]. The Cunningham correction factor is applicable to low and sub-micron particles due to the dominance of the slip velocities. Re is fundamentally linked to the drag force exerted over the sphere, as the laminar flow changes to turbulent, the correlation must be adjusted. The Stokes drag coefficient correlation of the particle for $Re_p < 1$ which describes laminar flow is found to be:

$$C_d = \frac{F_D}{\frac{1}{2}\rho_f A(\vec{v}_g - \vec{v}_p)^2} = \frac{24}{Re_p} \quad (34)$$

Where A is the characteristic area. The true shape of a particle tends to be irregular and can be simulated based on shape factors which is discussed in the next section. Various approximations are used when evaluating spherical particles; the aerodynamic diameter which uses a unit density of 1 g/cm³, equivalent sphere diameter and Stokes equivalent sphere are three such methods. All methods use terminal velocity conditions identical to the true irregular shaped particle [204,205]. The Stokes diameter (d_{stk}) and equivalent diameter (d_{sph}) method also use identical particle densities ρ_p with the latter also using an equivalent volume to the actual particles. The aerodynamic diameter is evaluated as the following:

$$d_{ae} = d_{stk} \sqrt{\frac{\rho_p}{\rho_0}} \quad (35)$$

Where, ρ_p and ρ_0 is the particle and unit density respectively which allows the aerodynamic diameter to be evaluated with the a particle of similar unit density [205]. The aerodynamic diameter in Eq. (35) is an approximation that can be applied to particles larger than 0.5 μm . The terminal velocity occurs when the sum of the buoyancy and drag forces are equal to the

gravitational force which produces zero acceleration [202,205]. If known, this can be used to determine the diameter for each method described previously. This is expressed as:

$$v_{ts} = \frac{\rho_p d_p^2 g C_c}{18\mu} \quad (36)$$

Where g is the gravitational constant similar to Eq. (32) description and a slip correction factor is used while set to unity in case of no slip condition. If the v_{ts} is held constant when transposing to determine the actual particle diameter, this can be swapped for the aerodynamic, equivalent diameter and Stokes diameter depending on the other known variables such as density and the Cunningham correction factor. Eq. (36) can be transported to yield the following:

$$d_p = d_{sph}, d_{ae}, d_{stk} = \sqrt{\frac{18v_{ts}\mu}{\rho_p g C_c}} \quad (37)$$

Particles where turbulent conditions are occurring requires a different approach as the Stokes drag law assumptions are no longer valid. Various correlations have been developed to model drag upon a sphere based on specific ranges of Re . Schiller and Nauman is one such standard drag correlation for $1 < Re < 800$ [206,207] but Morsi and Alexander correlations [208] further disaggregate the Re range compared to both Eq. (34) and the Schiller and Nauman correlations. Morsi and Alexander drag is as follows and is typically preferred:

$$C_D = \frac{24}{Re_p} \text{ for } Re_p < 0.1 \quad (38a)$$

$$C_D = \frac{22.73}{Re_p} + \frac{0.0903}{Re_p^2} + 3.69 \text{ for } 0.1 < Re_p < 1.0 \quad (38b)$$

$$C_D = \frac{29.1667}{Re_p} - \frac{3.8889}{Re_p^2} + 1.222 \text{ for } 1.0 < Re_p < 10.0 \quad (38c)$$

$$C_D = \frac{46.5}{Re_p} - \frac{116.67}{Re_p^2} + 0.6167 \text{ for } 10.0 < Re_p < 100.0 \quad (38d)$$

$$C_D = \frac{98.33}{Re_p} - \frac{2778}{Re_p^2} + 0.3644 \text{ for } 100.0 < Re_p < 1000.0 \quad (38e)$$

$$C_D = \frac{148.62}{Re_p} - \frac{4.75 \times 10^4}{Re_p^2} + 0.357 \text{ for } 1000.0 < Re_p < 5000.0 \quad (38f)$$

$$C_D = -\frac{490.546}{Re_p} - \frac{57.87 \times 10^4}{Re_p^2} + 0.46 \text{ for } 5000.0 < Re_p < 10000.0 \quad (38g)$$

$$C_D = -\frac{1662.5}{Re_p} - \frac{5.4167 \times 10^6}{Re_p^2} + 0.5191 \text{ for } 10000.0 < Re_p < 50000.0 \quad (38h)$$

Although the Reynolds number and coefficient of drag is dependent on the terminal settling velocity, under turbulent conditions this is unknown at the initial solution stage. An iterative process must be used until convergence. The terminal speed is determined similarly to Eq. (32) force balance but with buoyancy neglected and gives [202]:

$$v_{ts} = \frac{4\rho_p d_p g}{3C_D \rho_f} \quad (39)$$

3.5.1.4.2 Non-Spherical Particles

As the particle shape may vary and therefore particle drag, the equivalent diameter method uses the irregular shapes actual volume (V_p) to determine the equivalent diameter which is based upon the assumption of a perfect sphere. This can be found by:

$$d_{sph} = \left(\frac{6V_p}{\pi} \right)^{1/3} \quad (40)$$

To increase the accuracy of the approximations a shape factor can be included to negate the assumption of a perfectly spherical particle which physically is unlikely. The shape factor will have a significant effect upon the drag force and will alter the flow dynamics being investigated. The shape factor that is used in the commonly applied CFD modelling software, ANSYS FLUENT, is based upon the correlation developed by Haider and Levenspiel [209]. The correlation assigns a shape factor from 0-1 with one being a perfect sphere, $0.677 < \phi < 1$ an isometric solid and $0 < \phi < 0.677$ being a non-isometric solid (i.e., Disks). The coefficient of drag formula is expressed as:

$$C_D = \frac{24}{Re_{sph}} (1 + b_1 Re_p^{b_2}) + \frac{b_3 Re_{sph}}{b_4 + Re_{sph}} \quad (41)$$

Where the constants are found by the following:

$$b_1 = \exp(2.3288 - 6.4581\phi + 2.4486\phi^2) \quad (42a)$$

$$b_2 = 0.0964 + 0.5565\phi \quad (42b)$$

$$b_3 = \exp(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3) \quad (42c)$$

$$b_4 = \exp(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3) \quad (42d)$$

The above equations depend upon the shape factor in Eq. (43) derived by Wadell [210] to model shapes with equal volumes but different surface areas through dimensionless analysis. This is expressed as a ratio of the surface area of a particle having an equivalent volume as the particle (s) to the actual surface area of the particle (S) [187,209,210] and is independent of the particle size:

$$\phi = \frac{s}{S} \quad (43)$$

Haider and Levenspiel [209] reported that substituting the above Eqs. (42a) into Eq. (41) produced the following correlation that was used in Figure 24:

$$C_D = \frac{24}{Re_{sph}} \left(1 + \exp(2.3288 - 6.4581\phi + 2.4486\phi^2) Re_{sph}^{0.0964+0.5565\phi} \right) + \frac{\exp(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3) Re_{sph}}{\exp(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3) + Re_{sph}} \quad (44)$$

This was found to be accurate in predicting the coefficient of drag with shape factors not equal to one. Where shape factors are equal to one, Eq. (38a) can be used as this was derived for spherical particles. The design chart in Figure 24 employed an alternative correlation for determining the coefficient of drag and can be found in Haider and Levenspiel [209].

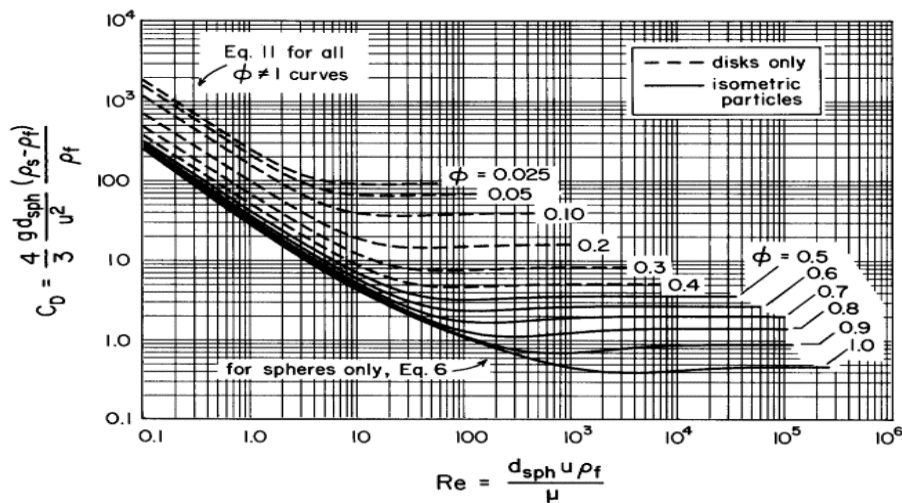


Figure 24. Design chart for drag coefficients for free-falling spherical and non-spherical particles [209].

The dimensionless quantities for the terminal velocity (u_*) and diameter (d_*) can be found by [209,211]:

$$u_* = u_t \left[\frac{\rho_f^2}{g\mu(\rho_p - \rho_f)} \right]^{1/3} \quad (45)$$

$$d_* = d_{sph} \left[\frac{g\rho_f(\rho_p - \rho_f)}{\mu^2} \right] \quad (46)$$

This non-dimensional analysis allows various settling velocities, diameters and shape factors to be determined as can be seen using the design chart in Figure 25.

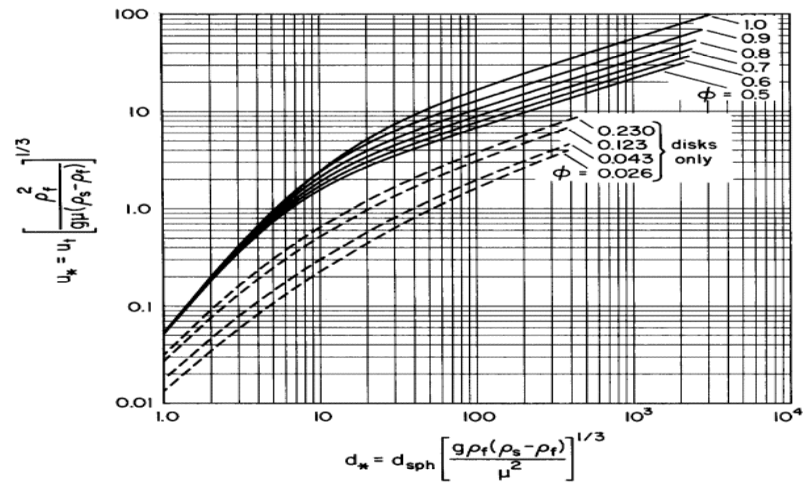


Figure 25. Design chart for determining terminal velocities for free-falling spherical and non-spherical particles [209].

3.5.1.4.3 Stokes Number Theory

As St is used to determine how a particle responds to fluid, St values less than one are more likely to follow the fluid streamlines rather than their original trajectory. Non-Stokesian particles will be much greater than unity due to its large inertia and tend to follow the particles initial trajectory. The general St equation is shown below:

$$St = \frac{t_0 \bar{v}_f}{L_C} = \frac{t_0}{\tau_0} \quad (47)$$

Where t_0 is the particle relaxation time, L_c is the characteristic length and τ_0 is the characteristic time scale of the flow [212]. The characteristic length depends on the type of problem and fluid domain, this could be an obstacle [201] or evaluated using the Kolmogorov length and time scales [213]. In this instance the characteristic length was assumed to be the total hydraulic diameter for non-circular orifices such as rainhoods or AERs. The particle relaxation time for a particle is:

$$t_0 = \frac{\rho_p d_p^2}{18\mu} \quad (48)$$

For particles where the Re_p is much greater and the Mach number is much less than unity (i.e., compressible flow), modifications are to be applied to Eq. (47). Israel and Rosner [214] demonstrated for the non-Stokesian regime that St takes the form of:

$$St_{eff} = \Psi(Re_p)St \quad (49)$$

Where the non-Stokesian correction factor is found to be:

$$\Psi(Re_p) = \frac{24}{Re_p} \int_0^{Re_p} \frac{dRe'}{C_D(Re')Re'} \quad (50)$$

Evaluating and integrating using the limiting boundary condition where $Re_p \rightarrow 0$, therefore Eq. (38a) is equal to Stokes flow drag Eq. (34) which gives $\Psi = 1$, the correction factor is described by:

$$\Psi(Re_p) = \frac{3 \left(\sqrt{c} Re_p^{\frac{1}{3}} - \tan^{-1} \left(\sqrt{c} Re_p^{\frac{1}{3}} \right) \right)}{c^{\frac{3}{2}} Re_p} \quad (51)$$

The constant c is found to be 0.158 and this relationship is shown in Figure 26; various correlations have been developed to model the drag upon a particle. Figure 26 demonstrates that Eq. (47) would underestimate the drag without the correction factor used in Eq. (49) as the particle Reynolds number increases [61].

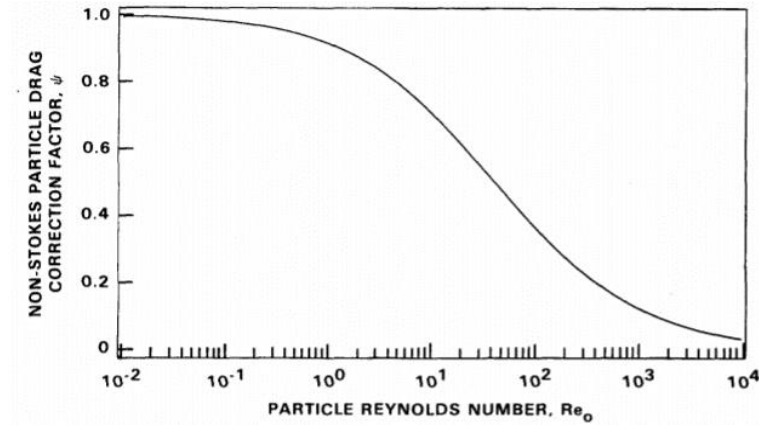


Figure 26. Non-Stokesian particle drag correction factor [214].

3.5.1.4.4 Froude Number

The influence of gravity must also be considered when determining which factors impact the dynamics of the particle. The Froude number is also a dimensionless number which determines if the effect of gravity is negligible. This number is expressed as the ratio between the inertial and gravitational forces, and larger values suggest inertial dominance [138]. This is as expressed for flow over a sphere as:

$$Fr = \frac{\bar{v}_f^2}{gd_p} \quad (52)$$

3.5.1.5 Discrete Phase Modelling

PM dispersion was simulated using the discrete phase model (DPM) method throughout the thesis. Modelling PM concentrations in urban wind flow require an Eulerian-Lagrangian approach. DPM models solid particles through the specification of their concentrations, mass flow rates, diameters and particle drag correlations such as Cunningham correction or shape factors. The Eulerian model represents the fluid flow and determines the state of the fluid through conservation laws based on diffusion and convection [32]. The Lagrangian approach is used to calculate the trajectory of individual particles discretely as it is dispersed in the fluid medium [32]. The trajectory of a particle is resolved by integrating the force balance on the particle. The force balance equation which equates the particle inertia with external forces in a cartesian co-ordinate system is expressed as:

$$\frac{du_i^p}{dt} = F_D(u_i - u_i^p) + \frac{g_i(\rho_p - \rho)}{\rho_p} + f_i \quad (53)$$

Where u_i , u_i^p and f_i is the fluid phase velocity, particle phase velocity and additional forces respectively in the i^{th} direction. $F_D(\bar{u}_i - u_i^p)$ describes the drag force per unit particle mass. The prediction of the dispersion of the particles can be accounted for by the use stochastic tracking methods known as the discrete random walk (DRW) model. This method estimates the particles path lines based upon turbulent diffusion and was chosen as the particle were modelled coupled with the fluid flow, allowed to interact and trajectories determined through the DRW method. DRW accounts for successive particle-eddy interactions based upon its initial conditions and locations [197]. The estimation of the particle dispersion is dependent on the integral time scale and the time spent in turbulent motion along the particle path. The particle Lagrangian integral time scale for small tracer particles can be approximated as [187]:

$$T_L = C_{LT} \frac{1}{\omega} \quad (54)$$

Where no universal value for C_{LT} has been established, C_{LT} has been found to be approximately equal to 0.15 for RANS models. The DRW model assumes that velocity fluctuations associated with the lifetime of the turbulent eddies follow a Gaussian probability distribution [215]. Considering the local root mean square (RMS) of the velocity fluctuations (turbulent kinetic energy) and assuming isotropy, the Gaussian distributed velocity fluctuations is expressed as:

$$u'_i = \zeta \sqrt{u'^2_i} = \zeta \sqrt{2k/3} \quad (55)$$

Where ζ is a normally distributed random number and results in the eddies have a characteristic lifetime, length scale and velocity scale. The end of said interaction occurs when one of two criteria is achieved; the lifetime of the eddy expires or the particle crosses the eddy boundary [216]. The characteristic lifetime of the eddy can be shown as a constant in Eq. (56) or through a uniform random number r in Eq. (57).

$$\tau_e = 2T_L \quad (56)$$

$$\tau_e = -T_L \ln(r) \quad (57)$$

The alternative condition where the particle crosses the eddy boundary within the eddy lifetime ($t_{cross} < \tau_e$) is expressed as:

$$t_{cross} = -\tau \ln \left[1 - \left(\frac{L_e}{\tau |u_i - u_i^p|} \right) \right] \quad (58)$$

Where τ is the particle relaxation time, L_e is the eddy length scale and $|u - u_p|$ is the magnitude of the relative velocity.

3.5.2 Material Properties and Operating Conditions

The type of fluid and solid materials must be defined for the model in question and their physical properties assigned numerical values to variables such as density and viscosity. Additionally, the operating conditions must also be defined and include the effect of gravitational acceleration and vector alignment with the model axis. Moreover, AHUs are typically located in environments subjected to standard atmospheric pressure and the initial environmental condition must also be initialised before solution activities can begin.

3.5.3 Boundary Conditions

The geometry and its corresponding grid were created to represent the particle laden fluid flow subjected to atmospheric conditions upon a rooftop of a commercial building. Thus, numerical models were created based upon best practices for fluid flow in an urban environment. The fluid domain boundaries were defined to represent the surrounding atmosphere and determine the direction of the fluid flow relative to the AHU. Similarly, the effect of the buildings, roads where applicable, and the AHU infrastructure boundaries must be defined. This was achieved through boundary conditions that are imposed upon the faces of the AHU models and civil infrastructure created at pre-processing.

The fluid velocity, pressure and direction can be set using a velocity inlet. This is used to control the entry and exit of fluid and solid particles within the fluid domain. Upstream of

the AHU, the velocity magnitude and the direction were set as normal to the boundary face. Additionally, a velocity inlet was also used for AHU fresh air intake but with negative numeric values and uniform profile in order to induce suction. A pressure outlet was used downstream of the AHU as only the static pressure from the fluid domain is required and all other variables are interpolated from the adjacent cells. A wall was assigned to the building, road and AHU surfaces under a no slip boundary condition. Finally, a symmetry condition was chosen for the domain top which allowed undisturbed fluid flow away from the rooftop.

Boundary conditions were imposed at the freestream inlet upstream of the AHU for the design scale studies in Chapter 5 and 6 and at the road surface for the urban canyon model. The former models PM concentrations were defined in a plane, injected normal to the inlet boundary using a surface release and the PM concentration were adjusted by the wind velocities. This method allows continuous delivery of PM particles into every cell and a uniform distribution regardless of the wind speed as the PM concentration is scaled to the cell size. A slight modification was made to the urban canyon models as PM emissions from a traffic source would be injected normal to the urban canyon wind vectors in real case studies. A low injection velocity of 0.01 m/s was used normal to the road surface and calibrated to not disturb the wind flow patterns but allow the PM to become entrained in the fluid flow. In an unsteady simulation the PM particles time step is the same as the time step used for the fluid.

3.5.4 Transient/Steady State Conditions

CFD Fluent allows two types of simulation depending on the problem scope and engineering complexity. Steady state conditions assume an unchanging process over time and requires less computational resources in comparison to transient methods. Although the steady state version is limited by its application, a transient model was therefore chosen, and a monitor used for checking steady state conditions. This method was preferred due to increased accuracy and the ability to average PM concentrations over a set time frame in spite of the longer solve times.

3.6 SOLUTION

3.6.1 Algorithm (Pressure-Based Segregated Solution Method)

In general, the instantaneous velocity field is unknown and various algorithms have been developed for velocity-pressure coupling. The most common methods are the pressure based segregated solution method. The discretised governing equations require an iterative method based upon a guess and correct algorithm over the staggered grid used in the finite volume method. The velocity-pressure coupling requires that the pressure and velocity are stored at different nodal points to prevent non-physical results. This is achieved through the use of a staggered grid. The momentum equations are offset from the original grid cell centre so that their cell centre is located on the centre of that cells face. This has the advantage of removing the need for interpolation of the velocity components as they are evaluated at the cell faces. A pressure based segregated method is an iterative solution method that is generally preferred when more than one variable is present. This method solves each variable sequentially as it assumes there is only one unknown variable. As there is a pressure derivative term within the momentum equations, the continuity equation must be solved initially using a pressure correction term. This is the foundation of the pressure-velocity coupling methods as there is no pressure term within the continuity equation. The original segregated solver is known as the semi-implicit method for pressure linked equations (SIMPLE) procedure. Variations to this method have been developed and the SIMPLE-consistent (SIMPLEC) method removes the under-relaxation factor of the pressure correction term to speed up convergence [217]. The following procedure describes the solution process of the pressure-based segregation algorithms:

1. The pressure field is estimated to start the procedure
2. The guess velocity components are then estimated
3. The pressure correction term is used in the discretised continuity equation and an approximate solution obtained
4. The pressure correction term is used to update the pressure and velocity terms
5. All other transport equations are solved over a scalar field
6. Solution is repeated until the desired convergence is achieved or in other words the solution error is at an acceptable predefined level

3.6.2 Monitors

Monitors are typically placed in areas of interest that could lead to useful results that match the project scope and objectives. They are used to collect variable data across iterations or time steps and provide feedback on the transient nature of the problem in hand and record variables of interest. In this thesis, PM concentrations were monitored for steady state conditions and the collection of ambient and AHU PM concentration in order to configure each model's AE.

3.6.3 Discretisation Methods

The finite control volume method transforms the governing equations into discretised linear algebraic equations using the integral form of the Reynolds transport equation. The computational domain is discretised into a finite number of cells where the discrete values are stored in place of the exact continuous solution [218]. Two common methods exist for evaluating the variable gradients between the cells, but the most prevalent methods are the Green gauss cell-centred and node based finite volume approach. The cell centred approach stores information in nodes at the centre of the cell. The node-based approach stores information at the vertices and uses the nodal values to interpolate the face values. The node based approach has been found to achieve greater accuracy but is more computationally expensive [187].

3.6.3.1 *Spatial and Temporal Discretisation*

Higher order schemes were employed for discretisation of all variables to limit the effect of numerical diffusion that occurs from first order schemes and improve accuracy. Truncation error ($T.E$) also occurs from discretisation of the linear algebraic equations over a finite grid. As the grid spacing (Δx) tends towards zero and the numerical solution approaches the true solution, the truncation error is eliminated. This occurs as the truncation error occurs from neglecting higher order terms present from the Taylor series expansion of the discretised algebraic equations in discretised space [218]. The order of the scheme (p) will determine the magnitude of the truncation error ($\Delta x^p \propto T.E$) [182]. This implies that decreasing the grid spacing and/or increasing the order of the discretisation schemes will have a significant effect upon the truncation error.

ANSYS FLUENT contains several schemes for spatial discretisation with varying orders of accuracy. The gradients were evaluated using the Green-Gauss node-based method and the

second-order pressure interpolation scheme was employed. Second-order upwind discretisation schemes were used for the momentum, turbulent kinetic energy, and specific dissipation rate. The temporal discretisation schemes are analogous to the spatial methods, where Taylor expansion is applied to time step (Δt) [218]. Temporal discretisation was achieved with a bounded second-order implicit time integration method. The methodology used for quantifying magnitude of the error and grid independence is addressed in Section 3.7.1.

3.6.4 Parallel Processing

The allocation of computational resources and availability can have a huge influence on the simulation solve time in real terms. Several PCs were used with varying levels of cores and RAM, where the individual PC used typically employed 5 cores (i.e., 10 processors) to achieve parallel computing. RAM ranged from 16-64GB. The Fluent programme's splits the mesh into multiple partitions and assigned the selected area to a particular node, therefore solving multiple partitions simultaneously.

3.7 QUALITY CONTROL

3.7.1 Grid Independence Verification

The Grid convergence index (GCI) method was used to estimate the ordered discretisation error associated with CFD studies. GCI was derived from the generalised Richardson extrapolation method by Roache for the purpose of quantification of numerical uncertainty with regards to spatial and temporal discretisation errors [219]. This method has been used in numerous studies and has proven to be a popular method among similar CFD Eulerian-Lagrangian model cases [220–222]. The relative error of the grid independence test requires solutions to be acquired from three grids with different resolutions by adjusting the cell size by a constant refinement ratio and the GCI in Eq. (59) can then be found from [202]:

$$GCI = \frac{f_s e_a}{r^p - 1} \quad (59)$$

Where the factor of safety (f_s) is 1.25 as recommended by Roache for three or more grids [219], e_a is the approximate relative error (i.e., fine grid variable-coarse grid variable/ fine grid variable), r is the grid refinement ratio taken as the constant cell size change between

two sequentially refined grids and p is the order of accuracy (based upon second order methods, theoretically $p = 2$). The full procedure of estimating the uncertainty due to discretisation is outlined by Celik [223].

3.7.2 Numerical Model Validation

Numerical model validation is typically required in order to test that accuracy of the models chosen to replicate the physical environment. The level of validation required is typically dictated by the nature of the problem as certain engineering situations cannot be experimentally tested at full scale. For example, a full-scale urban street canyon experimental test of pollutant dispersion would consist of a scaled model in a wind tunnel. The turbulence and DPM models would be identical, but the length scales would be a different order of magnitude. Where possible a full-scale wind tunnel test would be preferred but, in this thesis, this was not achievable due to the length scales involved. At a design level, the AHU validation models were based on a full-scale aerosol samplers AE (GSP) due to similar characteristics with a scaled AHU. In a full-scale urban environment, the validation of an AHU positioned on a building rooftop downstream of a PM traffic source also required the use of experimental data from a scaled street canyon model. Therefore, validation was achieved with models analogous to a full-scale AHU and/or urban environment.

3.7.3 Convergence

The CFD process is said to converge as the output variables solution value error is reduced to an acceptable predefined threshold. Residual definition of the variables is one element of checking a solution is running correctly. All residual limits were set to FLUENTs default minimum criteria of 10^{-3} at the time step end but the models all achieved a minimum convergence of 2×10^{-4} . The convergence of the solution is not only based upon the residuals converging to an acceptable level. In addition, the mass flow rates are summed across the inlets and outlets and the relative error checked for mass imbalances. The net mass imbalance within the models ran were found to be extremely small indicating a converged solution. Finally, a variable of primary interest is monitored for steady state conditions to also ensure a reduction in any inaccuracies in the post processing data extraction activities, in this thesis, ambient and AHU PM concentrations were monitored.

3.8 POST PROCESSING

3.8.1 Quantitative Data Outputs

Quantitative data can be extracted from the use of area weighted averaged monitors recording variables of interest at the boundaries and within relevant cells. The placement of surface/line monitors at strategic locations of interest throughout the domain gathered PM concentrations from the ambient environment and ventilation system in order to calculate AE. Moreover, the monitored average PM concentrations were extracted from a steady state solution. This essentially defined the termination point for each simulation so that an average concentration can be extracted from a large sample pool. This can then be plotted in the form of an XY plot against various design and environmental variables such as velocity ratios, ambient wind speeds, position, orientation and St.

The PM surface monitors were configured so that PM concentrations are recorded at every time step and a Microsoft Excel worksheet of the solution were created. An example of this process is shown in Figure 27 where the ambient PM concentration reaches steady state instantly as this was monitored at the velocity inlet. The AHU concentration does not start to reach a steady state configuration until approximately 5s. This occurs due to the distance the ambient PM has travelled before the ventilation system draws in the PM at the AHU inlet where the surface monitor was placed.

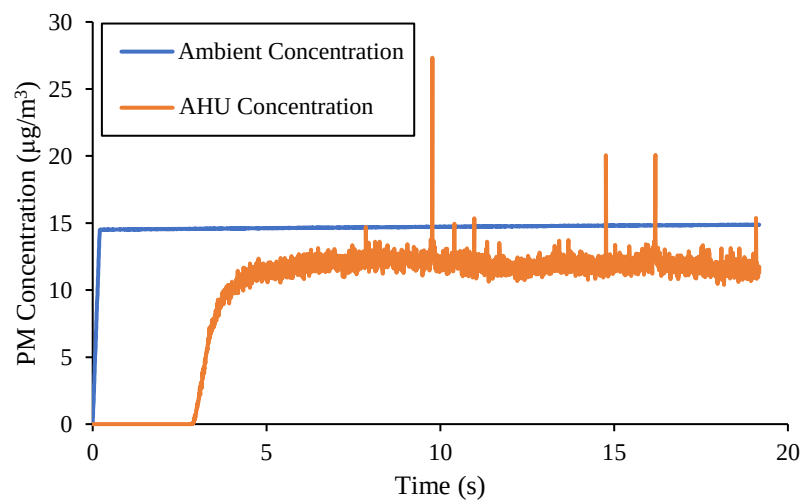


Figure 27. Ambient and AHU PM monitor graph at a wind speed of 2 m/s.

3.8.2 Flow Field Visualisation

The post processing stage of a CFD simulation allows the user to analyse visual representations of the model's outputs. Visual representation methods are an extremely powerful tool for the analysis of fluid flow dynamics and pollutant dispersions around an AHU. Experimental field tests monitor pressure drops and record PM concentrations at specific points but provide no visual results for observation. Graphical analysis allows the user to completely examine the entire fluid domain using vector and contour plots. Depending on the type of geometry used (i.e., 2D or 3D), multiple planes can be used for plotting contour and/or vector plots at specific locations. Planes are generally used for contour plots, but other outputs such as y^+ can be plotted around the walls of a 3D model which is beneficial to assessing the accuracy of the grid with regards to the turbulence model. The contour plots should be used in conjunction with vector plots to fully analyse the process. Boundary layer separation and reattachment which generates eddy formations within the fluid domain can be analysed using contour-vector velocity plots as shown in Figure 28. The vector plots also plot the magnitude and direction of the fluid throughout the domain. The quantitative analysis will provide xy plots of the AE but an explanation for AE differences can be assessed through the analysis of different flow patterns.

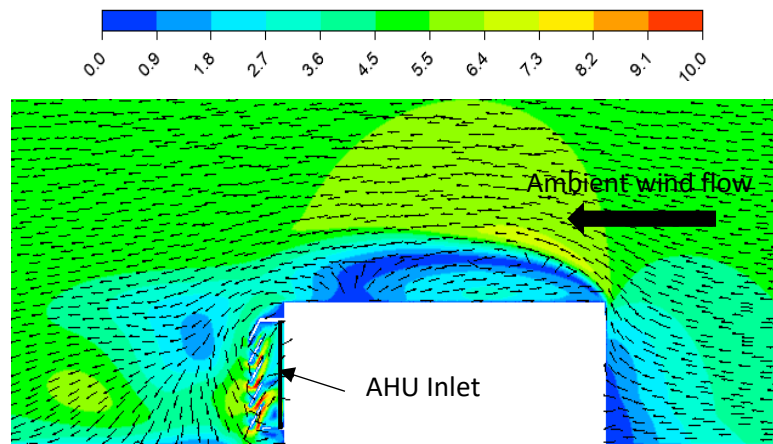


Figure 28. Vector-contour plot of wind flow for rear facing AHU at an ambient wind speed of 5 m/s and AHU flow rate of 3400 m³/hr.

4 VALIDATION OF NUMERICAL MODELS

Different methods and models from other experimental research studies were used for validation and were performed based upon the length scales of the environment the AHUs were tested in. Chapters 5 and 6 are concerned with the numerical analysis of an AHU at rooftop level and are used for designing AERs. The rooftop level approach allows a greater number of simulations to be run in comparison to an analysis of an AHU in a full-scale urban environment (i.e., urban canyons, isolated multi-storey buildings, etc). Further simulations are required within the urban canopy layer to determine how a pollutant can impact an AHU regardless of the inlet attachment and is addressed in Chapter 7. Therefore, different turbulence models, boundary conditions and drag models have been validated against experimental results depending upon the application and scale. The following section details the procedure and assumptions used at the rooftop level (referred to here as the design scale). and within an urban boundary layer.

4.1 DESIGN SCALE

The airflow in the computational domain was considered to be incompressible and turbulent flow was modelled using the RANS $k-\omega$ SST model described in Section 3.5.1.3 [199]. PM dispersion was simulated using the aforementioned DPM method and the particle drag was modelled using Haider and Levenspiel correlations described in Eq. (41)-(43) for non-spherical particles with a shape factor of 0.4. This shape factor was found to be the best fit after a trial and error assessment where models were tested within the 0-1 range with 1 being a spherical particle. The validation of the numerical models used in the analysis of an AHU at rooftop level required experimental results that could be associated with the relationship between the St and AE. This required experimental results that capture the AE of single particle diameter concentrations of particles. A reflect boundary was used at the wall surface and the initial particle velocity was assumed to match the wind speed. The particles were assumed to be inert, and the particle sizes examined can be viewed in Figure 30.

The first stage of model validation involved testing the mathematical models used for modelling the AHU against measured results by Kenny et al. [145], which involved measuring the AE of personal inhalable samplers in low air movement environments. The physics involved in both tests were analogous to each other with the differences arising from the larger geometrical scale of the AHU compared to an air sampling device. This would provide a good indication of the validity of the current model as a wind tunnel test would

also use a scaled-down physical model of an AHU that would be similar in size to a full-scale personal inhalable aerosol samplers tested by Kenny et al. [145]. The model dimensions and boundary conditions are shown in Figure 29 for the 3D GSP sampler geometry used to calibrate the DPM model at a flow rate of 3.5 l/min under a freestream velocity of 0.5 m/s.

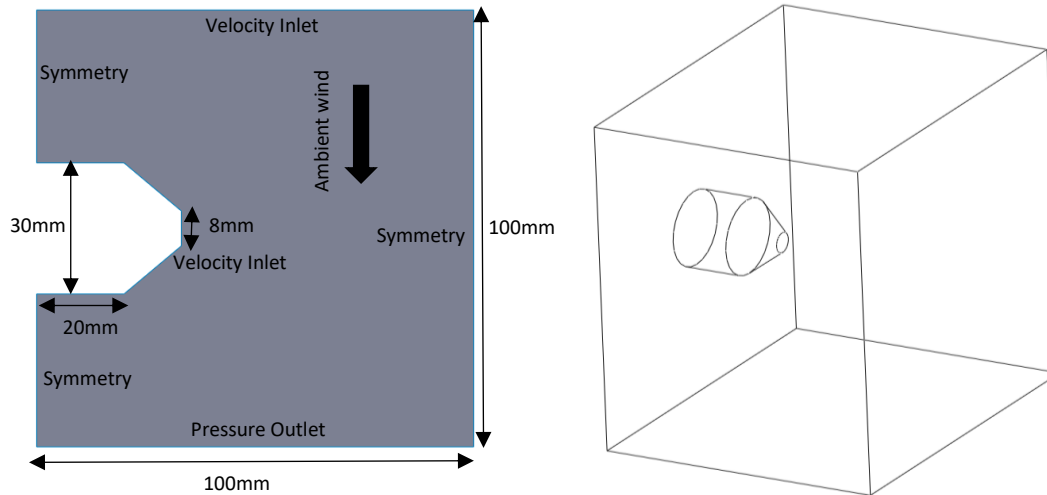


Figure 29. GSP sampler geometry cross section and 3D model.

The 3D CFD model and mean of Kenny's experimental results were found to have an R^2 of 0.94 indicating the line accounts for 94% of the variation and a correlation coefficient of 0.69, as illustrated in Figure 30a. The CFD predictions tend to underestimate the larger diameter particles and account for the 0.69 correlation where a value of 1 would represent perfect agreement. In addition, the correlation coefficient was examined where the CFD and experimental AE were assumed to be 0% when no PM concentration was present (i.e., intercept set to zero) and also resulted in a good agreement with a slope of 0.94 indicating an agreement of 94% or approximately a 6% error. The error bars represent the standard deviation of experimental measurement and the CFD samples were within these values taking into account both methods of analysis. More importantly the difference between both linear trends becomes larger as the particle diameter increases as illustrated in Figure 30a.

The results from the 3D CFD model were also plotted against the spread of the Kenny data for comparison in Figure 30b. The numerical model predicted the AE of the smaller diameter particles very well as illustrated in Figure 30b and the only the 26 μm diameter particles exceeded the experimental range of values by 9%. The other discrepancies between the

experimental and CFD results were primarily for particles with larger diameters. The AE of the 74 μm diameter particle concentrations resulted in the largest discrepancy between the CFD and experimental results. Although the deviation between the numerical results and experimental of 74 μm diameter particle AE were attributed to the number of tests conducted by Kenny et al. [145]. It would be reasonable to expect an increase in the size of the sample pool would have yielded a lower minimum AE for the 74 μm diameter particles as both the 58 and 90 μm diameter particles have lower AE than the recorded CFD average of the former. The experimental AE 90 μm diameter particles were found to experience a lower minimum AE but fell within the experimental range equalling the lowest recorded AE within this range as shown Figure 30b.

Additionally, the CFD model uses an equivalent volume method as described previously to determine the shape factor. This is not an exact physical representation of the particle shape but uses correlations to define the drag. As the shape factor was held constant, the error discrepancy associated with the larger particles became more significant as the particle drag increased with diameter. Mark et al. [224] found that the aloxite dust used within the Kenny experiments have radically different shape factors across the dust diameter range tested. For example, the smallest diameter particle such as 6-18 μm have the most irregular shaped structure whereas the 90 μm particles are nearly spherical. Their shape factor is reduced after 18 μm , but still are still not spherical, resulting in the variation for the 26 μm diameter particle AE between the CFD and experimental. Moreover, while the shape factor of the aloxite powder varies depending on the particle diameter, the diameter distribution curves according to Mark et al. [224] are not truly monodisperse. Using a geometric standard deviation, the particles can range about the mass median aerodynamic diameter by 1.17-1.36 depending on the diameter. Therefore, the CFD models using a single diameter particle are not completely representative of the dust and is a limitation of the modelling approach. Kenny tried to minimise this effect during testing but attributed the experimental error based on the bias between the inhalable convention and the experimental tests where a bias for

Finally, Kenny measured the concentration using gravimetric analysis technique and determined the sampling efficiency whereas this model examined the aspiration efficiency, therefore there will be slight differences in the AE but for the GSP sampler, Kenny got around this by measuring the filter and the holder restricting losses to only the area between the inlet and the filter. Furthermore, the GSP sampler experimental results when compared

to the inhalable convention were found to result in a bias up to 20% for the larger particle diameters.

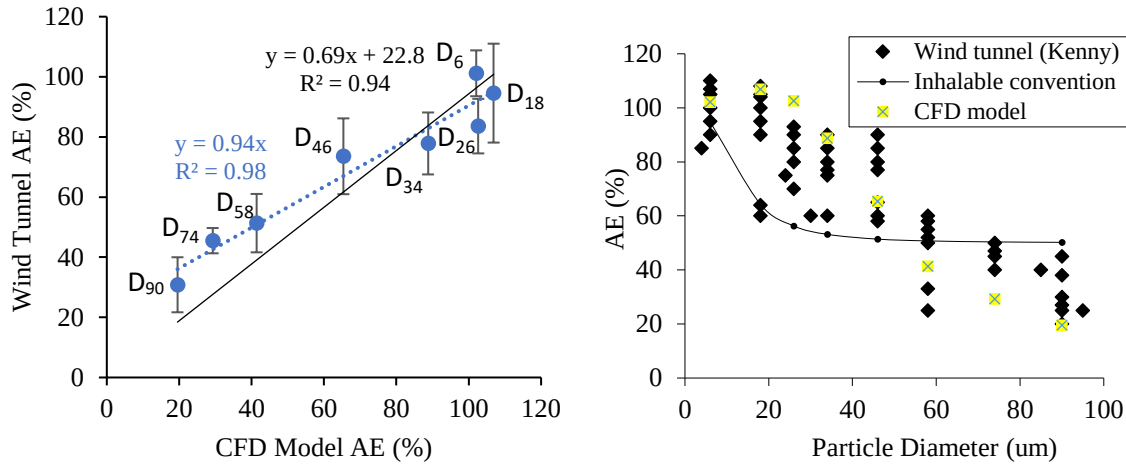


Figure 30. Comparison between Kenny et al. [145] and a 3D CFD model method for (a) correlation, and (b) AE vs particle diameter.

