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Experimental study of a round jet impinging on a flat surface: Flow field and vortex characteristics in the wall jet

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ABSTRACT

Impinging jets are widely used in cooling applications. Here, particle image velocimetry measurements were performed to study the flow field (focusing on the wall jet) and vortex characteristics of a round air jet, impinging on a flat surface at three Reynolds numbers, $Re = 1{,}300$, 6,260 and 12,354 (based on nozzle diameter, D, and jet exit velocity), and stand-off distance, $4.75D$. In the wall jet, self-similarity (outer layer scaling) of the mean radial velocity, rms values of velocity fluctuations and Reynolds shear stress was obtained for $Re = 12{,}354$. At $Re = 1{,}300$, impinging primary vortices generated highly coherent primary-secondary vortex pairs that were convected along the wall. In contrast, at the two highest Re, primary vortices broke-up into small-scale structures prior to impingement and vortex pairs were only revealed after conditionally averaging the data. Their strengths, areas and numbers were analyzed using the instantaneous swirling strength and vorticity distributions. Primary vortex strength peaked at break-up or impingement ($Re = 1{,}300$) and reduced during interaction with the secondary vortex. Analyzing the different contributions to the averaged vorticity equation revealed that stretching and realignment due to the mean flow always strengthened the vortices while turbulent diffusion mainly weakened them.

1. Introduction

Impinging jets are commonly used in many different industrial applications for the cooling of electronics or turbine blades as well as for drying textile or paper and for metal cutting, amongst others. While their application is widespread and many studies have focused on the heat transfer characteristics of impinging jets (Johnson and Han, 1991; Fox et al., 1993; Behnia et al., 1998; Behnia et al., 1999; Geers et al., 2006), the detailed flow behavior is still not yet fully understood due to the complex flow dynamics upon and after impingement on the surface. An impinging jet issued from a converging nozzle changes from a high speed, nearly uniform flow having thin shear layers at the nozzle's exit to a transitional and fully developed radially expanding, turbulent wall jet after impingement. Typically, three regions can be distinguished: (i) the free jet (Yule, 1978), (ii) the impingement region (Nishino et al., 1996), and (iii) the radially expanding wall jet (Launder and Rodi, 1981). Each of these regions is characterized by different turbulence mechanisms making it difficult to perform accurate numerical simulations (Zuckerman and Lior, 2007).

Adding to the complexity of the impinging jet's flow field and heat transfer characteristics is its dependence on a large number of parameters such as (i) the jet Reynolds number, $Re = U_jD/\nu$, where U_j is the jet exit velocity, D is the jet nozzle diameter, and ν is the fluid kinematic viscosity; (ii) the nozzle to plate distance, H/D, where H is the distance between the jet nozzle exit and the target surface (see Fig. 1); (iii) the jet exit velocity profile and turbulence level (Hoogendoorn, 1977); (iv) the jet configuration (such as confined or not) and shape of the nozzle (Lee and Lee, 2000). The fact that the impinging jet's flow field depends on so many different parameters, complicates the comparison between different literature results.

While many studies have focused on a jet issued from a long pipe characterized by a fully developed turbulent pipe flow profile (Behnia et al., 1998; Behnia et al., 1999; Cooper et al., 1993; Hadžiabdić and Hanjalić, 2008; Hall and Ewing, 2006), less have focused on a jet issued from a converging nozzle (Shademan et al., 2016; Landreth and Adrian, 1990; Didden and Ho, 1985) where the jet is characterized by a potential core region that may extend up to 4 to $5D$. Nishino et al. (1996) provided detailed 2D and 3D particle tracking velocimetry measurements of the turbulence characteristics including 1st, 2nd and 3rd order moments as well as the turbulent kinetic energy (TKE) budget in the impingement region of an axisymmetric jet issued from a converging nozzle ($D = 40$ mm, $H/D = 5.86$ and $Re = 13{,}000$). Several numerical

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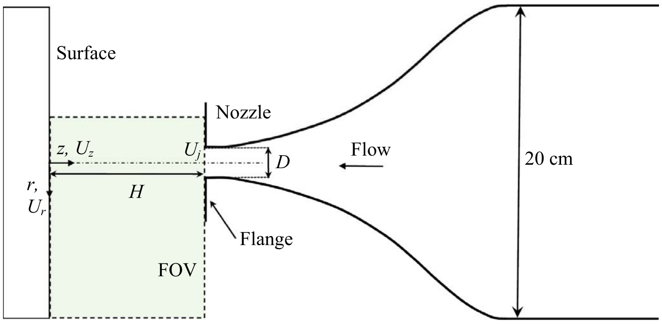

Fig. 1. Schematic layout of part of the experimental setup including the employed coordinate system and field of view (FOV).

studies were setup to reproduce the extensive hot-wire anemometer measurements performed by Cooper et al. (1993) at $Re = 23{,}000$ and 70,000 ($2 \le H/D \le 10$). For example, Behnia et al. (1998) showed that results obtained using the "normal-velocity relaxation turbulence model (V2F model)" were in excellent agreement with Cooper et al. (1993) in contrast to the widely used k-ε model that did not properly resolve the flow and greatly over-predicted the heat transfer rates. Here, k denotes the TKE and ε the TKE dissipation rate. A year later, Behnia et al. (1999) showed that jet confinement leads to decreasing heat transfer rates when the target surface is placed very close to the jet's nozzle ($H/D < 0.25$). In addition, they showed that jet inlet conditions strongly affected the impingement region's heat transfer characteristics. Hadžiabdić and Hanjalić (2008) performed large eddy simulations (LES) of a round impinging jet ($Re = 20{,}000$, $H/D = 2$) on a flat plate in order to obtain better insight into the turbulence structure and the heat transfer characteristics. They confirmed the occurrence of negative TKE production at the stagnation point previously measured in several experimental studies (Geers et al., 2006; Nishino et al., 1996; Geers et al., 2004). They also showed that the Reynolds shear stress in the radially expanding wall jet was not proportional to the mean velocity gradient as assumed in the eddy viscosity hypothesis (Pope, 2000) widely adopted in numerical studies. A possible reason for this may be the wall impingement of large-scale, primary vortices generated as a result of Kelvin-Helmholtz instabilities in the round jet's free shear layer (Yule, 1978). Their interaction with the near-wall turbulence led to the generation of secondary vortices (Didden and Ho, 1985; Harvey and Perry, 1971; El Hassan et al., 2012) thought to be responsible for the Nusselt number peak obtained at a radius of approximately 1.5D from the stagnation point (Lee and Lee, 2000). Furthermore, asymmetric impingement of these primary vortices due to azimuthal instabilities caused jet flapping.

