Experimental Thermal and Fluid Science 68 (2015) 722–732

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Impingement pressure characteristics of swirling and non-swirling turbulent jets

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 21 July 2015
Accepted 21 July 2015
Available online 29 July 2015

Keywords:
Gaseous jets
Turbulent swirl
Impinging
Pressure
Flow visualisation
Velocity

ABSTRACT

This paper experimentally investigates the effects of swirl on the impingement surface pressure for an incompressible, turbulent, swirling impinging air jet. The swirl flow is generated aerodynamically, where the nozzle can achieve a seamless progression from non-swirling to high swirling flows. Hotwire anemometer is used to measure velocity components. A digital micromanometer with flush-mounted pressure taps on the impingement plate is used to measure static pressures on the impingement surface. The effect of swirl number (S), nozzle-to-plate distance (H) and Reynolds number (Re) on the pressure distribution is examined for $S = 0$–1.05, $H = 1D$–$6D$ and $Re = 11{,}600$, $24{,}600$ and $35{,}000$.

For low swirl flows, the coefficient of pressure (Cp) shows a non-swirl like behaviour with maxima at the stagnation point. For medium-to-high swirls, maximum Cp shifts radially outward from the stagnation point and becomes relatively flat with increasing S. The stagnation pressure reduces nonlinearly with increasing swirl intensity and follows a quadratic relationship for a given Re. For any S, the pressure distribution is found to be independent of Re for low swirl numbers (up to $S = 0.3$), but it varies up to $r/D = 2$ for larger swirl numbers. A negative Cp (flow separation) occurs near the stagnation region for $H = 1D$, however, vanishes at larger H. For very high swirl number ($S = 1.05$) and at $H = 1D$, three different regions are recognised on the impingement surface from the stagnation point: a rotating, reversed inward flow at $r/D \leqslant 0.5$, a transition and less stable region at $0.5 < r/D \leqslant 0.75$ and an outward flow with stronger tangential component at $r/D \geqslant 1.0$. These surface pressure results may significantly affect the heat transfer characteristics as well as wall shear stresses for future impinging jet studies.

1. Introduction

Impinging jets are widespread in industrial applications due to their ability to affect heat and mass transfer rates on surfaces [1–4]. In a typical impingement jet, the flow field is divided into three regions, namely the free jet region, the stagnation (or impingement) region and the wall jet region. The free jet region that occupies most of the flow domain is largely characterised by both the (conical) potential core around the axis where the axial velocity is 95% of centreline velocity at the nozzle exit [5] and its shear layer. In the impingement region, on or close to the impingement surface and symmetrical about the geometric centreline, jet impact causes streamline curvature towards radially outward direction and a rapid decrease in axial velocity with a corresponding rise in static pressure. The wall jet region, which is further out (radially), then forms around the impingement region where the axial deceleration of the flow causes lateral spread near the surface. Although excellent historical [6–9] and recent [10–13] treatise exist on the flow field characteristics of turbulent impinging jets and the characteristics of three distinctive flow regions, relatively fewer works have attempted to resolve the pressure distribution in the stagnation and wall jet regions or the effects of relatively high swirl on the potential core. The impartation of swirl into an impinging jet further complicates the flow field with fundamental interpretation becoming more challenging if swirl is generated geometrically by means of helical inserts or guide vanes. This is because geometrical swirl generation causes dead zones to form on the axis and limits the range of swirl numbers, results in a bifurcation of a single jet into multiple jets [14–17], is likely to distort the flow and alter heat transfer characteristics as well as impingement pressure distribution. Adding to this complexity is the anticipated role of swirl induced flow reversal and/or instability at certain free jet conditions [18,19]. These geometry induced flow perturbations may be avoided through aerodynamically generated swirl flows (i.e., without any inserts or guide vanes), which is the focus of the present study.

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http://dx.doi.org/10.1016/j.expthermflusci.2015.07.017
0894-1777/

Existing research on swirling impinging jets largely populated with surface heat transfer characteristics and studies have reported varied outcomes in relation to the effects of swirl on impingement surface heat transfer. Lee et al. [15] as well as Ianiro and Cardone [17] observed a reduction in heat transfer with swirl, which may be affected by flow blockages formed around the centreline from the use of geometric swirl generation (helical inserts). In contrast, Wen and Jang [20] as well as Ichimiya and Sukamoto [21] discovered enhanced heat transfer at the surface (around the stagnation point). This finding may be attributed to swirl induced mixing via the formation of vortices on the impingement surface and larger entrainment of (cool) ambient air. As such, there appears to be a fundamental disparity in the understanding of whether swirl improves or deteriorates impingement heat transfer and remains an issue worthy of further investigation. Moreover, despite numerous research into impinging non-swirling turbulent jets, it is evident that there is limited reporting of the (surface) pressure field which would help in validating turbulence models in computations, particularly near-wall flow features or surface characteristics. Pressure distributions were overlooked in the majority of earlier studies because the focus was on heat transfer. Notably, resolving pressure distributions along the impingement surface may also influence boundary layer development and help characterise the nature of jet spread. Bayder and Ozmen [22] identified a relationship between pressure distribution and turbulence intensity and its effect on the transition from laminar to turbulent boundary layer flow in the wall jet region of non-swirling impinging jets. Likewise, Katti and Prabhu [11] used pressure data to propose a theoretical relationship between wall static pressure and heat transfer at the stagnation point for a single Reynolds number (*Re*) and nozzle-to-plate distance (*H*). The following is a brief overview of the research conducted to date on the pressure distribution of turbulent (gaseous) impinging jets, for both swirling and non-swirling conditions.