A second model was tested, analysing the GSP inlet when facing into the wind as the Kenny et al. paper described the GSP inlet as positioned vertically and did not elaborate if this was the inlet itself or the inlet plane. The results from Figure 31 show a similar trend as Figure 30 where the greatest error occurs with larger diameter particles. The mean of 3D CFD model Kenny's experimental results were found to have an R^2 of 0.86 indicating the line accounts for 86% of the variation and a similar correlation coefficient of 0.71 as Figure 30.

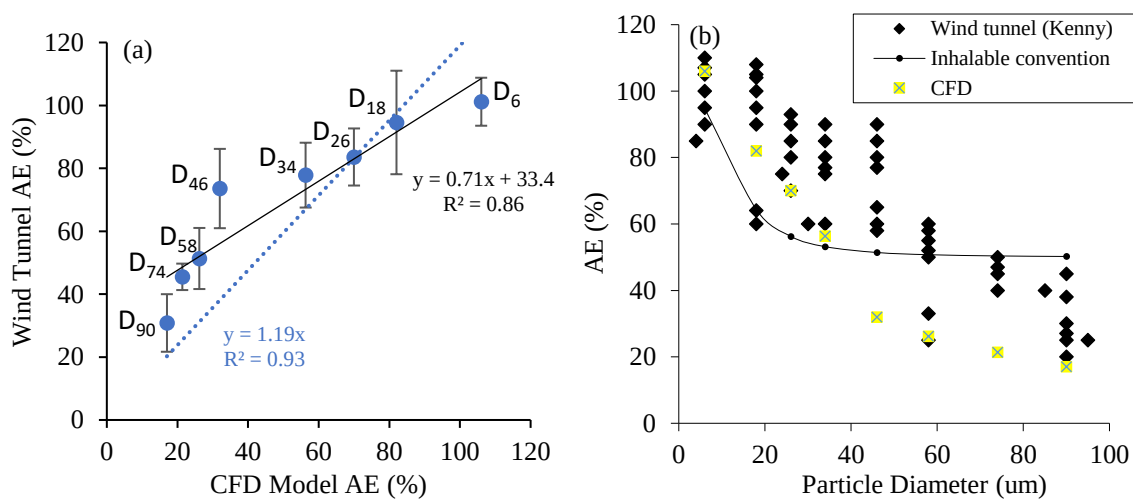


Figure 31 Comparison between Kenny et al. [145] and a 3D CFD model method for (a) correlation, and (b) AE vs particle diameter where the inlet is positioning facing into the wind.

4.2 URBAN ENVIRONMENT

In order to fully analyse the dynamics involved in the field testing of a novel AER-AHU and a commercial AHU, validation was required for particle laden flow in an urban environment. This is to ensure the dynamics of pollutant dispersion upon the rooftop of a commercial building situated in an urban street canyon environment are optimised to the critical physical realities. In the urban canyon model, a $PM_{2.5}$ source is required to replicate the physical conditions experienced during high traffic volumes in urban areas. Therefore, a user-defined function (UDF) was used to account for the drag of the particle depending on their respective diameter and the drag correlations were adapted from the Cunningham correction factor in Eq. (9-10) [203] and Alexander and Morsi correlations in Eq. (15) [208]. In addition, the UDF must also account for the urban boundary layer profile using an exponential function known as power law wind profile outlined in Eq. (31). Validation of the urban canyon required a two-stage approach to confirm the turbulence and DPM models appropriateness for a urban street canyon environment.

4.2.1 Turbulence Model Validation of an Isolated Urban Canyon

The first of the two validation models in an urban environment examined the viability of the $k-\epsilon$ RNG turbulence model in an urban street canyon. The boundary conditions were based upon recommendations from Walton and Cheng [225]. The model width and height were configured to match the experimental test model used by Allegrini et al. [196] where the street canyon had an unit aspect ratio as shown in Figure 32. A grid size of 0.002 m was used inside the street canyon and a standard wall functions based upon the findings of both Allegrini et al. [196] and Hao et al. [194]. Although it should be noted that the full length of the wind tunnel in the streamwise direction was not modelled due to the mesh density required for a 3D model. Instead to replicate the wind profile within the wind tunnel test, the aforementioned power law UDF was used where $\alpha=0.1$ (i.e., smooth surface exponent) and was measured 0.4 m upstream of the urban canyon. This was found to be an excellent match to the aluminium surface as shown in Figure 33a.

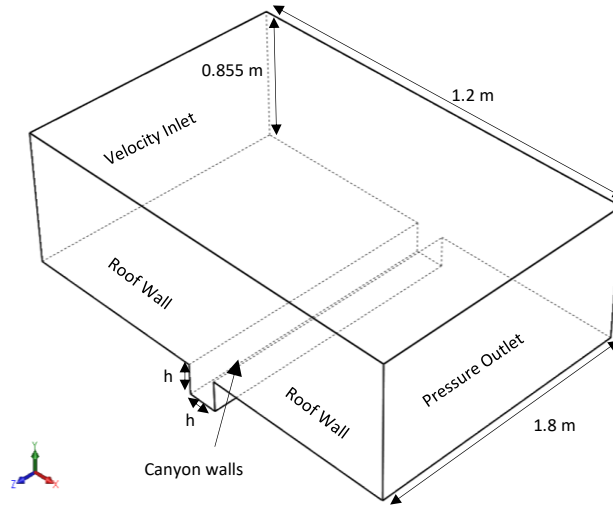


Figure 32. Urban canyon geometry for turbulence model validation based upon dimensions from Allegrini et al. [196] wind tunnel tests on buoyant flows in a street canyon. Note: $h=100\text{mm}$.

A normalised horizontal profile of vertical velocity magnitudes in the centre of the street canyon was compared to the wind tunnel results. The results found the numerical model was able to predict the vortex within the canyon centre and is in good agreement with the physical model and is therefore an acceptable turbulence model for urban flow dynamics. The slight variation between the experimental and numerical results as seen in Figure 33b can be attributed to the no slip condition employed upon the walls.

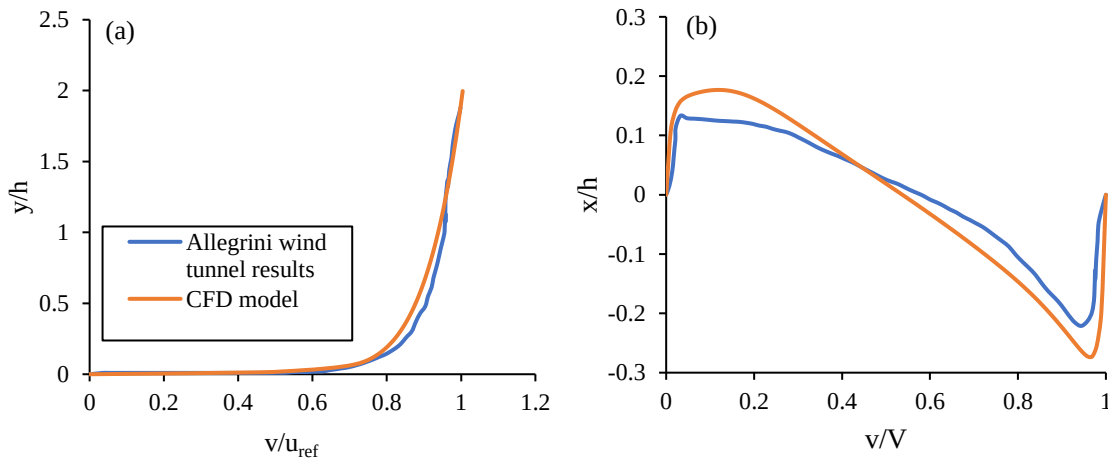


Figure 33. Comparison between $k-\epsilon$ RNG with standard wall function and Allegrini wind tunnel results on an urban canyon [196] where (a) normalised wind profiles 0.4m from the windward side of the urban canyon (b) normalised centreline vertical velocity wind profiles. Note: $U_{ref}=1.45\text{ m/s}$.

4.2.2 DPM Model Validation Within an Urban Environment

The second stage of the numerical model validation for the urban environment scale examined pollutant dispersion within an urban street canyon and compared the numerical results to experimental results from Meroney et al. [168].

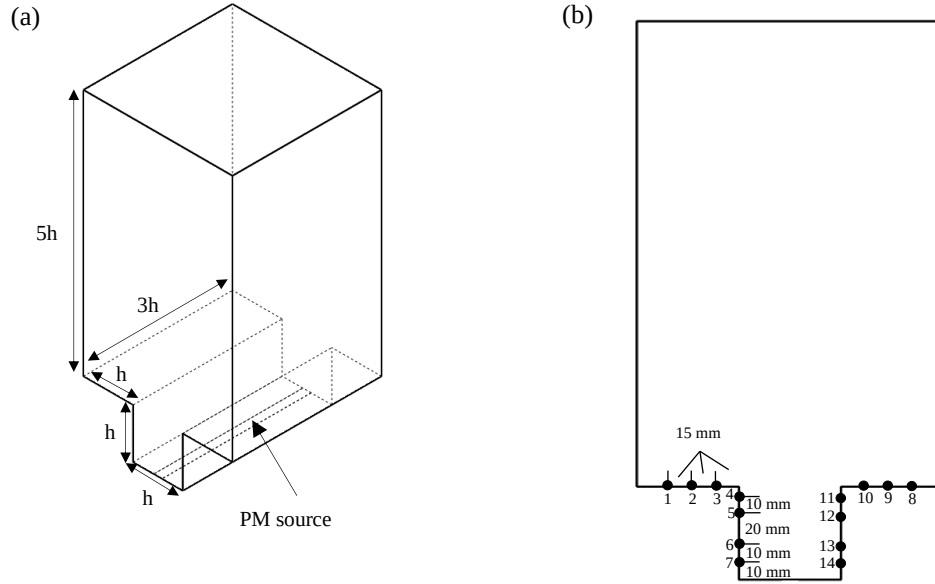


Figure 34. Urban canyon geometry and sampling points for validation based upon dimensions from Meroney et al. [168] wind tunnel tests on pollutant dispersion in a street canyon. Note: $h=60\text{mm}$.

The power law wind profile was calibrated with $\alpha = 0.2$ and $U_{\text{ref}} = 2 \text{ m/s}$ as per recommendations for flow in an urban environment [168] and was configured with a UDF for wind velocity, turbulence intensity and dissipation outlined in Eq. (31), (33-34). A line source was used to model the effect of traffic emissions within the urban canyon as shown in Figure 34a and $\text{PM}_{2.5}$ was created with another UDF describing the distribution curve from a diesel vehicle PM filter [226] shown in Eq. (60) in Chapter 7, and employing the Cunningham coefficient drag laws in Eq. (9-10). The same boundary conditions and turbulence model employed in the previous Section 4.2.1 where the numerical turbulence model was compared with an experimental wind tunnel test in an urban canyon was used. The PM concentrations in the street canyon and on both the upstream and downstream building rooftops were measured and their respective sampling locations are illustrated in Figure 34b. This validation model was concerned with ensuring the PM dispersion within an urban environment matched physical test results for a range of particle dimeters that represent $\text{PM}_{2.5}$. Using a similar methodology by Xia and Leung [227], the PM concentration

sampled are normalised at each location, where sampling point 7 concentration is the known maximum concentration and is used as a ratio to the other measured concentrations (i.e., C/C_7).

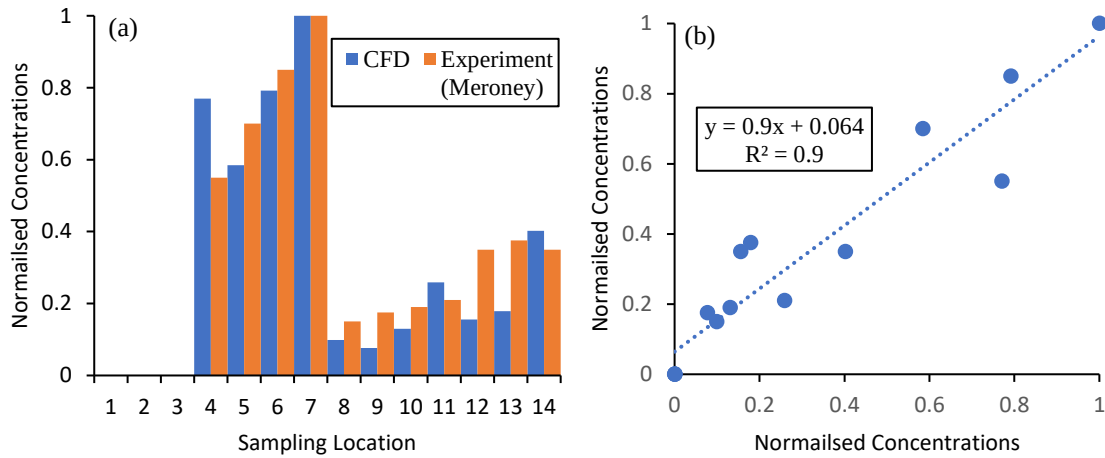


Figure 35. Comparison between numerical DPM model and Meroney et al. [168] wind tunnel results on an urban canyon where (a) normalised concentration comparison (b) linear correlation; between experimental and numerical results.

This approach to analysing the validity of the discrete phase model in comparison to physical phenomena is shown in Figure 35a where the normalised CFD results are compared to the experimental results. Furthermore, a regression curve with a correlation coefficient of 0.9 and R^2 of 0.9 demonstrates that the numerical model results are a good fit with the physical wind tunnel tests as 90% of the data falls on the linear trendline as illustrated in Figure 35b. From the numerical perspective, limitations within the CFD model include the use of a single street canyon compared to Meroney et al. [168] multi canyon experimental rig and the variations between the dynamics of $PM_{2.5}$ concentrations and the air/ethane gas used in the experimental tests. In addition, the higher concentrations observed at point 4, was due to the formation of a stagnation zone on the leeward side of the street canyon, which led to a slightly elevated PM concentration. This caused a slight decrease in PM concentrations on the windward face of the street canyons and rooftop. Experimentally, there is no information provided in the Meroney et al. [168] paper of the sampling probes diameters, flow rates used during the experiment and also specified a $\pm 5\%$ bias between the true concentration and the measured. Therefore, monitor points were placed within the cells directly adjacent to the urban canyon walls and their average concentrations monitored over time. Each of the

aforementioned points would all contribute to 10% error found based on the correlation coefficient of 0.9.

5 NUMERICAL INVESTIGATION ON THE INGRESS OF PARTICULATE MATTER FROM AMBIENT AIR INTO THE INLET OF A BUILDING AIR HANDLING UNIT

This chapter is based on the work summarised in Considine et al. [228] and provides a more in depth account of the research.

5.1 INTRODUCTION

The transportation of ambient particulate matter (PM) from outdoor air into the inlet of a mechanical building ventilation system is poorly understood. No studies have examined the effect commonly used commercial AHU inlet designs (i.e., rainhoods) have upon the migration of PM from the ambient environment into the building ventilation system, and the implications of this on building energy consumption and IAQ. A large volume of literature exists upon the design of PM samplers considering AE and this chapter of the thesis seeks to build upon the knowledge of the AE of a large ventilation system. Recently the AE concept has been reverse-engineered to intentionally reduce the AE of large aspirating systems (i.e., building ventilation system) as described in Section 2.8.

Previous work focused on a scaled prototype incorporating an array of circular orifices and a full-scale model tested in an urban environment [6,151]. The full-scale test consisted of a comparative analysis between a rear-facing AER-AHU against a forward-facing AHU with a commercial inlet attachment. The objective of this study was focused on analysing the various environmental and HVAC design variables that could impact the AE of an AHU. Furthermore, this will determine if the lower AE generated by the rear-facing AER-AHU test conducted by Morgan et al. [151] occurred due to the differing orientations relative to the wind direction and/or through the novel array of circular orifices.

By determining the AE of existing AHU inlet designs, we aim to establish the dynamics of PM concentrations passing from the ambient environment to indoor spaces. We also aim to establish the baseline AE for existing rainhoods, which have not been designed with PM control in mind, but nonetheless possess an AE. Establishing this baseline will enable the direction of PM control improvements to be defined. Understanding the particle dynamics of current systems is also vital to identify means to reduce indoor air pollution and building energy consumption, through lowering of AE, in-AHU particle concentrations and

consequently the pressure drop on HVAC filters. In the following sections, the design, grid development, and numerical modelling of the aforementioned problem are described. CFD was used to conduct this assessment, and validation of the CFD models used were presented in 4.1, as well as the analysis of the dynamics of PM concentrations for two common commercially available AHU inlet designs.

5.2 NUMERICAL MODEL SET UP

5.2.1 Computational Domain and AHU Inlet Designs

A 2D and 3D model of a building AHU was constructed using design modeller and SOLIDWORKS respectively and meshed in ANSYS 18.1. The model was constructed to simulate the geometry of a typical AHU sitting on the roof of a flat roofed building. The AHU could be mounted at any orientation relative to ambient wind on a flat roof in practice, but based upon studies conducted by Wen & Ingham on aerosol samplers [19,21], the most pertinent positions for examination were found to be FF (0°) and RF (180°) orientations. Therefore, both orientations for a 2D and 3D AHU model were created where the latter is illustrated in Figure 36. The numerical model was based upon a real AHU with dimensions of 2.01 m (L) × 0.755 m (H) × 0.85 m (W) and an AHU filter inlet with a surface area of 0.36 m². This real AHU will later be used to test the rain hood designs used here and new AER-AHU prototypes in the field and is addressed in Chapter 8. A slight variation to the 2D models occurred as an overhang was used for a roof hood (not the inlet attachment) but removed for ease of meshing in the 3D models as it was deemed to have no influence over the flow dynamics.

There is currently no literature available with recommended distance to the domain boundary for flow over an AHU, but the flow dynamics are analogous to flow around a building. The upwind and top boundary were created at a distance of 5H from the AHU. The lateral height of the domain was 3.5H from the sides of the AHU wall to the domain boundary for the 3D mode only. Finally, the boundary downwind of the AHU was set to 10H from the AHU to allow assumption of stress free boundary at the domain exit. The upstream, downstream, lateral and top boundaries of the computational domain were chosen based upon the recommendations of Tominaga et al. [23,24] and correspond with the recommended blockage ratio of < 3% for a 3D model. The computational domain consisted of a pressure outlet, wall, symmetry, and a velocity inlet for the AHU inlet and ambient air. A uniform

Figure 1 consists of three sub-diagrams labeled (a), (b), and (c).
 (a) A 3D schematic of the computational domain. It is a rectangular box with a central smaller box representing the AHU. The AHU is labeled 'Roof/AHU wall' and 'AHU Velocity Inlet'. The domain is labeled 'Symmetry' on the left and 'Pressure Outlet' on the right. The top surface is labeled 'Velocity Inlet'. The origin (0,0,0) is marked at the bottom right corner. Dimensions are given as 10H for the AHU length, 5H for the AHU height, and 3.5H for the AHU width. The reference height is 5H. The ambient flow direction is indicated by an arrow labeled 'Ambient Flow'. The reference height is also labeled Z_{ref} . A coordinate system (x, y, z) is shown at the bottom right.
 (b) A side view of the AHU unit. It is a rectangular block with dimensions L (length), W (width), and H (height). A green horizontal band is visible on the front face.
 (c) A detail view of the AHU unit showing the inlet and outlet flow paths. The inlet is labeled 'L_inlet' and the outlet is labeled 'L_outlet'. The inlet and outlet heights are labeled 'z'. A coordinate system (x, y, z) is shown at the bottom left.

Two different inlet configurations were created for testing in ANSYS FLUENT as shown in Figure 36b-c and both are commercially available on the EU market but their exact manufacturer's information has not been included due to data sensitivity. Inlet 1 is a generic design consisting of a single large orifice, typically installed on both ventilation fans and AHU's. Inlet 1 is designed to prevent rain droplets from entering the AHU, and this is achieved by angling the inlet face downwards. The geometry of the Inlet 2 design has similar orientations to Inlet 1 but instead uses a louver design (i.e., $\beta < 90^\circ$) that has multiple and smaller orifices. Again, the original purpose of the design is to prevent the ingress of rainfall

which is achieved by the louver structure. The cross section of both inlets tested are shown in Figure 36b-c and their corresponding dimensions can be found in Table 4. The airflow velocity at the orifice also plays a role in PM transport into the ventilation system and is determined also from the dimensions in Table 4 using their total orifice surface area. The comparison of Inlet 1 and Inlet 2 was intended to enable the comparison of the AE of the most commonly found AHU inlet geometries in practice.

Table 4. Inlet geometry properties for each commercial Inlet shown in Figure 36.

Model	Orifice height (m)	β	No. of orifices	z (m)	y (m)
Inlet 1	0.380	64.25 °	1	0.309	0.365
Inlet 2	0.051	60 °	5	0.121	0.092

5.2.2 Environmental and HVAC Operation Variables

Several other variables were also investigated to determine their effect on AE for large aspirating systems as shown in Table 5. This includes the wind direction ($\alpha= 0^\circ$ and 180°) relative to the AHU which accounts for the orientation of the AHU where the AHU was rotated and the boundary's held constant. The wind speed ranged from 1-10 m/s and tested in intervals of 1 m/s, when examining the impact of an AHU's flow rate. Typically, the flow rates of an AHU will vary depending upon the building demand throughout the day and will result in ventilation velocities of between 1-3 m/s (i.e., flow rate from 1296-3888 m³/hr) for Inlet 1. The effect of the ventilation velocity and wind speeds were examined with Inlet 1 using a particle diameter of D_{2.5} (2.5 μ m diameter particles), as particles of this size within the PM_{2.5} range have been found to affect the health of human beings more adversely.

Finally, a comparison between the two inlet geometries was investigated using their corresponding St across a range of wind speeds, orientations and particle sizes as shown in Table 5. Four different velocity ratio's (R), with both yaw angle orientations, were tested which amounted to eight different case comparisons between Inlets 1 and 2. For each case, St was varied by changing the particle diameter which ranged from D = 2.5 μ m to D = 90 μ m. The hydraulic diameter for a rectangular orifice was used as the characteristic length ($C_L=2ab/a+b$) where a and b represent the length and sides respectively of the orifice. This amounted to for Inlet 1 is 0.584 m and 0.38 m for Inlet 2. Ambient wind velocities of 1.5 m/s, 2.5 m/s, 5 m/s and 7.5 m/s were used to vary both R and St. An AHU design flow rate

of 3400 m³/hr (i.e., ventilation velocity of 2.6 m/s) was used for each case and was based upon the AHU model tested by Morgan et al. [151] and used later in Chapter 8 of this thesis.

Table 5 Case studies detailing the environmental and HVAC operations tested within this rainhood AE investigation for an AHU.

Case study 1: Building HVAC Operating Conditions Assessment for D2.5 Particle Concentrations	
Ambient air	
Wind speed	1, 2, 3, 4, 5, 6, 7, 8, 9, 10 m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0 °), RF (180 °)
AHU attachment	Inlet 1
AHU flow rate	1296, 2592, 3888 m ³ /hr
PM particles	
Particle diameters	2.5 µm (D _{2.5})
Particle drag	Irregular – shape factor 0.4
Particle density	2 g/cm ³
Case study 2: Aspiration Efficiency Comparison of a Generic and Louvered Commercial AHU Inlet	
Ambient air	
Wind speed	1.5, 2.5, 5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0 °), RF (180 °)
AHU attachment	Inlet 1, Inlet 2
AHU flow rate	3400 m ³ /hr
PM particles	
Particle diameters	2.5, 10, 20, 35, 50, 65, 90 µm (D _x)
Particle drag	Irregular – shape factor 0.4
Particle density	2 g/cm ³

The air viscosity and particle density were held constant at 1.79E-05 kg/ms and 2 g/cm³ respectively. The PM mass flow rate was also calibrated within the model based upon an average wind speed of 6 m/s to produce a mean concentration of 7 µg/m³ as described by Morgan et al. [151], which was observed at roof level in Dublin City Centre, Ireland. Steady-

state conditions for both PM concentrations and velocity were monitored during the modelling process. Concentrations of PM were monitored at both the ambient and AHU velocity inlets and a time-averaged sample over 10s period was collected under steady-state conditions in order to calculate AE.

5.2.3 AHU Grid Verification at Design scale

A grid verification check was conducted on the grid density to ensure the quality of the solution are not affected and grid independence has been achieved. The grid arrangement used in the full-scale model testing of the commercial rainhoods and AER-AHU design were verified using the well-known and internationally accepted GCI described in Section 3.7.1. This approach employs three grids that have been refined (i.e., grid cells become smaller) to determine the grid discretisation errors [219]. An error band can be configured for the finest grid with respect to an extrapolated true solution, and the results can be used where GCI values are low to determine if grid independence has been achieved [223]. A coarse, medium and the fine grid were created with an average cell size of 0.08 m, 0.04 m and 0.02 m respectively, and were used to discretise the AHU body and relevant flow regions within the domain. The grid was designed near the wall to achieve a Y^+ that is approximately equal to 1. A minimum cell size of 0.0001 m and an average cells size of 0.005 m was applied around and inside the cylindrical AER inlets (i.e., relating to chapter 6) and/or commercial rainhood walls. In addition to determining the spatial discretion errors, GCI also accounts for errors incurred by temporal discretisation. Therefore, a time step of 5×10^{-4} s, 1×10^{-3} s and 2×10^{-3} s were used to ensure the time step was also grid independent.

The grid independence test results were based on the sampled velocity magnitudes extracted at a total of 110 locations upstream, above the AHU centre and downstream of the AHU body at z/z_{ref} of 0.2 and 0.35, 0.55 respectively as shown in Figure 37. The maximum GCI of the finest grid was found to result in an acceptable value of 6.5% as this ensures the velocities do not experience large changes and an average value of 0.5%. Of the 110 locations examined, 8% of the sampled velocities exhibited oscillatory convergence in zones where eddy formation has occurred due to boundary layer detachment as can be seen in Figure 37b-c such as close to the AHU roof and near the AHU inlet.

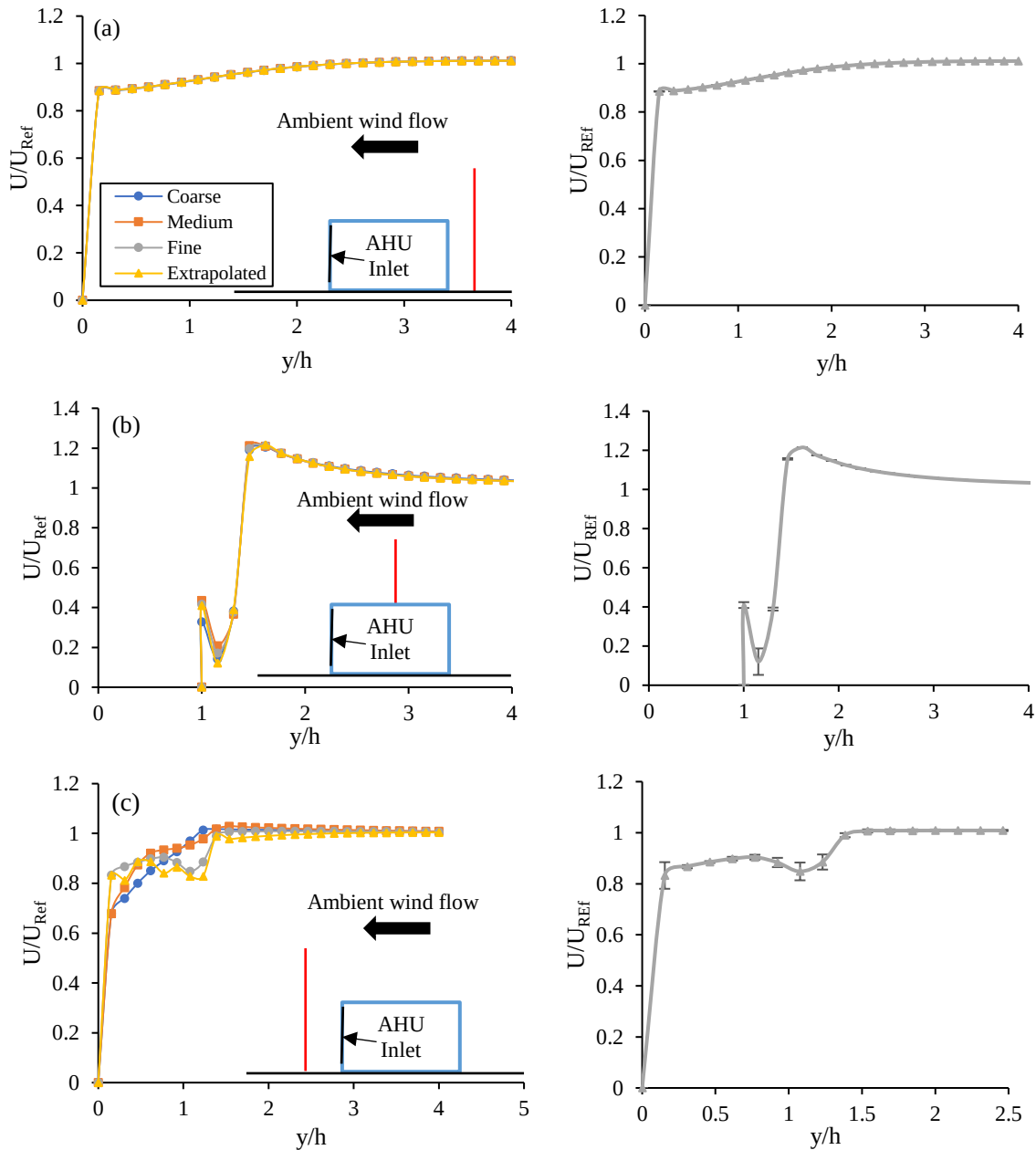


Figure 37. Velocity profiles and error bars for grid independence study of a rear facing AHU conducted (a) upstream of the AHU body (b) above the centre of the AHU body, and (c) downstream of the AHU Inlet; at a reference wind velocity of 7.5 m/s.

5.3 RESULTS

5.3.1 Building HVAC Operating Conditions Assessment for D_{2.5} Particle Concentrations

The effect upon AE of varying the ventilation flow for the AHU with Inlet 1 was assessed as the flow rate within a building HVAC system will change depending on the building's fresh air supply demand. The magnitude of the corresponding suction velocity will influence

the surrounding environments air flow field and have a significant impact on the concentrations of PM drawn into the ventilation system, as previous literature would suggest. An analysis on the response of AE to the ventilation flow rates and ambient wind velocity is shown in Figure 38 for a FF and RF AHU relative to the wind direction. As the ventilation velocity of the AHU increased, there was typically a corresponding increase in AE for both a FF and RF AHU. The exception being for the FF AHU where only a negligible difference in AE was observed between ventilation velocities of 2-3 m/s. The results also show that there is little variation in AE as the ventilation velocity changed for a forward-facing AHU at low wind speeds.

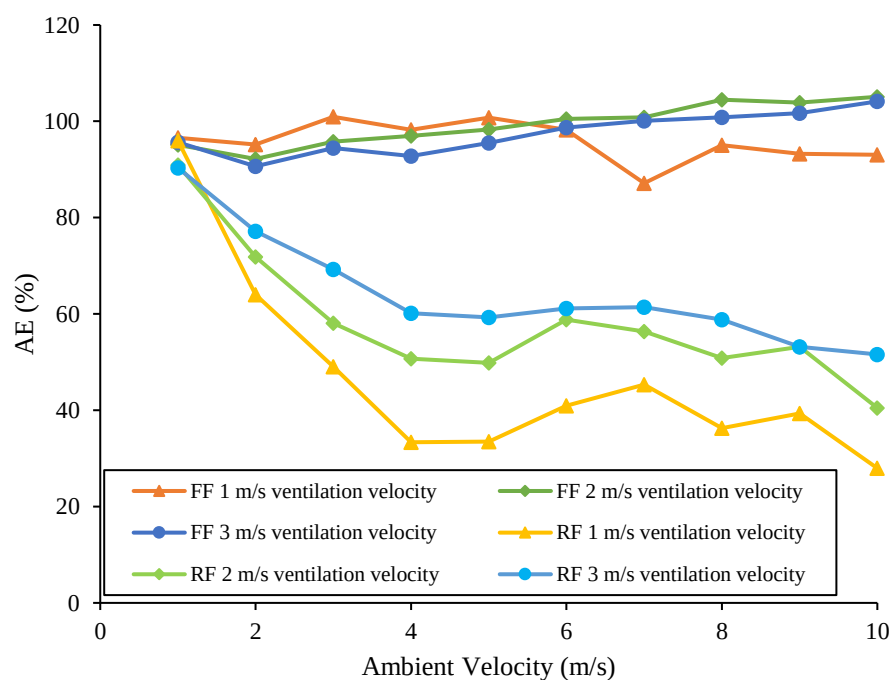


Figure 38. Effect of ventilation velocity and ambient wind speed on the AE for AHU-Inlet 1 for $D_{2.5}$ particle concentrations.

The AE of the FF AHU was found to increase as the ambient wind speed increases at a ventilation velocity of 2 and 3 m/s. This trend was not observed at a ventilation velocity of 1 m/s where there was no major discernible difference in AE across the wind speed range tested. This suggests that the momentum at the AHU inlet was not large enough to induce particle rebound and entrainment conditions as opposed to the larger ventilation velocities where AE continually increased and eventually exceeded the ambient PM concentrations. Beyond 5 m/s in ambient wind speed, the difference in AE between the lowest and both larger flow rates become increasingly large. At a wind speed of 10 m/s there is approximately

a 12% difference in AE at the lowest ventilation velocity in comparison to the highest. The RF AHU with Inlet 1 in Figure 38 was found to more effective at reducing PM concentrations in the ventilation system in comparison to its counterpart, the FF AHU, even at the highest flow rate. Similarly, the RF AHUs lowest flow rate was found to produce lower AE values than the higher flow rates at all wind speeds tested. The rear-facing configuration resulted in significantly different AE values and a higher variability about the mean AE compared to the forward-facing configuration. This was attributed to the turbulent conditions that forms around the AHU inlet and boundary layer separation which appears to have a major effect on the ambient PM concentration gradients.

When examining the RF AHU at a constant ventilation velocity, results tended towards lower AE at mid to high ambient wind speeds in comparison to low wind speeds of 1-2 m/s where a large increase in AE was observed. At wind speeds larger than 3 m/s, there was not a significant difference in AE values across their respective ambient wind speed range. This suggests that as the particle momentum increases, AE decreased, and a negative linear correlation was observed as illustrated in Figure 38.

The average AE was examined in Table 6 using the results from the wind velocity distribution in Figure 38 over the ambient wind velocity ranges of 1 to 10 m/s. The results show a large variation in the mean AE between ventilation velocities for the RFAHU. It can be postulated that this is attributed to the variance of the data sets caused by the wake formation and momentum of the AHU inlet. Furthermore, a linear decrease in the average AE over the velocity range was observed for the RF AHU. While no significant difference in the average AE was found when changing flow rates for a FF AHU.

The results have shown that the orientation of the AHU with respect to ambient wind direction has a considerable effect on the AE. This is due to the sudden change of direction that the particle must undergo to be drawn into the ventilation system for the RF AHU. Considering the mean ambient particle concentration (averaged over wind speed range 1-10 m/s) of $20 \mu\text{g}/\text{m}^3$ used the resulting mean concentrations in the forward and rear-facing AHUs ranged between $19\text{-}20 \mu\text{g}/\text{m}^3$ and $9.3\text{-}12.8 \mu\text{g}/\text{m}^3$, respectively, as taken from the results in Table 6. Differences in particle concentration of this kind in the AHU inlet are likely to have a significant impact on the loading rate of particulate matter on downstream filters, which in turn would greatly impact on building energy consumption. A limitation of this analysis lies in the fact that single diameter particle sizes were modelled using CFD here

and are compared to concentrations of $PM_{2.5}$ from the field which contains a range of particle sizes. A wider range of particle sizes are examined in the following section (2.5 to 90 μm).

Table 6. Mean AE across ambient wind velocity range of 1-10 m/s for $D_{2.5}$ particle concentrations taken from case study 1 with AHU Inlet 1.

Ventilation velocity	Forward-facing Inlet 1		Rear-facing Inlet 1	
	Average	S.D.	Average	S.D.
1 m/s	95.8%	4.1 %	46.6%	20.1 %
2 m/s	99.6%	4.4 %	58.1%	14.1 %
3 m/s	97.4%	4.3 %	64.2%	11.8 %

5.3.2 Aspiration Efficiency Comparison of a Generic and Louvered Commercial AHU Inlets

An analysis of the two inlet configurations was conducted to investigate if their different design characteristics have any notable effect on AE, based upon their corresponding St as illustrated in Figure 39. The results showed that for both AHU inlets and the four wind speeds tested here, the RF AHU is substantially more effective at reducing PM concentrations for all particle sizes in comparison to the FF AHU. Again, this was found to be the most important variable with regards to reducing AE and its effect is more discernible with both increasing particle size and ambient wind speed. As both the momentum and inertia of the particles becomes larger, the particles are more likely to maintain their original trajectory and not that of the AHU fluid streamlines. Either increasing one variable or both will make it increasingly more difficult for the AHU inlet to draw in the particles. Therefore, as the particle momentum rises both through increased mass and faster wind speeds, AE was seen to decrease in Figure 39 with increasing St . The resulting AE trendline tended towards zero for all the wind speeds tested for both RF Inlet 1 and 2. For example at a wind speed of 5 m/s and 7.5m/s where $St \gg 1$, AE was found to be less than 1% as illustrated in Figure 39c-d. In the case of both lower wind speeds in Figure 39a-b, there was a continuous decrease in AE as the St increased.