While the previously described studies were performed at relatively small H/D, Shademan et al. (2016) studied the turbulence characteristics of a turbulent jet ($Re = 28{,}000$) issued from a converging nozzle and impinging on a flat plate at a large stand-off distance ($H/D = 20$) using mainly LES as well as 2D particle image velocimetry (PIV) for flow field validation. They showed that in contrast to jets impinging at small H/D ratios (Hadžiabdić and Hanjalić, 2008), the large scale, primary ring vortices generated in the free shear layer lost coherence and did not generate secondary vortices upon impingement.

After impingement, a radially expanding wall jet (Launder and Rodi, 1981; Bakke, 1957; Glauert, 1956) is formed that becomes self-similar away from the stagnation point exhibiting a linear growth of the jet thickness and a maximum velocity that varies as r^{-1}, where r is the radial coordinate extending from the jet axis (Fig. 1). Wygnanski et al. (1992) and George et al. (2000) investigated different scaling laws applicable to a two-dimensional, turbulent plane wall jet. While Wygnanski et al. (1992) found that the bulk of the flow is self-similar, George et al. (2000) proposed a similarity theory for the turbulent plane wall jet valid in the limit of infinite Re, where inner layer scaling denotes normalization by the friction velocity and ν, and outer layer scaling normalization by the maximum wall-parallel velocity and the wall jet's half-width. George et al. (2000) further hypothesized that the inner layer of the wall jet and the zero-pressure-gradient turbulent boundary layer are the same, which can be used to determine the skin friction. Guerra et al. (2005) based on measurements of the velocity and temperature profiles in the wall jet ($H/D = 2.0$, $Re = 35{,}000$) concluded that the velocity profile in the near wall region can be described by a slightly revised "law of the wall" (Pope, 2000). For an oblique impinging jet (20° angle, $Re = 130{,}000$) on a smooth surface ($H/D = 22$), Özdemir and Whitelaw (1992) showed that strong azimuthal dependence was obtained and the boundary layer approximations were inapplicable.

The heat transfer characteristics of impinging jets have been studied extensively and a typical observation is that the Nusselt number (Nu) distribution displays a maximum slightly away from the stagnation point (See Hadžiabdić and Hanjalić, (2008) and references herein). This offset seems to coincide with the length of the potential core or when a potential core is absent, depends on the incoming turbulence level, the Reynolds number and the impingement of large scale, primary vortices leading to the creation of secondary vortices (Hadžiabdić and Hanjalić, 2008; Didden and Ho, 1985). The convective heat transfer characteristics are strongly coupled with the flow field and although the classic Reynolds analogy breaks down in the vicinity of the stagnation point of an impinging jet, away from it a good correlation between the instantaneous skin friction and Nusselt number distribution has been found (Hadžiabdić and Hanjalić, 2008).

Despite the substantial body of research available on the flow and heat transfer of impinging jets on flat surfaces, there is still a need for detailed experiments especially regarding the generation of secondary vortices and their interaction with the primary ones, thought to be of major importance to the local heat and mass transfer characteristics. The present PIV study focuses on the flow field in the radially expanding wall jet, created by a round air jet ($Re = 1300$, 6260 and 12,354) impinging on a flat surface ($H/D = 4.75$). In particular the distributions of primary and secondary vortex strengths, areas and numbers are determined using the instantaneous vorticity and swirling strength. The evolution of conditionally averaged primary and secondary vortex pairs along the wall is analyzed by evaluating different terms appearing in the averaged vorticity equation. The experimental setup and data processing are described in Section 2 while mean velocity, root-mean-square (rms) values of the fluctuating velocity components and Reynolds shear stress distributions are presented in Sections 3 and 4. The instantaneous vortical flow structure, its statistics and conditionally averaged characteristics are analyzed in Section 5. A summary and discussion of the results is presented in Section 6.

2. Experimental setup and data processing

Experiments were performed using a small open-loop wind tunnel consisting of a centrifugal blower, diffuser, screens and honeycomb section and several contractions. For more detailed information the reader is referred to (Sabban et al., 2012). The jet was issued from a contraction (attached to the exit of the test section) changing smoothly from a square cross-section of 20 × 20 cm^2 to a round cross-section having an exit diameter of $D = 20$ mm (area contraction ratio of 100:1, see Fig. 1) and a flanged end (diameter 80 mm). Note that the flange was used in order to prevent the generation of large-scale disturbances at the nozzle exit and was similarly sized as the one used by Bakke (Bakke, 1957). Investigated jet exit velocities were $U_j = 1.04$, 5.00 and 9.87 m/s corresponding to jet Reynolds numbers, $Re = U_jD/\nu = 1300$, 6260 and 12,354. The round jet impinged at the center of a vertical, flat gypsum plate (20 × 20 cm^2) placed at $H/D = 4.75$. At this distance, the