Fluctuating Heat Transfer to an Impinging Air Jet in the Transitional Wall Jet Region

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Abstract

The current research investigates convective heat transfer from a heated surface to a normally impinging axisymmetric air jet. The wall jet region is examined from the stagnation point to a radius of 7 nozzle diameters. Within this range the wall jet undergoes transition from laminar to turbulent flow. Both time averaged and fluctuating heat transfer data are obtained. In the present study, profiles of time averaged heat transfer data are used to identify zones of transitional flow for a range of Reynolds numbers and wall-to-jet distances. The hot film sensor is then used to measure fluctuating heat transfer in zones of particular interest. No artificial excitation is applied to the jet. Spectra obtained for the fluctuating heat transfer at various radial positions in the wall jet and at various test conditions are reported and linked to the local flow structure.

Introduction

Convective heat transfer to an impinging air jet is known to yield high heat transfer coefficients and is thus of interest for applications such as the cooling of hot surfaces in manufacturing processes. To date impinging air jets of many and varied geometries have been used in a wide range of applications including cooling of turbine blades and drying of paper and textiles. Considerable research has already been conducted into the area of impingement jet heat transfer [1], [2], [3] etc.

Studies of jets impinging with low nozzle to plate spacings have indicated that the wall jet undergoes transition to turbulence. The mixing induced turbulence 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). It is for this reason, according to Goldstein et al. [4], that the stagnation point Nusselt number is a local minimum at H/D = 2. Huang et al. [5] 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. [6] 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. [7]. At extremely low H/D (< 0.25) the heat transfer profile exhibits two lateral peaks as explained by Colucci et al. [8]. 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 [8]. These peaks vary in radial position with H/D and Reynolds Number.

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. [9]. However, the fluctuations in surface heat transfer due to the vortices induced in the free jet were not reported. Another study by Liu et al. [10] investigated the fluctuating heat transfer to an acoustically excited impinging air jet. It was determined that exciting the jet at certain frequencies had the effect of enhancing or reducing both local and area averaged heat transfer. The focus of the present investigation is fluctuating heat transfer measurements in an impinging jet.
without acoustic excitation. The objective is to obtain experimental data which will clarify the convective heat transfer mechanisms in the transitional wall jet region.

**Experimental Set-up**
The experimental rig is presented in figure 1 below. The nozzle setup is a pipe of 20 diameters in length chamfered at its exit. This nozzle issues a hydro-dynamically fully developed turbulent jet with minimal entrainment. The experimental rig allows for the variation of nozzle to surface spacing (H/D) from 1 to 10. Both the plate and nozzle carriages are mounted on traversing rollers so that a profile up to 7 diameters from the geometric centre can be investigated. Tests are carried out for a range of flow rates, corresponding to a Reynolds number range from 8,000 to 30,000.

![Figure 1: Experimental Rig Overview](image_url)

An electrically heated flat copper plate, approximating a uniform wall temperature boundary condition, is used and a flush mounted micro-foil heat flux sensor provides time averaged heat transfer data for local and area averaged Nusselt numbers. Fluctuations in surface heat flux are measured with a hot film sensor in conjunction with a constant temperature anemometer. This sensor consists of copper leads on a thin (0.051mm) Upilex S Polyimide film substrate. Nickel sensor elements are electron beam deposited onto the polyimide substrate to a thickness of < 0.2µm. A Constant Temperature Anemometer (C.T.A.) from Dantec controls the films temperature. The C.T.A. is essentially a Wheatstone bridge where the hot film is considered one of the resistors on the bridge. It is therefore possible to vary the temperature of the hot film by varying the resistance of the other resistors within the bridge. The output voltage or the voltage required to maintain the temperature of the hot film at a certain temperature is proportional to the heat flux.

**Results**
For each test condition, a profile of time averaged Nusselt number is obtained. Of particular interest are the profiles for low nozzle to plate spacings, an example of which is shown in figure 2 below:
Figure 2: Normally Impinging Air Jet Nusselt No. Profile, Re = 8000, H/D = 1

Figure 3: Normally Impinging Air Jet Nusselt No. Profile, H/D = 1
The variation in local heat transfer shown in figure 2 is consistent with the results from previous studies, [2], [11]. Thus, the heat transfer peaks at the stagnation point and then falls off as the laminar boundary layer thickens. The profile exhibits secondary peaks where the boundary layer undergoes transition to turbulence, the radius at which this happens being dependent on the Reynolds Number. This radius represents the point where the laminarising effect of the jet pressure gradient is no longer significant. Beyond these secondary peaks the heat transfer declines with further distance from the stagnation point as both the velocity reduces and the turbulent boundary layer thickens.

Another example of these heat transfer profiles are presented in figure 3. This experimental set-up was used to identify points of interest for the acquisition of fluctuating heat transfer data.

The fluctuating heat transfer variation with increasing radial distance from the stagnation point was investigated and a representative sample of the spectra acquired are shown in figure 4 below:

![Fluctuating Heat Transfer Spectra for H/D = 1; (A) Stagnation Point, (B) Laminar Region, (C) Transition Region, (D) Turbulent Region](image)

The spectra above show the initiation, growth and demise of a heat transfer frequency band. The sharp peaks evident in the spectra are known to be caused by the filtering process employed and can be ignored as they have no heat transfer significance. At the point of impingement (figure 4.A) no dominant frequency band is evident as this is a
stagnation zone. Towards the end of the laminar region (figure 4.B) a broad peak is established in the power spectrum. This is thought to be due to a flow structure that rolls up in the free jet region and propagates along the wall jet. This dominant frequency band grows and its centre frequency increases within the transition to turbulence region (figure 4.C). Finally within the fully turbulent boundary layer the frequency band disappears. In this case, (figure 4.D) the flow exhibits no definitive structure.

Differences between the frequency spectra at different Reynolds Numbers can be related to the time averaged heat transfer profiles. It is evident in figures 2 and 3 that the Reynolds number does not effect the radial position of the heat transfer valley which occurs at approximately r/D = 1.21. This valley is only influenced by the nozzle to impingement surface spacing where it occurs at r/D = 1.14 for H/D = 0.5. The Reynolds Number will however effect the position of the lateral peak which is located at r/D = 1.49 and r/D = 1.64 for Re = 8000 and Re = 10000 respectively. It is for this reason that spectra acquired at specific r/D are actually positioned at different locations within the boundary layer. The effect of this is most notable in figure 4.C where the frequency band occurs at a higher frequency range for the higher Reynolds Number.

Conclusions
It has been established for a jet impinging normally at H/D = 0.5, 1 and Re = 8000, 10000, that the wall jet is initially laminar and transition to turbulence occurs between 1.14 and 1.21 diameters from the stagnation point. These regions within the wall jet have been identified using the time averaged heat transfer profiles. Further investigation of the fluctuating heat transfer within the wall jet revealed frequency bands, which grow within the transition region and diminish as the wall jet transitions to turbulence. The frequency behaviour of the flow in the wall jet region can be used to vary the heat transfer by artificially exciting the jet.

References