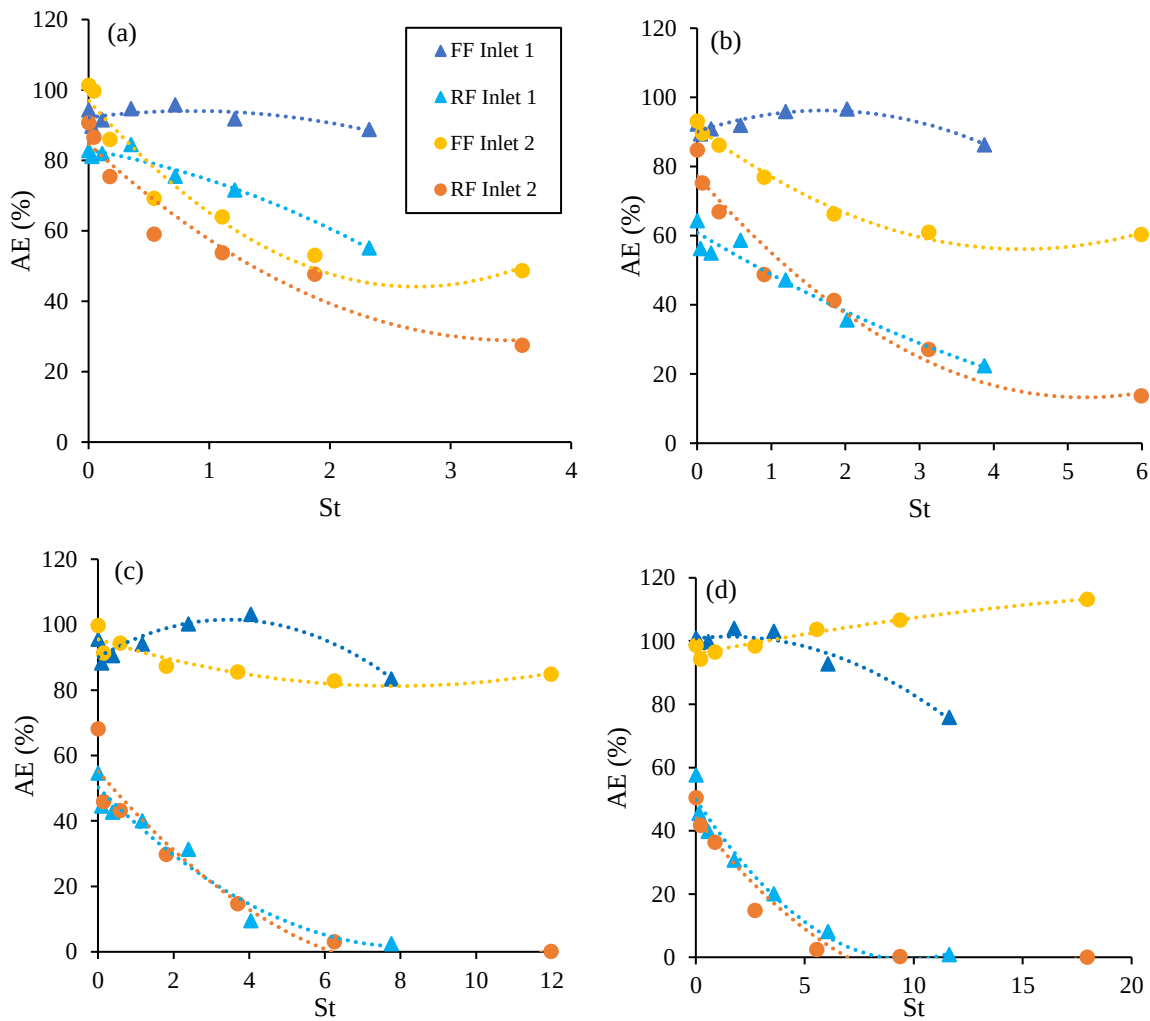


Figure 39. Variation of aspiration efficiency as a function of Stokes number for commercial AHU inlets where (a) $R=0.6$ (b) $R=1$ (c) $R=2$ (d) $R=3$ and an AHU flow rate of $3400 \text{ m}^3/\text{hr}$. Note: particle diameters and wind speeds shown in Table 5, case study 2.

Whereas the FF AHU Inlet 1 typically recorded high similar AE values regardless of particle size and it was found that the geometric design had a major effect. In the case of Inlet 1 which incorporates a single large orifice and is more open to the atmosphere, there was not much variation in AE as the wind speed or particle diameter changes. Conversely the louvered model, Inlet 2, generated larger AE values when both wind speed and particle diameter increased. This occurred as the louvered wall surface area is greater in comparison to Inlet 1 and therefore more exposed to the oncoming wind. The particle motions will be largely dominated by the convective turbulent flow and inlet placement relative to the wind. Variation in particle concentration gradients within the fluid domain were generally affected by diffusion and convective transport throughout. Wall-bounded flow and areas with decreasing turbulence also generated conditions for turbophoresis of inertia dominated

particles. For example, the convective mass transport of PM of varying size into the AHU inlet will lead to greater impaction on the louvered walls. This creates conditions that are more susceptible to secondary aspiration through particle entrainment and rebound, especially with increasing particle diameter due to inertial impaction.

The variation in AE between both types of FF AHU's was largely at higher St and their differences were negligible at $St \ll 1$. The louvered model generated AE as high as 113% at a wind speed of 7.5 m/s and its highest St value, while Inlet 1 only incurred an AE of 76%. Considering that the RF AHU Inlet 1 and 2 resulted in $AE < 1\%$ at equivalent conditions, there would be a significant difference in the PM filter loading rate. Previous studies on the human mouth and nose, and on thin-walled aerosol samplers, have shown an averaged AE range between 20-105% across similar ambient wind speeds for particle diameters up to 100 μm [4,229]. Where the FF Inlet 2 outperformed Inlet 1 with the same orientation was in the St range of 1-5 (i.e., mid-sized particles and slower speeds). Instead AE was reduced with decreasing wind speed and in contrast with the AE of Inlet 1, resulted in very little variation in their respective trendlines and between particle sizes.

The results from Figure 39 illustrate the difference between RF Inlet 1 and 2 with regards to AE and their trendlines were not as dissimilar as the forward-facing AHU's. The RF Inlet 2 at $R = 0.6$ was more efficient at reducing PM concentrations, as St increases. Although at the minimum St number, Inlet 1 was preferred. As the wind speed increased and $R = 1$, the RF Inlet 1 generated lower PM concentrations within the ventilation system. At the highest wind speed of $R = 2$ and $R = 3$, there was very little variation in the results between both inlets. Inlet 2 was found to be more efficient and approached zero at a lower St number. The variation in the profiles as R changes are due to the effect of increasing wind speed on particle momentum, in particular for the RF configurations. Results from RF AHU Inlet 1 of the D_{90} particle AE is 27.5 %, 22.4 %, 0% and 0% for 1.5 m/s, 2.5 m/s, 5m/s and 7.5m/s respectively. As particle momentum reduces, the particles are deposited closer to the AHU leading to higher AE. Similar observations can be drawn from the rear-facing Inlet 2 results as R changes. As shown in Section 2.3.5, the PM size distributions can vary region to region and therefore the reduction in AE for the larger particles could provide greater benefits in for example, a desert region. Sandstorm events and larger particle from natural sources could have a greater influence on a filters loading rate compared to Dublin, Ireland.

In contrast, the FF AHU variation in profiles are more dependent on particle momentum, which is greater near the AHU Inlet for this orientation due to the alignment of the velocity vectors and their impaction with the AHU inlet configuration walls. The FF Inlet 1 is mostly open to the atmosphere with a single large orifice, the values are typically between 90-103%, which would be expected (i.e., close to ambient concentration). A larger variation is seen with FF Inlet 2 due to the aforementioned build up on their respective louver walls at high wind speeds. AE lowers with increasing St at low R values for Inlet 2 as the particle momentum is not high enough to generate significant impaction conditions and force the larger particles beyond the louvered inlets into the AHU. Again, the velocity ratio, R , has a major influence on AE due to its relationship with St through the effect of changing ambient wind velocity. Generally, there were only minor differences in AE between both inlets at the higher wind speeds and the inlet design was not as dominant as seen at the lower wind speeds.

The mean AE was examined in Table 7 at various R values and shows that for both the FF and RF Inlets, Inlet 2 had the best performance levels overall. In particular the RF AHU Inlet 2 was particularly effective at $R = 0.6$ and $R = 3$ and the difference in AE from the R range 1-2 was small. This further signifies the importance of the orientation of the AHU with respect to the prevailing wind direction and the inlet geometry design on AE over a range of PM sizes and wind speeds. The main variation occurred with the FF AHU's datasets. AE increased linearly for Inlet 2 as R increased and was ranged from 75-102%. The FF AHU Inlet 2 was the only configuration that demonstrated this relationship. Whereas both Inlet 1 orientations and the RF Inlet 2 displayed a negative linear relationship between R and AE as shown in Table 3. Albeit, FF Inlet 1 AE values were reasonably similar and only a slightest decrease in AE was observed as R increased and was ranged from 92-97%. While the two most pertinent positions were examined in this study, the literature on AE, typically found that a side facing (SF, 90°) or any angle investigated within this range will have AE values between the FF and RF results. Therefore, those orientations were not modelled in this study as they were not required for a design study but the SF has been accounted for in Chapter 7 numerical study of an AHU in a full urban environment.

Considering a mean total PM concentration, C_o , of $20 \mu\text{g}/\text{m}^3$ across a range of St (i.e., 2.5-90 μm) within the ambient freestream air entering the model domain. At low ambient wind velocities (i.e., $R=0.6$), the mean total PM concentrations, C , between the commercial inlets would range between $15.2\text{-}19.4 \mu\text{g}/\text{m}^3$ and $12.6\text{-}15 \mu\text{g}/\text{m}^3$ for AHU Inlet 1 and 2 respectively.

This would result in a significant difference in the filter loading rate with a constant PM source emission. The ranges are different for each model due to the increasing variation in AE when R increases as shown in Table 7.

Table 7. Mean AE across an equivalent aerodynamic particle range for commercial Inlets 1 and 2 at a constant R value.

R	Forward-facing inlet				Rear-facing inlet			
	1		2		1		2	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
0.6	97%	2.7 %	75%	21.4 %	76%	10.3 %	63%	22.6 %
1	94%	3.6 %	76%	13.8 %	49%	14.8 %	51%	26 %
2	92%	6.9 %	89%	6 %	32%	19.3 %	29%	24.9 %
3	92%	9.9 %	102%	6.6 %	29%	20.5 %	21%	21.6 %

5.3.3 Comparative Analysis into the Similarities Between the Aspiration Efficiency of 2D and 3D Numerical AHU Models

The 2D models representing a cross section on the YZ plane of the AHU centre were developed to determine if 2D models produced similar results to the 3D models and is a viable method for examining AE. The results were mixed on the applicability of using a 2D approach when examining the impact upon AE of the AHU flow rate and ambient wind speed. Some models were an excellent match, while others had large discrepancies in AE. The FF 2D and 3D models shown in Figure 40a have reasonably similar trendlines at ventilation velocities of 2 m/s and 3 m/s.

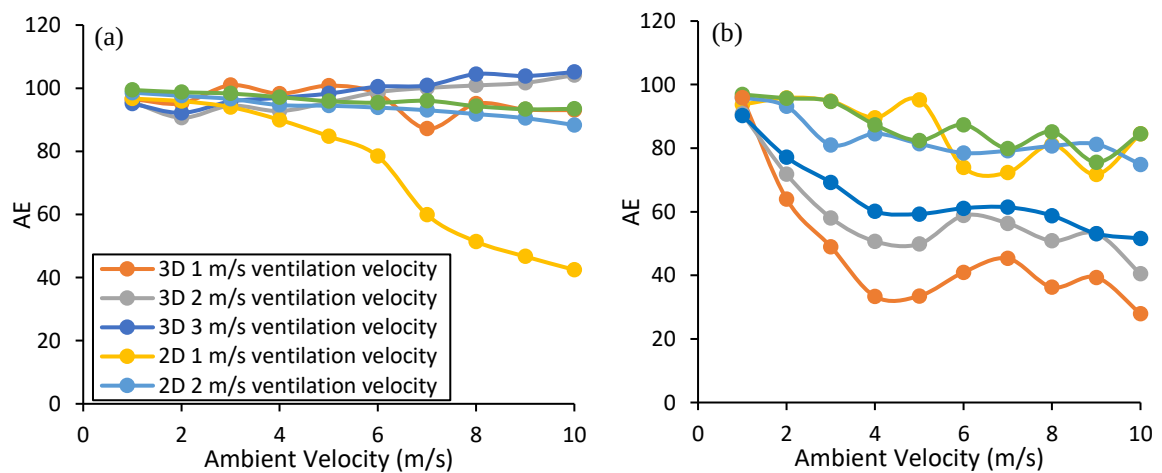


Figure 40. Comparison between the AE of $2.5 \mu\text{m}$ diameter particles with a 2D vs 3D model through the effect of ventilation velocity and ambient wind speed on the AE for AHU Inlet 1 where (a) Forward-facing (b) Rear-facing; for $D_{2.5}$ particle concentrations.

Whereas at the lowest flow rate of 1 m/s, there exists a noticeable difference in AE above a wind speed of 4 m/s which becomes larger as the wind speed increases. The differences between both methodologies becomes more significant when examining the results from the RF model in Figure 40b. There is greater uncertainty to the 2D model results with no clear variation in AE as the AHU flow rate changes across the 1-10 m/s wind speed range. The 2D models all resulted in a much higher magnitude of AE across the wind spectrum tested in comparison to the 3D models apart from 1 m/s.

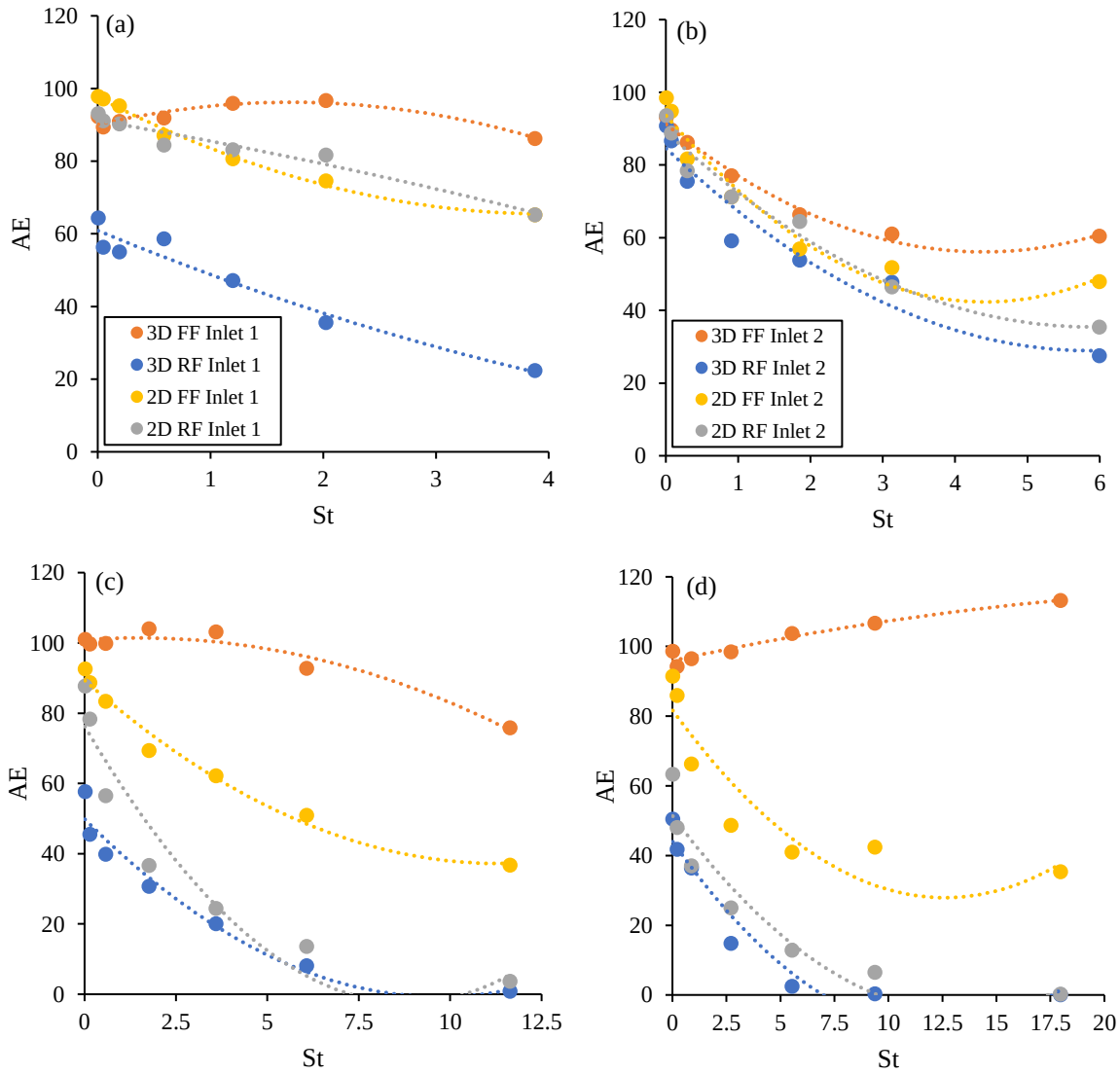


Figure 41. Comparison between the AE of a 2D vs 3D model for both Inlets at a wind speed of (a-b) 2.5 m/s (c-d) 7.5 m/s; and an AHU flow rate of 3400 m³/hr; taken from case study 1 with AHU Inlet 1.

The variation in AE as the St number changes was also examined for both inlet designs with 2D numerical simulations. At the lower wind speed of 2.5 m/s in Figure 41a-b, the 2D louver

model trends are similar to the 3D for both orientations but again drastically different for the generic Inlet 1. Only as the particles become larger and the wind speed increases does the 2D and 3D results match each other for Inlet 1 when rear-facing as shown in Figure 41c. At a wind speed of 7.5m/s the 2D FF Inlet 2 in Figure 41d is also not representative of the 3D model. However, the RF Inlet 2 2D and 3D trendlines are similar with only a slight increase in AE for the former.

As expected, the average AE across the St spectrum of the 2D models is lower for the forward-facing in contrast to the rear-facing in Table 8. Only at the lower wind speed of 2.5 m/s and for Inlet 2 is there a reasonable match between the average AE when compared with Table 7. And the error difference is not as significant for higher wind speeds when considering RF models as the particle momentum becomes dominant.

Table 8. Mean AE across an equivalent St range for 2D commercial Inlets 1 and 2 at a constant R value.

R	Forward-Facing Inlet				Rear-facing Inlet			
	1		2		1		2	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
1	85%	13 %	74%	20%	84%	10 %	72%	18 %
3	69%	23 %	62%	22%	42%	31 %	31%	23 %

5.4 DISCUSSION

5.4.1 Analysis of the Ambient Wind Velocity Vector Distribution for the Generic and Louvered AHU Inlets and the Effect of the Boundary Layer upon AE

The numerical model was found to be effective at analysing the PM dispersion over an AHU on a building rooftop. The AE of the various AHU configurations tested was found to be analogous to the characteristic performance of PM monitoring equipment published in previous investigations [3,133,140,142]. Decreasing the ventilation velocity and/or increasing the ambient wind speed for a FF AHU caused the impaction of the particles into the inlet generating higher AE at equivalent St values.

In the case of FF AHUs for both Inlets in Figure 42a-b, it can be seen that there is no variation in the vector orientations around the AHU inlet as the wind speed increases. The only noticeable effect is the change in magnitude of the velocity vector field around the AHU inlet. Inlet 1 is more open to atmosphere and both the trends illustrated in Figure 39 and the mean AE in Table 7, demonstrated the lack of variation in AE as R increased.

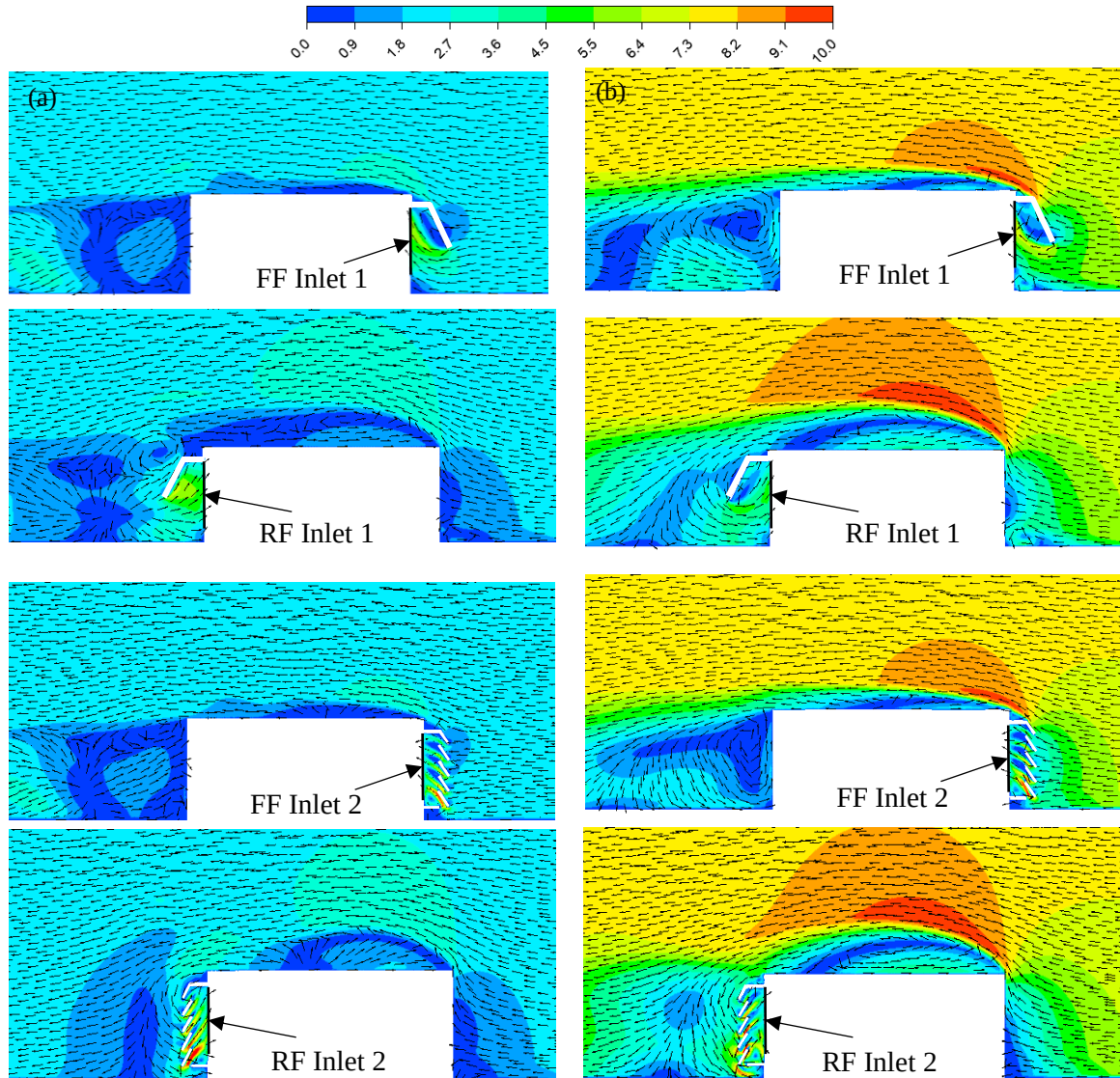


Figure 42. Wind flow field analysis (m/s) on YZ plane intersecting the centre of a FF and RF AHU at a wind speed of (a) 2.5 m/s (b) 7.5 m/s; and an AHU flow rate of 3400 m³/hr.

As shown previously, the performance of Inlet 2 was significantly different from Inlet 1. This was attributed to the dissimilar inlet designs. A rise in the AE of Inlet 2 was observed as the wind speed rose in comparison to Inlet 1 where AE was constant as St increased. This occurred as there was a large proportion of the particle laden wind flow being directed onto the walls on forward-facing Inlet 2 due to the louvered design as illustrated in Figure 42a-b,

and this was the cause of secondary aspiration. This generated PM concentration within the ventilation system that were greater than the ambient PM concentrations. Whereas, Inlet 1 only had a single face that diverts the ambient flow into the inlet and over the AHU roof and did not provide conditions for secondary aspiration.

There is a significant variation in the ambient flow field dynamic for a rear-facing AHU for both Inlet 1 and 2 in comparison to the forward-facing AHUs, as shown in Figure 42. Inlet 1 at the lower wind speed of 2.5 m/s generated an eddy upon the face of the Inlet geometry when the boundary layer detaches at the edge of the AHU body. As the wind speed increases to 7.5m/s, no eddy formation occurred at this location due to increases in the momentum of the ambient wind forcing the fluid down the slope of the Inlet 1 walls. In contrast, the flow field of Inlet 2 had a vector distribution similar for both speeds and is analogous to Inlet 1 at a wind speed of 7.5 m/s. The only variation is the point where the boundary layer reattaches in front of the AHU, with Inlet 1 reattaching the furthest from the inlet. The velocity vectors observed for a RF AHU Inlet 2 in Figure 42a-b demonstrates a large proportion of the ambient flow being diverted into the louvered faces after boundary layer detachment. Smaller particle diameters are more susceptible to following the fluid streamlines and this was attributed to the slightly higher AE observed in Figure 39 at low St for both Inlets. Upon examination of the rear of the AHU on the FF AHU, a large stagnant zone has formed. When the inlet is positioned here (i.e., RF AHU), the stagnant zone has been either eliminated or drastically reduced in scale and magnitude by the suction force of the AHU inlet.

A wind flow field analysis was also conducted on the mid plane of the AHU (i.e., 0.5h on ZX plane) as shown in Figure 43. At a wind speed of 2.5 m/s, there is very little variation between the FF configurations. Although the RF AHU inlets when compared generate slightly different vector flow fields. The re-circulation zones in front of Inlet 1 are larger than Inlet 2. This created a larger mixing zone around the AHU that led to higher mean PM concentrations being drawn into the AHU as shown in Table 7. In particular the impact on AE becomes more noticeable as the St number increases. Whereas Inlet 2 has a smaller recirculation zone but with more intense circulation. The suction force of both inlet types also created stagnant zones on the side of AHU which did not occur in the forward-facing AHU's. As the wind speed increased to 7.5 m/s, the flow dynamics are very similar but with a noticeable increase in the velocity magnitudes. The recirculation zones in front of the rear-facing AHU inlets has become larger. Yet the increase in particle momentum led to a decrease in potential for the particle trajectory to follow the ambient air streamlines. This

was seen previously where the higher wind speeds for the RF AHU were accompanied with lower AE for equivalent aerodynamic particle diameters.

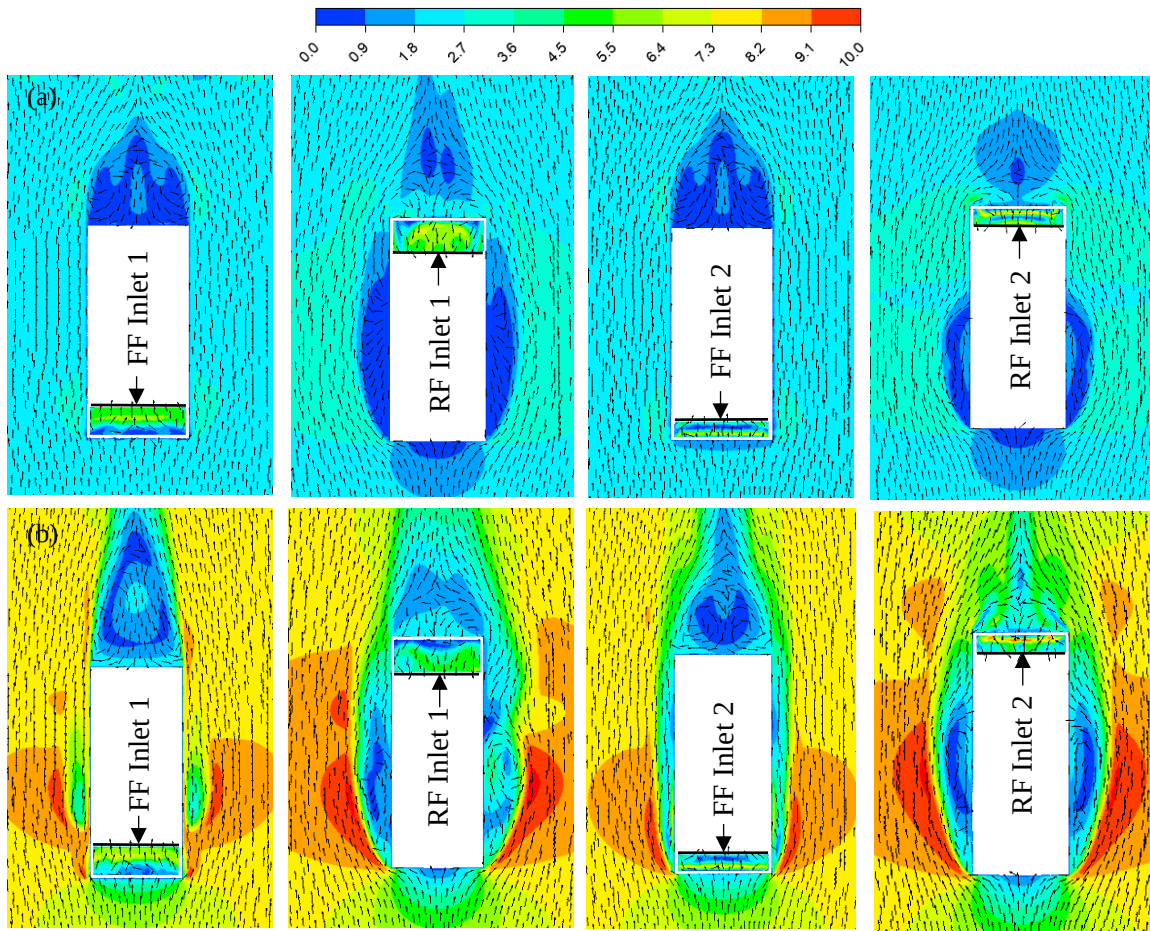


Figure 43. Wind flow field analysis (m/s) on ZX plane at 0.5h of both FF and RF AHU at a wind speed of (a) 2.5 m/s (b) 7.5 m/s; and an AHU flow rate of 3400 m³/hr.

Finally, Figure 42 and Figure 43 demonstrated the variation in the flow patterns at both the interface between the ambient environment and inlet design, and near the AHU filter inlet. A small stagnant zone formed on the underside of Inlet 1 walls as boundary layer separation occurred through both a combination of the wind and AHU ventilation velocity. The results show the stagnant zone expanded in size as the wind velocity increased for both a forward and rear-facing AHU Inlet 1 configuration. Inlet 2 had a smaller internal compartment (i.e., from AHU inlet to louvered faces and to AHU inlet) but multiple ports. Boundary layer separation is especially prominent for the FF AHU inlet 2 as the wind comes into contact with the louvered faces and separates at the rear of each louver blade. The exception being the louvered blade located closest to the ground. This was attributed to the slightly different design to the other louver openings due to the flat base which also generated higher velocities

at the environment/AHU interface. The stagnant zones are much larger for forward-facing AHU as the ventilation flow rate air vectors direction are more closely aligned with the oncoming wind increasing the speed of the flow over the walls of AHU Inlet 1 or 2.

5.4.1.1 2D Analysis of the Ambient Wind Velocity Vector Distribution

Comparing the velocity vectors of the fluid flow between a 2D and 3D models shows that the flow patterns are similar for a FF AHU at both high and low wind speeds as shown in Figure 44. Therefore the differences in AE arise from the DPM model used and the application of 2D geometries and their associated trajectories to the solid PM particles. At low St (i.e., in the fine PM range), the particles will be more readily directed into the AHU inlet and this results in similar AE values. Large variations occur when the particle diameter is increased and the particles are more likely to maintain their original trajectories and the use of a single plane model did not result in any secondary aspiration.

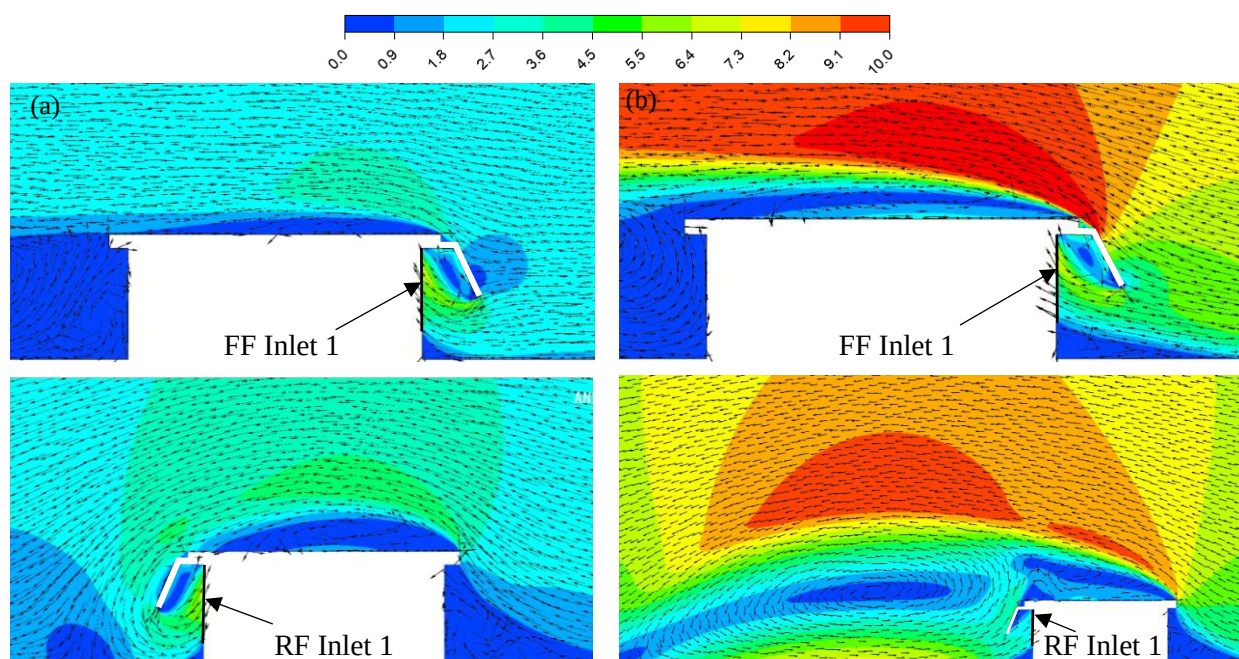


Figure 44. Wind flow field analysis (m/s) on YZ plane intersecting the centre of a 2D FF and RF AHU at a wind speed of (a) 2.5 m/s (b) 7.5 m/s; and an AHU flow rate of 3400 m³/hr.

Although there are significant differences in the wind flow patterns around the AHU for the RF models. This resulted in varying AE when comparing both particle diameters wind speeds as shown in Figure 41 between 2D and 3D models. The restrictive 2D models resulted in a large eddy formation in front of Inlet 1 and flow re-attachment occurred far down stream of the AHU compared to the 3D model at high wind speeds. At a wind speed of 2.5 m/s,

both models had similar reattachment points but the 2D model did not capture the eddy formation on the rainhood and the flow patterns were more simplified.

5.4.2 Rooftop Particulate Matter Concentration Distribution Contours

The PM concentrations contours in Figure 45 illustrate the variation in AE as the St number increases. The first set of pictures in Figure 45a depict the dispersion characteristics of $D_{2.5}$ concentrations for both inlet types in a FF and RF orientation relative to the wind direction. The contours show a higher concentration being drawn into the filter inlet for the FF AHU and this would coincide with the larger AE values seen in Figure 41 in comparison to the RF AHU's. Similarly, the D_{90} concentrations shown in Figure 45b, illustrate a large amount of PM being drawn into the FF system for both AHU Inlet 1 and 2.

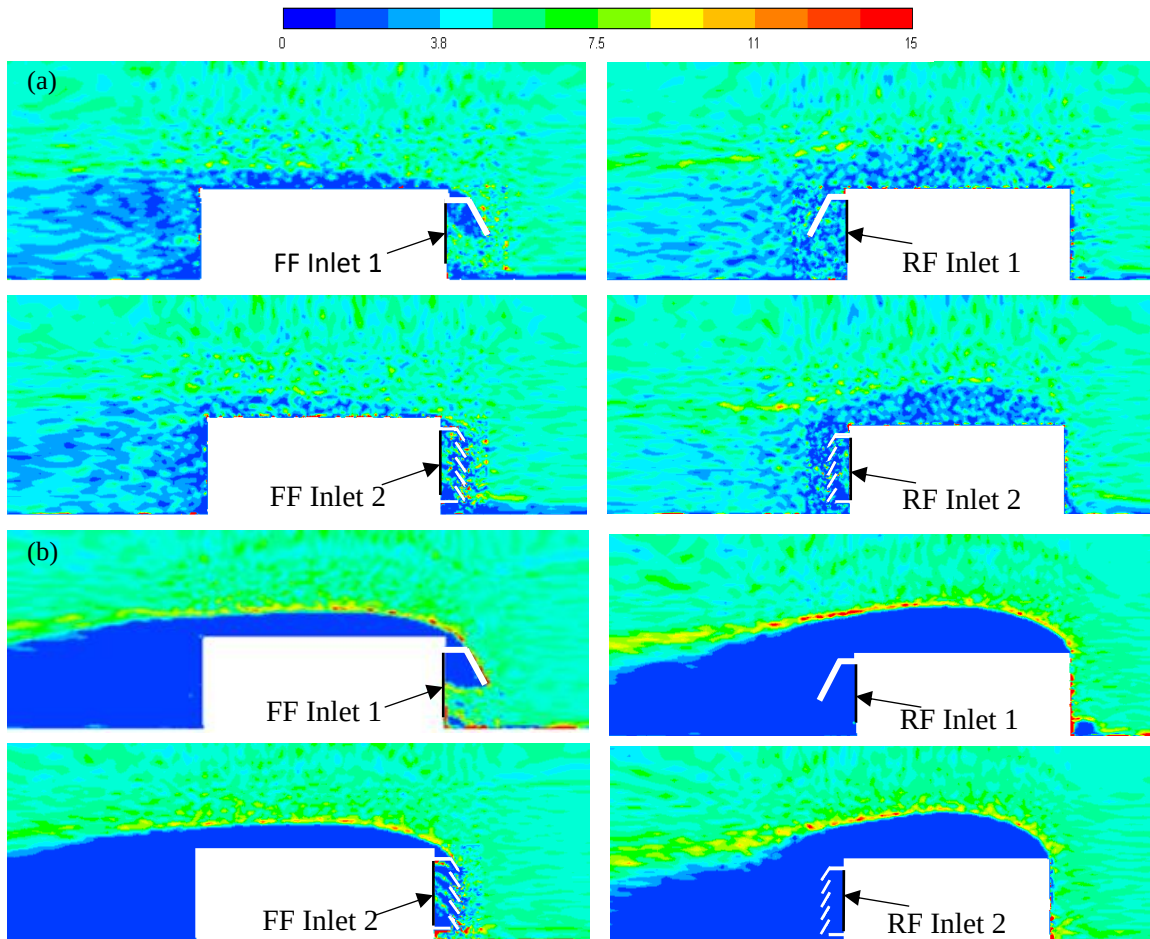


Figure 45. PM concentrations contour ($\mu\text{g}/\text{m}^3$) on YZ plane intersecting the centre of the AHU where (a) $D_{2.5}$ (b) D_{90} ; with an AHU flow rate of $3400 \text{ m}^3/\text{hr}$ and wind speed of 7.5 m/s .

The RF AHU for both inlets contours in Figure 45b demonstrate why there is such a massive difference in AE between the smaller and larger particles. The larger particle follows their original trajectory and are not drawn into the system or settle near the AHU Inlet, which caused $AE < 1\%$. Whereas the FF AHU Inlet 2 at this wind speed exceeded the ambient concentrations, from secondary aspiration and this phenomenon can be seen at the bottom of the inlet. A large concentration has built up and is being drawn into the ventilation system. In comparison, the D_{90} PM concentrations in Inlet 1 were less than 100% as the build-up on the geometry face was displaced over the AHU roof and not into the filter inlet. The PM contours were also examined on a plane perpendicular to the plane in Figure 46. There were similar PM concentration patterns where the lighter particles are more abundant around the AHU inlet's and the larger particles follow their original trajectory. Of interest is how the FF AHU inlet impacts the fluid flow around the AHU sides. In Figure 46b, the side eddy formed by the suction effect of Inlet 1 altered the boundary layer around the AHU, leading to a variation in the PM dispersion. In contrast, Inlet 2 did not generate these conditions and the boundary layer has become thinner around the AHU.

