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Parametric analysis of a round jet impingement on a heated plate

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ABSTRACT

In this study, the flow and heat transfer characteristics of a round air jet have been experimentally investigated in details using two techniques: Particle Image Velocimetry (PIV) and the Laser Doppler Velocimetry (LDV). The measurement of the mean velocity components are compared, and agree well with the experimental data obtained by Baydar (1999). The distributions of the velocity, turbulence quantities and temperature profiles are analyzed in the main characteristic regions of the jet where the heat transfer occurs. Parametric variations were conducted to produce information about the influences of the Reynolds number (Re = 1000, 2000, 3000), the distance between the pipe exit and the flat impingement plate ($h/d = 1$ and $h/d = 2$) and the temperature of the plane ($T_p = 22$ °C, 54 °C, 96 °C) on the impinging jet flow field.

1. Introduction

Jet impingement is widely used in industrial applications where convective heat and/or mass transfer rates are required. Therefore, it widely covers such areas of application as well as various production processes and materials' processing, cooling (Giulio, 2002) or heating systems (Webb et al., 1992; Chander and Ray, 2005). The impact of air system is also used in various industrial processes like paper drying, cooling of electronics (Hollworth and Durbin, 1992) and shaping glass (Hsieh and Lin, 2005). There have been various other applications in the food industry (Li and Walker, 1996; Sarkar and Paul Singh, 2004), and over the last few decades, the air impinging jet has been applied to air conditioning and ventilation (Karimipanah, 1996; Karimipanah and Awbi, 2002).

The impinging jet can be characterized by four different flow regions (Polat et al., 1989; Beltaos and Rajaratnam, 1974; Popiel and Trass, 1991). The first is the region where the flow establishes itself. It extends from the nozzle exit to the apex of the potential core. The behavior of the flow is the same as the free jet where the plate does not affect the flow. The mean velocity is almost uniform. This region can be divided into the potential core region, the developing flow region, and the developed flow region (Sarkar and Paul Singh, 2004). Rajaratnam (1976) showed that in the fully developed jet flow, the jet broadens linearly and the centerline velocity decays linearly. The second is the region of impingement. Here the jet is deflected from the axial direction due to the presence of a solid wall. The pressure takes on a maximum value at the stagnation point and it decreases monotonically from its maximum value. In this region, the vortices impinge on the plate which causes a fluctuation in pressure over the wall. Ding et al. (2003) illustrated the presence of the helical structure when the vortex ring impinges onto the plate. It is indicated by the spread of the fluid over the axis of the jet in the impingement region. Further from this zone, where the velocity of the jet is parallel to the plate, the wall jet region starts. The fluid in this region spreads out radially over the plate, with a maximum radial velocity and with a growing boundary layer. Adverse pressure gradients in this region can lead to the separation of the radial flow. The vortices observed by Ding et al. (2003) are breaking in the wall jet zone (Meola et al., 2000).

The study of impinging jet has gained a lot of interest due to its structural configuration. As such, it is necessary to investigate the effects of the different geometrical and fluid property parameters on the jet behavior. Previous investigations have shown that the heat transfer and the dynamic behavior produced by a round impinging jet is affected by a number of parameters including the nozzle-to-plate distance (h/d), the jet Reynolds number (Re and velocity profile at the nozzle exit) (Viskanta, 1993) and the geometry of the nozzle (Molana and Banooni, 2013). An experimental parametric study was performed by Tummers et al. (2011) using the Laser Doppler Anemometry (LDA). Their study reports on the detailed measurements of turbulent flow in the stagnation region of an impinging jet issuing from a round pipe. The distance between the pipe exit and the flat impingement plate is 2D, and the Reynolds number is 2.3×10^4. These data allowed the determination of the wall shear stress

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Nomenclature

Symbols

d	diameter of the jet nozzle (m)
h	distance between pipe exit and impingement plate (m)
Re	Reynolds number (Re= $v_{0\max} d/\nu$)
T	temperature (°C)
T_a	ambient temperature (°C)
T_p	temperature of the plate (°C)
u	mean longitudinal velocity (m s^{-1})
v	mean vertical velocity (m s^{-1})
x, y	axial and vertical coordinates (m)

Greek symbols

ν	kinetic velocity of air (m^2 s)

Subscripts

0	exit of the jet
max	maximum value

Superscripts

–	Reynolds average
'	Fluctuation

distribution. Previously, Cooper et al. (1993) made measurements of the flow field in the radial wall jet at Reynolds numbers of 23,000 and 70,000 and nozzle-to-plate distances of 2 and 3 diameters. They identified characteristics of the turbulence structure in the near-wall region of the flow and examined the mean and fluctuating velocity profiles along the plate. The turbulent velocity profiles for different nozzle-to-plate distances are also shown. It was noted that the turbulence levels noted are higher and the impingement zone of the jet is at a distance of 2–3 diameters from the stagnation point. Another experimental investigation to determine velocity and pressure distributions in the impingement region of an impinging circular jet has been made by Baydar (1999). They have experimentally investigated the flow structure for a Reynolds number range of 300–10,000 and a nozzle-to-plate spacing range of 0.5–4. The characteristic of an impinging circular jet was found to be sensitive to the nozzle-to-plate spacing. Due to the presence of the impingement plate causing the deceleration, the flow deflects at about a jet diameter above the impingement plate.

