# Heat Transfer to an Obliquely Impinging Air Jet

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## Abstract

The current research is concerned with the measurement of convective heat transfer to an impinging air jet for a range of test parameters which include Reynolds numbers, (Re) of 10000 and 20000; nozzle to impingement surface distance, (H/D) from 0.5 to 2, and angle of impingement, ($\alpha$) from 45° to 90° (normal impingement). Both time-averaged and fluctuating heat transfer is investigated. In this range of low nozzle to impingement surface distances, the wall jet undegoes transition from laminar to turbulent. The transitional boundary layer is identified from the time-averaged heat transfer profiles. A flow structure initiates in the shear layer of the free jet and then impacts on the plate and moves along the wall jet. The corresponding fluctuating heat transfer is reported. It is shown that the flow structure grows initially as it moves radially from the stagnation point and eventually fades with further increasing radial position as the boundary layer becomes fully turbulent.

## Introduction

Convective heat transfer to an impinging air jet is known to yield high local and area averaged heat transfer. Such a jet is of interest for the cooling of electronic components and gas turbine blades and for manufacturing processes such as grinding. A grinding process produces very high local temperatures, which, if not cooled, would have an adverse affect on the metallurgical composition of the work-piece. For this reason the enhancement of local or stagnation region heat transfer is investigated in the current research.

The turbulence induced by mixing from entrainment does not penetrate to the centre of the free jet at low nozzle to plate spacings, normalised by the nozzle diameter (H/D). An investigation by Gardon and Akfirat [1] has shown that at low nozzle to plate spacings, $H/D < 2$, the wall jet region transitions from laminar to turbulent. It is for this reason, according to Goldstein and Timmers [2], that the stagnation point Nusselt number is a local minimum at

H/D = 2. Huang and El-Genk [3] report that the primary lateral peak occurs at a normalised radial position of r/D = 1.8 - 2, for H/D = 1 and Re > 13000. Baughn et al. [4] present results that show a local heat transfer peak at r/D = 2, for Re = 23000 and H/D = 2. A similar effect was reported by Lee et al. [5]. At extremely low H/D (< 0.25) the heat transfer profile exhibits two lateral peaks as explained by Colucci and Viskanta [6]. The inner peak is due to the thinning of the laminar boundary layer and occurs consistently at r/D ≈ 0.5. The secondary peaks are due to a transition from laminar to turbulent flow in the wall jet [6]. These peaks vary in radial position with H/D and Re.

Studies of fluctuating heat transfer in jet flows have been limited. The effect that the vortex control of a free jet has on the eventual heat transfer to the jet from an impingement surface was investigated by Hwang et al. [7]. However the fluctuations in surface heat transfer due to the vortices induced in the free jet were not reported. Control of the vortex roll by acoustically exciting the free jet has been investigated by Liu and Sullivan [8]. Both enhancement and reduction of jet heat transfer have been shown to depend on the excitation frequency.

The focus of the present investigation is fluctuating heat transfer measurements in an impinging jet without artificial excitation. The objective is to obtain experimental data that will clarify the convective heat transfer mechanisms in the transitional wall jet region.

## Experimental Setup

The experimental test rig is presented in figure 1.

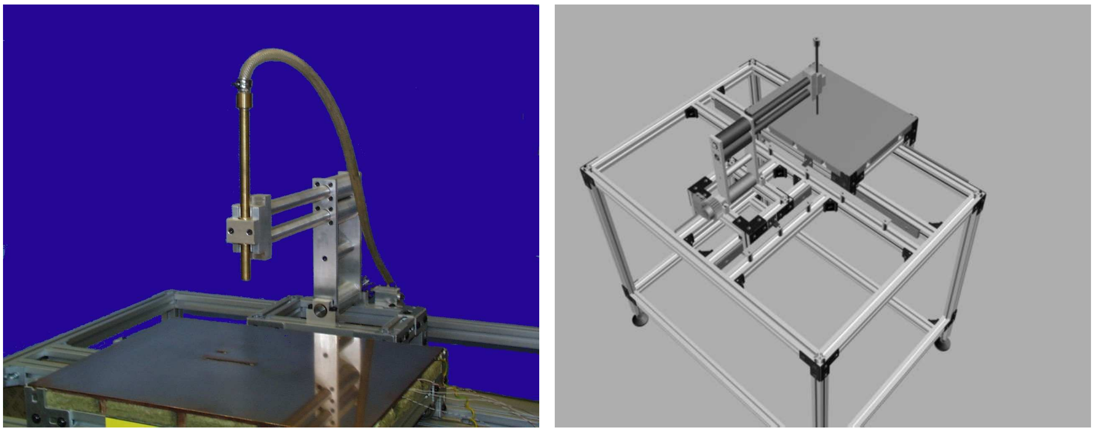

Figure 1: Experimental Rig Photograph (left) Schematic (right)