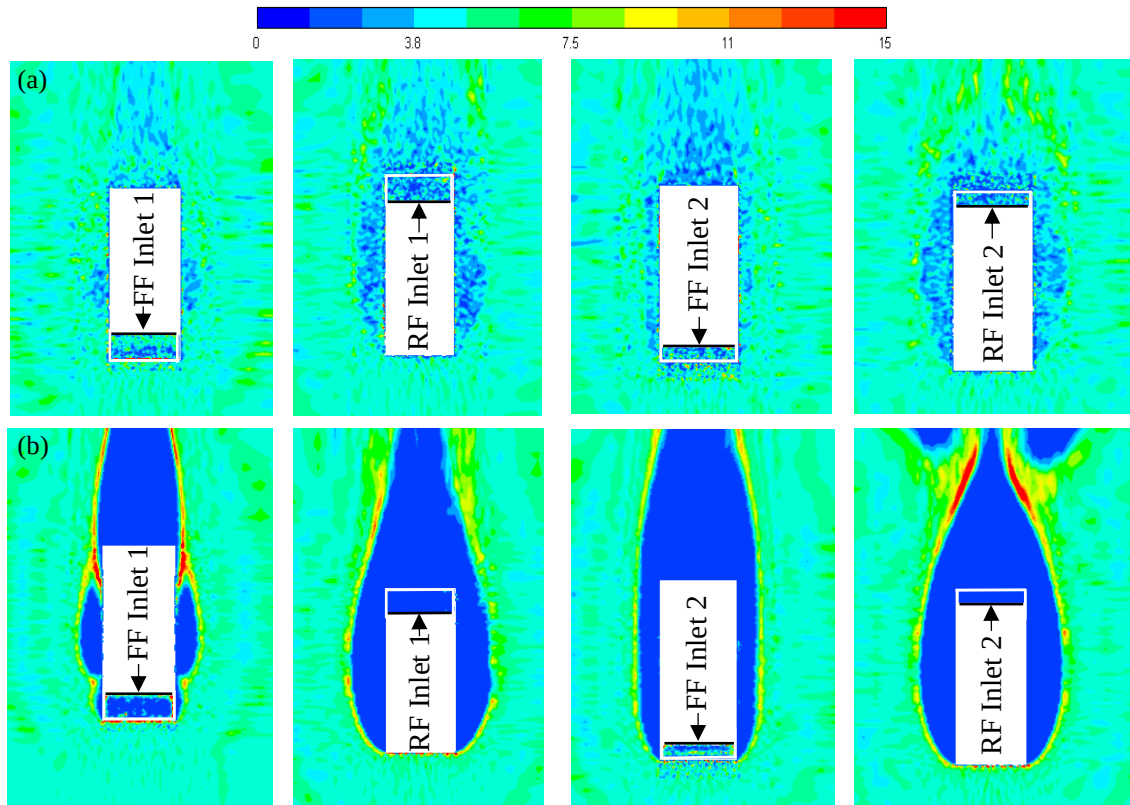


Figure 46. PM concentrations contour ($\mu\text{g}/\text{m}^3$) on ZX plane intersecting the AHU at 0.5h where (a) $D_{2.5}$ (b) D_{90} ; with an AHU flow rate of $3400 \text{ m}^3/\text{hr}$ and wind speed of 7.5 m/s .

5.4.3 Commercial Inlet Design and their Implication upon AE Concepts

The concept of AE has been previously used in the design and performance assessment of PM monitoring devices when an AE of 100% is desirable to ensure the quality of measurements. However, the reverse is most desirable (i.e., AE of 0%) for a ventilation system. The design of each inlet examined here did not consider their impact on AE and subsequent concentration of particles entering the ventilation system, as their primary purpose is rain cover not air pollution control. However, each design was shown to induce differing AE values at different magnitudes of St. The inlets were quite different in their designs considering the difference in the number of orifices, orifice size, aerodynamic design, and inlet surface area. This implies that a combination of various AE concepts could be used to reduce the concentration of particles entering the ventilation system and consequently deposited on the filter or transported into the building. Inlet 2 was more effective at lower velocity ratios and for a RF AHU. The particles had a sharper trajectory and the spread of the inlets from the ground to the roof of the AHU caused lower AE at higher St numbers. The larger particles will also tend to settle towards the ground where the single orifice is drawing a large volume of air from.

Conversely at lower St values, Inlet 2 was less efficient at preventing the transportation of the particles into the ventilation system as there were more streamlines being directed onto the louvered face in comparison to the single face used by Inlet 1. This effectively stipulates potential design criteria for limiting the entry of small and large particles in the development of future commercial inlets designed with consideration of AE concepts. Furthermore, the results show significant scope for development of new AHU inlet designs that could respond to changes in wind direction. Considering the significant variation in AE between a FF and RF AHU, irrespective of the inlet configuration, a novel PM control system for an AHU that responds to the wind direction could lead to substantial energy savings.

The results from Figure 38 found the lowest AE occurred with the combination of a RF AHU and low ventilation flow rates. Lowering the intake velocities for any novel commercial inlet attachment would also be of added benefit but is more difficult to achieve. This was attempted by Morgan et al. [151] when designing an AER with an array of cylindrical orifices which incur intake velocities < 1 m/s. But designing an AER with larger orifices that lowers intake velocities while maintaining the same surface area as the AHU body is difficult and even more so as the AHU's become larger. For the cylinder diameters to become larger and lower the intake velocity, a number of cylinders would need to be removed, lowering

the array number. This would result in small gains to the intake velocity and worsening conditions when facing into the particle laden wind. This approach is again limited by the available surface area in the AHU body face. AER designs in Chapter 6 that consider the wind direction were determined to be a more viable route for lowering AE for this reason. In the case of Inlet 1, the intake velocity is essentially at its minimum without overly extending the rainhood away from the AHU body. Louvre designs could be lowered further such as Inlet 2 but the increase to the intake surface area would again be small as the louvres orifices are restricted by the number of ports and angle of the louvre blades.

5.4.4 Effect of PM Filter Loading on Energy Consumption

The built environment has been identified as a key consumer of energy across the world with HVAC systems in particular accounting for a large proportion of a buildings energy consumption. The AE values found across a range of typical building operating and environmental conditions here has a major effect upon the ventilation fans energy consumption. The rate of PM loading upon the filter for the FF AHU will reach saturation and consequently the maximum pressure drop over a much shorter interval of time as a result of the higher AE of its inlet. Therefore, the addition of a commercial inlet that reduces AE will provide several positive contributions to the operation of a building. There will be a reduction in the instantaneous PM filter loading, an increase in the filter lifespan and improved cleanliness of the indoor air by reducing PM concentrations within the ventilation system.

The energy costs and IAQ implications will depend upon the classification of filters being used (i.e., its efficiency at removing PM of a specific size). Filters designed to have a higher capture rate of smaller particles will be susceptible to a faster saturation time due to smaller pores and the increased likelihood of trapping larger particles. Furthermore, PM characteristics will vary region to region depending on the particle size, distribution, concentration, and composition of anthropogenic and natural sources. Knowledge of the AE of the AHU being installed would allow designers to extrapolate the concentrations entering the AHU relative to field measurements within said ambient environment.

5.5 CONCLUSIONS

A need for the development of next-generation commercial AHU inlets that are designed to reduce AE has been identified. The results from this study show a significant scope for a

reduction in AE for large ventilation system as AE typically approached 100% for fine particles, especially at low ambient wind speeds. The orientation of the AHU is a major factor in the AE of the ventilation system and was found to be significantly lower for a rear-facing AHU. A linear decrease was observed in the average AE of the RF AHU's for both configurations as the ambient wind speed increased. Whereas the FF AHU inlet 1 showed no significant change as R increased and Inlet 2 experienced a linear increase in the average AE. Decreasing the AHU flow rate (i.e., ventilation velocity) led to a significant reduction in AE at a constant wind speed for a RF AHU but remained essentially unchanged for the forward-facing configuration. Furthermore, the results also showed a preference for an array configuration with smaller orifices and a louver design across a range of St.

6 A NUMERICAL ANALYSIS OF PARTICULATE MATTER CONTROL TECHNOLOGY INTEGRATED WITH HVAC SYSTEM INLET DESIGN AND IMPLICATIONS ON ENERGY CONSUMPTION

This chapter is based on the work summarised in Considine et al. [230,231] and provides a more in depth account of the research.

6.1 INTRODUCTION

This chapter aims to address and quantify the AE of an AER that is of similar scale to an AHU body dimensions; determine if cylindrical orifices can result in lower PM concentrations entering the ventilation system, when compared with results from existing commercial rainhood configurations. Both a passive and active AER control system for PM will be examined to determine if the next generation of AER devices are suitable for implementation in the HVAC industry. The AER systems will be tested and compared as the wind speed and direction are varied, replicating conditions typically encountered upon a rooftop. In addition, the relationship between the AE of the ventilation system and the particle size is also explored. The outcomes from the analysis of a next-generation AER will result in lower energy consumption. However, a reduced pressure drop in the filtration technology will also increase filter lifespan and improve IAQ. This will also advance our knowledge of particle dynamics in the ambient environment as PM migrates from the outdoor environment into indoor spaces.

The study was structured to provide an overview of AE concepts and insight into the effectiveness of inlets designed to reduce PM intake as shown in Figure 47 outlines the structure of this chapter. The modelling procedure was similar to the previous Chapter 5 and was created to allow replication studies and lay out the CFD modelling methodology chosen to represent particle laden fluid flow around an AER-AHU. The results section details the findings from the study and analyses how each novel AER design created within this study impacts AE as the value of St changes, considering different wind orientations relative to the AHU inlet, and the influence of wind speed. A discussion was included and completes the in-depth analysis of the outcomes from the modelling study and evaluates the potential energy savings incurred by AER technology. Finally, the conclusion which emphasised the

main findings from the project and discussion on potential further improvements and expansion of AE concepts into other sectors.

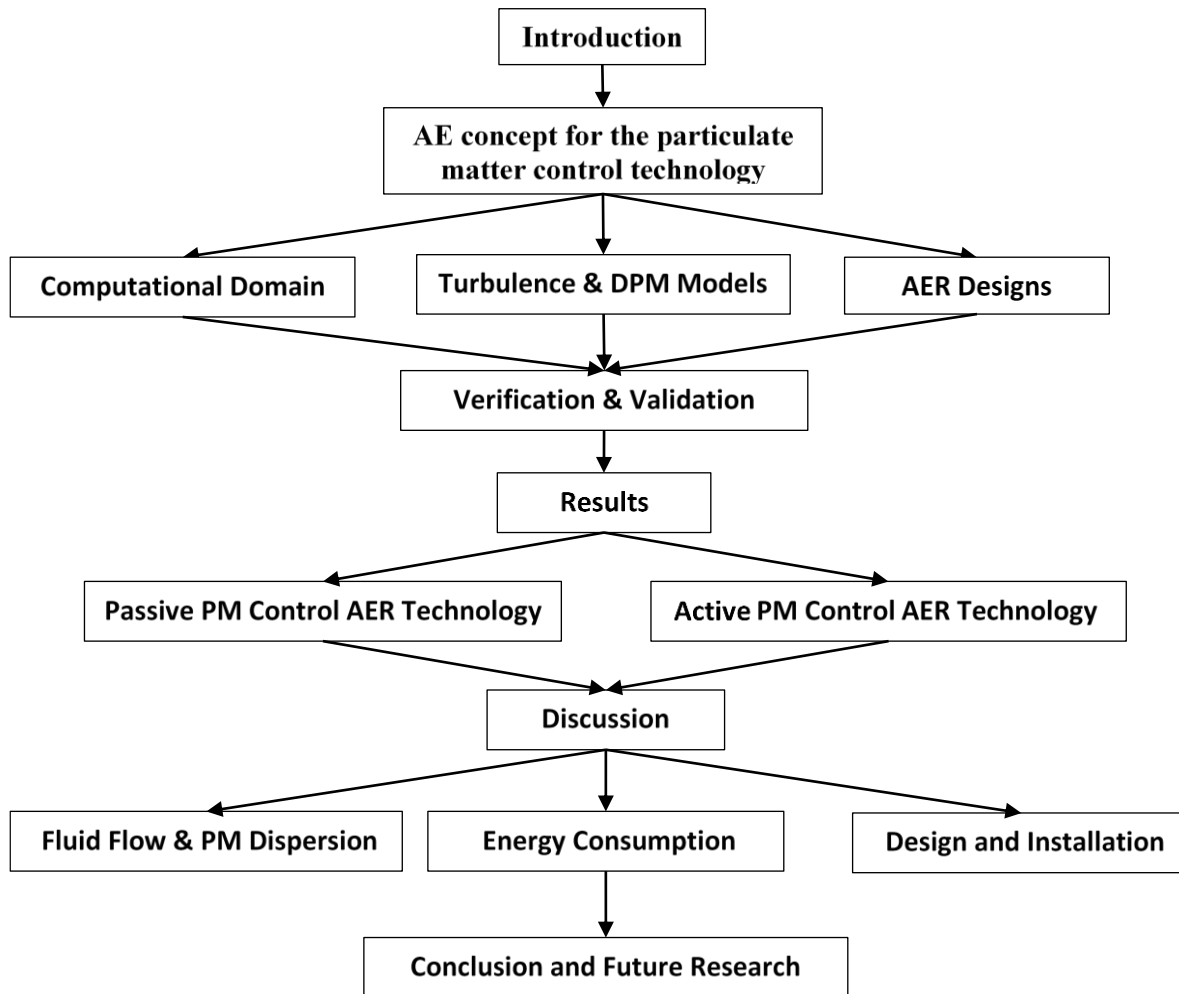


Figure 47. Structure chart for developing AER technology and analysis.

6.2 NUMERICAL MODEL SET UP

6.2.1 3D AER Model Computational Domain

A study of the impact of novel PM control devices upon concentrations entering a ventilation system was conducted using a new inlet design comprising an array of cylindrical tubed orifices known as an AER. Various AER-AHU designs were developed using SOLIDWORKS in 3D for geometry creation, and the models were tested using CFD in ANSYS Fluent 18.1. The AER prototypes were all connected to an AHU and placed within a particle-laden ambient wind flow on a flat building rooftop, as illustrated in Figure 48a.

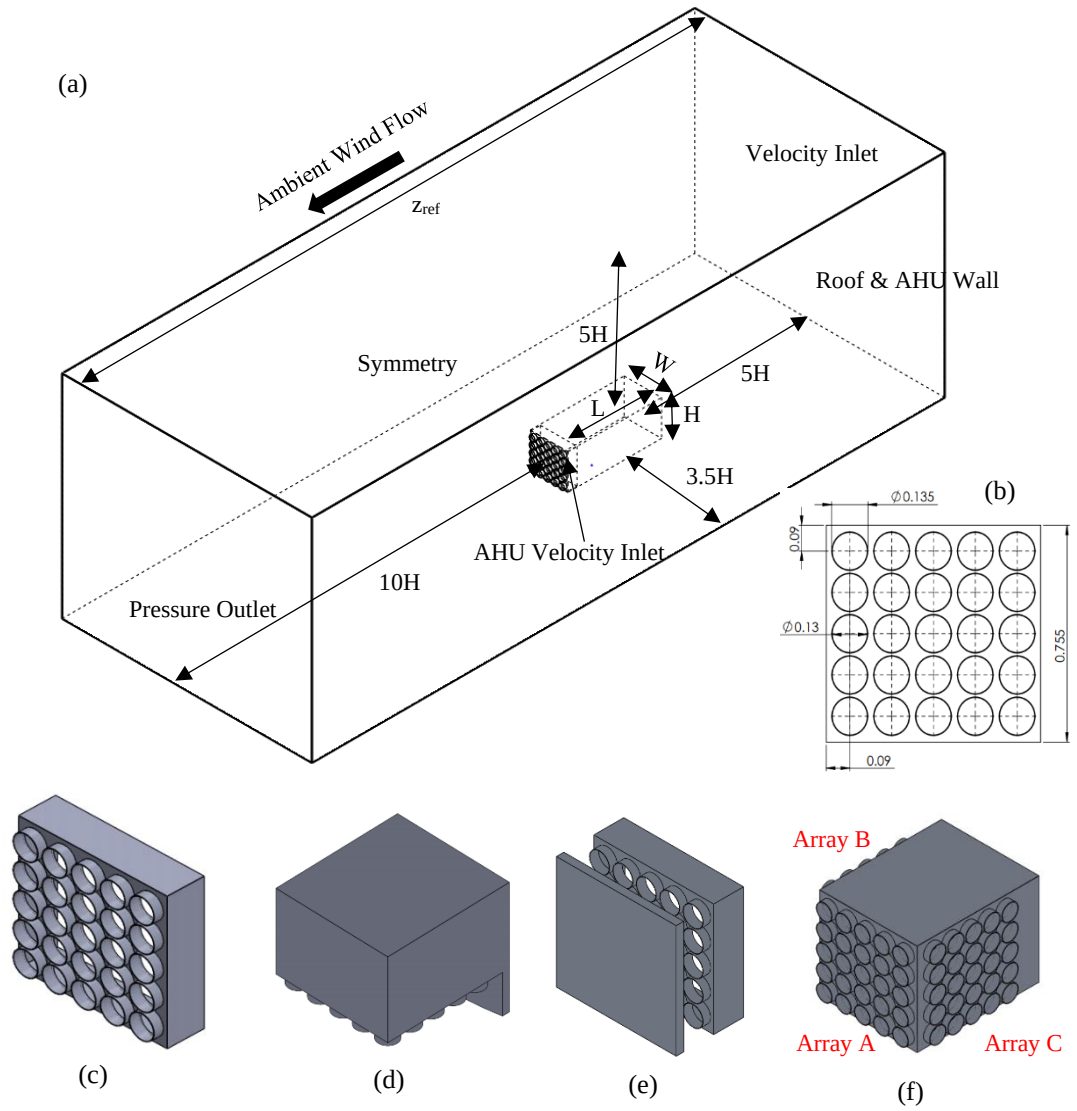


Figure 48. (a) 3D computational fluid dynamics model with associated boundary conditions for a rear-facing AHU relative to the ambient wind flow with an AER attachment and (b) the cross-sectional illustration of the 5×5 130mm diameter array of cylindrical orifices. A 3D graphical representation of each AER design is shown in: (c) Case 1; (d) Case 2; (e) Case 3; (f) Case 4. Note: For a forward-facing orientation, the AHU model is rotated 180° from the above position.

Each case study investigated examined the AHU filter inlet positioned both facing into the wind (FF) and away from the wind (RF). Various studies on aerosol samplers [3,6,138,142] and an AHU with existing commercial inlets from Chapter 5 used the same approach as these positions were found to represent the most extreme scenarios with respect to AE. Therefore, two models of each prototype were developed for examination of their effectiveness at reducing the PM concentrations of each AER at opposite wind directions. The fluid domain was designed with similar practices and methodologies employed in the study of wind flow

around a building. Therefore the height of the domain and upstream dimensions were created to be 5H from the AHU body, 3.5H either side of the AHU body and downstream was 10H to allow eddy development, as shown in Figure 48 and matches the numerical model design used in Chapter 5 [188].

The AHU body was also configured as before in Chapter 5 for a direct comparison with the AHU employing rainhoods with a height (H), width (W) and length (L) of 0.755 m, 0.8 m and 2.01 m, respectively. The termination point and surface area monitor for the AHU concentrations was chosen to be where a HVAC panel filter is typically installed. The filter is designated as a velocity inlet in the computational domain and has a surface area of 0.36 m². An AHU ventilation flow rate (q_v) of 3400 m³/hr was used for each model tested. Furthermore, the upstream boundary was also designated as a velocity inlet, downstream as a pressure outlet and the top and side boundaries were configured with symmetry boundary conditions. The rooftop and AHU bodies were represented by a wall boundary with a no-slip condition, and a uniform velocity profile was used to represent the wind flow across a flat roof.

6.2.1.1 Aspiration Efficiency Reducer Case Studies

The AER case studies were all designed with a 5 x 5 number array of 130 mm orifices, each with a 50 mm long cylinder as shown in Figure 48b. The AERs were sized in this manner in order to induce a ventilation velocity of approximately 2.5 m/s in the cylindrical tubes and match the AHUs body dimensions. Smaller orifices are to be tested in the 2D models but using cylindrical orifices ensures a greater loss of the array's surface area as the diameter increases, thus increasing the ventilation velocity. Four different AER-AHU inlet designs (Figure 48 c-f) were developed and their performance as PM air pollution control devices was simulated. The variations between the inlet designs were based on their orientations relative to both the ambient wind and the AHU filter where the inlet is located, and the number of arrays as shown in Figure 48c-f. In all cases, a primary consideration was the impact of ambient wind direction on device performance, whereby past research [6] and results from Chapter 5 have shown that AE increased considerably when the ambient wind was facing the AHU inlet. The four cases were therefore designed to explore the potential to avoid this most unfavourable ambient wind condition.

The height and width of each case study is identical to the AHU body dimensions and only the length changes depending on the design where Case 1, 2 and 4 length extends 0.2 m, 0.87 m and 1 m from the AHU body respectively. Case 1 involves an AER array positioned perpendicular to the oncoming wind and in front of the inlet where the panel filter would be located, as shown in Figure 48c. The design was chosen to replicate previous studies [6,151] that assumed cylindrical orifices will impact AE, inducing similar results to aerosol sampling studies. Case 2 examined the AER inlets positioned parallel to the rooftop (i.e., 0.26m from roof to AER body) and was hypothesised to be an advantageous design as the inlets are never facing directly into the particle-laden ambient wind, regardless of ambient wind direction. Previous studies have shown that a cylindrical orifice positioned at a 90 degree angle to the oncoming particle laden wind resulted in lower AE when compared with a sampler facing into the wind [3,229]. Case 3 incorporated a 50mm thick barrier in front of the inlet array used in Case 1 with matching width and height. This was designed to prevent PM flowing directly into the cylinder array when the ambient wind direction was unfavourable. Case 4 examined a three-sided inlet and was used to determine the potential for an active control system operating based upon ambient wind direction data, whereby individual sides of the AER could be closed using a smart damper system when the ambient wind direction is blowing directly on Array A, B or C.

The four AER case studies were analysed using their corresponding St to evaluate the effect on AE as both the particle diameter is varied from 2.5-50 μm and across a wind speed range of 2.5-7.5 m/s. A smaller range of particles were tested for AERs as the 50 μm particle diameter provided similar results as a particle concentration with 90 μm diameter in Chapter 5. Similarly, the wind speed range was reduced, and this allowed more tests to be run on different designs. This corresponds with the typical wind speed values experienced upon the rooftop of a commercial building [153]. Both of these variables were varied in a parametric study based upon the relationship between their St and AE. Particle density (ρ_p) was 2 g/cm³ and the fluid viscosity 1.79x10⁻⁵ kg/ms for ambient air. An idealised square duct was used to represent the characteristic length of the AER, and this approximation was determined through the square of the summed cylinder areas (i.e., $L_c = \sqrt{[cylinder\ inlet\ surface\ area \times number\ of\ cylinders]}$). The characteristic length for each AER case study was found to be constant at 0.576 m as neither the pipe diameter nor the number of cylinders on a single face was altered. St was assumed to be equivalent for the AER-Case 4 array C as the arrays are on different faces. Concentrations of PM were

monitored at both the ambient and AHU velocity inlets and a time-averaged sample over 10s period was collected under steady-state conditions.

Table 9 Case studies detailing the environmental and HVAC operations tested within this AER PM control investigation for an AHU.

Case study 1: Louvre model (Baseline) vs AER Case 1	
Ambient air	
Wind speed	1.5, 2.5, 5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0 °), RF (180 °)
AHU attachment	Inlet 1, AER Case 1
AHU flow rate	3400 m ³ /hr
PM particles	
Particle diameters	2.5, 10, 20, 35, 50 µm (D _x)
Particle drag	Irregular – shape factor 0.4
Particle density	2 g/cm ³
Case study 2: Passive AERs	
Ambient air	
Wind speed	1.5, 2.5, 5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0 °), RF (180 °)
AHU attachment	AER Case 1, AER Case 2, AER Case 3
AHU flow rate	3400 m ³ /hr
PM particles	
Particle diameters	2.5, 10, 20, 35, 50 µm (D _x)
Particle drag	Irregular – shape factor 0.4
Particle density	2 g/cm ³
Case study 3: Passive vs Active AER	
Ambient air	
Wind speed	1.5, 2.5, 5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0 °), RF (180 °)
AHU attachment	AER Case 1, AER Case 4
AHU flow rate	3400 m ³ /hr

PM particles

Particle diameters	2.5, 10, 20, 35, 50 μm (D_x)
Particle drag	Irregular – shape factor 0.4
Particle density	2 g/cm^3

6.2.2 2D AER Model

A 2D numerical model was developed of an AHU to simulate particle laden fluid flow using ANSYS Fluent 18.1 as shown in Figure 49a. The boundary conditions of the fluid domain are identical to the 3D model and fluid domain dimensions. An array of 25 mm orifices was used to represent the AER-AHU and determine if reducing the orifice size could have an effect on PM ingress into the ventilation system. The models were not classified as additional case studies to the 3D models, as 2D models cannot capture the effect of cylindrical orifices and are more akin to channels under this set up. Models were also created both without and with deflector plates as illustrated in Figure 49b-c respectively in order to divert the flow away from the AHU inlet, regardless of the AER/rainhood design. The deflector positioning was varied depending on the orientation of the AHU to the upstream ambient wind.

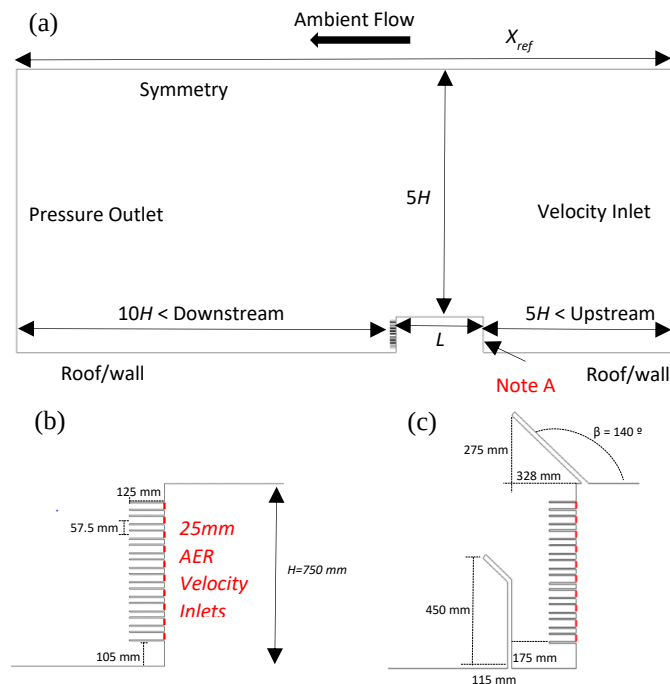


Figure 49. (a) 2D computational domain for a rear-facing AER-AHU relative to the ambient wind flow. (b) AER-AHU; (c) AER-AHU with deflectors. Note A: Location of AER inlets for forward-facing AHU.

The AHU flow rate was set to 2.55 m/s and is based upon ventilation velocities of the 3D models in Section 6.2.1 and ambient low and high wind velocities of 2.5 m/s and 7.5 m/s respectively were tested. A range of particle sizes were tested from 2.5-90 μm diameter similar to Chapter 5 in order to determine if the smaller orifice could effect AE for very large diameter particles. This was not deemed necessary for the 3D models due to the larger orifices of 130mm and the quick solve times associated with 2D modelling ensured computational resources were not unduly burdened.

6.3 RESULTS

6.3.1 Effect of Wind Orientation and Wind Speed upon Aspiration Efficiency

The four case studies representing the different AER prototypes tested were compared at a wind angle of 0° and 180° relative to the AHU velocity inlet, as shown for AER Case 1 in Figure 50. This ensures for the former wind angle; that the oncoming particle-laden wind is flowing directly at the inlet where the filters are located. A previous study and results from Chapter 5 demonstrated this wind angle incurred the maximum AE across a range of particle diameters [6]. The other most pertinent position is a RF AHU as the filter inlet is now facing away from the wind. This orientation has been found to lead to the lowest AE and is preferable over the FF configurations as described in Chapter 5. The performance of each AER inlet analysed within this study is largely dependent upon its geometry, design and ambient wind speed.

Figure 50 clearly shows that the relationship between the wind speed and the wind orientation relative to the AHU inlet. The AE of the FF AER Case 1 was found to increase as the wind speed and particle diameter increased. Critically AE was found to exceed the ambient concentration at a wind speed of 7.5 m/s where values greater than 100% were recorded for FF AER Case 1. This occurs with larger diameter particles as they have greater momentum and are more likely to maintain their original trajectory. Depending upon the design of the AER, this can lead to varying levels of secondary aspiration as the AER walls will create conditions for particle impaction, re-entrainment and rebound.

Conversely, the RF AER Case 1 resulted in a decrease in AE as both the wind speed and particle diameter increased. AE was found to be less than half the ambient concentration at the fastest wind speed across the entire particle range and the trendlines predict AE will

approach zero as particle diameter increased. AE ranged from 9-46% for an RF AER Case 1 in comparison to a range of 93-112% for the FF. The implication of reductions in particle concentrations entering an AHU to 9-46% of ambient levels is clearly significant for indoor air quality and fan energy consumption. At lower wind speeds, the variation in AE at 2.5 m/s between a FF and RF AER Case 1 was reduced. This was attributed to the lowering of the particle momentum, and as a consequence, the particles are more readily diverted into the AHU inlet, especially for the RF configuration. At the lowest wind speed tested for RF AER Case 1, AE ranged from 60-80%, and its FF counterpart ranged from 85-93%.

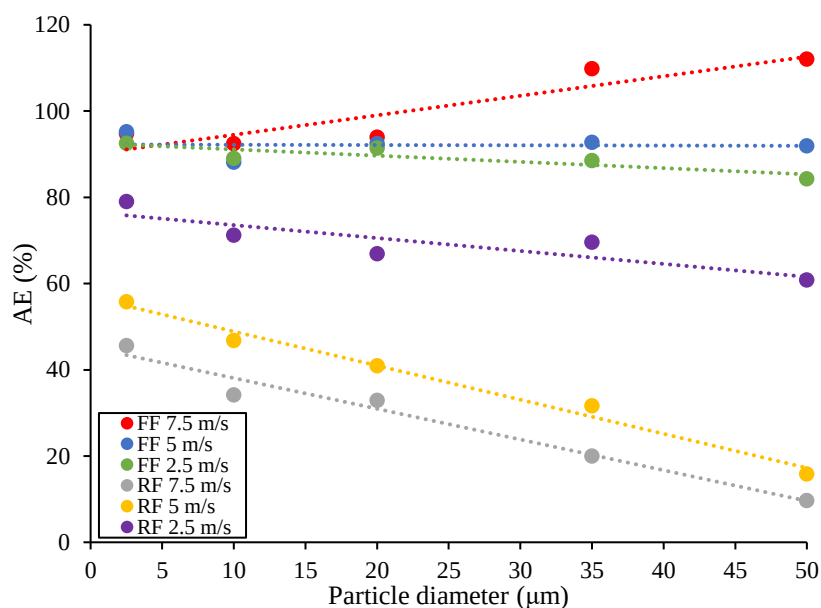


Figure 50. Analysis of the impact wind speed (m/s) and particle diameter (μm) have upon the AE (%) of AER Case 1 design, incorporating an array of 130 mm cylindrical orifices and a design flow rate of $3400 \text{ m}^3/\text{hr}$.

6.3.2 Aspiration Efficiency Comparison between AER Case 1 vs Louvre Model

Figure 51 illustrates the performance of AER Case 1 and a commercial louvre-style rainhood examined in Chapter 5 using their corresponding St to examine the impact on AE. The louvre rainhood in Figure 51a appears to be more efficient than AER Case 1 at a wind speed of 2.5 m/s, as the St number becomes larger (i.e., particle diameter increases). Most importantly, AER Case 1 was found to be more efficient at reducing particles within both the coarse and fine PM ranges, where AE was lower for both $D_{2.5}$ and D_{10} diameter particle concentrations. This trend continued in Figure 51b-c at the higher wind speeds of 5.0 m/s and 7.5 m/s. The results show that AER Case 1 was more efficient at reducing the ingress of smaller diameter

particles (i.e., $St \ll 1$) in comparison to the louvre rainhood. As mentioned in the previous section, secondary aspiration contributed to recorded AE values greater than the ambient concentration, which is analogous to the secondary aspiration observed in the louvre rainhood. The mass transport of inertia dominated particles in convective flow creates conditions that are vulnerable to particle impaction, rebound and entrainment. In particular, inlets that contain a large surface area such as louvre walls or pipe walls generate high AE values, especially as the wind speed increases.

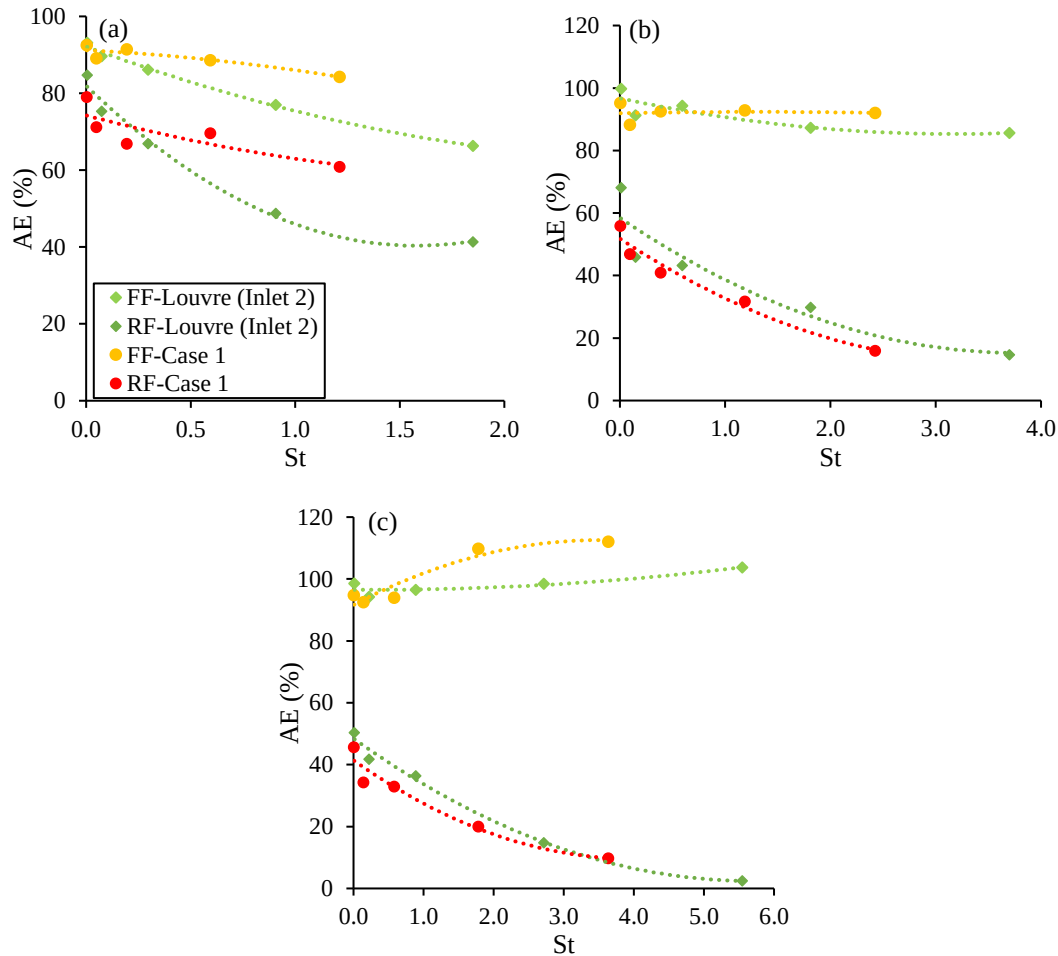


Figure 51. Analysis between a commercial louvre rainhood and AER Case 1 design with an array of 130 mm cylindrical orifices for an AHU at a design flow rate of 3400 m³/hr and tested at an ambient wind speed of (a) 2.5 m/s (b) 5.0 m/s (c) 7.5 m/s.

Again, the results show that the AER Case 1 resulted in lower AE of $D_{2.5}$ and D_{10} diameter particle concentrations in comparison to the louvre model for the RF configurations. There was a 5-13% difference in AE depending upon the wind speed for $D_{2.5}$ particle concentrations, whereas the discrepancy range reduced for D_{10} particle concentrations to between 1-6%. As the particle diameter increased at wind speeds of 5.0 m/s and 7.5 m/s

there is minimal variation in AE between the RF louvre rainhood and RF AER Case 1. AER Case 1 also resulted in more significant AE for larger particles at the lowest wind speed of 2.5 m/s due to the design of the inlet attachment and their impact on the velocity vector field around the AHU inlet. The louvre rainhood results in the vectors angling towards the ground and generating a greater force near the rooftop surface. While the AER array impacts the flow field closer to the roof of the AHU and the louvre model does not.

6.3.3 AE Comparison of Passive AER-AHU Inlet Array's

Figure 52 shows the result of the simulation for the ground facing attachment AER Case 2 and the shielded AER Case 3. Both resulted in the most promising performances, generating lower AE values across the full range of St for the ambient wind speeds of 2.5 m/s, 5.0 m/s and 7.5 m/s. This occurred as the array of cylindrical orifices velocity vectors from the AHU inlet are orientated to be perpendicular with the oncoming wind for AER Case 2 in contrast to AER Case 1, where cylinders are facing into the wind and parallel with the filter inlet. The velocity vectors of the aforementioned AER Case 1 are aligned with the ambient wind vectors, which led to higher AE than AER Case 2. For this reason, the barrier was installed in AER Case 3 to prevent said alignment and also to reduce AE.

AER Cases 2 and 3 for FF configurations were better at reducing the concentration of larger diameter particles from entering the ventilation system. The particle trajectories must undergo a greater change in direction and divert from their original trajectory. Therefore, as the St number becomes larger and as a consequence momentum, as becomes larger, AE becomes lower for FF AER Case 2 and 3 as the particles cannot be diverted as readily into the ventilation system. Furthermore, the ventilation velocity vectors in AER Case 2 are aligned in the opposite direction to the gravitational vector field, ensuring that as the particle diameter increases, AE decreases. AER Case 3 operates on the principle of inducing boundary layer separation near the AHU inlet in order to lower AE. At the higher wind speed of 7.5 m/s, FF AER Case 3 efficiency increases as the St number becomes larger. The design of the AER barrier allows the particles to follow the flow separation and be transported away from the array of cylindrical ports. Whereas the FF AER Case 2, while similar in design, restricts flow movements within the space between the ground surface and the AER surface. Therefore, smaller particles cannot enter this space as easily due to the turbulent motions of the fluid within this space. As the particle diameter reduces in size and where $St \ll 1$, FF

AER Case 1, 2 and 3 all generated lower AE values in comparison to the commercial louvre rainhood at the same orientation.

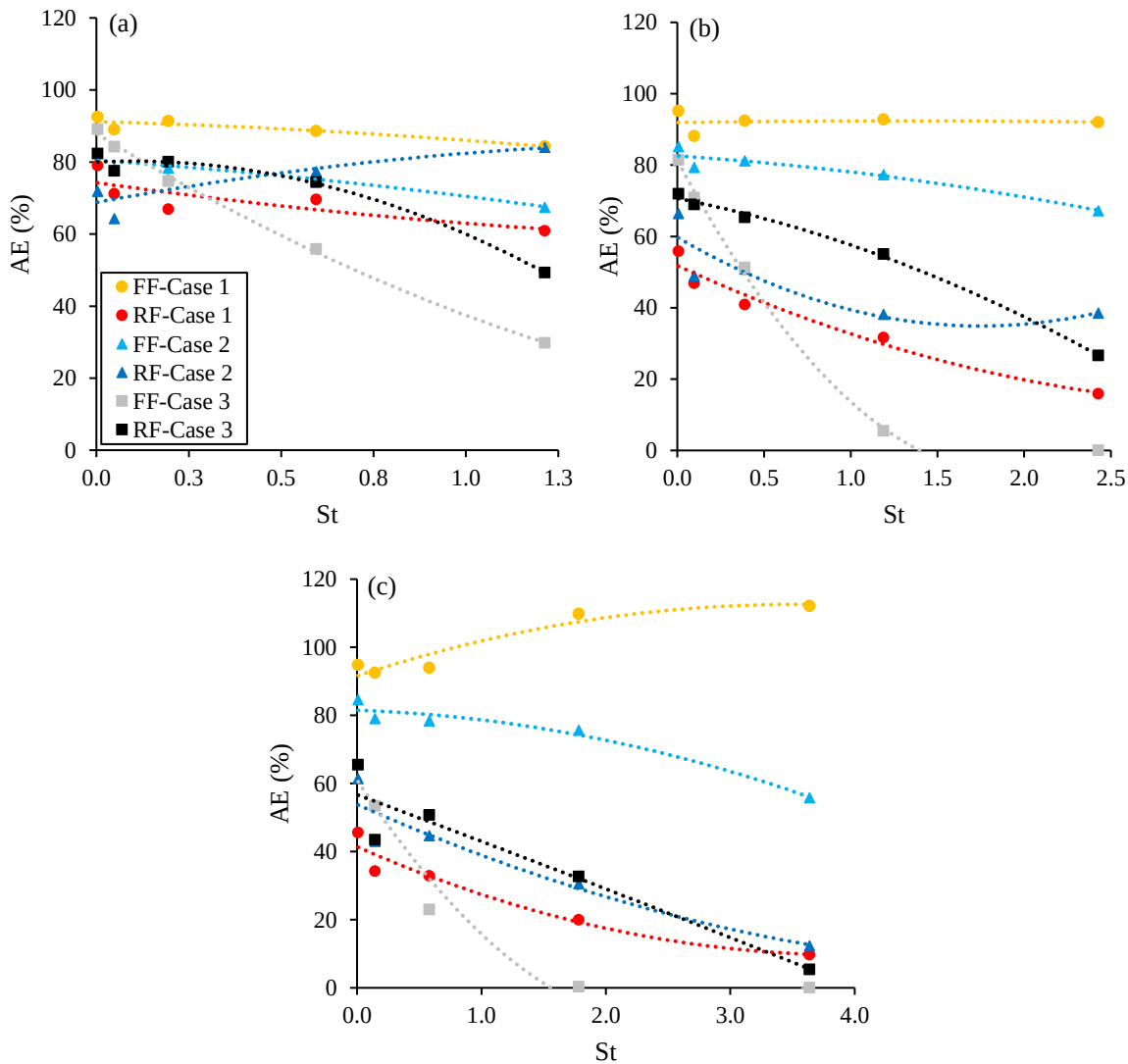


Figure 52. Analysis between passive AER designs with an array of 130 mm cylindrical orifices for an AHU at a design flow rate of 3400 m³/hr and tested at an ambient wind speed of (a) 2.5 m/s (b) 5.0 m/s (c) 7.5 m/s.