Many authors have characterized the development of large-scale structures in the near field of the radial wall jet, produced by the impinging jet with nozzle-to-plate distances less than 4 diameters. In fact, Narayan et al. (2004) reported measurements of flow field and heat transfer rates of a turbulent jet impinging normally on a heated plate. They examined the influence of two nozzle-to-surface spacing $h/d = 0.5$ and $h/d = 3.5$, corresponding to the potential-core and transitional jet impingement, respectively. They used the Laser Doppler Anemometry technique (LDA) to determine the mean velocity and turbulence intensity in the near-wall jet flow. Also, they calculated the local heat transfer coefficients. They reported that the heat transfer data exhibits high rates in the impingement region for transitional jet impingement and decay in heat transfer coefficient for the potential-core jet impingement. The fluid flow results indicate that past impingement, locations of high streamwise fluctuating velocity variance occur in the wall jet flow for both nozzle spacing. The local heat transfer characteristics and the dynamics behavior of the air jet impingement at the nozzle-plate spacing of less than one nozzle diameter have been experimentally examined using an infrared thermal imaging technique by Lytle and Webb (1994). The flow structure was investigated via the Laser Doppler Velocimetry and the wall pressure measurement in the Reynolds number range $3600 < \mathrm{Re} < 27600$ is examined. The effects of the accelerating fluid between the nozzle-plate gap as well as the significant increase in local turbulence leads to substantially increased local heat transfer with decreased nozzle-plate spacing. In the case of jet impingement at nozzle-plate of less than the potential core length of $h/d < 4$, an experimental investigation is done by Guerra et al. (2005). Measurement was conducted for one nozzle to-plate spacing ($h/d = 2$) and a Reynolds number of 35,000. Experimental data for the pressure distribution, velocity and temperature fields were obtained. The mean temperature profiles were measured through thermocouples. The heat transfer data confirmed the existence of a minimum in the temperature profile away from the wall. An experiment has been carried out by Zhou and Lee (2005) to investigate the effect of the nozzle-to-plate spacing and jet Reynolds number on the heat transfer augmentation. Results show that the nozzle-to-plate spacing has a significant influence on the flow structure and heat transfer of impinging jet. For the nozzle-to-plate spacing of $0.2 \le h/d \le 1.0$ and jet Reynolds numbers in the range of $3000 \le \mathrm{Re} \le 50{,}000$, the mean velocity and turbulence intensity profiles of the free jet downstream of the jet nozzle are measured. They concluded that a smaller nozzle-to-plate spacing and a larger Reynolds number give a higher heat transfer rate in the impingement region.

Despite the extensive work on this subject, the dynamic and heat transfer characteristics of an impinging air jet still need more interest. Thus, the present work will provide an experimental study of a round jet impinging normally to a flat plate subjected to a temperature change (T_p). Two measurement techniques were used in the experiment: Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV). The results from the experimental measurement are comparable with those presented by Baydar (1999). The aim of this research is to determine the influences of the Reynolds number (Re = 1000, 2000 and 3000), the height between the nozzle and the plate ($h/d = 1$ and $h/d = 2$) and the temperature imposed on the impact surface (T_p = 54 °C, 96 °C), on the dynamic development, the turbulent flow and thermal characteristics.

2. Experimental setup

2.1. Experimental conditions

Our work focuses on identifying the dynamic characteristics and thermal properties of an air jet impinging a flat plate in a non-dimensional way. All variables are non-dimensionalized by the maximum nozzle exit velocity $v_{0\max}$ on the jet axis and by the nozzle diameter d.

The experiments were conducted for a jet emitted from a nozzle of circular section; with a diameter d; on a flat plate perpendicular to the flow and operated at three different temperatures: 22 °C, 54 °C and 96 °C. The flat plate was located at variable distances from the jet nozzle ($h/d = 1$ and $h/d = 2$) (Fig. 1). The range of numbers of the Reynolds numbers ($\mathrm{Re} = v_{0\max} d/\nu$) has been chosen to characterize different flow regimes: Re = 1000, 2000 and 3000.

The trajectory of the flow being definable by the Cartesian coordinate system and the origin of this system (x, y) were placed at the center of the flat plate (Fig. 1). This choice is motivated by the symmetry of the resulting flow.

The experimental setup is shown in Fig. 2. The system essentially consisted of a PVC pipe-nozzle with a diameter (d) of 25 mm and a length of 560 mm. The air jet impinged vertically on a flat plate and the surface was made of copper, of dimensions 210 × 170 × 8 mm^3. It is located at a distance h from the nozzle. This distance could be varied using a mechanical jack. The use of copper is recommended because it is a metal that conducts heat well (thermal conductivity 389 W/mK), and the temperature distribution is uniform over the entire surface of the plate. The use of a digital regulator (type 30 760) has enabled us to maintain the temperature of the plate constant upon the impact of the jet. In all experiments, the jet is seeded