A 550 mm × 475 mm × 5 mm horizontal copper plate is heated from below by an electric silicone-rubber heating element. This approximates a uniform wall temperature boundary condition. A jet of air issues from a long (20 diameters) pipe with a 45 chamfer at its exit. The flow condition from such a nozzle is a hydro-dynamically fully developed turbulent jet with minimal entrainment. The airflow is metered using a volume flow meter to an accuracy of 1%. The meter consists of a Laminar Flow Element (L.F.E.), which is a restriction that is designed to force the air along a parallel path across which the differential pressure is measured and so the Poiseuille equation is valid. The flow meter is rated up to 400 l/min, which corresponds to a Reynolds number of 40,000 approximately for the nozzle diameter used (13.5 mm). However a Reynolds number up to 20,000 is only considered in here.

Two flush mounted sensors are used for heat transfer measurements. An RdF micro-foil heat flux sensor, which uses the operating principle of a thermopile, is used for time-averaged data. The temperature difference across a substrate of known conductivity and thickness produces a voltage proportional to the heat flux. This sensor however has poor spatial and time resolution. A Senflex hot film sensor is used in conjunction with a TSI Constant Temperature Anemometer (C.T.A.) to acquire fluctuating heat transfer data. The sensor consists of copper leads on a thin (0.051 mm) Upilex S Polyimide film substrate. Nickel sensor elements are electron beam deposited onto the polyimide substrate to a thickness of $< 0.2\ \mu$m. The C.T.A. is essentially a Wheatstone bridge where the hot film forms one arm of the bridge. It is therefore possible to vary the temperature of the hot film by varying the resistance of another arm of the bridge. The output voltage, or the voltage required to maintain the temperature of the bridge is proportional to the power or heat dissipated from the bridge.

Both the nozzle and plate are placed on carriages on perpendicular tracks. This allows for measurement of the heat transfer in 2 dimensions in the range from -10 to +20 diameters. The nozzle is clamped and can be varied in height above the plate from 0.5 to 10 diameters. The nozzle assembly can also be angled from 15° in 15° intervals to the plate. This experimental rig is therefore designed beyond the required range of parameters for the current tests.

## Results

Heat transfer to the impinging air jet has been investigated for a radial distance up to 7 diameters from the stagnation point. The effect of both Re, and H/D on the time-averaged heat transfer is shown in figure 2.The mean heat transfer from the plate to the jet is known to peak at the geometric center of the jet and decays with increasing radial distance for large H/D. However it has been shown that at smaller H/D (< 2) the mean heat transfer profile exhibits secondary peaks that occur at approximately 1.5 to 2 diameters from the geometric center. The shape of this profile is due to the wall jet boundary layer that forms and as such the flow regimes within the boundary layer can be identified. The heat transfer decreases rapidly with increasing radial distance from the stagnation point as the laminar boundary layer thickens. It then increases to a lateral peak as the wall jet boundary layer undergoes transition to turbulence. The heat transfer decreases monotonically thereafter as the local flow velocity decreases.

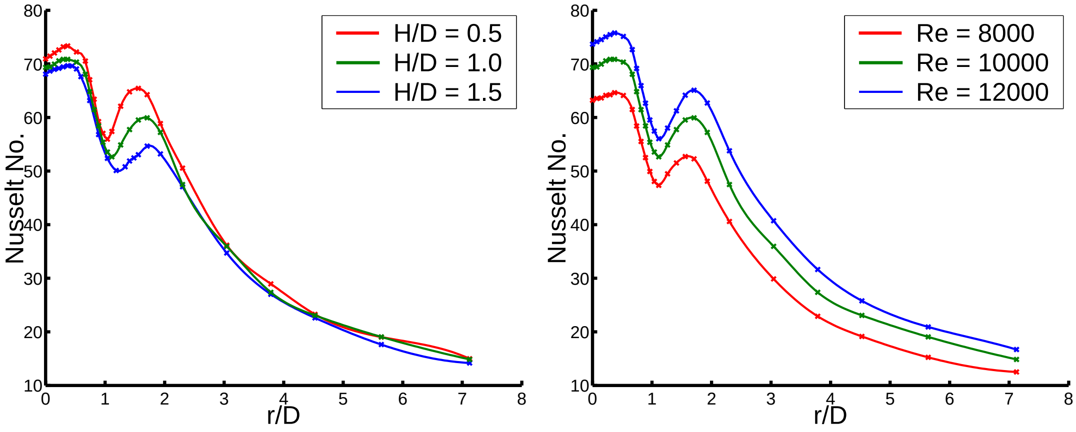

Figure 2: Nusselt No. Profiles, $\alpha = 90°$; Re = 10,000 (left), H/D = 1 (right)