The results suggest that the cylindrical orifices are more efficient at reducing particle concentrations that are classified as a health hazard, such as particles with $D_{2.5}$ and D_{10} diameters. For example, at a wind speed of 2.5 m/s, AER Case 2 generated an AE of 82.5% and 78.2% for $D_{2.5}$ and D_{10} particle diameter concentrations, respectively. In contrast, the louvre rainhood and AER Case 1 and 3 resulted in AE over 89% for both particle diameters and a similar observation can be drawn for the other wind speeds. As previously discussed, AER Case 1 is more efficient than the louvre model, but the variations are not large,

especially at low wind speeds. RF AER Case 1 requires a larger turn of direction than the RF AER Case 2 or 3. The particles have a shorter path to travel from the ambient environment into the ventilation system in comparison to AER Case 1. Furthermore, RF AER Case 2's body extends from the AHU body a greater distance in the wind flow direction, and this also contributed to an increase in AE in comparison to RF AER Case 1. As the flow separates from the AHU body, AER Case 1 can only draw in PM from the edge of the eddies created, but the ground facing AER's inlets are entirely positioned within the eddy zones leading to higher AE.

6.3.4 Active PM Control Technology Concept

The results of the simulation of AER Case 4 are shown in Figure 53f. This was designed to engage the inlet arrays that are subjected to a wind direction that is either side-facing (SF) or RF with respect to the oncoming wind through an active damper system.

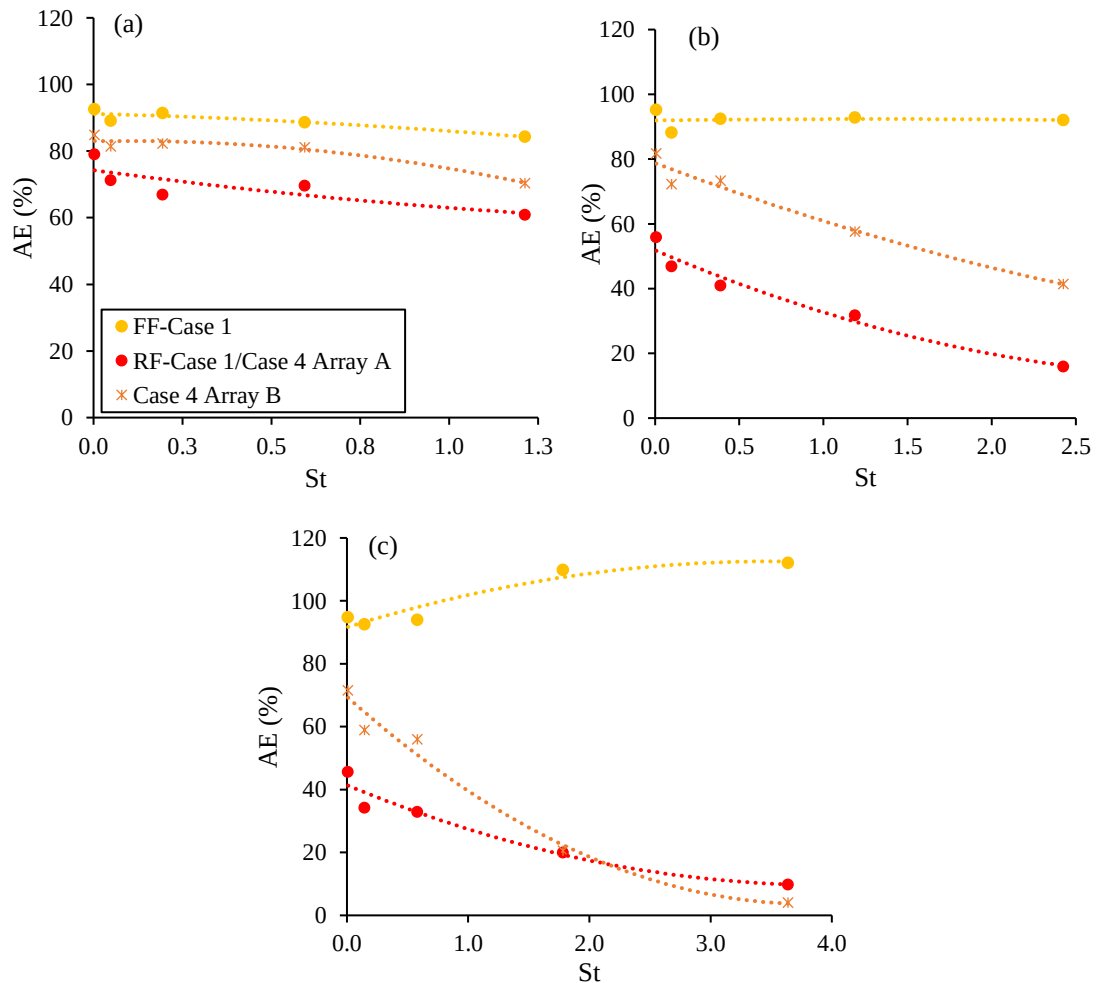


Figure 53. Comparison of AE between a passive AER and an active AER for an AHU at a design flow rate of 3400 m³/hr and tested at an ambient wind speed of (a) 2.5 m/s (b) 7.5 m/s.

Essentially by activating dampers, it would be possible to open one side of AER Case 4, and this would eliminate a FF AER inlet or any conditions that would create a wind orientation from 0-89°. The results from Figure 53 illustrate the potential impact this could have upon a HVAC filtration system. With this prototype, the worst-case scenario of the ingress of PM concentrations would arise from Case 4 Array B as the inlet array is perpendicular to the oncoming particle-laden wind. Considering that for AER Case 1 the worst performances occurred with the now eliminated FF configuration, the active system could lead to substantial energy savings, and this can be seen for both wind speeds in Figure 53a-c. There are significant improvements in decreasing AE at the lower wind speed of 2.5 m/s and a significant difference in performance at the higher wind speed of 7.5 m/s.

6.3.5 Analysis of the AER-AHU Average Aspiration Efficiency Across their Respective St Ranges

The mean AE of each AER Case were examined in Table 10, and large differences in AE were found between AER designs, wind speed and wind orientation relative to AHU inlet. The most basic AER Case 1 was found to generate similar values and trends across the entire spectrum of variables analysed as the commercial louvre-style rainhood. AE rose with increasing wind speed for a FF AHU, and as expected, AE decreased when facing away from the wind (RF). The louvre rainhood performed slightly better under the mean AE criteria as this design is more efficient at reducing the concentration of larger particles entering the AHU. It should be noted that generally, the louvre rainhood was more inefficient when considering the AE of particles $\leq 10\mu\text{m}$. The most significant variation in AE occurred with AER Cases 2 and 3, principally when comparing their values across different wind speeds and orientations. There was no significant variation in the mean AE for FF AER Case 2 as the wind speed changed. However, AE was found to decrease for the RF AER Case 2 as the wind speed increased and was more efficient than its FF counterpart, with the former and latter AE ranging from 38-75% and 75-78%, respectively. A similar trend was detected for AER Case 3 where the model was more efficient facing into the wind rather than away. Both of these models are in contrast to AER Case 1 as the RF configuration performed best. Finally, the active system could incorporate the best of AER Cases, and this shows when comparing the forward-facing passive AER's where the AER Case 4 array B was superior to AER Case 1 and 2 with a range from 42-80%. Moreover, this system also outperforms the RF AER Case 3 and overall results in the lowest AE.

Table 10. Mean AE of each AER case study examined across their respective St range ($2.5\text{--}50\ \mu\text{m}$) at a constant wind speed and AHU flow rate of $3400\ \text{m}^3/\text{hr}$.

Wind Speed		2.5 m/s		5 m/s		7.5 m/s	
Orientation	Inlet	Average	S.D.	Average	S.D.	Average	S.D.
FF	1	89 %	3.2 %	92 %	2.5 %	101 %	9.5 %
	2	76 %	5.6 %	78 %	6.7 %	75 %	11.1 %
	3	67 %	24.3 %	42 %	37.3 %	28 %	30.1 %
	4-B	80 %	5.61 %	65 %	15.9 %	42 %	28.5 %
	Louvre	83 %	10.8 %	92 %	5.7 %	98 %	3.5 %
RF	1/4-A	70 %	6.6 %	38 %	15.3 %	28 %	13.9 %
	2	75 %	7.3 %	49 %	11.5 %	38 %	18.3 %
	3	73 %	13.4 %	58 %	18.4 %	40 %	22.5 %
	Louvre	63 %	18.1 %	40 %	19.9 %	29 %	19.9 %

6.3.6 Analysis of the Impact on Aspiration Efficiency of a 2D AER-AHU with Small Orifices and Deflector Plates

An analysis was conducted at varying ambient wind speeds, to determine the effect on AE for an AER-AHU, both with and without deflectors. The model was tested at both FF and RF orientations and across their respective range of St , that varied depending on the wind speed and particle diameter. The AE results at a wind speed of 2.5 m/s are shown in Figure 54a and demonstrate the effectiveness of placing deflectors around the AER-AHU inlet for both AHU orientations at low wind speeds. The AE of the forward-facing AER-AHU with deflectors was found to experience slightly lower AE values as the St increased above one. At $St < 1$, there is no major difference in AE with or without the deflectors. The RF AHU was far more effective at reducing the particle concentrations within the ventilation system in comparison to the FF AHU, especially at $St < 1$ and with deflectors deployed in front of the AHU inlet.

Critically, with the RF AHU there is a considerable difference in AE with decreasing St with and without deflectors. Where $D_{2.5}$ and D_{10} diameter particles were modelled, there was a 18% and 29% difference respectively at their corresponding St . This will result in lower concentrations drawn into the ventilation system at the AHU inlet. This implies significant gains in energy savings from a reduced particle loading upon the filters and lower harmful particulate matter emissions within the indoor environment. As the St exceeds a magnitude of three the difference in AE is negligible but again significant energy saving will occur up to $St = 3$.

The ambient wind speed was increased to 7.5 m/s in order to examine the effect of the deflectors upon the AE of the AER-AHU. The results illustrated in Figure 54 show that the deflector plates have no major effect on AE for a FF AER-AHU. The trendline shows that the performance of the AER-AHU with and without deflector system are undifferentiated across the St range examined but can vary at specific individual St . Inspection of the rear-facing AER-AHU results show similar performance levels at lower St . A 14% and 22% difference in AE occurred for $D_{2.5}$ and D_{10} particles respectively with the deflector system compared to without.

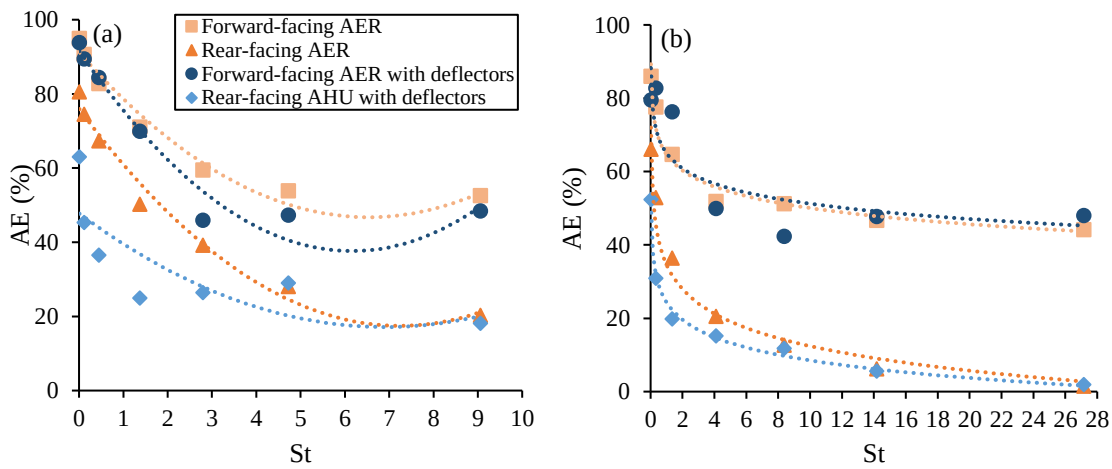


Figure 54. Aspiration efficiency of an AHU-AER with/without deflectors at $R = 1$, where the ventilation velocity is 2.5 m/s.

6.4 DISCUSSION

6.4.1 Impact of an AER Device on the Ventilation Aerodynamics and PM Dispersion Around an AHU

6.4.1.1 3D Passive AER Case 1-3

The design of the AER's were created for the purpose of lowering AE by engineering the fluid flow dynamics around the AHU body and based upon the factors influencing AE while also not altering the normal operating conditions of the AHU. AER Case 1 showed AE trendlines that were quite similar to the commercial louvre rainhood results. As shown in Figure 55a, the wind flows directly through the orifice arrays when facing into the wind and generates AE close to 100% as the particles have not been impeded. As the AHU inlet is

positioned facing away from the wind, this led to a much lower AE as boundary layer separation has occurred, and the AER is now positioned within a wake zone.

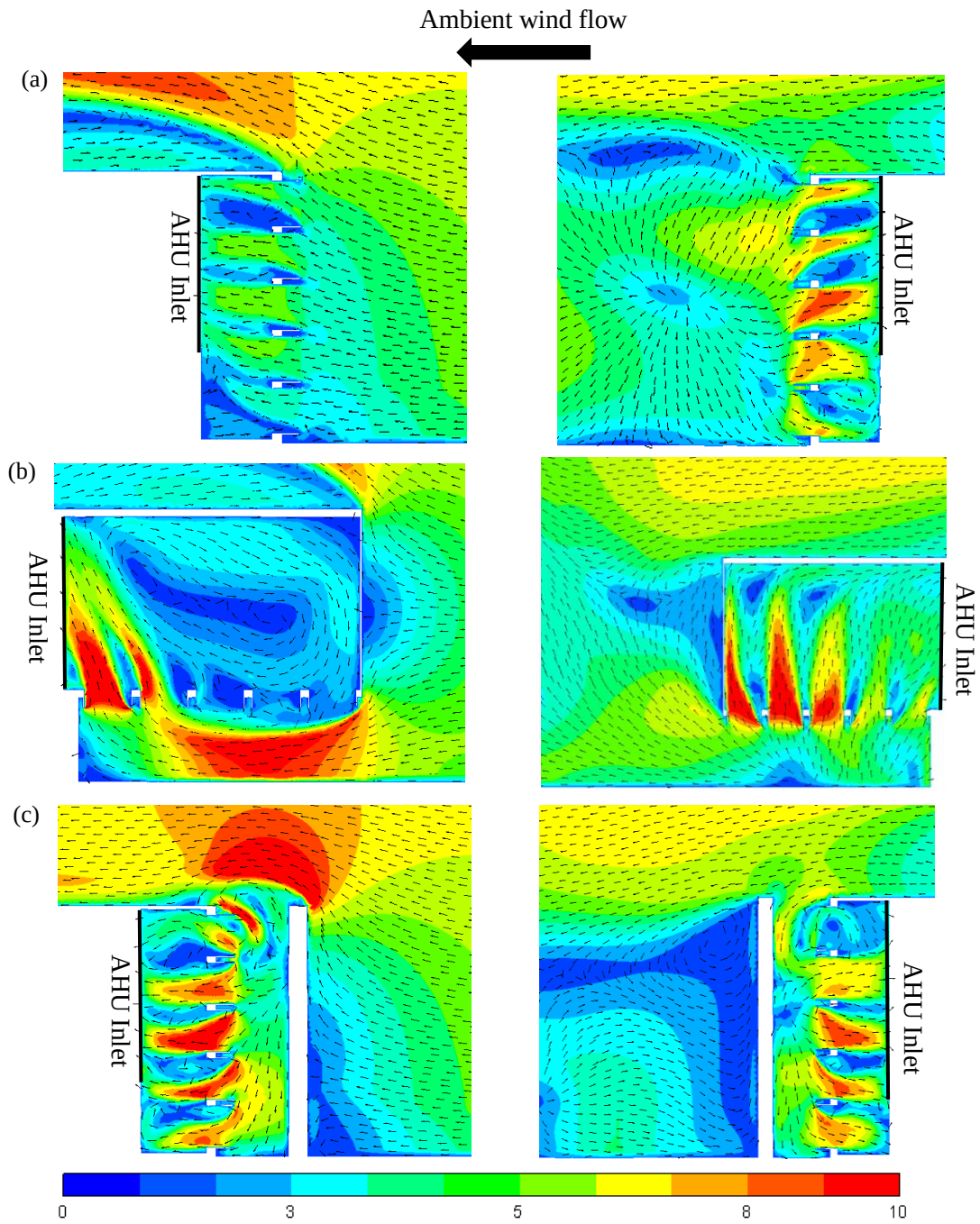


Figure 55. Fluid flow vectors and contour analysis (m/s) on YZ plane intersecting the centre of the AHU body at a ventilation flow rate of $3400 \text{ m}^3/\text{hr}$ where the following illustrates (a) AER Case 1 (b) AER Case 2, and (c) AER Case 3; for a wind speed of 7.5 m/s .

The variation in the environmental flow dynamics with the intention of lowering AE further than AER Case 1 was achieved with AER Cases 2 and 3. The ground-facing array of inlet's

in Figure 55b illustrates a difference in the fluid velocity depending upon the cylindrical inlet as the air enters at the cylinder interface coupling the indoor-outdoor environments. The row of inlets located near the AHU body in the FF model has a much higher ventilation velocity as the wind is restricted between the AER wall and the rooftop wall. Conversely, the rows of inlets located furthest from the AHU body in RF Case 2 experienced a similar velocity magnitude to the FF Case 2 inlets near the AHU body. In this scenario, the wind flow cannot re-attach closer to the AHU body and, as a consequence, forces the fluid into the inlets at a faster rate. However, more of the cylinder inlets are engaged in drawing particles for the RF model into the ventilation system. AE was still lower as the particles were less likely to be diverted from their original trajectories due to boundary layer separation from the AHU body. The inclusion of a barrier in front of the inlet array in AER Case 3 essentially removed the FF configuration but also negatively affected the AE when rear-facing in comparison to AER Case 1.

In Figure 55c, the RF AER Case 3 barrier is now a hindrance and delaying full boundary layer separation until further downstream after the barrier, increasing AE. Where the wind blows directly at the barrier, boundary layer detachment occurs at the edges of the barrier boundary wall and results in the lowest AE overall. This demonstrates the ability for further improvement of an AER system by engineering the airflow around the AHU with the purpose of diverting the particles away from inlets with strategically placed deflectors. Furthermore, the barrier could also be designed as an active control system and operate using similar technology to dampers. The damper would open under a RF condition and result in the lowest AE for both orientations, utilising the best conditions from AER Case 1 and 3.

The dispersion of PM concentrations containing $D_{2.5}$ and D_{50} particles were assessed in Figure 56 for AER case 2 and illustrates the reasons for the variation in AE between particle sizes and wind direction. As expected, a higher accumulation of $D_{2.5}$ particle concentrations can be observed entering the AHU inlet where the filter is located for the forward-facing model compared to the rear-facing as shown in Figure 56. However, this also occurs for PM concentrations with larger diameter particles, where there is a minute concentration of D_{50} particles entering the filter for a rear-facing model. For example, there is a less concentrated cloud of PM underneath the AER when facing away from the wind for AER Case 2 rather than into the wind.

Furthermore, the difference in the concentration levels between the smaller and larger particles, coincided with the typically lower values of AE found for the latter. In regard to the impact the AER design has upon AE, the contour figures clearly illustrate in the FF models that AER Case 1 results in larger concentrations of PM loading the filter in comparison to AER Case 2 and 3. AER Case 1 only performs more efficiently facing away from the wind but the discrepancies in AE are small for the RF model, whereas there are significant differences in AE when contrasting the other AER FF cases.

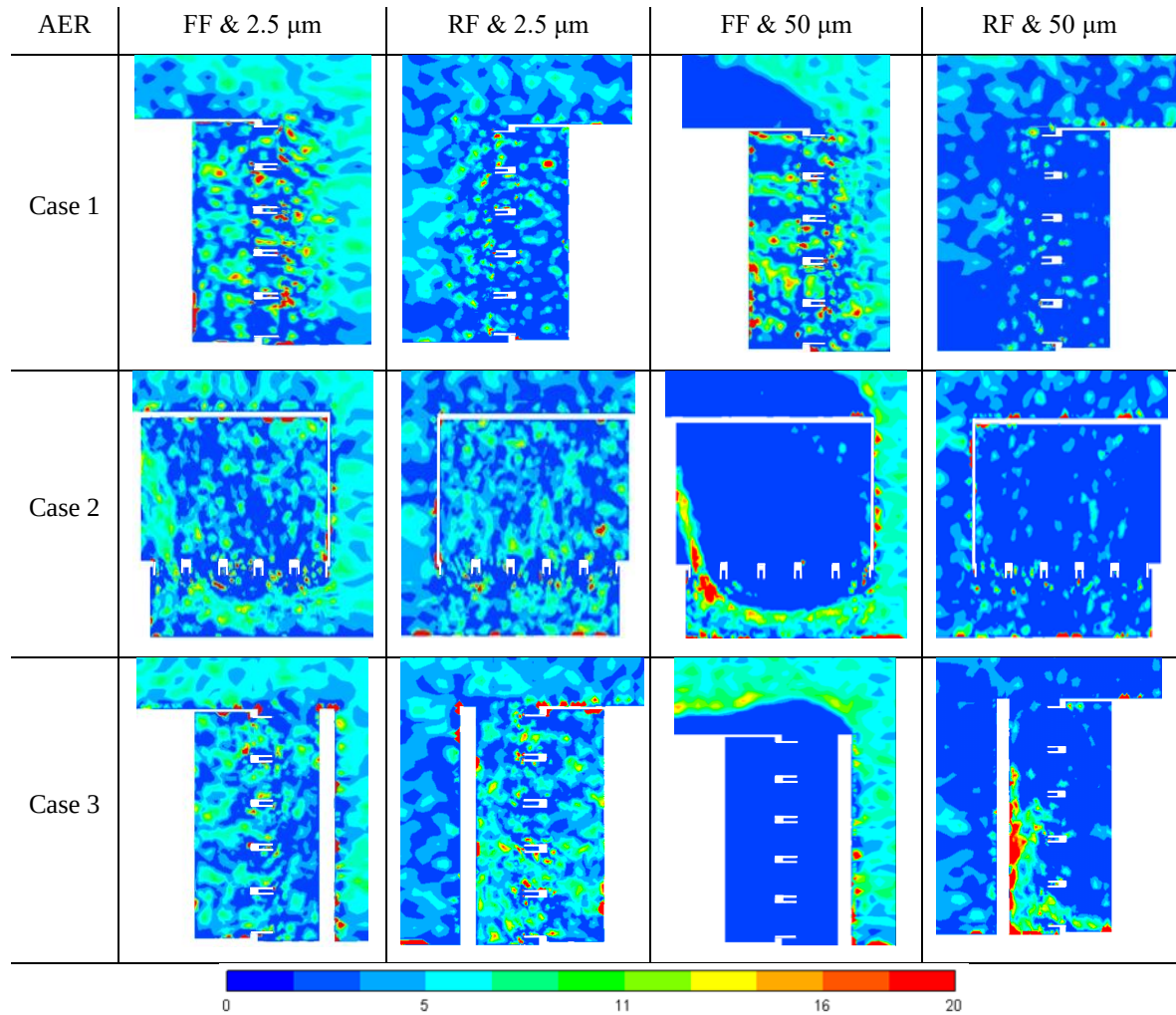


Figure 56. Particle concentration ($\mu\text{g}/\text{m}^3$) contours for passive AERs at Rear Facing (RF) and Forward Facing (FF) wind speed of 7.5 m/s, and a ventilation flow rate of 3400 m^3/hr .

6.4.1.2 2D AER with 25mm Orifice Array and Deflector Plates

The variation in AE can be attributed to the change in the aerodynamics around the AER-AHU inlet. The results from velocity vectors of AER-AHU in Figure 57a-b without deflectors are analogous to the 2D models from Chapter 5 where similar flow patterns were

observed for AHU commercial rainhoods. The ambient wind flow for the forward-facing AER-AHU without deflectors is drawn directly into all ten orifices. For the rear-facing counterpart model, the ambient flow detaches at the back of the AHU and reattaches directly in front of the AHU inlet.

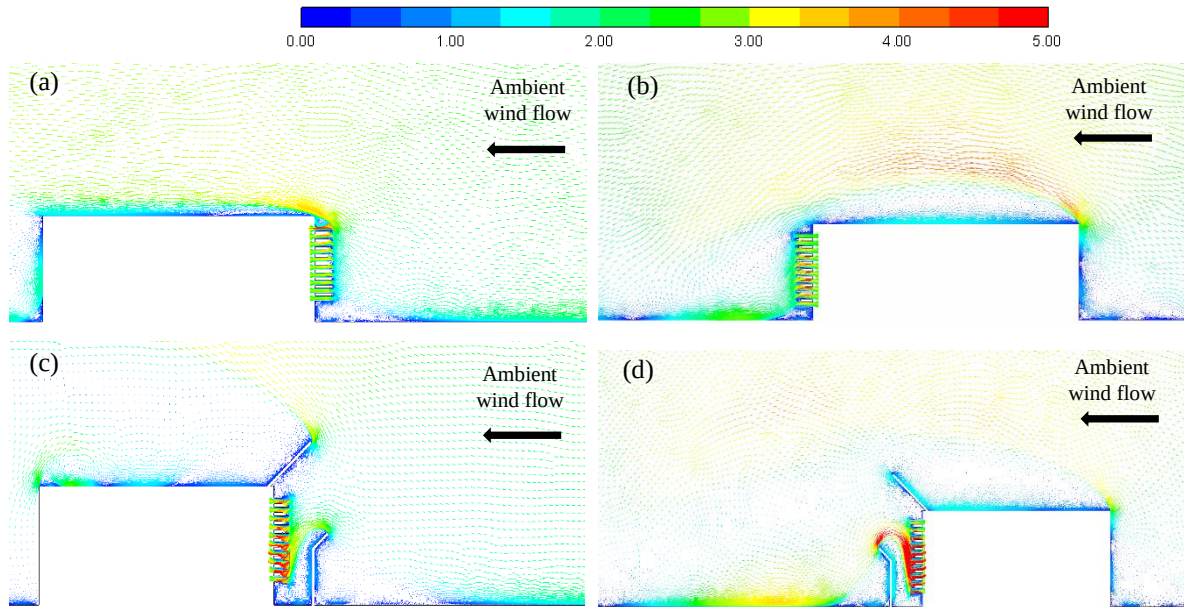


Figure 57. Velocity vectors (m/s) of ambient wind flow around an AER-AHU at $R=1$ where (a) forward-facing without deflectors (b) rear-facing without deflectors (c) forward-facing with deflectors (d) rear-facing with deflectors.

Examining both the forward and rear-facing models with the deflectors in Figure 57-d shows that they have had a profound impact on the flow dynamics around the AER-AHU inlet. An increase in the magnitude of the velocity can be seen for the lower inlet orifices and a stagnant zone has formed between the upper inlets and the roof deflector. This in combination with the ground deflector has diverted a portion of the flow upwards and around the roof deflector. The most significant difference was detected in the rear-facing AER-AHU with deflectors. The reattachment of the boundary layer has occurred further downstream and consequently the size of the wake zone has increased greatly in front of the AER-AHU.

The flow similarly to its forward-facing counterpart has split upwards and downwards at the deflectors, although the flow is not diverted around the AHU but is associated with the eddy formation in front of the ground deflector. We can examine the $D_{2.5}$ as these have the lowest St and therefore have a faster response time to the AER-AHU inlet. The results from the contours of $D_{2.5}$ particle concentrations demonstrate the variation in the particle distribution

for each model as shown in Figure 58a-d.

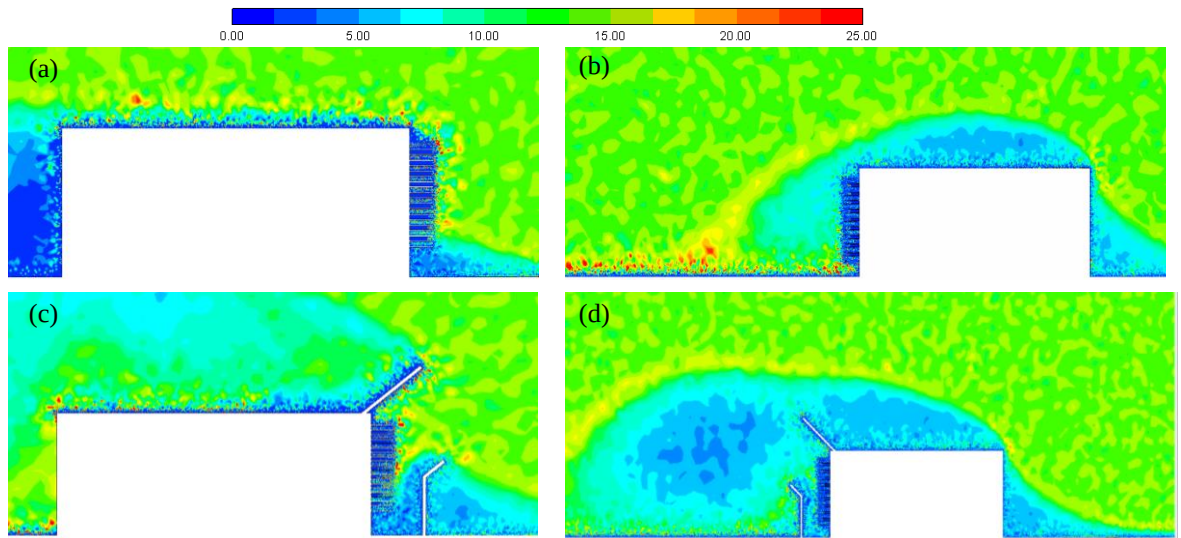


Figure 58. Contours of $D_{2.5}$ particle concentrations ($\mu\text{g}/\text{m}^3$) at $R=1$ where (a) forward-facing without deflectors (b) rear-facing without deflectors (c) forward-facing with deflectors (d) rear-facing with deflectors.

A larger proportion of the orifices in the forward-facing AER-AHU without deflectors were exposed to more ambient PM in comparison to with deflectors. This led to the slight decrease in AE with the deflectors that gradually became larger as the St increased. A more far-reaching effect of the deflectors can be seen when comparing Figure 58b and Figure 58d. The large eddy formation and increase in the height of the detached boundary layer has resulted in lower $D_{2.5}$ particle concentrations around the AHU. The interface between the boundary layer and the freestream flow has also experienced an increased mixing effect resulting in higher concentrations than the ambient environment concentration. This higher concentration is deposited closer to the AHU inlets without deflectors which is then drawn into the orifices. The significant difference in the concentration gradients led to very large difference in AE.

Again, as St becomes larger the deviation in AE between both models is reduced and performance levels are similar. There is not much variation in the velocity vectors at a wind speed of 7.5 m/s for both configurations of the FF AER-AHU in Figure 59a and c in comparison to their equivalent configuration at the low wind speed of 2.5 m/s. Although the magnitude of the velocity flow field is larger, the stagnant zone underneath the AER inlets without deflectors has increased in size and an equal ventilation velocity for each orifice

exists. There has been significant change to the RF AHU without deflectors as a large eddy has now formed in front of the AER-AHU inlet as illustrated in Figure 59b. Similarly, to the low wind speed analysis with deflectors and RF, the eddy has formed but increased in size and magnitude as shown in Figure 59d. The results suggest that for both orientations increasing the velocity magnitude generates lower AE for equivalent particle sizes due to difference in magnitude of the St. For the RF AHU, in combination with St, the wake effect is also a dominant factor in controlling the trajectory of the microparticles.

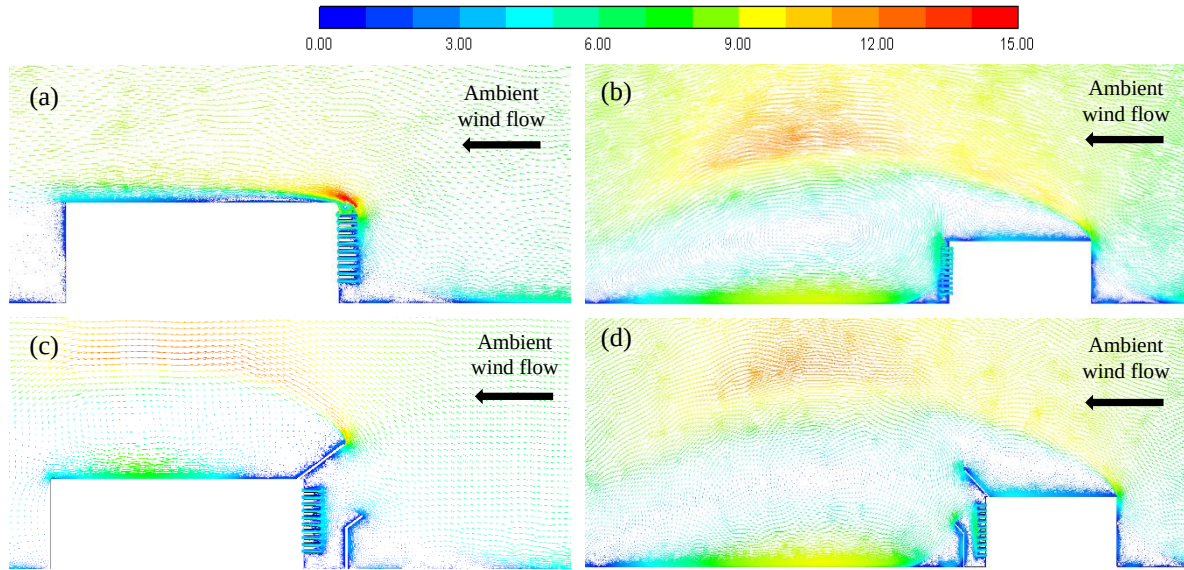


Figure 59. Velocity vectors (m/s) of ambient wind flow around an AER-AHU at $R=3$ where (a) forward-facing without deflectors (b) rear-facing without deflectors (c) forward-facing with deflectors (d) rear-facing with deflectors.

The $D_{2.5}$ particle concentrations showed a similar magnitude to the ambient concentration for the forward-facing AHU without and with deflectors as shown in Figure 60a-b respectively. The bottom three orifices without deflectors are positioned within a wake zone and where the particle concentrations are lower. Where the deflectors were installed, the bottom orifices also appear to be exposed to lower concentrations in comparison to the upper orifices. Hence, there was no significant difference in AE between both models. The variation between the rear-facing AER-AHU model is evident in the particle concentration gradients within the wake zone for both models. Without the deflectors, there is higher concentration of $D_{2.5}$ particles in the centre of the eddy in comparison to with the deflectors as observed in Figure 60. This caused the lower AE values in combination with the deflectors directing the particles away from the AER-AHU inlet. Although the results from the 2D models limit the particle trajectories and ignore the impact of the AHU sides flows. The wind

flow analysis in Chapter 5 Figure 43 around the AHU centre where the plane was parallel to the rooftop demonstrated the importance of the side flows on AE and therefore signifies the limitations induced with 2D modelling. AER Case 3 is essentially a basic version of the deflectors, and a more complete analysis of different deflector designs is required with 3D models that are comparable to the 2D model. The results from the 2D models suggest that further modifications to AER Case 3 could result in greater improvements and reduced filter loading.

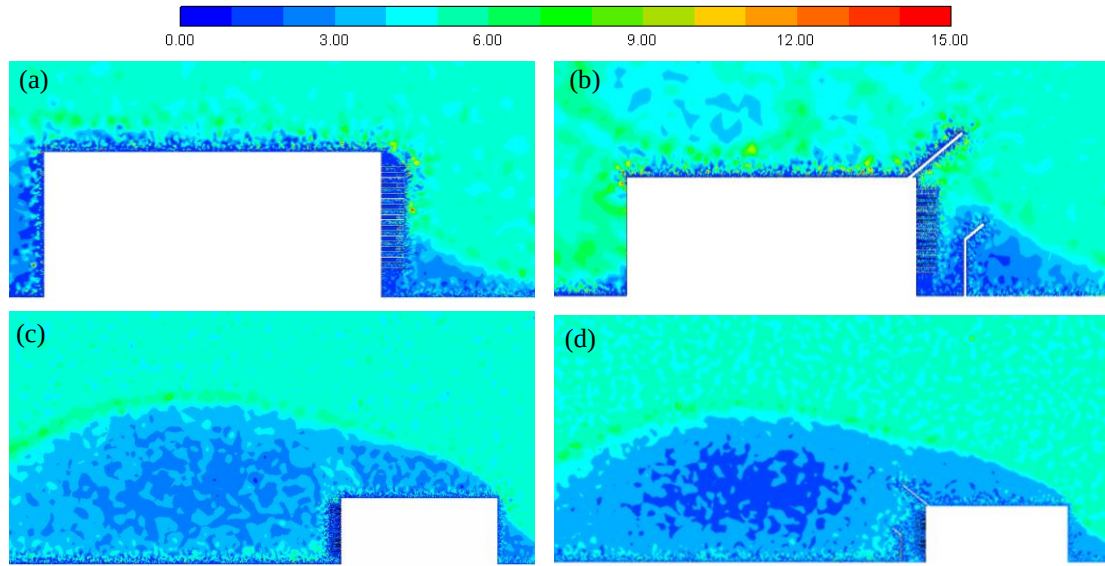


Figure 60. Contours of $D_{2.5}$ diameter particle concentrations ($\mu\text{g}/\text{m}^3$) at $R=3$ where (a) forward-facing without deflectors (b) rear-facing without deflectors (c) forward-facing with deflectors (d) rear-facing with deflectors.

6.4.2 Environmental Considerations and Implications for Energy Consumption

For illustrative purposes, a filter with a grade ISO ePM1 85% [232] was chosen to analyse the impact an AER device could have on the AHU energy consumption in Dublin, Ireland. The characteristic of the filter according to the particle loading curve and subsequent pressure drop can be seen in Appendix Section 11.2, and the lab test was conducted by the manufacturer according to ISO 16890:2016 [117]. As this filter test used A2 fine dust, which is representative of the characteristics of PM_{10} concentrations for filter grading, an ambient PM_{10} concentration of $20 \mu\text{g}/\text{m}^3$ was used. This is representative of ambient PM concentrations in Dublin city centre and was chosen to determine the energy consumption variation between the filter manufacturer recommendation and existing commercial rainhoods. Furthermore, an AHU flow rate of $3400 \text{ m}^3/\text{hr}$ as recommended by ISO

16890:2016 was used to analyse the filter loading rates and corresponds with the flow rates used to configure the AE of each case study. The initial pressure drop induced by a fabric filtration system can range from 50-150 Pa depending upon the grade of filters and its ability to remove a minimum arrestance rate of particles based on their respective diameters. Typically the final pressure drop at filter saturation is 200 Pa and 300 Pa for filters with removal efficiencies $< 50\%$ and $\geq 50\%$ for PM_{10} , respectively [117].