In non-swirling jets with large nozzle-to-plate distances ($H > 8.3D$) the stagnation pressure (P_s) is inversely proportional to the square of the impingement distance i.e., $P_s \alpha (H/D)^{-2}$ where D is the nozzle diameter [7,23]. However, in the near field and for small nozzle-to-plate distances ($H \leqslant 5.5D$), P_s does not vary with H/D and approximates to the dynamic pressure, which agrees with the experiment by Giralt et al. [8]. At $H \leqslant 5.5D$, Beltaos and Rajaratnam [7,23] identified the impingement region to extend up to $1.2D$ from the impingement wall and $r/D \approx 1.4$ from the stagnation point where the pressure drops to the ambient value. However, other results have indicated that when the impingement surface is positioned very close to the nozzle ($H \leqslant 0.5D$), a constant pressure zone (equal to) P_s is developed around the stagnation point, where this zone grows with decreasing H values [24]. Lytle and Webb [24] also reported that the stagnation pressure and radial pressure distribution were not significantly dependent on *Re* and *H* in non-swirling jets except very close to the nozzle exit plane ($H = 0.2D$), which agrees with recent experimental and numerical studies [11,22,25,26]. For impingement at $H = 0.2D$, the impingement surface pressure is about three times larger than pressure at other *H* values and is attributed to the rapid decrease of axial velocity as the jet transcends the impingement zone. At $H = 0.2D$, there is a slight decrease in P_s with increasing *Re* but no explanation was reported in the literature [22]. Finally, sharp pressure drops have been observed at $r/D \approx 0.5$, where the pressure drop occurs more distant (radially) from the geometric centreline with increasing *Re*. As such, it is evident that even for non-swirling impinging jets at $H \leqslant 6D$, some uncertainty exists on the effects of *H* on P_s and the underlying flow dynamic effects at such flow conditions.

The effect of swirl on the pressure distribution of turbulent impinging jets is scarce in the literature. Apart from experimental investigations into the surface pressure distribution of annular swirling jets [27,28], which impose fundamentally different flow behaviour due to multiple shear layers, there is little data for pressure distributions of turbulent swirling jets. Most swirling impinging jet studies largely deal with the mean and turbulent velocity characteristics upstream of the impingement surface [16,29–33]. These studies reveal that the formation of flow recirculation between the nozzle exit and the impingement surface depends on the swirl number ($0.3 \leqslant S \leqslant 0.5$) and the impingement distance ($H = 2D$–$6D$). However, in almost all of these studies, swirl is generated geometrically by helical inserts or guide vanes inside a nozzle. This causes the formation of dead zones on the flow centreline and may also lead to vane-induced trailing vortices which may further complicate interpretations of the link between swirl and pressure distribution on the impingement surface.

This research uses an aerodynamically generated swirling jet which seamlessly transitions from non-swirling to highly swirling flows for the same Reynolds number (*Re*). Analysing the effects of swirl on the impingement pressure distribution helps provide a fundamental understanding of the factors affecting (surface) heat and mass transfer. Methods used in this paper include performing pressure field measurements combined with flow visualisations at the impingement surface. In addition, Constant Temperature Anemometry (CTA) is used to acquire velocity field and boundary condition data so as to provide opportunity for subsequent CFD modelling. Test conditions investigated span a range of swirl ($S = 0$–1.05) and Reynolds numbers ($Re = 11{,}600$–$35{,}000$) as well as impingement distances ($H = 1D$ to $6D$). Section 2 details the swirl nozzle, experimental set-up, test cases and the jet inlet velocity profiles. Section 3 discusses the results followed by the conclusions in Section 4.

2. Experimental techniques

2.1. Swirl nozzle

Fig. 1 shows an illustration of the swirl nozzle used in this study along with the coordinate system, where x indicates the streamwise direction and y–z defines the nozzle exit plane at $x = 0$ mm. The brass nozzle is modular and assembled from seven sections (A, T, C, 3 × S and N). The lower axial section (A) is 50 mm in diameter and includes two diametrically opposed ports with a settling chamber occupied by two layers of 20 mm hexagonal aluminium honeycomb (3 mm cells) and four mesh screens (0.8 mm wire diameter). Flow conditioning reduces large-scale turbulence and straightens the flow [34,35]. The emerging axial flow then enters section T, which introduces the swirling motion via three tangential ports of 12 mm diameter. Aerodynamic swirl generation helps avoid trailing vortices from radial vanes [33] and allow a seamless transition from non-swirling to swirling jet flows. In addition, this technique avoids the complications arising from dead (central) ribs associated with geometrical swirl generation [16,27]. Aerodynamic swirl generator design adopted here allows varying swirl numbers independent of Reynolds number to be tested. The contraction section (C) is designed to aid flow coalescence and has a smooth internal contour that ends at zero (straight) gradient. Section C is based on a cubic polynomial contour (defined below), which minimises boundary layer separation and improves flow uniformity after the contraction [34,36–38]:

$$R_c = \frac{D_i}{2} - \frac{3}{2}(D_i - D_e)\left(\frac{x}{L}\right)^2 + (D_i - D_e)\left(\frac{x}{L}\right)^3, \quad (1)$$

where R_c is the radius of the nozzle contraction section and is a function of x, D_i and D_e (D_i and D_e are the contraction inlet and exit diametres, respectively). The resultant area contraction ratio over