As evident from figure 2 the position of the peaks and troughs of the heat transfer profile are dependent on both Re and H/D. Increasing both Re and H/D has the effect of delaying the transition to fully turbulent flow in the wall jet. H/D also has a significant effect on the relative magnitude of the secondary peak. With a smaller jet to plate spacing the secondary peak becomes closer in magnitude to the stagnation point peak. The trough also moves closer to the geometric center. These two effects are due to the accelerated flow as the air escapes from the lip of the jet.

Obliquely impinging jets have also formed part of this study. The stagnation point is found to be somewhat displaced in the uphill (acute angle of the jet) direction as illustrated in figure 3.The heat transfer profiles in figure 4 identify the location of the stagnation point as it occurs at the point of peak heat transfer for the range of parameters investigated. It is also evident that there exists an optimum angle of impingement to maximise the heat transfer to the jet. From figure 4 at H/D = 6 this lies at $\alpha = 75°$ . H/D also affects this optimum angle as the peak heat transfer occurs at $\alpha = 45°$ for H/D =1. As with the case of normal impingement secondary peaks occur when H/D is low. The flow regimes within the boundary layer are once again easily identifiable. It is clear that decreasing the angle (the acute angle) of impingement the stagnation point moves further from the geometric centre. This also has the effect of delaying the transition to fully turbulent flow in the downhill direction as evident from figure 4. The decay of heat transfer with increasing distance form the stagnation point is very steep in the uphill direction and less so in the downhill direction. This is obviously more pronounced for smaller angles of impingement.

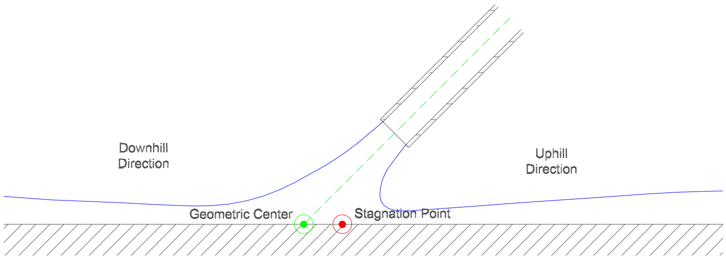

Figure 3: Variation of Stagnation Point from Geometric Centre

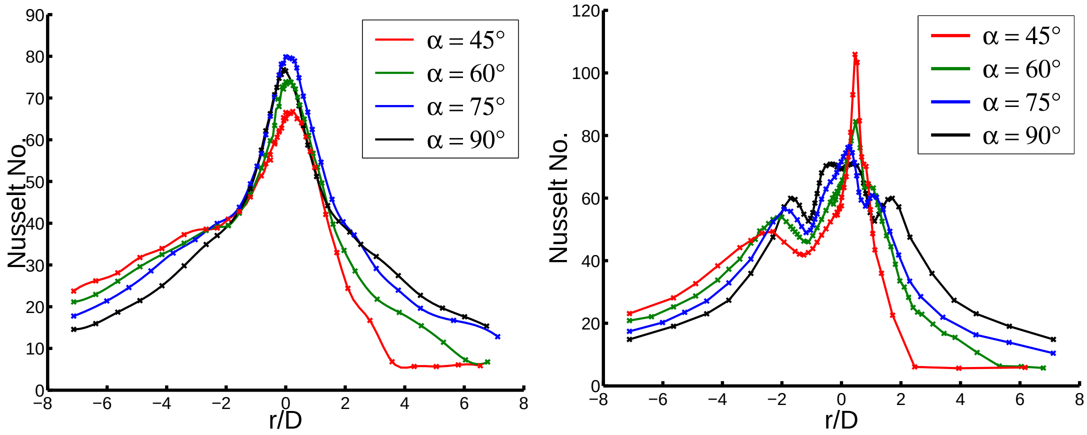

Figure 4: Nusselt No. Profiles, Re = 10000 H/D = 6 (left) H/D = 1 (right)

Further investigation into the heat transfer within the transitional boundary layer included the acquisition of fluctuating heat transfer data. One such investigation is detailed in figure 5. The frequency spectra reveal a peak that initiates in the transitional boundary layer. This fluctuation in the heat transfer is thought to be a result of a vortex that rolls up or initiates in the shear layer of the jet on exit from the nozzle. This organised flow structure subsequently moves along the jet and impacts with the plate. It then moves along the wall jet thereby affecting the local heat transfer. The frequency peak appears to grow in magnitude as it moves radially but eventually decays as the wall jet transitions and becomes fully turbulent.