Figure 61 shows the viability of the passive and active AERs with respect to current commercial models where AE was averaged across all wind speeds and directions for particles $\leq 10 \mu m$ and was used to adjust the filter loading rates. The pressure drop of each AER prototype generated a lower final pressure drop over the equivalent length of time needed for saturation of the filter in the laboratory test (325 days, Table 11).

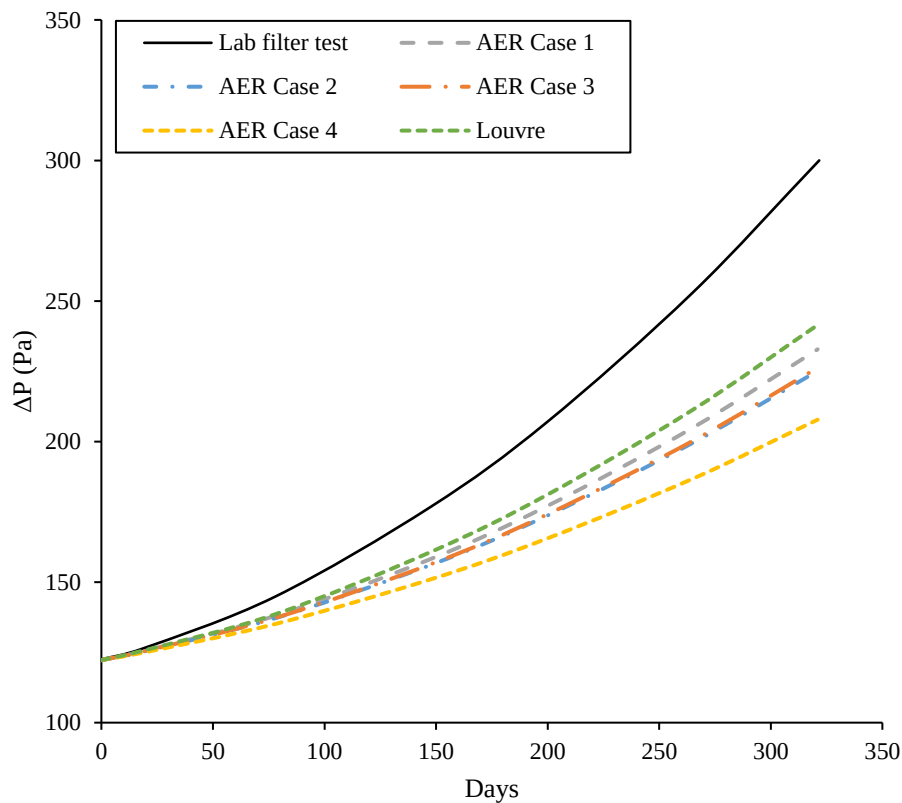


Figure 61. Pressure drop over time until filter saturation according to ISO 16890:2016 of a grade ISO ePM1 85% filter saturation [117,232] at an ambient PM_{10} concentration of $20 \mu g/m^3$ and an AHU flow rate of $3400 m^3/hr$.

The active AER system (Case 4) presented the lowest pressure drop over time and provided better control over the effect wind direction has upon AE. Although an active system would

require energy to control the dampers, the power requirements would be very small in comparison to the energy saved from a lower filter pressure drop. Typically, a damper is installed for controlling the flow of fresh air and a modification of the current system could be achieved without incurring any additional energy costs. Each of the passive cases performed particularly well with particles $\leq 10 \mu\text{m}$. However, AER Cases 2 and 3, where the inlets are facing the ground or shielded by a barrier preventing the occurrence of particle-laden wind flowing directly through the orifice array unimpeded resulted in greater energy savings. The energy consumption of the fabric filtration system can be quantified using the filter energy consumption formula described in Eq. (1) [233].

Table 2 illustrates both the energy and monetary cost savings associated with each AHU add on attachment that separates the ambient environment and the building ventilation system. In addition, the results suggest filter saturation in a dynamic environment instead of a laboratory setting will occur over a longer period of time due to the variation in the averaged AE over wind speed and direction for particles $\leq 10 \mu\text{m}$. The presence of a commercial rainhood or an AER device and the orientation of the AHU relative to the prevailing wind direction will result in PM_{10} concentration lower than the ambient environment entering the ventilation system.

Table 11. Energy and economic cost estimation based on particle loading rates of a filter with an AHU attachment over the lab filter lifespan of 321 days based on the estimated parameters.

	$\overline{\text{AE}}_{\leq 10\mu\text{m}}$	Filter saturation	$\overline{\Delta P}$	Energy consumption	Energy cost	Energy cost savings per filter		AER vs Louvre Energy cost savings	
	%	Days	Pa	KW/h	0.22 € Kw/h	€	%	€	%
Filter		321	198*	2888.9	635.6	-	-	-	-
Louvre	77.5	414	173.4*	2529.3	556.5	79.11	12.4	-	-
AER Case 1	74.0	435	168*	2449.4	538.9	96.69	15.2	13.66	3.2
AER Case 2	70.7	455	165.8*	2417.7	531.9	103.66	16.3	23.58	4.4
AER Case 3	71.2	452	167.3*	2439.6	536.7	98.85	15.6	15.38	3.5
AER Case 4	62.6	514	157.4*	2294.8	504.9	130.70	20.6	24.77	9.3

* Average pressure drop calculated over filter saturation time period of 321 days

The commercial and AER models had an extended filter life span ranging from 89-189 days in comparison to the laboratory dust filter loading test. However, the time to filter saturation has been extended by 21-38 days for the passive AER's (i.e., Case1-3) and by 100 days for the active AER system when compared with the commercial louvre model. Overall, this

resulted in a large variation in the amount of energy consumed by each system and generated significant cost savings over the filter lifespan. Even when evaluating with the lower return rate of the energy savings range 3.2-9.3%, this represents an excellent opportunity for a lower carbon footprint with minimal capital investment. The potential impact on both the environment and economic benefit to the consumer due to the number of filters typically installed in commercial or industrial buildings worldwide would be significant in comparison to the existing commercial infrastructure in use.

In addition, creating an annual database representative of the local weather patterns and the natural and anthropogenic PM sources could also lead to an increase in building energy efficiency. This includes mapping conditions around the building ventilation system to optimise the AER design, e.g., selecting a ground facing AER case 2 might be preferred in desert regions where sandstorms are prevalent and larger diameter particles are present in abundance. Indeed, this local information could be useful to simply orient the existing AHU to be predominantly rear-facing regardless of its inlet design and further extend the lifespan of the filter.

6.4.3 Installation, Design Considerations and Limitations for Passive and Active PM Control System for an AHU

The deployment of AER's into the ventilation equipment market and the type installed will largely depend on the building design, rooftop layout, geographical location, climate and local air quality characteristics. Each simulation examined the most extreme conditions the AHU is subjected to, but the dynamic nature of any environment means that there is a large variation in the wind angle. Therefore, the passive AER Case 2 and 3 have the advantage that the array of cylindrical inlet's are never positioned facing into the wind. While AER Case 2 and 3 were less efficient when the AHU body is rear-facing, they nonetheless have substantially improved performance due to the reduction in AE when facing into the wind. This would imply that, on average, this would be the most advantageous configuration when actually operating in a dynamic urban or rural environment. However, it should be noted that AER Case 2 is limited by space considerations and accordingly, the size of the AHU. The other passive design, AER Case 1 and 3 are not restricted by space as such and are of a similar size to a commercial louvre rainhood.

The most efficient system is the active AER design, Case 4, however, this system will require a larger capital investment to create an efficient monitoring system and achieve a higher level of PM control. While similar issues with the space restrictions may occur with this design as AER Case 2, therein lies a greater scope for design improvements to this system. The system will also require a novel control system for the dampers that takes advantage of the current energy usage by saying a damper controlling the fresh air supply inlet (i.e., AHU inlet). Furthermore, the system must be controlled by local anemometer data to ensure the array is not facing the wind.

Finally, the implementation of a deflectors system under 2D analysis demonstrated the viability of a strategically placed deflector system that manipulates the particle laden fluid flow away from the AHU. In essence, the 3D models of AER Case 2 are analogous to the deflector plates but are a more basic design and 3D parametric study of deflector plate positioning, size and angle would be required to further develop this technology, tested at both AHU inlet orientations relative to the wind direction. The variation in AE for the small 25mm orifice arrays used in the 2D models also resulted in similar trendlines and AE magnitudes at equivalent particle diameters as the 2D louver rainhood (Inlet 2) used in Chapter 5, Figure 41.

6.5 CONCLUSIONS

In conclusion, the use of AER as a form of PM control has been successfully demonstrated as a positive addition to a HVAC system. AER technology could be deployed as an additional component to existing air pollution control technology such as fabric filtration systems, and thus act as a prefilter. Overall, the AER devices resulted in lower concentrations of PM entering the ventilation system through lowering AE. This was primarily achieved through the engineering of boundary layer separation on the AHUs. The varying levels of AE for each prototype depended upon the particle diameter, wind direction and speed. As such, understanding the local environment characteristics and flow dynamics (i.e., local data of PM size distribution and prevailing wind conditions) around the AHU, is vital to the optimum performance of a HVAC system. Engineering particle inertia in order to lower AE by diverting particles away from the AER inlets and ensuring the wind cannot blow directly into the filter without impedance (i.e., Case 2 and 3) led to lower potential energy consumptions.

Deployment and installation of AER devices to AHUs around the world could contribute to the goal of net-zero buildings using an environmentally friendly solution. This paper demonstrated the ability to design an air pollution control device that accounts and/or responds to the impacts of wind direction in order to reduce AE. In addition, the AER device's also resulted in lower AE for fine and coarse particles in comparison to a commercial rainhood. Considering the number of HVAC filters in operation worldwide, the potential energy and monetary cost savings that could be achieved are significant. The lower particle loading rates increase the life span of a filter leading to a lower average pressure drop over a set period of time and/or longer periods of time to filter saturation. Based on this assessment, the AER could contribute to greener buildings through a decrease in energy consumption and both labour and material costs incurred by maintenance activities. Four AER prototypes were found to be a more efficient air pollution control attachment in comparison to commercial rainhoods currently used in industry and the key findings include:

- AER Case 1 was found to be more efficient than the commercial Louvre model tested in Chapter 5 and had a lower average AE of 74% for particles $\leq 10 \mu\text{m}$ compared to 77.5 %. Furthermore, AE was significantly lower when Case 1 was facing away from the wind and is analogous to studies on air pollution samplers [3,142], aspiration characteristics of human nose and mouth [4,5,147] and another study on a prototype AER [6].
- Whereas the other passive AER devices, Case 2 and 3, were designed to prevent the cylindrical orifices inlets facing into the wind and under certain conditions altered the effect of the wind upon their AE resulting in a much lower average AE of particles $\leq 10 \mu\text{m}$ at 70.7% and 71.2%. Both of these models also resulted in a large difference in mean AE across the entire St range when facing into the wind. Although the RF configuration for AER Case 2 and 3 did not improve upon AER Case 1 and typically had slightly higher AE. Overall, both models were superior.
- The active AER system (Case 4) incurred the lowest AE as the prototype incorporates the advantages of the passive AER's into the design. This resulted in the lowest average AE at 62.6% for particles $\leq 10 \mu\text{m}$. Ensuring the array of inlets are always facing away from the wind will lead to substantially lower PM concentrations entering the ventilation system.
- Comparing the potential energy demands incurred by each prototype, a 3.2-9.3% energy savings was observed as a result of AER deployment in comparison to a

commercial Louvre rainhood. The filter lab tests, when adjusted based upon the AE of PM_{10} particles, demonstrated a 15.2-20.6% energy savings.

Using AE index as a measurement of PM control efficiency in a ventilation system is a growing area of research and requires further investigation to enhance and improve our ability to develop low-AE technology. The results from this paper demonstrated the potential improvements that could arise from alterations to the aerodynamic shape of the AER attachments as well as the AHU body. The locations where the ambient fluid flow separates, and attaches could positively impact the AE of the system without incurring any additional pressure losses. In addition, the outcomes from AER Case 3 demonstrate the potential viability of placing deflector plates around the AHU in order to manipulate the external fluid flow away from the inlet. Using the factors affecting AE as a form of PM control, whether passively or through an active system, still requires more experimental verification through a wind tunnel or field tests (see Chapter 8). Finally, the AE concept could be expanded to other types of ventilation systems such as vehicles, computers, building vents and windows.

7 VARIATION IN DISPERSION OF PARTICULATE MATTER EMISSIONS FROM A STREET CANYON ACROSS A BUILDING ROOFTOP AND OPTIMISATION OF AN AHUS ROOFTOP POSITION

7.1 INTRODUCTION

This chapter expands upon existing body of literature by examining the impact the outdoor environment has upon the indoor by using AE as the primary measurement metric when assessing an AHUs position and orientation on a building rooftop located near a traffic emission source from an urban street canyon. The impact of traffic emissions on the AHU filtration system as $PM_{2.5}$ is dispersed across the rooftop of a building is poorly understood as the studies on pollutant distribution in urban canyons described in Chapter 2 usually neglect the presence or position of an AHU on the rooftop. The variation in air pollution concentrations across roof level is also an area of research which has received little attention. The relationship between an AHU's fresh air intake AE based on the proximity and orientation to traffic source emissions requires further investigation. In addition, the impact of the wind dynamics on an AHU's AE has only been examined with a uniform wind profile and this paper addresses this gap by incorporating a wind profile based on the power law into numerical models. Finally, the study addressed how the orientation and position of an AHU on a rooftop in an urban environment impacted the energy consumption of each case study and quantified the related energy costs using a representative background $PM_{2.5}$ concentration adjusted through their respective AE. This provided the ventilation $PM_{2.5}$ concentration until filter saturation occurred and will provide an indication of the improvements in energy consumption and IAQ that could be achieved through careful building services planning considerations for HVAC system positioning and orientation.

7.2 NUMERICAL MODEL SET UP

Numerical models were created to estimate the influence a symmetrical urban canyon has upon pollutant dispersion at roof level and the associated impact on an AHU filtration system. Each three-dimensional model was created on SOLIDWORKS 2018 and simulated using computational fluid dynamic (CFD) software ANSYS 18.1 Fluent. The models assess the ingress of $PM_{2.5}$ from the street level into the AHU at three locations (pos-1, pos-2 and

pos-3) on the centreline of the building rooftop, as shown in Figure 62 in order to assess its impact on AE. The AHU was situated 300 mm from the windward side of urban canyon 1 for pos-1 and mirrored for pos-3 on leeward side of urban canyon 2, whilst the AHU body was centred with the rooftop centre for pos-2. Additionally, the AHU inlet was positioned facing into the wind (0°), perpendicular to the wind (90°) and away from it (180°) on the building rooftop, referred to again as FF (forward-facing), SF (side-facing) and RF (rear-facing) respectively hereafter. This amounted to 21 case studies across three wind speeds, AHU orientations and rooftop positions relative to the polluted urban street canyon as shown in Table 12. The AHU incorporated a louvre style rainhood attachment shown in Figure 62 and is a replica of the models and dimensions used in Chapter 5 (i.e., AHU commercial Inlet 2). A double urban canyon comprising three storey buildings at height of 12m was used to ensure the dynamics at both ends of the rooftop were captured correctly and an aspect ratio of 1 was maintained for the canyon dimensions in each model in order to simulate skimming flow.

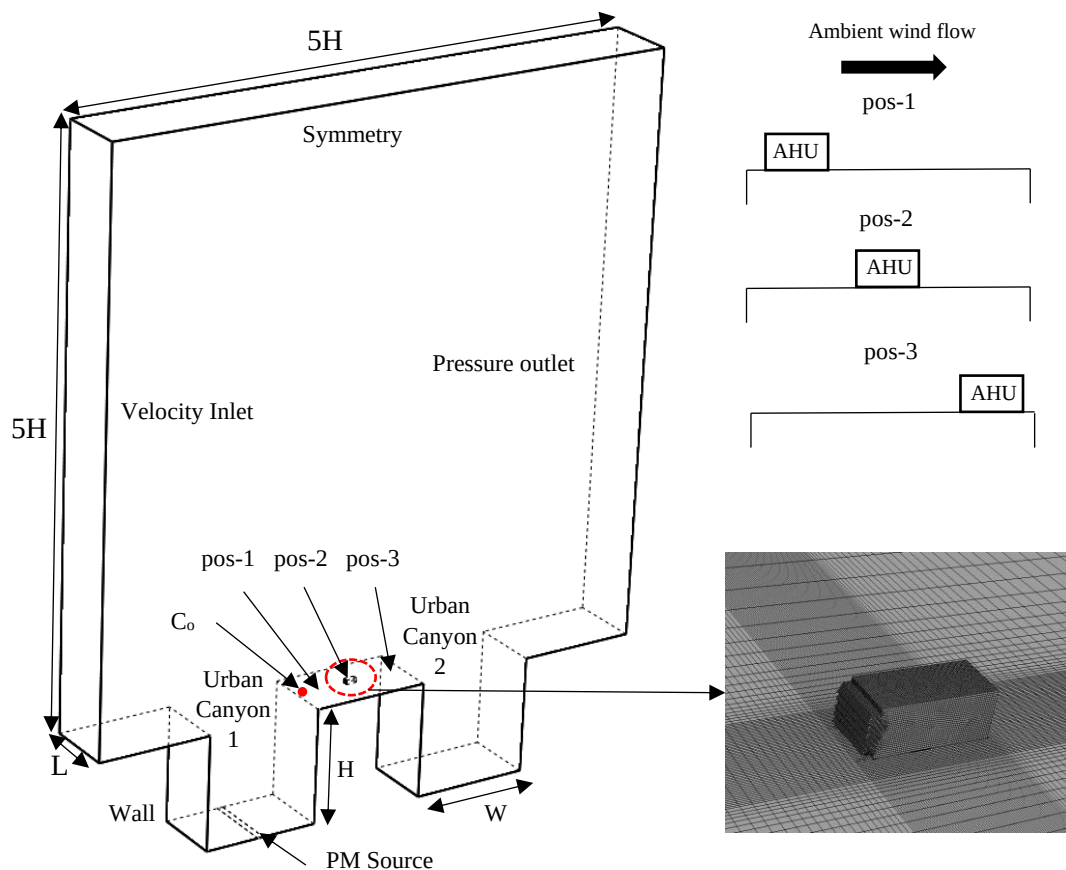


Figure 62. Computational domain of symmetrical urban street canyons with a $PM_{2.5}$ source and rooftop AHU (Note: $W=L=H=12m$).

To ensure the dynamics of pollutant dispersion upon the rooftop of a commercial building situated in an urban environment are captured correctly, a PM_{2.5} source was selected to replicate the physical conditions experienced during high traffic volumes in urban areas. Therefore, a UDF was used to account for the drag of particles depending on their respective diameter. The UDF was created to model particle drag across a range of diameters less than 2.5 micron injected at 0.01 m/s at the PM_{2.5} source shown in Figure 62. The particle diameter distribution was configured with a Rosin-Rammler expression in FLUENT and works by organising the particles into groups based on their respective diameters (d). The method determines the mass fraction of particles (Y_d) with a diameter greater than d from a dataset by assuming an exponential relationship between d and Y_d :

$$Y_d = e^{-(d/\bar{d})^n} \quad (60)$$

Where $\bar{d}$ is the average diameter and n is the spread. Tang et al. [226] found d and Y_d for particulate emissions from a diesel vehicle exhaust to be 0.55 and 2.44 respectively. A minimum and maximum particle size of 0.1 μm and 1 μm was also chosen based on the particle distribution table and fitting curve used to derive $\bar{d}$ as shown in Appendix Section 11.2. The modelling of the particle drag force required a UDF capable of capturing slip factors for sub-micron particle diameters and are typically modelled through the Cunningham coefficient described in Eq. (9-10).

In addition, the UDF accounted for the urban boundary layer profile using an exponential function known as the power law wind profile described in Eq. (31). Furthermore, this method requires an actual representation of the urban boundary layer velocity turbulence intensity (k) and dissipation (ϵ) profiles and used Eq. (33) and (34) respectively to achieve this. Reference wind velocities of 2.5 m/s, 5 m/s and 7.5 m/s were chosen to capture a range of different weather conditions, and these were configured based on the height of an anemometer from the building rooftop of 10m (i.e., 22m from the street canyon road). The boundary conditions for the model consisted of a pressure outlet downstream of the urban canyons, a wall for the building surfaces and AHU body, a velocity inlet for the AHU orifices and upstream of the urban canyons, and symmetry condition for the sides and top of the domain. Concentration of PM were monitored at location C_o for the ambient as shown in Figure 62 and at AHU inlets for the ventilation and a time-averaged sample over 250s period was collected under steady-state conditions.

Table 12 Case studies detailing the environmental and HVAC operations tested within this investigation into the performance of an AHU in an urban environment.

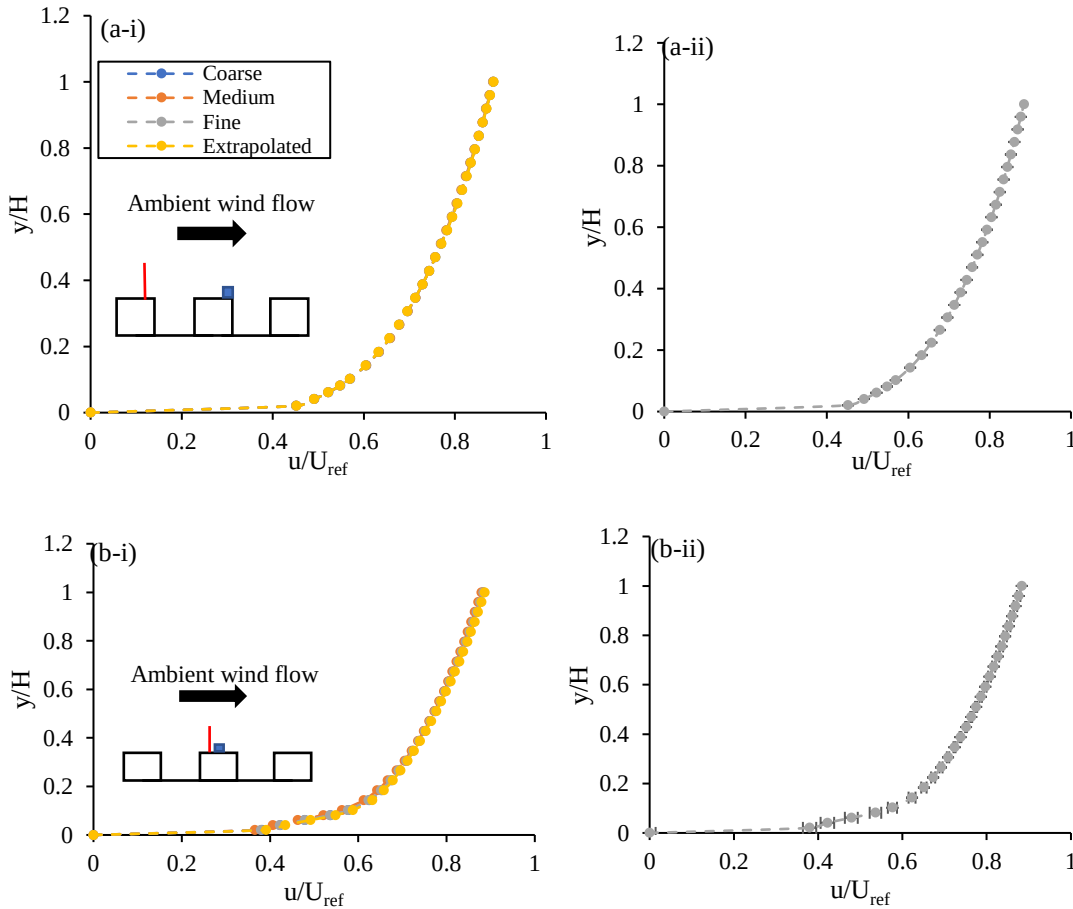
Case study 1: Impact of wind speed and orientation on the AE of AHU from a local PM _{2.5} source	
Ambient air	
Wind speed	2.5, 5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0°), SF (90°), RF (180°)
AHU attachment	Inlet 2
AHU flow rate	3400 m ³ /hr
AHU position	2 (rooftop centre)
PM particles	
Particle diameters	PM _{2.5}
Particle drag	Cunningham correction factor
Particle density	1.4 g/cm ³
Case study 2: Assessment into the influence an AHU's rooftop positioning and orientation has on the AE for PM _{2.5}	
Ambient air	
Wind speed	2.5, 7.5, m/s
Air viscosity	1.79E-05 kg/ms
Design	
AHU orientation	FF (0°), SF (90°), RF (180°)
AHU attachment	Inlet 2
AHU flow rate	3400 m ³ /hr
AHU position	1 (windward side), 2 (rooftop centre) , 3 (leeward side)
PM particles	
Particle diameters	PM _{2.5} (range from 0.1-1 µm) – See appendix 11.2
Particle drag	Cunningham correction factor
Particle density	1.4 g/cm ³

A transient scheme with a time step of 0.25s and convergence of the scaled residuals were set to a minimum of 2×10^{-4} for continuity, x-momentum, y-momentum, turbulent kinetic energy and turbulence dissipation rate. Time-averaged samples were collected at the AHU inlet and upwind of the AHU at the rooftop edge as designated in Figure 62 where a monitor was used to calculate the C and C₀ respectively and consequently determine the AE of the AHU's tested. Finally, the AE will be used to analyse the variation in energy consumption by adjusting the filter loading rates using the ambient concentration as a reference. Similar,

to Chapter 6 the relationship between the average pressure drop ($\overline{\Delta p}$) over the working life of the filter and the energy consumption is then accounted for by Eq. (1).

7.2.1 Full-Scale Urban Street Canyon with AHU Grid Verification

Three grids were developed, and the cells refined in order to measure the discretisation error using GCI to quantify the uncertainty for an urban street canyon with an AHU located on a building rooftop downwind of a local PM source. The coarse, medium and the fine grid were designed with an average cell size of 0.06 m, 0.045 m and 0.03 m respectively used around the AHU body and throughout the domain. A maximum cell size of 0.3 m was used in the urban canyon with the finest grid and followed an equivalent ratio sizing as the AHU body. This resulted in cell count of 1,035,044, 1,580,272 and 2,572,022 for each grid and grid refinement factor (r) of 1.5. To ensure consistency and a constant Courant number, a timestep of 0.25 s, 0.375 s and 0.5 s were used for the fine, medium and coarse grids respectively. In this instance, the velocity magnitude was measured and extracted at 125 discrete locations throughout the domain.



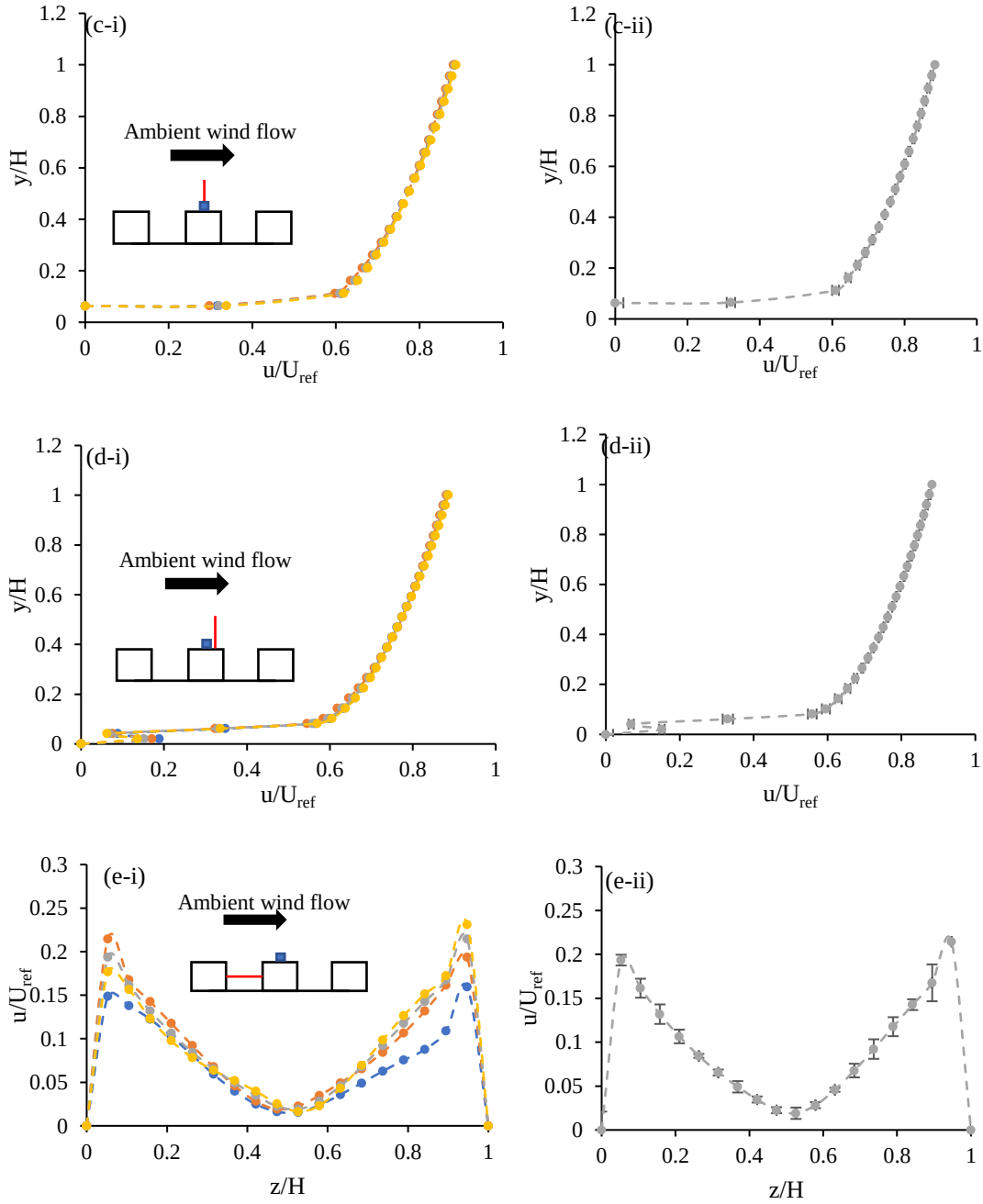


Figure 63. (i) Velocity profiles and (ii) error bars using GCI methodology for a forward-facing AHU on top of a building rooftop at locations (a) upstream of the urban canyon at $x/x_{tot}=0.13$ (b) upstream of the AHU at $x/x_{tot}=0.475$ (c) above the centre of the AHU body at $x/x_{tot}=0.5$, and (d) downstream of the AHU $x/x_{tot}=0.525$ and (e) centreline of the urban canyon upstream of the AHU at $y/y_{tot}=0.1$; $U_{ref}=7.5$ m/s. Note: The redline represents the sampling locations and the blue square the AHU body.

The velocity profiles extracted in Figure 63 examined locations of interest and if there grid density was sufficient to capture the flow dynamics at locations (a) upstream of the urban canyons and measured in the undisturbed wind, (b) upstream of the AHU body, (c) above

the AHU roof centre, (d) downstream of the AHU body, and (e) the urban canyon centre. Finally, the maximum GCI was approximately 23% which occurred in Figure 63e and the fine grid induced an average error of 3% throughout the domain. This is reasonable as indicated by each profile comparison where there is not a significant variation between the medium and fine grid and the latter was the chosen model for this study.

7.3 RESULTS AND DISCUSSION

7.3.1 Analysis of the Effect of $PM_{2.5}$ Traffic Emission upon the AE of an AHU in an Urban Environment

The impact of a $PM_{2.5}$ traffic emission source on a building ventilation system was examined in Figure 64 at three different wind orientations and wind speeds while positioned at the centre of the rooftop. The results showed that there was a minimal variation in AE as the wind speed increased for both an AHU inlet positioned facing into and away from the particle laden wind. Albeit a slight reduction in AE was observed for the AHU louver inlet positioned parallel to the wind (i.e., SF). This was to be expected when employing a power law wind profile in a symmetrical urban canyon due to the difference in the length scales between an urban boundary layer and the small height of an AHU. In essence the wind profile from the rooftop to the top of the AHU would result in a near uniform profile due to the negligible variation in wind velocities for skimming flow in an urban canyon at the AHU height.

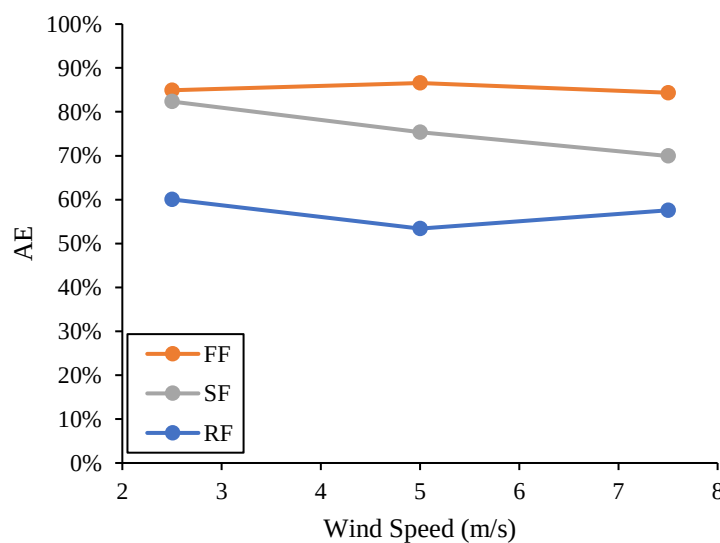


Figure 64. Analysis of the relationship between the AE of $PM_{2.5}$ and the orientation of the AHU inlet relative to the wind direction on a building rooftop at an AHU flow rate of $3400 \text{ m}^3/\text{hr}$.

The results from Figure 64 demonstrate the impact that the wind orientation has upon the AE of the AHU. The RF configuration led to lower AE magnitudes for each wind speed tested in comparison to both the FF and SF AHUs. Differences in AE between FF and RF configurations ranged from 26-35% which would incur a substantial variation in particle loading rates, especially in heavily polluted urban environments. Analogous AE studies on aerosol samplers [3,142], human aspiration studies [4] and other building ventilation studies [6,151] have all observed this phenomenon of lower AE for a RF orifices resulting in substantial lower concentrations entering buildings in this context. Increasing particle inertia results in lower AE when there are substantial changes in a particles trajectory. The AHU inlet facing into the wind ensures the particles are flowing directly at the inlet, requiring no major change in trajectory where these only have the potential to be impeded by the louvre walls of the inlet. The SF AHU resulted in AE values at low wind speeds similar to the FF AHU as particle inertia has decreased and the change in trajectory is not as significant as the RF AHU. Additionally, the louvre faces are positioned parallel to the wind direction which suggests increased particle build up in comparison to RF AHU but less than the FF AHU as the wind speed increases.

7.3.2 Optimum Placement Locations of an AHU on a Downstream Building in a Symmetric Urban Canyon

The optimum placement of the AHU on a building was investigated in Figure 65 at different rooftop positions that are located in the pathway of a traffic $PM_{2.5}$ source. Figure 65 shows that increasing the distance of the AHU position from the polluted urban street canyon results in a lower AE for both a low and high wind speeds. The $PM_{2.5}$ concentrations recorded at the edge of the building are dispersed in the uncontaminated air and diluted through turbulent conditions associated with convective transport and diffusion. The FF AHU located in pos-1 is the closest to the urban canyon and culminated in the highest recorded AE of 103 % and 122 % at a U_{ref} of 2.5 m/s and 7.5 m/s respectively. It is to be expected that the $PM_{2.5}$ concentrations when facing into the wind would be approximately equal to the ambient concentration in this location due to the short distance and transportation time.

At a low wind speed, AE exceeded the 100% through a combination of secondary aspiration and a higher ventilation rate of the urban canyon induced by lower ambient wind speed and decrease in the shear force effect associated with skimming flow. As the pollutant travels across the rooftop, the concentration levels of the ambient $PM_{2.5}$ are reduced and differences between AE for each location as the wind speed increases are not as pronounced. Irrespective

of the wind speed, considering the AHU location could lead to significant energy savings. From pos-1 to pos-3 there is a 60% and 33% reduction in AE at the lower and higher wind speed respectively. Although it should be noted that the RF AHU from Figure 64 outperformed each of the FF AHUs tested in pos 1-3 as illustrated in Figure 65, notwithstanding the wind speed. This suggests the inlet orientation relative to the wind direction is still the most important variable effecting the AE of a buildings ventilation system. The RF AHU also had similar AE regardless of the wind orientation and speed with only a very slight reduction of approximately 10% from pos-1 to pos-3.

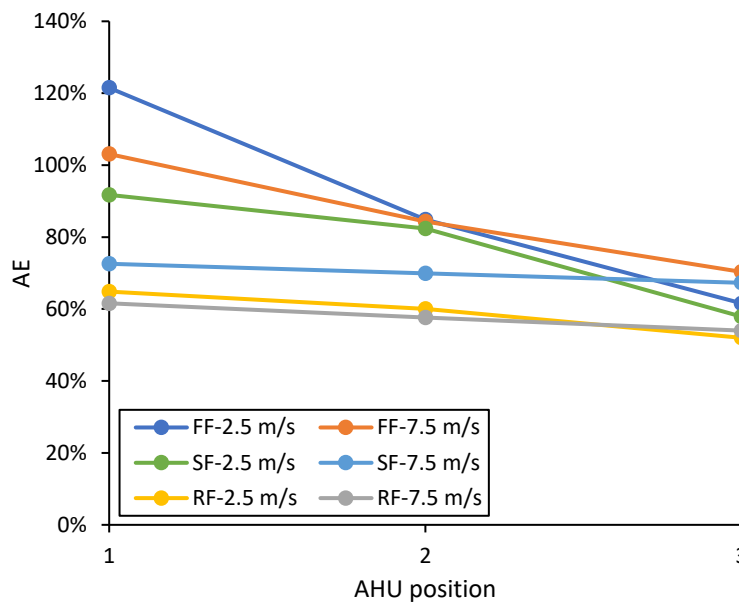


Figure 65. Analysis of the relationship between the AE of $PM_{2.5}$ and an AHUs proximity to a traffic emission source on a building rooftop at an AHU flow rate of $3400 \text{ m}^3/\text{hr}$.

The SF AHU also resulted in lower AE compared to FF AHU at each pos but was still not as efficient at reducing filter loading as the RF AHU. AE reduced at a greater rate across the building rooftop at low wind speeds and facing into the wind. The rate of change was not as significant and the difference in AE was much reduced as the AHUs orientation relative to the wind direction increased. The differences between AE at pos-3 for each of the orientations and across wind speeds is not as drastic and suggests the PM dilution at this point is significant in the clean air and the distance from the source is dominant in comparison to the AHU orientation and/or wind speed. At high wind speeds the change in AE across the rooftop, pos-1 to pos-3, for SF AHU is negligible but significant at low speeds where the difference in AE amounted to 34%. Again, the lower wind speeds will result in higher concentrations of PM on the rooftop and therefore lead to greater dispersion.

7.3.3 Varying Skimming Wind Speeds for a Symmetric Urban Canyon and the Effect on PM_{2.5} Dispersion around FF AHU on a Building Rooftop

Figure 66 illustrates the variation in wind velocities that the AHU was subjected to by the use of wind profiles representative of an urban environment. The stratified wind velocities did not affect AE for an AHU positioned at the rooftop centre as shown in Figure 64 where the difference in AE between wind velocities was negligible. The PM_{2.5} contours in Figure 67 demonstrated the difference in the outdoor air quality depending upon the wind speed. As the wind speed reduces, the shearing effect induced by the wind profile loses its impact at the boundary between the rooftop environment and the urban canyon. Moreover, lower air exchange rates between the urban canyon and rooftop environment lead to a reduced dilution of PM_{2.5} concentrations in the canyon and therefore higher concentrations where the boundary layer separation occurs at the windward side of the building with the AHU. This results in higher PM_{2.5} concentrations on the rooftop at lower wind speeds and also less dispersion due to lower turbulence intensity compared to higher wind speeds.

