Available online at www.sciencedirect.com
ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 3302–3314
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Jet impingement heat transfer – Part II: A temporal investigation of heat transfer and local fluid velocities

Tadhg S. O'Donovan *, Darina B. Murray

Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland

Received 1 August 2006; received in revised form 28 January 2007
Available online 5 April 2007

Abstract

Impinging jets are a means of achieving high heat transfer coefficients both locally and on an area averaged basis. The temporal nature of both the fluid flow and heat transfer has been investigated for Reynolds numbers from 10,000 to 30,000 and non-dimensional surface to jet exit distance, H/D, from 0.5 to 8. At the impingement surface simultaneous acquisition of both local heat flux and local velocity signal has facilitated a comprehensive analysis of the effect that fluid flow has on the heat transfer. Results are presented in the form of surface heat transfer and fluid velocity signal spectra, and coherence and phase difference between the corresponding velocity and heat flux signals. It has been shown that the evolution of vortices with distance from the jet exit has an influence on the magnitude of the heat transfer coefficient in the wall jet.

Keywords: Jet impingement; Heat transfer; Vortices; Spectra; Coherence; Phase

1. Introduction

Impinging air jets are employed in a wide range of applications for enhanced cooling, as detailed in the first part of this two part investigation. The effect of local mean velocities and turbulence intensities on the heat transfer has been outlined in part 1, whereas the objective of this part is to explore in more detail the influence of the turbulence characteristics of the flow on heat transfer. In particular, the effect of naturally occurring vortices on the mean heat transfer from the impingement surface is presented.

In a jet flow, vortices initiate in the shear layer due to Kelvin Helmholtz instabilities. As the vortices move downstream of the jet nozzle each vortex can be wrapped and develop into a three dimensional structure due to secondary instabilities. These secondary instabilities can lead to the "cut and connect" process as described by Hui et al. [1] and Hussain [2] in which the toroidal vortices break down into smaller scale motions, generating high turbulence. Vortices, depending on their size and strength, affect the jet spread, the potential core length and the entrainment of ambient fluid. In certain cases jet vortices can pair, forming larger but weaker vortices. In general, vortices pass in the shear layer of the jet at the same frequency as that at which they roll up but in the vortex pairing case the passing frequency halves as the vortices pair off. Turbulent jets have a fundamental frequency at which the pairing process stabilises and this is determined by the turbulence level of the jet. With distance from the jet nozzle the vortices break down into random small scale turbulence. It is clear that vortices influence the arrival velocity of the impinging jet flow and therefore influence the shape and magnitude of the heat transfer distribution.

Artificial jet excitation can control the development of vortices in the jet flow and therefore is thought to have the potential to enhance heat transfer from the surface. Liu and Sullivan [3] excited an impinging air jet acoustically and reported on the resulting flow and heat transfer distributions. It was found that, depending on the fre-

* Corresponding author. Tel.: +353 1 896 3878; fax: +353 1 679 5554.
E-mail address: tadhg.odonovan@tcd.ie (T.S. O'Donovan).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.01.047

Nomenclature

D	diameter (m)	U	velocity (m/s)
f	frequency (Hz)	x	distance from nozzle exit (m)
H	height of nozzle above surface (m)		
Nu	Nusselt number, hD/k (−)	*Greek symbols*	
Nu'	root-mean-square Nusselt number (−)	δ	distance between sensors (m)
r	radial distance from geometric centre (m)	μ	viscosity (kg/m s)
Re	jet Reynolds number, $\rho U D/\mu$ (−)	ρ	density (kg/m^3)
St	Strouhal number, fD/U (−)	Φ	phase (−)

quency of excitation, the area averaged heat transfer could be enhanced or reduced at low nozzle to impingement surface spacings. In the case where the jet is excited at a subharmonic of the natural frequency of the jet, the heat transfer is reduced; this frequency has the effect of strengthening the coherence of the naturally occurring frequency. The jet was also excited at a frequency higher than that of the natural jet frequency. In this case the excitation had the effect of producing intermittent vortex pairing, resulting in a break down of the naturally occurring vortices. The resulting transition to small scale turbulence effectively increases the heat transfer to the impinging air jet.

In recent times control of the jet vortex flow has attracted much research interest as the latest parameter identified as important for impinging jet heat transfer. Hui et al. [1] and Gao et al. [4] installed mechanical tabs at the nozzle exit to instigate streamwise vortical structures. These have the effect of increasing the secondary instabilities in the jet and therefore hasten the "cut and connect" process that breaks the vortices down into small scale turbulence. Hwang et al. [5] investigated the effect of acoustic excitation on a coaxial jet flow and explored the resulting effect on heat transfer. Hwang and Cho [6] continued this research for a wider range of test parameters. While the research to date has shown possible enhancement of the mean heat transfer at various excitation frequencies, much of this has been attributed to changes in the arrival velocities. The effect of the vortical flow structure on the local heat transfer has not been reported in depth.

The literature to date has shown that the heat transfer distribution over the impinging surface varies considerably with height of the jet nozzle above the surface. While abrupt increases in turbulence in the wall jet are used to explain the location and magnitude of secondary peaks in heat transfer the literature fails to provide an in depth explanation of the controlling heat transfer mechanism. The objective of this research is to understand the influence that the actual vortex flow structure, at various stages of its development, has on the convective heat transfer in the wall jet. Results are presented in the current investigation for a jet that is formed from a fully developed pipe flow impinging on a heated flat surface. Temporally simultaneous measurement and analysis of the surface heat flux and the local fluid velocity has revealed the effect that vortices have on both the mean and fluctuating heat transfer coefficient.

2. Experimental rig

The experimental rig consists primarily of a nozzle and a heated impingement surface. The flat impingement surface is instrumented with two single point heat flux sensors. Laser Doppler Anemometry is used to measure flow velocity and turbulence intensity at a point 3 mm above the heated surface, which was the closest possible given experimental constraints; this method has high spatial and temporal resolution. The experimental set-up is shown in Fig. 1. The experimental rig design and the heat transfer measurement techniques employed are described in detail in part 1 of this two part investigation.

The Laser Doppler Anemometry system is based on a Reliant 500 mW Continuous Wave laser from Laser Physics. This is a two component system and therefore the laser is split into 2 pairs of beams, that have wavelengths of 514.5 nm (green) and 488 nm (blue), to measure the velocity in orthogonal directions at the same point location. The four beams, each of diameter 1.35 mm, are focused on a point 250 mm from the laser head. The system works in backscatter mode and a base spectrum analyser (BSA) acquires and processes the signal to compute the velocity. Food grade polyfunctional alcohol liquid particles, typically 1–50 μm in diameter were used to seed both the jet flow and the ambient air.

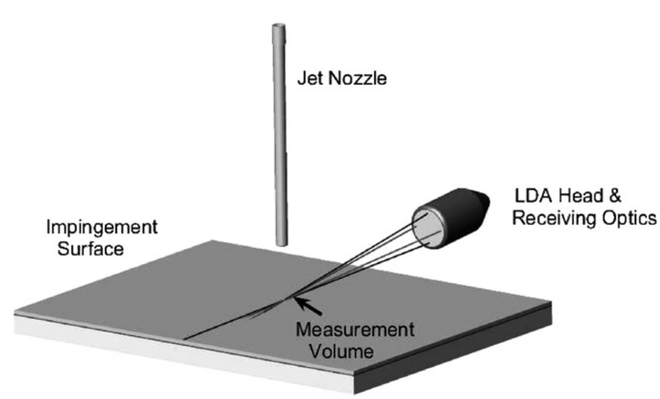

Fig. 1. Laser doppler anemometry measurement set-up.