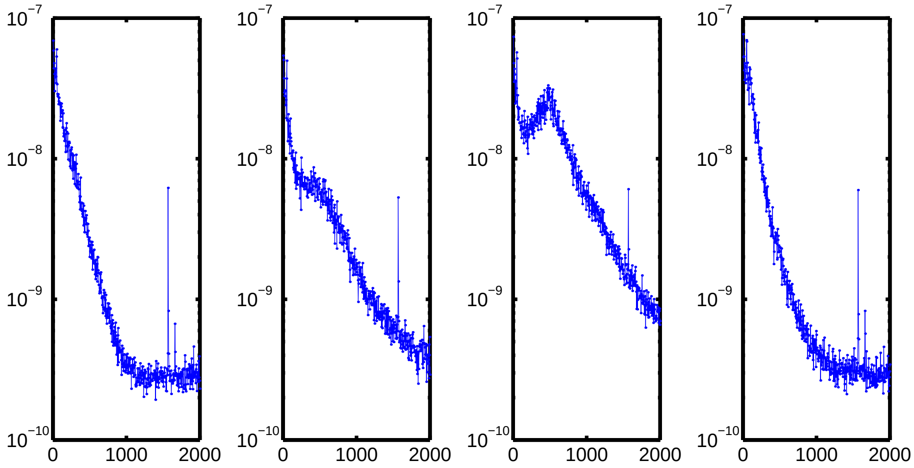

Figure 5: Fluctuating Heat Transfer Spectra, Re = 10000; $\alpha = 90°$ From left r/D = 0; 0.7; 1.3; 3.6

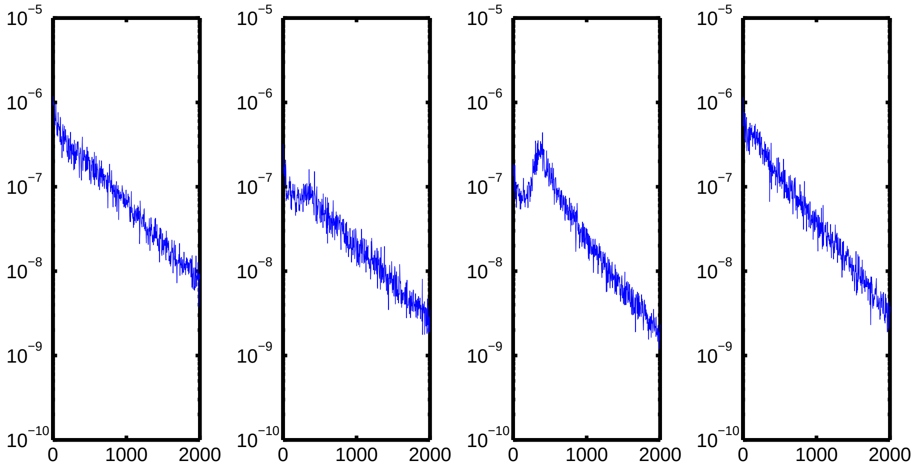

Figure 6: Fluctuating Heat Transfer Spectra, Re = 10000; $\alpha = 45°$ From left r/D = 0; 1.0; 1.6; 4.0

Figure 6 depicts the frequency spectra for an obliquely impinging jet of 45° in the downhill direction. As identified from the mean heat transfer profiles of figure 4 it is expected that the transitional boundary layer be elongated. Indeed the initiation of the frequency peak in this case is delayed in comparison to the normally impinging jet. Its growth and demise also occur at greater radial distances from the stagnation point.

## Conclusions

- Heat transfer profiles decay from a peak at the stagnation point with increasing radial distance for large H/D
- For small H/D ($< 2$) the mean heat trasnfer profile exhibites secondary peaks
- These peaks vary in position and magnitude with H/D and Re
- The shape of the mean heat transfer profiles help determine the flow regime within the wall jet boundary layer
- Obliquely impinging jets have a similar effect on the heat transfer but the stagnation point is displaced in the uphill direction
- H/D effects the angle at which maximum heat transfer occurs
- A frequency peak in the spectra of the fluctuating heat transfer in the transitional boundary layer has been identified

## References

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