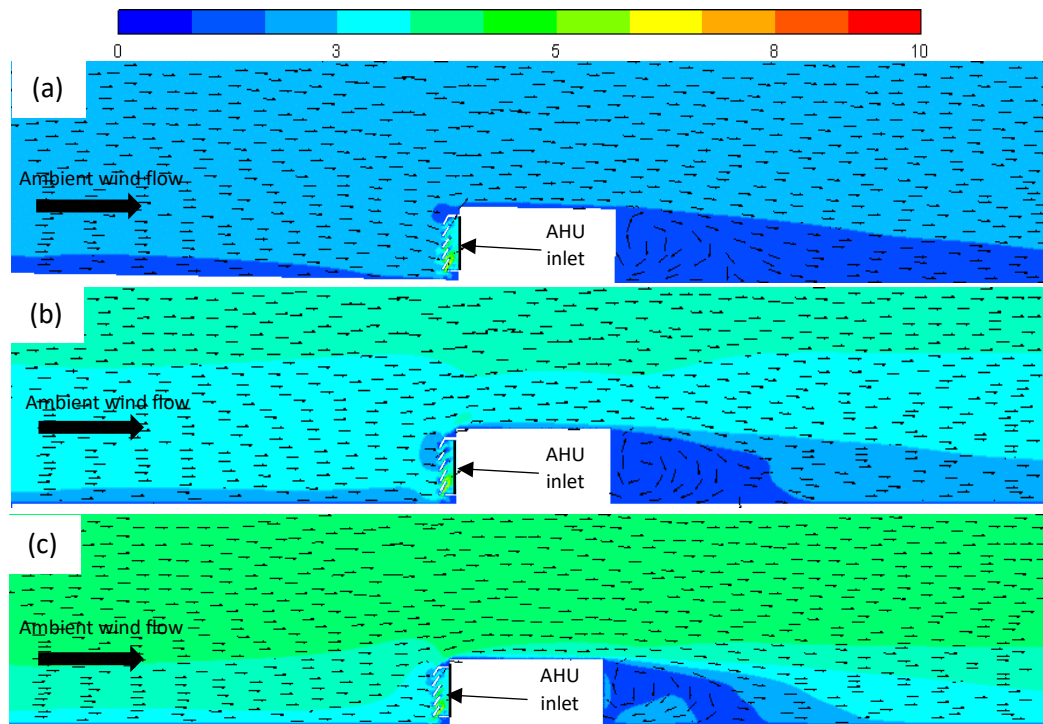


Figure 66. Wind flow analysis around a forward-facing AHU at an AHU flow rate of 3400 m³/hr on a building rooftop at position 2 with a plane intersecting the AHU centre at a wind speed (a) 2.5 m/s (b) 5 m/s (c) 7.5 m/s.

While AE might not be drastically dissimilar between wind speeds at the rooftop centre, the filter loading rate will be very different due to the reduction in the rate of diffusion,

convective transport and dilution under calm weather conditions. This can be seen Figure 67, where a larger concentration of $PM_{2.5}$ can be observed at the lowest U_{ref} of 2.5 m/s. The effect is less pronounced when comparing U_{ref} for 5 m/s and 7.5 m/s models as the $PM_{2.5}$ dispersion contours are relatively similar. Although the former has higher local concentration gradients of $PM_{2.5}$ throughout the plane in comparison to the latter.

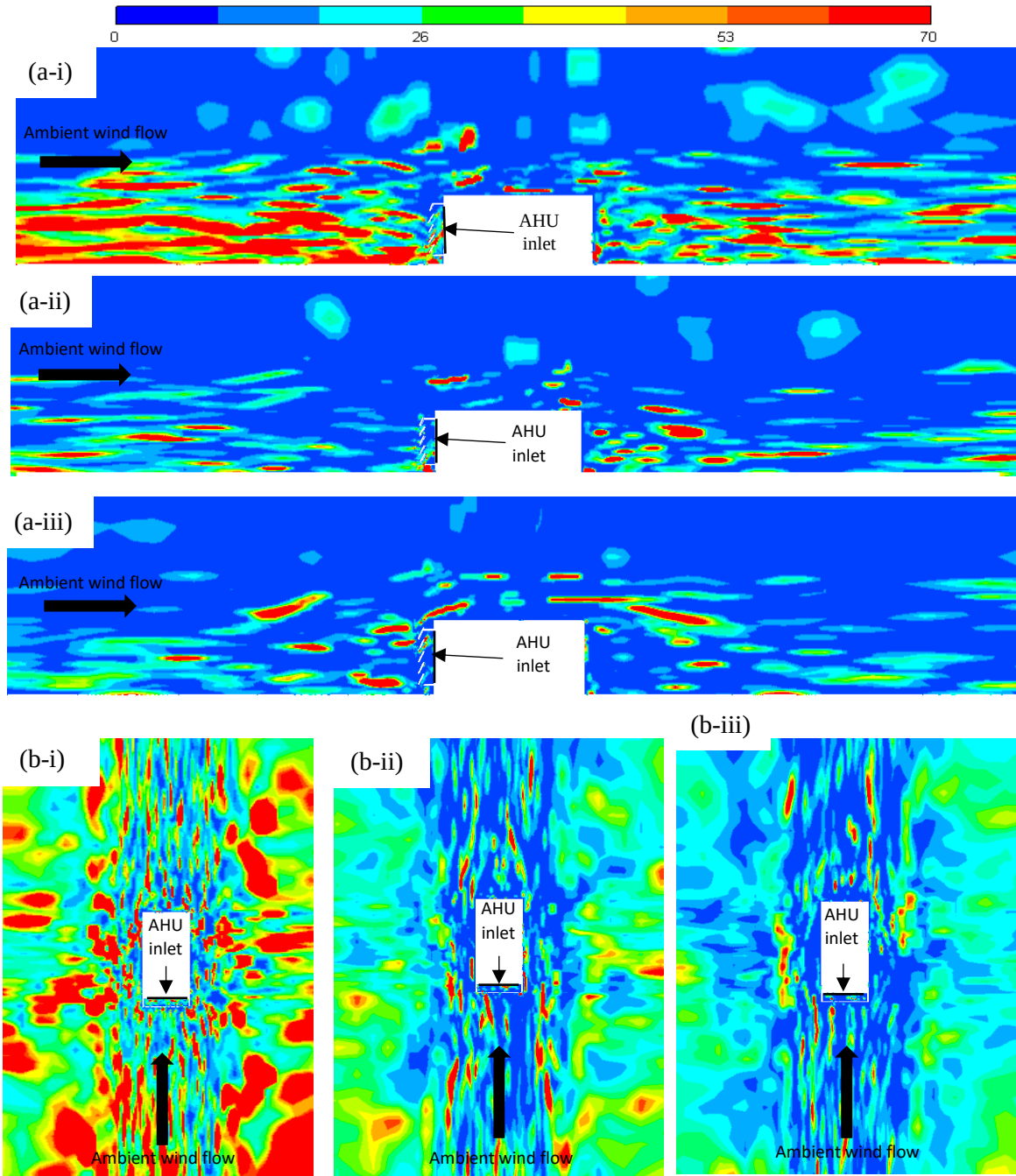


Figure 67. $PM_{2.5}$ ($\mu g/m^3$) dispersion contours around an AHU on a building rooftop in an urban canyon at (a) perpendicular plane (b) parallel plane; to the rooftop intersecting the AHU centre and a reference wind speed of (i) 2.5 m/s (ii) 5 m/s (iii) 7.5 m/s with an AHU flow rate of 3400 m^3/hr .

7.3.4 Analysis of the Fluid Flow Patterns at Different AHU Inlet Orientations Relative to the Wind Direction on a Building Rooftop

The particle laden wind vectors were examined in Figure 68a-b at a reference wind speed of 5 m/s for a FF AHU and were found to flow directly into the AHU inlet and a wake has formed at the end of the AHU body. The flow is predominantly parallel to the rooftop and ensures that ultimately the pollutant leaving the canyon is transported directly into the ventilation system filters for the FF orientation. There is little to no change in the particles trajectory in this scenario and coincides with the highest AE values observed in Figure 64 and Figure 65 when compared with the AE of SF and RF AHUs.

In contrast the wind vectors around SF AHU inlet in Figure 68c show a large change in direction. Away from the inlet the vectors are parallel to the AHU inlet and undisturbed by the suction force of the AHU. The wind vectors above the AHUs roof are also influenced by the inlet in this scenario and would suggest the particles have to be diverted from their original trajectory and therefore resulted in lower AE when compared to the FF AHU configuration. Similarly, Figure 68d, shows higher velocities on the windward side of the AHU louvre rainhood after boundary layer separation and portion of the flow not entering the AHU near the leeward edge of the louvre inlet. This model also resulted in large stagnant zones on both the windward and leeward aces of the AHU body, albeit the eddy in the leeward zone is off centre due to the effect of the AHU inlet suction.

Finally, the RF AHU was examined in Figure 68e-f and resulted in significant different flow patterns compared to both the aforementioned FF and SF AHU wind vectors. Here the boundary layer separation occurs upstream of the AHU inlet at the AHU bodies rear and re-attachment occurs downstream in front of the louvre walls. This resulted in the largest change in trajectory that particles must undertake to enter the AHU inlet, creating conditions for the lowest observed AE at 53% in comparison to 87% and 75% for its FF and SF counterparts respectively at pos-2. The wind flow splits in two directions, one portion directed into the AHU inlet and the other continuing downstream of the louvre walls, and suggests this accounts for approximately 50% of the ambient concentrations entering the AHU. Also of note is the difference in the wind flow around the AHU body where larger stagnant zones exist due to boundary layer separation when comparing Figure 68e-f with Figure 68a-b. This implies the FF AHU separation at the body is impacted by the inlets suction force, whereas the RF AHU inlet effect is minimal. Similar flow patterns were

observed with a uniform profile employed in Chapter 5 examining the PM control design characteristics of an AHU in a design setting rather than a full urban environment.

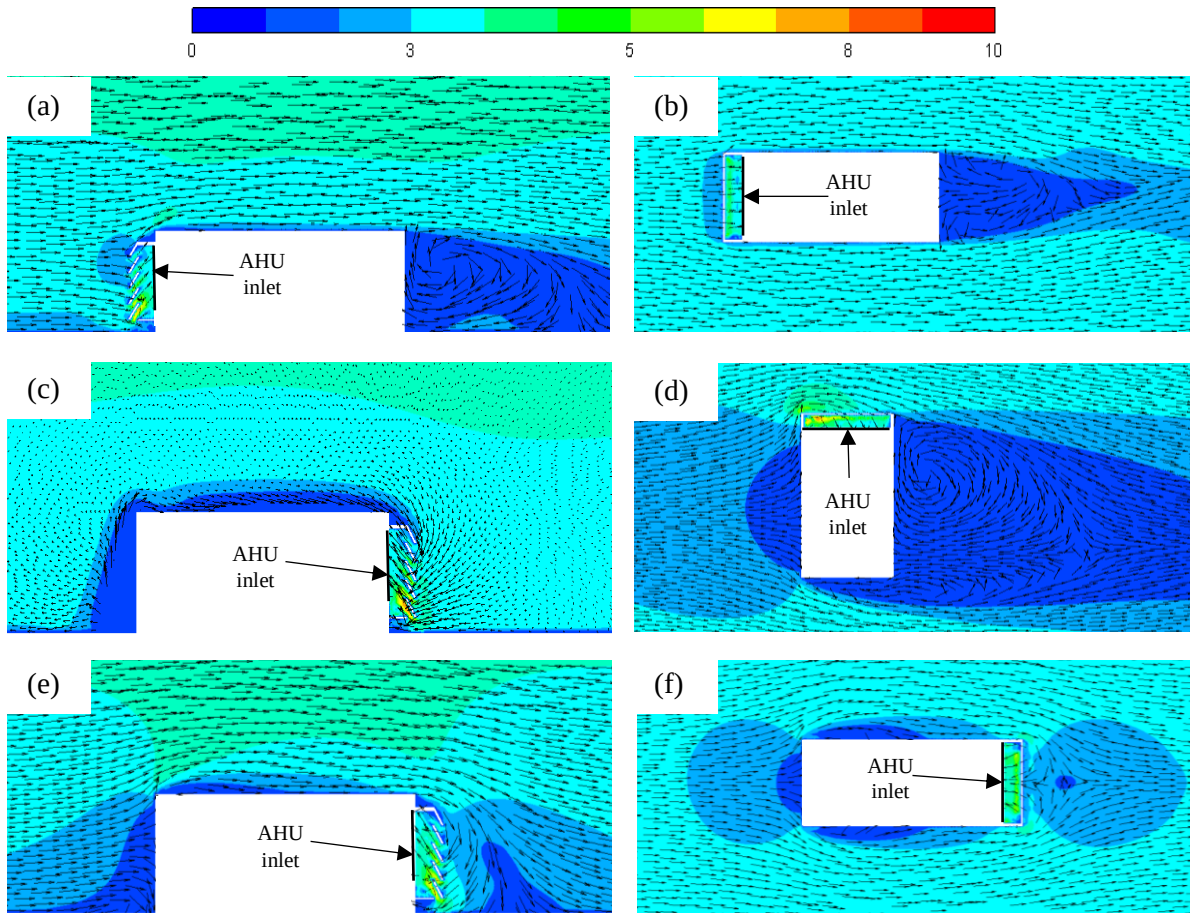


Figure 68. Wind flow analysis comparison between AHU inlet orientations at reference wind speed of 5 m/s and AHU flow rate of $3400 \text{ m}^3/\text{hr}$ on a building rooftop at position 2 intersecting the AHU body centre for (a) FF AHU perpendicular plane (b) FF AHU parallel plane (c) SF AHU perpendicular plane (d) SF AHU plane parallel (e) RF AHU perpendicular plane (f) RF AHU parallel plane; to the building rooftop.

7.3.5 Impact of Building Topography and Metrological Conditions on a Ventilation Systems Energy Consumption

AHU positioning here on a rooftop should be considered as a method for reducing energy consumption in the built environment and a control measure for limiting the influence of $\text{PM}_{2.5}$ on a building's energy consumption and indoor air quality. The simulated AE values at a reference wind speed of 7.5 m/s were used to quantify through illustrative means in Figure 69 the saturation times for a AHU filter with a grade ISO ePM1 85% [232] using the filter characteristic curves shown in Appendix Section 11.2. To achieve this, an ambient

PM_{2.5} concentration of 20 µg/m³ was assumed to model the filter saturation times for each scenario examined and an AHU flow rate of 3400 m³/hr based on filter classification testing procedures according to ISO 16890:2016 [117]. A fabric filtration system always generates an initial pressure drop due to increased resistance from the fabric, pre filter loading and will vary according to their energy classification.

Here the ePM1 85% filter incurred an initial pressure drop of approximately 122 Pa. Finally, the energy performance of each scenario in Figure 69 was assessed under equivalent filter loading times based on the time taken for filter saturation (i.e., 321 days) with an AE of 100% such as the lab filter test. The filter located in pos-1 with an FF orientation, had the highest AE and resulted in filter saturation occurring slightly before the lab filter test. The other scenarios demonstrated the potential energy savings through a flatter curve and a much lower pressure drop over the same time frame. Figure 69 demonstrates that after the first 50 days, the variation in energy consumption between each location and orientation will vary drastically and induce different levels of air quality in the ventilation system.

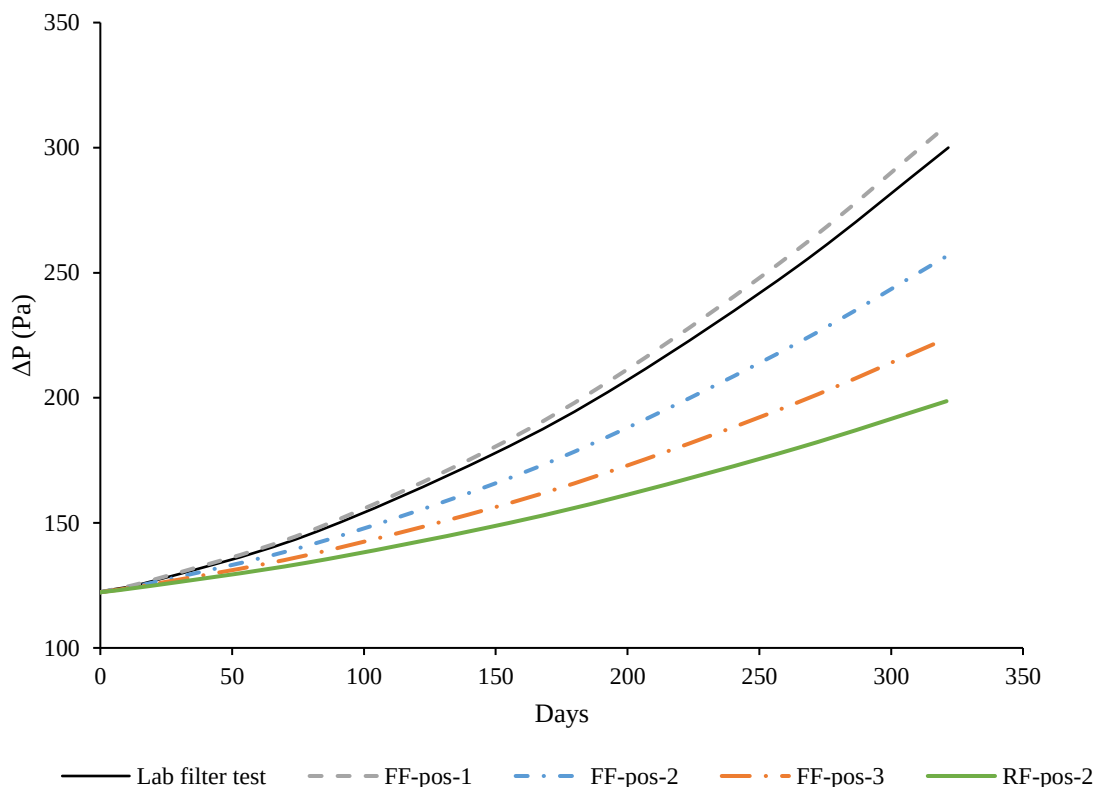


Figure 69. Comparison between pressure drop trends configured over the time taken for saturation of a ISO ePM1 85% filter.

The energy consumption (W) and costs were calculated using the average pressure drop of each trendline in Figure 69 for each case study. The results show a substantial difference in the average pressure drop and as a consequence alteration to the filter saturation time. FF pos-1 reached saturation 9 days before the filter lab test, whereas for FF pos-2 and FF pos-3 the filter would not become saturated for an additional 62 and 139 days respectively. In monetary terms, this translates to a savings benefit of € 62.32 for the former and € 111.24 for the latter which is a substantial difference considering this only considers the energy cost for one filter and does not account for material or labour costs. HVAC systems will commonly require many filters to achieve their desired air change rate, were a standard single filter caters for 3400 m³/h, this is only sufficient for a building occupancy of 11 people with a room volume of 1000 m³ and the recommended air change rates at 3-4 per hour according to ASHRAE guidelines for an office space and a minimum 10 L/s per person [234]. The largest gains are attributed to RF pos-2 where 25.8% energy savings was realised and incurred monetary savings of € 135.01 per filter or for standard operating procedures, two filter changes per annum saves € 270.02. Considering the centre placement of the AHU and the higher ambient PM concentrations at pos-2 compared to pos-3 based on their respective AE illustrates the importance of careful planning with regards to AHU installations. Significant savings can be achieved without any additional energy inputs using environmentally sound principles in order to lower the carbon footprint of the buildings. The results from Table 13 illustrate a potential return rate on energy savings of 9.8 % to 25.8 %. Finally, the higher rate of returns will apply for each RF position as AE remained relatively unchanged from pos 1-3 and across wind speeds. The SF AHU AE tended to fall between the FF and RF AHU AE at their respective position and the analysis in Table 13.

Table 13. Assessment of the impact vehicular emitted PM_{2.5} emissions have on the energy and economic cost estimations as the AHU location and orientation changes at a wind speed of 7.5 m/s over the lab filter lifespan of 321 days based on the estimated parameters.

	AE	Filter saturation	$\overline{\Delta P}$	Energy consumption	Energy cost	Energy cost savings per filter	
	%	Days	Pa	KW/h	0.22 € Kw/h	€	%
Filter		321	198*	2888.9	635.6	-	-
FF-pos-1	103	312	198.2*	2901.1	638.25	-2.91	-0.5
FF-pos-2	84	383	178.6*	2604.62	573.02	62.32	9.8
FF-pos-3	70	460	163.4*	2383.24	524.09	111.24	19.4
RF-pos-2	58	555	155.9*	2274.22	500.33	135.01	25.8

* Average pressure drop calculated over filter saturation time period of 321 days

7.3.6 Future Improvements, Limitations and Planning Considerations for Ventilation System in the Built Environments

The purpose of this investigation was to develop the first study on the AE of a building ventilation system in a heavily polluted full scale urban environment. For this reason, a simplified symmetric urban canyon subjected to skimming flow was chosen as this allowed a clearer analysis due to the predominantly parallel flow between the wind vectors and the rooftop. A limitation is that there are many building types, designs and scenarios that will impact AE and therefore these require further investigation. For example, isolated buildings and asymmetric urban canyons will induce boundary layer separation and more turbulent conditions upon the rooftop. Larger scale modelling of cities that consider multiple building designs and their ventilation system will also require further investigation and examination of the difference in PM concentrations between buildings. Also, the difference in building heights will cause rooftops to experience higher wind velocities under the same weather conditions and possibly different filter loading rates. Whereas Section 7.3.3 demonstrated the lower wind velocities flowing across the AHU in comparison to their respective U_{ref} . These models assumed a fully developed wind profile that is undisturbed when approaching the urban canyons. In addition, greater detail is required to capture a building rooftop where multiple services, boundary walls, plant rooms, etc. exist and the flow patterns will be much more complicated than what was modelled here. Other factors such as building exhausts and their proximity to an AHU should be modelled and analysed using AE as the primary measurement metric. Moreover, building planners and consultants should give due consideration to the local pollution sources near the building, AHU rooftop placement and environmental consideration such as the prevailing wind direction and surface roughness exponents for wind profiles.

7.4 CONCLUSIONS

In conclusion the paper demonstrated the importance of considering an AHU's location and orientation on a building rooftop and illustrated the potential reduction in the energy consumption of a HVAC system. As long as an AHU inlet is facing away from the wind instead of towards it, the results showed a 30-40% reduction in filter loading rates. A 50% reduction in the filter loading rates was observed through changes in position of the AHU to its furthest point on the rooftop from the traffic emission source. In monetary terms this translated into significant energy savings of 9.8-25.4% and for maintenance purposes longer saturation times until the recommended manufactures maximum pressure drop for filters is

exceeded. The study also found that the AHU will be exposed to higher concentrations of $PM_{2.5}$ as wind speed decreases and addressed future avenues of research with regards to building topography and pollution abatement measures.

8 FIELD TEST OF FULL-SCALE AHU INLET ATTACHMENTS DESIGNED TO LOWER A BUILDINGS ENERGY CONSUMPTION AND IMPROVE IAQ

8.1 INTRODUCTION

Full scale testing of the AER devices were conducted on a three-story commercial building located in the city centre of Dublin and compared with a commercial rainhood from Chapter 5. Testing AER devices in the field is required to fully assess their effectiveness at reducing PM filter loading in a two-stage AHU filtration system. The numerical modelling strategy used in Chapters 5-7 for AE testing employed methodologies that stipulates precise definitions of the weather conditions, AHU configuration and PM distributions. In reality, AHUs are installed in environments subjected to diverse and extremely dynamic real-world conditions. The ambient environmental conditions will fluctuate wildly through wind direction and speed, in addition to the PM concentrations magnitudes, chemical compositions distribution curves and proximity to local sources. The numerical models examined the most extreme scenarios such as FF and RF but the wind orientation relative to the AHU inlet will never adhere to such limited motions. Therefore, this chapter is concerned with evaluating AER devices under a long-term monitoring campaign where the difference in pressure across a fabric bag and a panel filter is collected until the recommended saturation limits occur or the manufacturer's recommended thresholds are reached. The goal of the study is to determine if an AER device can result in a reduced pressure drop across both filters and consequently lower the fan's energy consumption compared to an AHU fitted with a rainhood filters.

8.2 EXPERIMENTAL METHODOLOGY

8.2.1 Field Experiments Set Up

Two AHU's with a ventilation flow rate of 3400 m³/hr were installed side-by-side on the rooftop of TCDs Simon Perry building. The AHU body dimensions are identical to the numerical models used in Chapters 5-7. Both units incorporate a variable speed drive to maintain a constant flow rate over time as the system pressure rises due to the filter resistance increasing by PM loading. The purpose of running two identical AHU's side-by-side during field testing is to compare the performance of an AER-AHU with a control AHU

incorporating a typical rainhood inlet attachment currently used on the Irish HVAC market. The AHUs are positioned side-by-side at an adequate separation distance replicating the field set up from Morgan et al. [151] to ensure; quality control of the flow dynamics, the AHUs intakes do not interfere with each other and are within a distance where the local PM concentrations will be similar. The two AHUs were located on the roof of the Simon Perry building, which is located close to a major roadway with severe traffic congestion at peak times and situated within a highly built-up area of the Dublin city centre. This means the AHUs under live operating conditions will be subjected to concentrations of PM relative to Irelands levels which are typically within EU guidelines with respect to the concentration's levels seen nationwide.

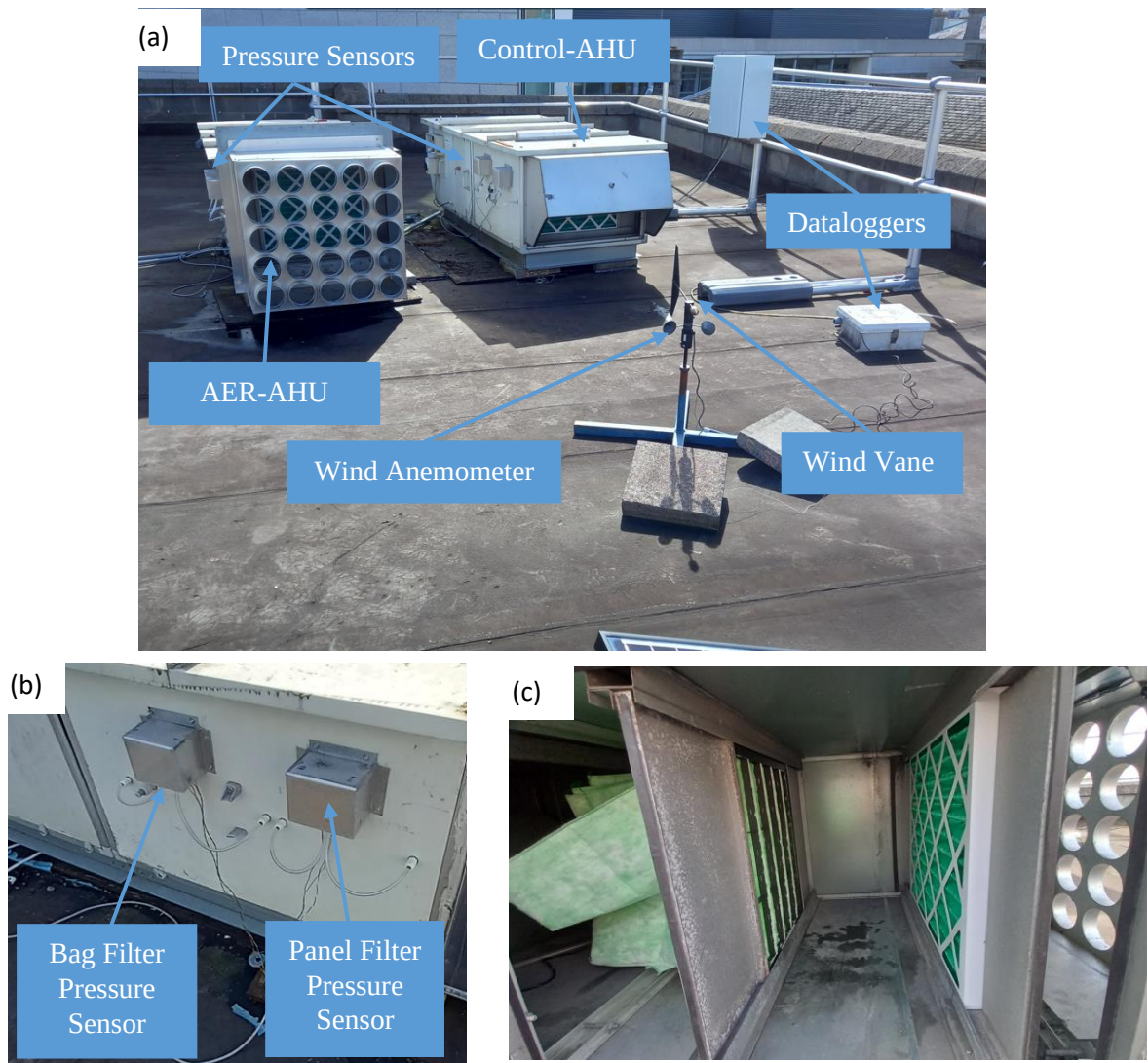


Figure 70. (a) Field experimental apparatus and instrumentation for monitoring PM filter loading rates and wind conditions (b) HVAC pressure sensors for monitoring Δp across a two-stage filtration system (c) Internal view of the AHU's ePM1 70% fabric bag filter and a coarse 60% efficiency panel filter.

Various environmental and design conditions were monitored during the testing phase. Instrumentation was installed to monitor the pressure drop across both the panel and bag filters during particle loading. The pressure drop was monitored on both units over a period of time using four SDP1000-L Sensiron pressure sensors that were installed and connected with pneumatic tubing upstream and downstream of each filter for both AHUs as shown in Figure 70b. The SDP1000-L sensors collected pressure data over 30-minute intervals and logged with a Keithley 7700 Bench Digital Multimeter. The AHUs were monitored until either AHUs ePM1 70% fabric bag filter, or coarse 60% efficiency panel filter shown in Figure 70c, exceeds the manufacturers recommended filter change limits of 100 Pa for the former and 50 Pa for the latter or due to time constraints, when a 1000 hrs of testing is reached, testing is stopped. The data was analysed over a total run time based on these limits and the final pressure drops analysed for comparable differences in filter loading rates. The HOBO U30-NRC Weather Station was mounted on the building roof at a height of 0.5 m to capture the local wind speed and direction averaged over 15-minute intervals with three samples and logged with a HOBO datalogger.

Finally, two AER designs and a generic rainhood are shown in Figure 71. Each inlet attachment was created based on AER designs Case 1 and 3 from Chapter 6 and compared with the Inlet 1 (rainhood) design from Chapter 5. The models were chosen for field testing and their designs have identical dimensions to the numerical models. AER Case 2 and 4 were not chosen for testing, due to the time constraints of a single test and increased risk of test failures making this unfeasible. The first case study involving AER Case 1 was conducted from the 24/02/2022 until 04/04/2022 and the second case study with AER Case 3 from the 12/05/2022 until 23/06/2022. The low pollution levels as recorded by Morgan et al. [151] in the city centre rooftop of the test building in 2017 indicate that the loading times in this environment will be exceedingly long at the chosen design flow rates and based on the low PM rooftop concentration levels. Both the AER-AHU and the control AHU inlets have been positioned facing a southwest direction as this is the known prevailing wind direction in Ireland and should result in a mostly FF configuration.

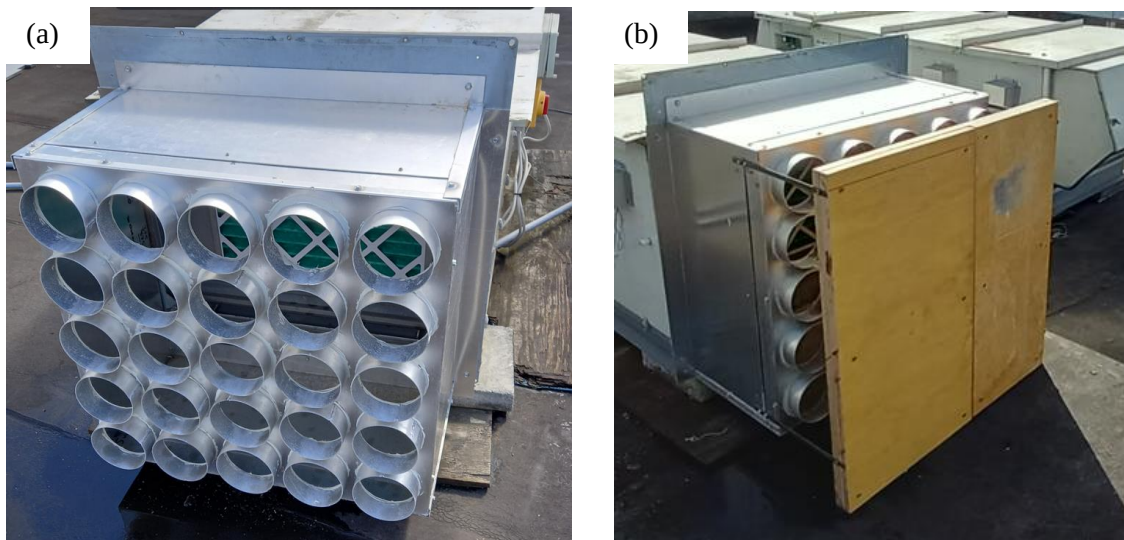


Figure 71. Real world AER-prototypes for AHU inlet attachment where (a) AER Case 1 (b) AER Case 3.

8.2.2 Wind Roses for Local Anemometer

The wind anemometer installed local to the AHU found that the wind direction was predominantly in the west to north-west direction rather than prevailing south westerly direction as shown in Figure 72. Although this angle means the wind, while not blowing directly at the AHU, is still a lot closer to a FF direction in comparison to the RF direction. The difference in the wind directions can be attributed to the local environment as the testing site is overshadowed by a larger building, potentially preventing undisturbed wind flow and creating a stagnant zone. Additionally, as the anemometer is installed approximately 0.5 m from the rooftop in front of the AHU, the wind flow may also be affected by boundary layer separation. And the potential for the wind direction to influence the in-AHU concentrations, could impact each AHUs performance as the particle laden wind flows across both AHU intakes. This was deemed necessary as the AHU's could not be located further apart without subjecting them to different PM concentrations and wind flows.

Finally the wind speeds are quite low compared to other studies conducted in Ireland where Sunderland et al. [153] in Figure 17 found wind speed averages ranged from 4-5 m/s and values exceeding 10 m/s. The reason being is the anemometer is 0.5 m from the rooftop, while typical wind resource studies capture wind speeds at 10-12 m above the building rooftop where the air is undisturbed. Although this is essential as the anemometer is capturing local wind speeds relative to the AHU rather than the wind speed high above the building rooftop. Furthermore, the wind speeds are in agreement with values witnessed in Figure 66 in Chapter 7, where the wind vectors ranged from approximately 1-4 m/s at the

AHU body height with reference wind speeds from 2.5-7.5 m/s at a height of 12 m from the building rooftop.

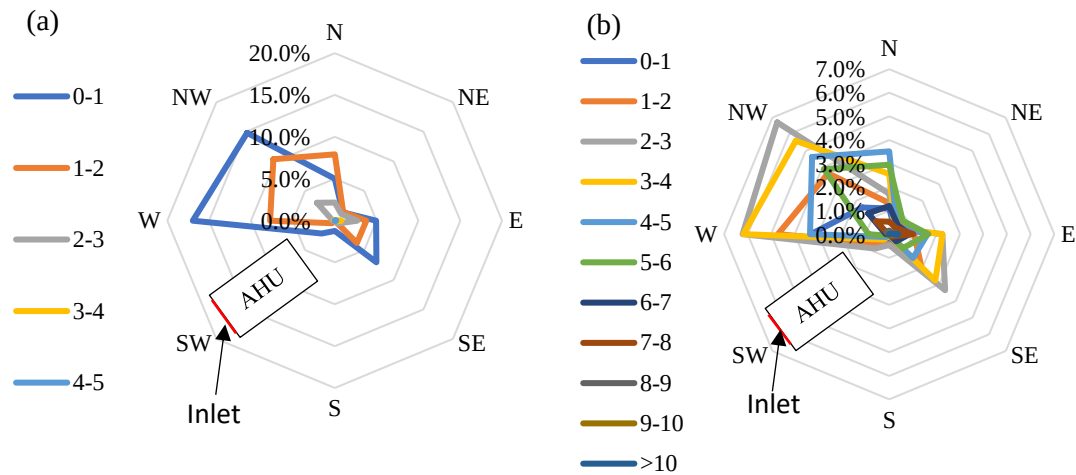


Figure 72. (a) Wind speed (m/s) (b) gust speed (m/s); rose for the anemometer installed at the AHU rooftop level.

8.3 RESULTS

The differential pressure across both the bag and panel filter for an AHU fitted with AER Case 1 and the control AHU with a rainhood is shown in Figure 73a. As expected, the finer bag filter induced a larger initial pressure drop than the panel filter before loading. The results show that over the 1000 hr monitoring period, there was very little change in pressure for both bag filters. The $PM_{2.5}$ and PM_{10} concentration on the rooftop in Dublin Ireland is relatively low as mentioned in the methodology compared to other cities with far greater pollution concentration levels. Therefore, a much longer monitoring campaign in Dublin would be required to either bring the filter to saturation/manufacturers limits in order to induce a loading curve with noticeable changes in the differential pressure. The results did not demonstrate if the AER produced a reduction in the ventilation particle concentration with diameters $<10 \mu m$ for this reason.

The panel filters loaded at a far greater rate and a substantial change in pressure was observed for both AHUs. The panel filters also had volatile trends where large spikes in pressure occurred and there is greater variability about the mean. For each AHU, one pneumatic tube is installed upstream of the panel filter which is more exposed to environmental conditions than the downstream tube. Moreover, the pneumatic tubes for the bag filter are also installed

internal to the AHU and not subjected to this effect. Of additional importance there was also no significant difference in their trends as there were similar performances in filter loading for both attachments.

This is further confirmed by the system pressure curves where the trendlines over the monitoring period were relatively similar. Although there was a slight increase in the control AHU pressure drop compared to AER Case 1 from day 30 to 40, but nothing that would make a significant difference to the AHUs energy demand. The 50-60 Pa change in the system pressure since loading began is largely driven by the panel filter loading and to a lesser degree, the bag filter. The panel filter has reached the recommended manufacturers increase limit of 50 Pa and would require replacement, but the bag filter is typically allowed a 100 Pa increase but has only rose by 10-15 Pa.

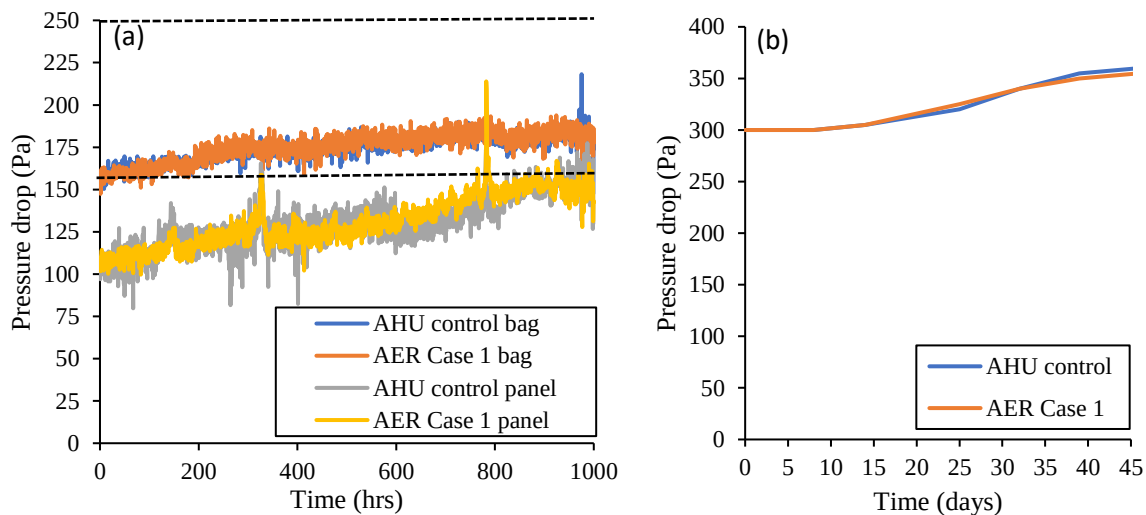


Figure 73. Filter pressure drop comparison over time period of 24/02/2022 until 04/04/2022 between AER-AHU Case 1 and a commercial AHU rainhood (Inlet 1) for (a) filters (b) system pressure.

Figure 74a illustrates the gains made from using AER Case 3 as a greater change in pressure occurred for the Control AHU panel filter. The AER Case 3 panel filter is only approaching the recommended 50 Pa increase in pressure at the end of the 1000 hr, whilst the control AHU has far exceeded the limit by approximately 40 Pa. The difference in pressure between both panel filters appears to be ever-increasing as time passes, thus demonstrating the effectiveness of AER technology designed to consider PM ingress with AE theory. Just to note, a sensor malfunctioned with AER Case 3 panel filter and the data was excluded from the analysis as the filter was still loading during this period.

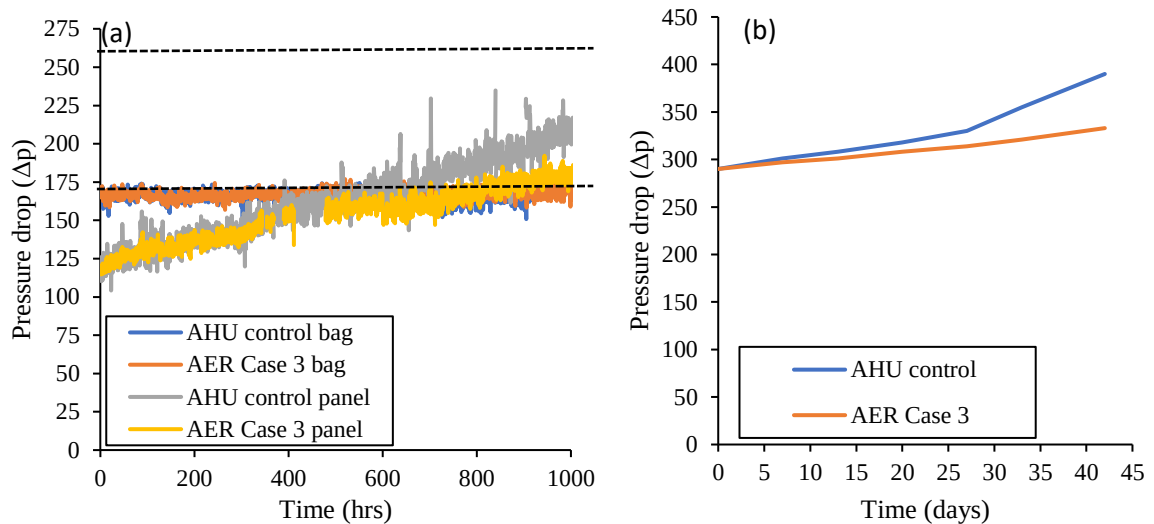


Figure 74. Filter pressure drop comparison over time period of 12/05/2022 until 23/06/2022 between AER Case 3 and a commercial rainhood (Inlet 1) for (a) filters (b) system pressure.

The trends for both bag filters in this test also found the same problem with loading rates as the particle accumulation was not great enough over the monitoring period to demonstrate a difference. Additionally, both bag filters remained relatively unchanged during this testing period whereas the other test did record a slight increase. The system pressure trends also found a greater change in pressure over the monitoring period in the control AHU compared to AER Case 3 and this coincides with the monitoring results from the filters. From the beginning the system pressure of the control AHU rose faster than the AHU fitted with AER Case 3 and the differences in pressure only grew larger over time. At day 27, the differences in pressure changed drastically which a significant increase in the control AHUs system resistance. For example, the pressure increased by 60 Pa in the final 15 days of testing for the control AHU but only by 19 Pa for AER Case 3.

According to Eurovent and ISO 16890:2016 filter classification guidelines, the filters are assessed for 6000 hours (i.e., yearly energy usage) [117,129]. Maintenance practices typically involve a 3-monthly change for the panel filter and 6-monthly change for the bag meaning 1500 and 3000 hours respectively rather than the manufacturer's recommendation. The recommended filter increase limit has been exceeded in a low PM concentration environment comparatively in a little under 1000 hours for the control AHU panel filter in both tests. At this point the filter will continue to load until filter saturation where an exponential relationship exists between the pressure increase and the rate of PM accumulation from this point incurring much larger energy usage.

8.4 DISCUSSION

8.4.1 Numerical Models vs Field Work

The results from the field test weakly confirmed the validity of the numerical models and their predictions. First and foremost, the term weakly is applied as the field test environment is extremely dynamic and will experience multiple wind angles and speeds, in addition to multiple other known and unknown variables when compared to CFD's rigidly defined boundary conditions. The CFD models were concerned with predicted AE, whereas the experiments gathered data on the filters pressure drop over time. Therefore, direct comparison were not possible but a qualitative analysis can be pursued due to the different loading rates between the bag and panel filter and each inlet attachment. The performance of both AERs against the control AHU rainhood were in agreement with the numerical model's predictions of lower filter loading rates for AER Case 3 panel filter, as this targets large particles. Additionally, no substantial differences in filter loading for AER Case 1 was observed compared to the rainhood used. Whilst an experimental study would be required for a strong comparison with controlled conditions in an extremely large wind tunnel in order to produce experimental AE trend lines for comparison with the numerical models.

AER Case 1 differential pressure trend as previously mentioned was relatively similar to the rainhood and a similar result was observed for the numerical models in the previous chapters, albeit through predicted AE. The modelling results suggested preventing a FF AHU incurred the greatest gains regardless of the impact at other wind orientation and was not incorporated with this prototype. As the numerical models predicted similar performance trends in filter accumulation for AER Case 1 and rainhoods, the other passive AERs such as Case 3 should reduce filter loading, especially for larger particles. The results found the panel filters loaded at different rates. This could be attributed to the low AE for larger diameter particles for AER Case 3 found in the numerical modelling studies. AE for example was less than 1% whereas the rainhoods were approximately 100% when facing into the wind. Finally, an energy and cost prediction comparison are not possible at present as more data would be required on both filters but will be completed in future work.

8.4.2 Visual Inspection of Panel Filters and AHU

Images were gathered of the panel filters condition while still in position in the control AHU and for both AER Cases. Comparing the image in Figure 75a of the control AHU filter state after the first test with AER Case 1 panel in Figure 75b demonstrates the difference in each

attachments ability to prevent large objects depositing on the filter surface. The former had a greater quantity of foreign objects, and the latter is relatively clean. The large single orifice inlet appears to draw in a greater number of objects such as leaves and environmental waste. Whereas the smaller ports of the AER appear to prevent the entry of such objects at a greater rate. The results from the second tests in Figure 75c-d images also found a similar occurrence in foreign objects where again the control AHU drew in a far greater number of foreign objects and deposited on the filter surface. AER Case 3 while not completely free of such objects, still looked cleaner and had less objects on the filter face. Finally, the field tests found that the AER prototypes were upon visual inspection as effective as the rainhoods at preventing rain droplets from entering the AHU. No water was observed within the AER Case 1 and 3 throughout the testing, ensuring the inlet attachment preforms their original function in addition to PM control.



Figure 75. Images of the panel filter condition at end of testing period (a) Control AHU panel filter in AER Case 1 comparsion (b) AER Case 1 panel filter (c) Control AHU panel filter in AER Case 3 comparsion (d) AER Case 3 panel filter.

8.4.3 Improvements in Testing and the Impact of Regional Air Pollution Sources

The main issue found with the field tests was the location, being that Ireland has relatively low pollution levels compared to other countries around the world, in comparison to developing nations such as India or China. The low PM_{2.5} concentration generally found resulted in a slow accumulation of PM on the fabric bag filters. Extremely polluted countries incur much larger urban concentrations where India's average human PM_{2.5} exposure is 83.2 µg/m³ compared to 10.6 µg/m³ in Ireland [235]. A more extensive campaign in multiple regional locations around the world would be required for a full evaluation of AER technologies effectiveness as a PM control mechanism. Furthermore, the regional locations propensity for natural disasters and/or phenomenon would need to be explored for site selection. A sandstorm in Cairo for instance would contain large diameter particles and could incur filter saturation quite quickly. Similarly, wildfires in Australia or California would have different particle diameter distribution curves and characteristics. Even areas subjected to active volcanos will have huge amounts of soot deposited on inhabited areas.

Additionally, improvements to the project set were explored by connecting PM_{2.5} samplers to the ventilation inlets in order to monitor the concentration entering the AHU. Low concentration levels and resolution of the samplers prevented any meaningful results for comparison. It is envisaged that this set up would work better in a more polluted environment. Finally, a heavily polluted area would decrease the time until saturation and reduce the length of the monitoring campaigns. This will reduce the likelihood of a system or sensor malfunction during a long-term testing campaign. AER Case 3 first test failed due to an issue with the filter installation and damage to the frame occurred. A sensor as previously mentioned had also stopped functioning in another test and required corrective action during the investigation.

8.4.4 Future Field Tests

Further field tests should be conducted on different inlet attachments and the effect of AHU positioning on the building rooftop. The AHUs could be positioned in opposite directions to each other with identical inlet attachments and determine if the filter loads at a different rate. Thereby, confirming the influence of the prevailing wind direction. Expanding the field further, green infrastructure could be trialled and placed around both the inlet and the body. For example, the barrier in Case 3 could be replaced with green wall or hedgerow. AER Case 2 was not trialled during this investigation but could provide more evidence of the

validity of designing inlets using CFD methods. The AHU could be positioned on opposite ends of a rooftop and monitored for pressure changes, ideally located near a heavily polluted area due to traffic emissions. Lastly, different filter grades could be trialled to determine the variation between different inlet attachments.

8.5 CONCLUSION

The result from the field tests were promising and found that AER technology could lower a building energy consumption by positively impacting the coarse panel filters loading rates. While the cylindrical orifices did not restrict entry to a greater degree than the rainhood, the barrier in front of the inlets proved to be an effective PM control mechanism. A difference of 57 Pa was found between the control AHU and AER Case 3 for the final system pressure measurements and only 5 Pa for AER Case 1. The results did not demonstrate how the bag filter was affected and this was attributed to the low concentration levels on the building rooftop for smaller diameter particle such as $PM_{2.5}$. Although the field test results did suggest the validity of the numerical modelling results which suggested more modest improvements for low St particle laden flow.

9 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

9.1 RESEARCH CONCLUSIONS

The research investigations within the four chapters of this thesis were pursued systemically and have provided a significant contribution to the current literature on AE. The potential for development of a new form of PM control technology for large aspirating systems was successfully demonstrated. In order to expand this area of research and identify gaps in the knowledge, an extensive literature review was undertaken to achieve this outcome. The AE of a building ventilation is a relatively new concept and was previously only applied to aerosol sampling probes and human nose and mouth. The author assessed the current state of building energy consumption and found HVAC systems were categorised as the largest consumer of energy in the built environment sector. Filtration systems in particular were identified for potential improvement by incorporating AE concepts into the operation of a building AHU. This would consist of developing an inlet design capable of restricting the entry of a significant portion of ambient PM concentration into the ventilation system. Additionally, the literature review found that considering urban building planning considerations when installing an AHU and using the local environmental characteristics to reduce AE could also be a viable control mechanism.

To achieve this, variables that could be influential in the transfer process of PM from the ambient environment to the indoor were identified. As there were no studies on how the existing HVAC structure performed with regards to PM control, the first investigation sought to develop AE knowledge on rainhoods that would be typically installed on the Irish and EU market. The study assessed a louvre style and a generic single orifice rainhood with changing building and environmental conditions using numerical models. A commercial building ventilation demands will vary throughout the day and the impact on AE as an AHUs flow rate fluctuates were examined. Moreover, the size of a particles diameter will have a significant impact on the trajectory and ingress into the AHU intake. St was used to evaluate each particles AE across a range of wind speeds in order to capture the various environmental conditions an AHU may be subjected to. Results showed that there was not a large difference in AE trends between both rainhood attachments. The investigation led to the creation of baseline AE trends that could be used for future evaluations against subsequently designed AERs. The findings from this study also outlined the variables that should be considered

when designing next generation AER prototypes, particularly the wind direction. In addition, the wind dynamics around the AHU were assessed for the first time and found the AHU inlet has a major effect on the AHUs and rooftops boundary layer which can lead to a significant alteration of a particle's trajectory.

Following the creation of baseline AE by examining existing HVAC infrastructure, this led to the development of AERs based on the dominant variable, wind direction, and incorporated an array of cylindrical orifices. Previous studies investigated the viability of cylindrical orifices with scaled AER models, and oversized AER field experiments and tested with inlets facing in different directions. This thesis sought to examine the impact of cylindrical orifice arrays with similar total surface area as a commercial rainhood as no studies had been conducted on an AER with equivalent dimensions to the AHU body. The study was further expanded by orientating the inlets facing the rooftop and another prototype where a barrier was placed in front of the orifice array. In addition to the aforementioned passive control AER prototypes, an active concept was modelled on the assumption of a wind monitoring system where the AHU would respond to wind direction changes and prevent particle laden wind flowing directly onto the filter. There were clear differences in both flow patterns and AE trends when comparing each of the AERs together but the standard orifice cylindrical array (i.e., Case 1). Performance metrics in this case were similar to the commercial louvre rainhoods. Results showed that there was scope for controlling the PM concentrations entering the AHU intake and new technology is required to address a buildings energy consumption. The study also quantified the energy consumption of each AER and the more commonly used louvre attachment under predefined conditions using their respective AE values. The investigation found a wide range of energy and monetary savings depending on the attachment where certain AER prototypes resulted in energy savings. The passive AERs Case 2 and 3 energy consumption over the period until saturation of 321 days incurred energy savings of 111.6 kw/h and 89.7 kw/h respectively amounting to monetary savings per filter based energy consumption of 3.5-4.4 %. Examining the active system, AER Case 4, the energy savings were as high as 234.5 kw/h, more than the double the passive AER savings and a 9.3 % reduction in monetary costs associated with energy usage.

The literature review found additional gaps in knowledge with regards to urban and building planning considerations and AHU deployments on building rooftops. Careful consideration of a buildings surrounding environment could be used as a form of PM control for a

ventilation system. Evaluating an AHUs proximity to local pollution sources and designing a system where the AHU is positioned at the maximum distance allowable by the rooftop dimensions would be advantageous. Additionally, the impact of the AHUs inlets rooftop orientation relative to the prevailing wind direction was also examined. The previous inlet design investigations findings on AERs and commercial rainhoods demonstrated the importance of the wind direction and suggested further analysis was required in a full urban environment. The numerical models quantified the effect on AE as the distance between the AHU inlet and heavily polluted street canyon increased and results showed AE was significantly reduced for a FF AHU by increasing the distance between the PM source and AHU. Although the rate of change from the windward face of the building to the leeward for a SF AHU was less and the RF AHU resulted in AE values that were approximately similar irrespective of the AHU rooftop position. Using the same methodology for calculating the energy consumption as the AERs previously, considering an AHUs position and orientation generated significant energy and monetary savings. A RF AHU regardless of its position AE of 58% incurs energy savings of 614.68 kw/h compared to the filters performance at 100% AE and results in a 25.8% savings on the energy costs. Whereas a FF AHU located next to the PM source exceeded the filter AE by 3% generating a negative outcome on energy cost savings by -0.5%. Although this becomes savings of 19.4 % at the furthest deployment position from the PM source on the rooftop.

The previous investigations were all concerned with parametric numerical analysis in order to provide a clearer picture into how large ventilation systems AE respond to building and environmental conditions. In reality, the real-world conditions are more dynamic and require field experimentation to determine the success of AER technology as a form of PM control in comparison to commercial rainhoods. The field study used AHUs situated side-by-side in an urban environment and fitted with AER attachments designed within this thesis and the other with a generic rainhood. The results showed there is scope for improvement based on AER technology and inlet design and a lower pressure drop was successfully demonstrated. Placing a barrier in front of the AER inlet led to a cleaner panel filter over the testing period when compared to a commercial rainhood as the latter resulted in an extra 57 Pa increase in the system pressure compared to the latter. While AER Case 1 only had a 5 Pa difference in the system pressure relative to the rainhood over the same monitoring period.

9.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The use of AE as a PM control mechanism for large ventilation systems is still in its infancy and relatively few studies have been conducted. Significant gaps in the literature were identified that were not addressed within this thesis and will form the basis for future research projects. These include the following:

9.2.1 Future Design Investigations

The investigations carried out within this thesis focused on addressing the inlets designed based on AE theory which primarily considered wind direction and cylindrical orifices. Expanding the numerical investigations to examine other orifice shapes could result in further improvements to the design, either through a lower footprint or AE. For example, the development of ground facing louvre inlets would lead to a potential decrease in streamwise geometry length, but the AE would need to be reassessed. The increase in the inlet surface area with a rectangular orifice would be substantial compared to the cylindrical orifices, thus leading to an AER that is not as restricted by the available rooftop space.

The other effective passive prototype AER Case 3 used a barrier in the form of a flat wall in order to prevent particle ingress into the AHU, but the aerodynamic shape could be improved with deflectors or a cone. Such a design could further manipulate the wind flow to a greater degree than the current design leading to a larger diversion of particle trajectories away from the influence of the inlets suction force. Additionally, strategically placed deflectors on the AHU rooftop could further decrease AE. The 2D analysis conducted within this project had a major limitation on the particle motions and removes the impact of the side eddy actions on the deflectors. The optimum location of the deflectors also requires a 3D numerical parametric study on deflector design & positioning. The barrier could also be replaced with green infrastructure around the AHU body and the inlet in order to lower AE. This could incur increased particle deposition on the leaves rather than with a solid wall, thus lowering filter loading. The investigation would have to focus on flora not susceptible to large leave lost based on the findings from the visual inspection in Chapter 8 Figure 75 and determine if they are an effective control mechanism.

Finally future investigations will be required to develop a net free energy control system for AER Case 4 (active). This system resulted in the lowest AE but would require a significant field campaign and design that responds to the wind direction and demonstrates a lower pressure drop without incurring any extra energy consumption. Modification to the current

AHU infrastructure could achieve this as a damper is typically installed with a motorised control in order to provide the correct ratio of fresh to mixed air. Moreover, a simple solar panel could be used to power the motor if required and a cost optimal analysis done on the proposed payback period through an energy savings vs capital investment comparison.

9.2.2 Future Urban Environment Investigations and Development of Building Planning Guidelines

The full urban environment investigation in Chapter 8 was confined to an urban canyon with an aspect ratio of one. While the literature in this field is well established for urban wind flows, there is a dearth of knowledge on the AE of a ventilation system in different urban building configurations. AE studies should be undertaken to expand the area to include aspect ratio variation, asymmetric buildings, building arrays and real-world case studies for the optimum AHU orientation and rooftop placement. Furthermore, the single and inline building is also of interest due to the effects of boundary layer separation at the rooftop impacting PM dispersion around the AHU body. Wind speeds will vary on a rooftop depending on the building's height and urban surface roughness and the impact on AE requires additional analysis for further optimisation.

Urban wind studies also tend to ignore all plant and rooftop infrastructures for simplicity, but their inclusion is required to accurately capture a building rooftops particle laden flow dynamics. Particles could accumulate leading to high concentration zones near the AHU inlet and a more enhanced analysis could lower a buildings energy consumption. For example, the AHU could be located in the transport path of emissions from nearby rooftop exhaust sources and local infrastructure could hinder or protect the AHU from PM ingress. Finally, the AE of passive ventilation in buildings has not been explored, in particular, the operation of the windows and their design characteristics. Assessing these parameters with the goal of reducing AE would also improve the IAQ by lowering PM concentrations entering the indoor microenvironments.

9.2.3 Future Experimental and Field Study Investigations

The field study demonstrated the success of the AER prototype with a barrier in front of the inlets and a similar performance between AER Case 1 and a rainhood but could only be compared to the numerical studies through a qualitative analysis. Both methods produce different outcomes where the former collected differential pressure data across the filter and

the latter AE. An experimental wind tunnel study is required for a full quantitative comparison where the AE is determined experimentally for a full-scale AHU which could be used for future validation and calibration of CFD models. Additionally, a controlled environment would allow for greater optimisation before a time-consuming field study is undertaken and determine the effectiveness of improved AER technology.

The field studies should also be expanded to environments with a higher level of PM pollution (i.e., China, India, Bangladesh etc.) due to both local anthropogenic and natural sources. This will provide a better analysis between a rainhood and an AER, as the panel and bag filter will load faster, overcoming the issues experienced by testing in Dublin, Ireland and discern if AER technology is effective for smaller diameter particles in the PM₁₀ range. Field studies should be conducted in multiple environment types such as near deserts where large sandstorms effect urban cities (Cairo), areas prone to wildfires (Australia, California) and other large scale natural events occur. The PM distribution curve of a location is extremely important as Ireland has few extreme weather events nor dust storms. High PM concentrations and dust cloud events would contain a greater abundance of larger diameter particles which were more effectively restricted entry into the ventilation system by AER use.

9.2.4 Other Real World AE Applications

AE has been reverse engineering for the design of building ventilation inlets in order to lower a buildings energy consumption. The theory could be applied to other real world applications not related to the built environment such as ventilation system intakes for vehicles, heavy machinery air intakes and grille design for computer ventilation. Analogous to building ventilation, both transport vehicles and heavy machinery could use less energy by ensuring lower filter loading rates. The orifice design dimensions would be of a smaller magnitude than the AHU orifices and additionally for vehicles, relative wind speeds ensure a fast moving particle and suggests a large scope for improvement. Lastly, the air intake orifice design for computer ventilation could also be improved by AE theories. Numerous studies have been conducted on dissipating heat for better energy performance through increased airflow or fin surface area. Although none on designing new orifices with low AE preventing dust being drawn into the system by the fan and covering the heat sink. Using AE to restrict the passage of large particles into the computer could results in substantial energy savings considering their widespread usage worldwide.

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11 APPENDICES

11.1 AHU MARKET RESEARCH

The AER device as shown in the literature review has been found to reduce the PM loading upon the filters within AHU's. This section addresses the potential market and current state of the HVAC infrastructure throughout Ireland. Surveys were conducted with two prominent AHU suppliers operating within Ireland which shall be known here forth as company A and B. Both companies had requested that their identity remain confidential due to the sensitive nature of the data provided. Requests to participate in the survey were made to 7 Irish HVAC companies but only two were willing to participate, again due to commercial sensitivities. The following list details the majority of the major HVAC suppliers operating within the Irish market:

- Carrier
- System Air
- SIG
- Novair
- Clint
- EDPAC
- Danann
- RPI
- Dalair
- Air Force
- Flakt
- Solda
- Vend Axis
- Train
- Komfort Air
- IV products Envistar
- Weger
- AAFMc Kay
- Lindab
- Nuaire

Company A and B conducted a survey which can be found in the appendix, but company B provided their total number of AHU's sold, projects where they were installed and their corresponding flow rates for all of 2017. The initial stage of the desk top study was concerned with understanding the type of information that might be relevant to the emerging AER market and the survey was designed based upon this review. Typically flow rates, average number of AHU'S installed within a project, type of motor, type of building (i.e., commercial or industrial) and categorisation of the flow rates.

The SEAI conducted an extensive survey of the commercial building stock in Ireland which was published on November 2015 [236]. This detailed the quantity of the commercial

building stock and the types of ventilation system installed as depicted in Figure 76 and Figure 77 respectively. The report detailed that there are 109000 existing commercial buildings throughout Ireland, but these figures did not include industrial premises such as pharmaceutical companies, food manufacturers, computer chip manufactures etc.

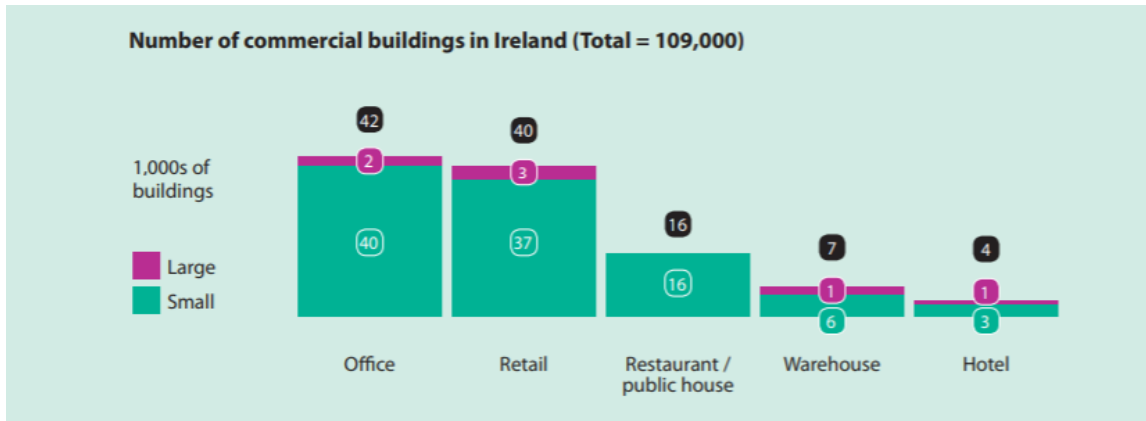


Figure 76. Breakdown of the number of commercial buildings within Ireland [236].

Of this 109000 the graph shown in Figure 77, a significant proportion of the restaurants and retails have mechanical ventilation, and overall approximately 20-25% of the commercial buildings have mechanical ventilation.

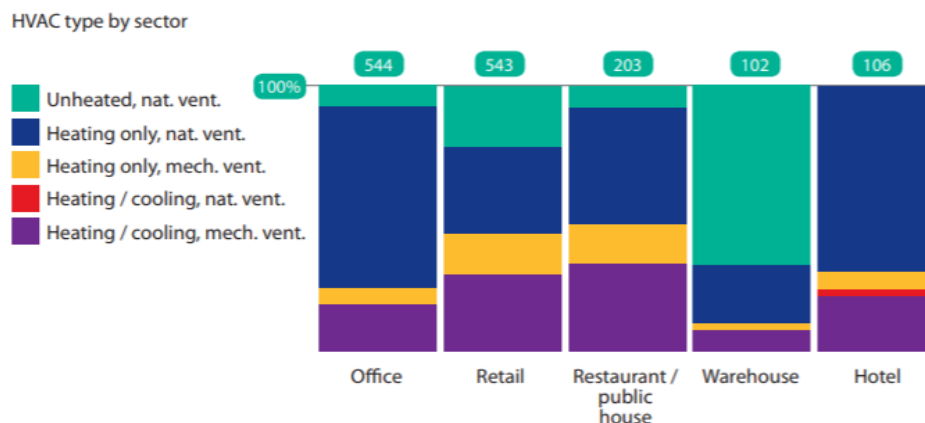


Figure 77. Breakdown of the types of ventilation systems within Ireland commercial building stock [236].

This is a large market for retrofitting the AER devices, both companies that were surveyed indicated that on average 2-3 AHUs were supplied per project. This would suggest the potential for the retrofitting of between 50,000-75,000 units with the AER device on existing commercial projects as of November 2015. Company A survey projected that they supply 60% of their AHUs to commercial and the remaining 40% to industrial buildings. Company

B who supplied a detailed analysis showed that industrial projects accounted for 25% of their business. If these percentages were used to extrapolate the potential market for AHU retrofits on industrial sites, this would amount to an additional 15000-30000 existing units. Taking the total of both types of buildings, the retrofit market could account for approximate installation of 100,000 AER devices total.

Company A and B gave varying categorisations when considering the size of the flow rates, with commercial buildings small and medium scale sized AHUs dominate. The industrial premises AHU's have an even split in the flow rate categories for company B. This is an important consideration when considering the AER devices product design. Morgan et al found that to maintain a low velocity of 1m/s, the AER design was much larger than the AHU inlet and a small AHU was used for this experiment. If the AER is to be installed on all AHUs of all size, then the AER device will have to be scaled to approximately match the size of the existing AHU inlet.

Table 14. Company sales 2017.

Company A			
	Small	Medium	Large
Units	$x < 1800 \text{ m}^3/\text{hr}$	$1800 < x < 28800 \text{ m}^3/\text{hr}$	$28800 < x < 54000 \text{ m}^3/\text{hr}$
Combined	15%	60%	25%
Company B			
Units	$x < 6000 \text{ m}^3/\text{hr}$	$1800 < x < 20000 \text{ m}^3/\text{hr}$	$20000 < x < 70000 \text{ m}^3/\text{hr}$
Commercial No. of units	50	31	8
Commercial % sold	56%	35%	9%
Industrial No. of units	10	10	10
Industrial % sold	33%	33%	33%

The above figures represented individual company's performances within Ireland but there are numerous HVAC suppliers operating within Ireland. Eurovent released figures for 2017 detailing the total worth of the AHU market in Ireland which amounted to 31.92M€ as shown in Figure 78 and a reported estimate of 3407 units sold. At present, this would rise to add approximately 12,000-15000 additional existing units since the SEAI report in 2015 to the 100,000 bringing the total retrofits to over 110,000. It is envisaged that with the development of a marketable product, the AER device would be supplied as a standard component with the new AHU's being installed. Providing an Irish company licences the technology, the

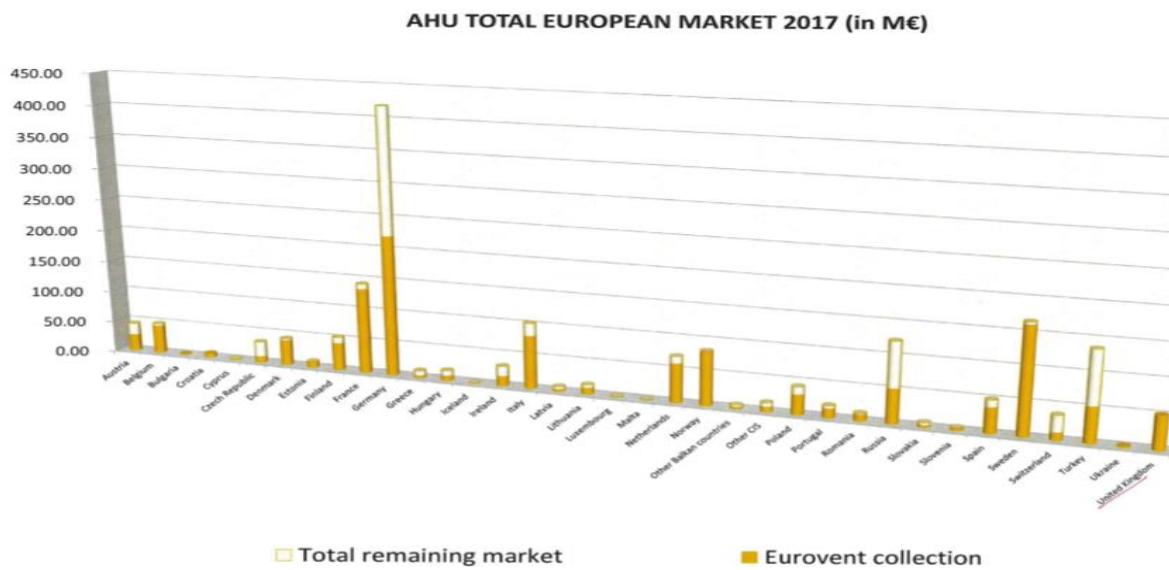


Figure 78. AHU European Market.

11.2 FILTER LOADING CURVE

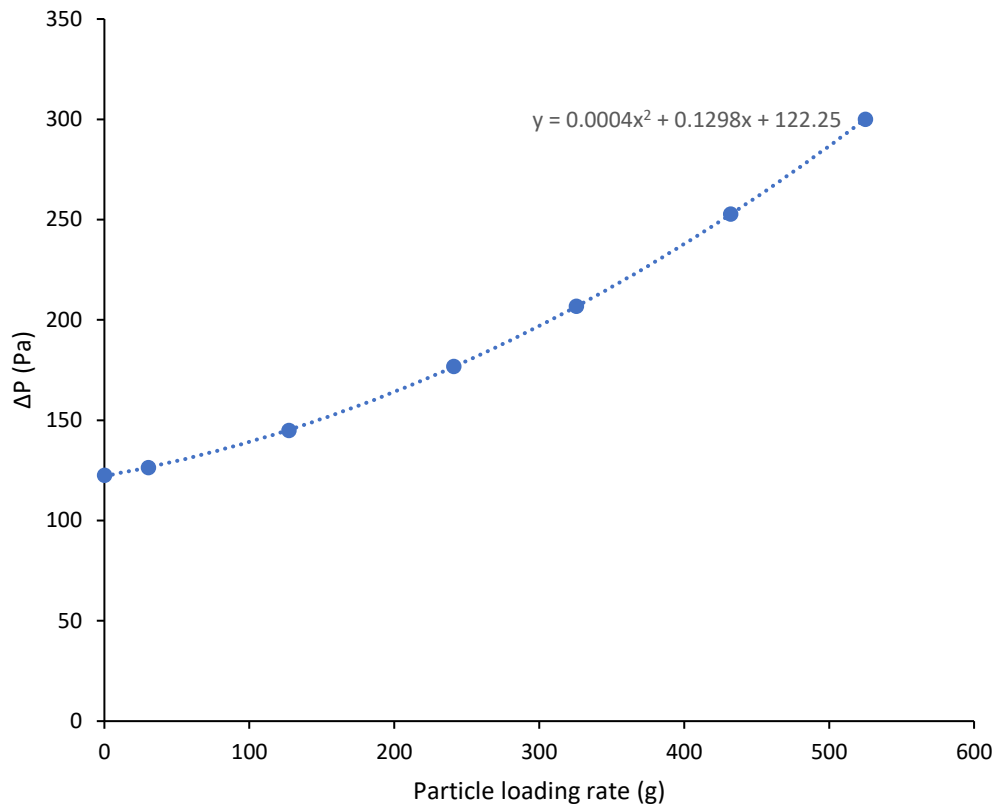


Figure 79. Pressure drop vs particle loading rate for a fabric filter grade of ISO ePM1 85% according to ISO 16890:2016 [117,232].

Table 15. Diameter range of diesel particulate emission [226].

Particle diameter range (μm)	Mass Fraction (%)
0.1-0.2	10.15
0.2-0.3	14.64
0.3-0.4	17.95
0.4-0.5	18.27
0.5-0.6	15.28
0.6-0.7	11.11
0.7-0.8	7.05
0.8-0.9	3.63
0.9-1	1.92

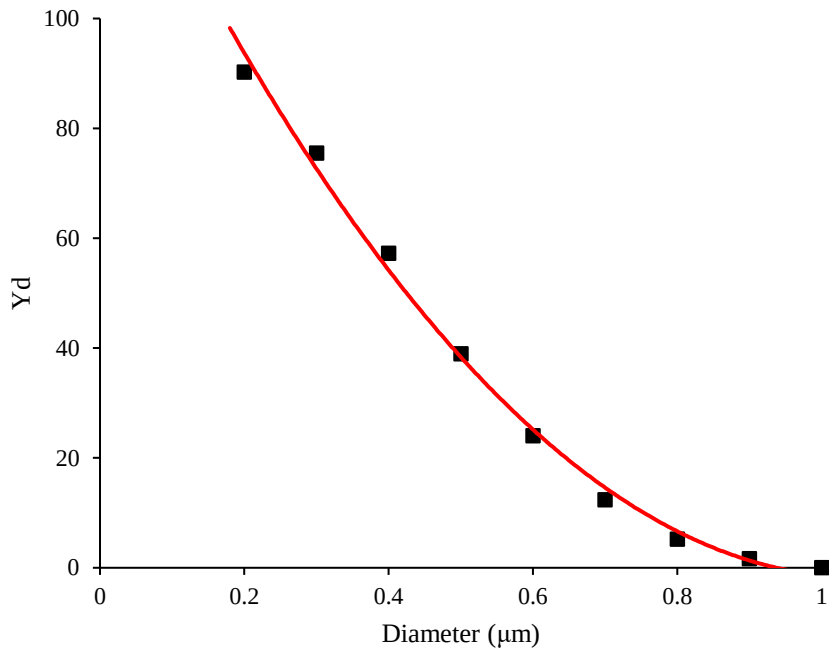


Figure 80 Mass fraction vs particle diameter fitting curve from Tang et al. [226].

11.3 WIND PROFILE AND PM_{2.5} USER DEFINED FUNCTIONS

/ UDF for specifying steady state velocity profile boundary condition */*

```
#include "udf.h"

DEFINE_PROFILE(unsteady_velocity_profile, t, i)
{
    real current_time;
    real x[ND_ND];
    real y;
    face_t f;
    current_time = CURRENT_TIME;
    begin_f_loop(f, t)
    {
        F_CENTROID(x, f, t);
        y = x[1];
        if (current_time < 10000)
```

```

    {
        F_PROFILE(f, t, i) = (5) * pow(((y-12) / 22), 0.2);
    }
    else
    {
        F_PROFILE(f, t, i) = 0;
    }
}
end_f_loop(f, t)
}

DEFINE_PROFILE(k_profile, t, i)
{
    real current_time;
    real x[ND_ND];
    real y;
    face_t f;
    current_time = CURRENT_TIME;
    begin_f_loop(f, t)
    {
        F_CENTROID(x, f, t);
        y = x[1];
        if (current_time < 10000)
        {
            F_PROFILE(f, t, i) = pow(0.1*(5) * pow(((y-12) / 22), 0.2),2);
        }
        else
        {
            F_PROFILE(f, t, i) = 0;
        }
    }
    end_f_loop(f, t)
}

DEFINE_PROFILE(diss_profile, t, i)

```

```

{
real current_time;
real x[ND_ND];
real y;
face_t f;
current_time = CURRENT_TIME;
begin_f_loop(f, t)
{
    F_CENTROID(x, f, t);
    y = x[1];
    if (current_time < 10000)
    {
        F_PROFILE(f, t, i) = ((pow((pow(0.1 * (5) * pow(((y-12) / 22), 0.2), 2)),
3/2))*(pow(0.09, 0.75)))/(y*0.41);
    }
    else
    {
        F_PROFILE(f, t, i) = 0;
    }
}
end_f_loop(f, t)
}

```

/ UDF for specifying drag laws for PM_{2.5} */*

```

DEFINE_DPM_DRAG(cunningham_drag_force, Re, p)
{

    real cd, Cc, drag_force;
    if (Re < 0.1)
    {
        cd = 24 / Re;
        Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
        drag_force = 18 * cd * Re / (24 * Cc);
    }
}

```

```

    return (drag_force);
}
else if (Re < 1)
{
    cd = (22.73 / Re) + (0.0903 / (Re * Re)) + 3.69;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 10)
{
    cd = (29.1667 / Re) - (3.8889 / (Re * Re)) + 1.22;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 100)
{
    cd = (46.5 / Re) - (116.67 / (Re * Re)) + 0.6167;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 1000)
{
    cd = (98.33 / Re) - (2778 / (Re * Re)) + 0.3644;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 5000)

```

```

{
    cd = (148.62 / Re) - (47500 / (Re * Re)) + 0.357;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 10000)
{
    cd = -(490.546 / Re) - (578700 / (Re * Re)) + 0.46;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
else if (Re < 50000)
{
    cd = -(1662.5 / Re) - (5416700 / (Re * Re)) + 0.5191;
    Cc = 1 + ((2 * 0.00000014) / P_DIAM(p)) * (1.257 + 0.4 * exp((-1.1 * P_DIAM(p)) /
(2 * 0.00000014)));
    drag_force = 18 * cd * Re / (24 * Cc);
    return (drag_force);
}
}

```