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Reynolds number effects in the near-field of a turbulent square jet

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ABSTRACT

High-resolution particle image velocimetry (PIV) was used to study the flow characteristics in the near-field of a turbulent square water jet issuing from a smooth contraction nozzle. Mean velocity and turbulence statistics are investigated over a range of jet Reynolds number Re_D (based on jet exit velocity and equivalent nozzle diameter) varying from 10,000 to 41,400. The influence of Re_D on the shear layer formation in terms of momentum thickness, Taylor length scale and the evolution of the turbulent/non-turbulent interface are also studied. The velocity measurements reveal that the jet in the near-field is dependent on Reynolds number at the lower end of the range ($Re_D = 10{,}000$) despite the fact that all exit jet profiles closely approximate a "top-hat" shape. It is shown that the jet shear layer grows faster at lower Reynolds number which, combined with an increase of the spanwise turbulence component (v_{rms}) along the jet centerline, suggest rapid axis switching. Much weaker Reynolds number dependence of the mean velocity, turbulence intensities, momentum thickness and jet centerline anisotropy (u_{rms}/v_{rms}) was found for square jets at $Re_D > 10^4$. The Taylor length scale calculated along the jet centerline decreases with increasing Reynolds number and asymptotes to a constant value for $X/D > 4$. The turbulent/non-turbulent (T/NT) regions of the jet have been identified using the velocity criteria proposed in the literature. Evolution of the T/NT interface and the effect of Re_D on the conditionally averaged streamwise velocity and vorticity are also investigated in the near-field of the jet. No jump of the conditionally averaged streamwise velocity and vorticity profiles was noted in the near-field of the square jet.

1. Introduction

Turbulent jets are employed in a variety of engineering processes such as mixing, combustion, ventilation and propulsion. Jets are an important topic of turbulence research as they represent a specific class of free shear flows that involve a rich variety of large and small scale phenomena. It is well known that the initial condition of the circular jet can substantially influence the own-stream flow characteristics [1,2]. In particular, shear layer instability and vortex generation occurring in the near-exit region play an important role in controlling the mixing process of the circular jet [3]. Due to the potential for enhanced mixing and entrainment, jets emanating from non-circular nozzles and orifices have been studied by many authors. Jets produced from elliptical nozzles as well as those with sharp corners, such as square, rectangular, triangular [4,5] and daisy-shaped [6] nozzles, have been shown to yield enhanced mixing and entrainment [7] due to the occurrence of axis-switching [8]. While there are an extensive number of studies that have explored the effect of Reynolds number on the mean flow and turbulence statistics in round jets, the Reynolds number effect on square jets has received significantly less attention.

The effect of Reynolds number on the evolution of flow structures in round jets has been investigated by Dimotakis [9], who put forward the idea of turbulent mixing transition. Dimotakis [9] proposed a critical value of Reynolds number of 10,000, beyond which flow properties such as mixing become a weak function of Reynolds number. The jet Reynolds number Re ($=DU_j/\nu$) was defined based on the diameter of the nozzle D, jet velocity at the nozzle U_j, and kinematic viscosity ν. Focusing on free shear layers and jets, Dimotakis [9] suggested that this critical Reynolds number is valid as long as the flow length scale is properly established. For shear layers, the appropriate length scale was proposed to be the width of the local shear layer. For round jets, the suggested characteristic length scale was the local jet diameter. For Reynolds numbers below the critical value ($Re < Re_{min}$), mixing is enhanced with increasing Re as a result of an increase in the interfacial area. For $Re > Re_{min}$, a fully developed turbulence state is achieved and a weak Reynolds number dependence is observed for all flow parameters. Evidence related to Re independence can be observed from the experiments by Ricou and Spalding [10]. They were

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Nomenclature

A	proportionality constant (–)	$\langle U \rangle$	conditionally averaged velocity (m/s)
D	equivalent diameter (m)	U_j	jet exit velocity (m/s)
k	turbulent kinetic energy (m^2/s^2)	$\overline{u'v'}$	Reynolds shear stress (m^2/s^2)
L_{CCD}	dimensions of CCD array (pixels)	v_{rms}	spanwise turbulence intensity (m/s)
L_{IA}	dimensions of interrogation area (pixels)	X, Y, Z	Cartesian coordinates
L_{PIV}	smallest scale resolved by PIV (mm)	y_i	interface location (m)
L_v	dimension of viewing area (mm)	ε	turbulent dissipation rate (m^2/s^3)
Re_D	Reynolds number (–)	η	Kolmogorov length scale (m)
Δt	temporal interval (s)	θ	momentum thickness (m)
u	instantaneous streamwise velocity (m/s)	λ_T	Taylor micro-scales (m)
u'	fluctuating streamwise velocity (m/s)	ν	kinematic viscosity (m^2/s)
u_{rms}	streamwise turbulence intensity (m/s)	ω	vorticity (s^{-1})
U	mean streamwise velocity (m/s)	$\langle \omega \rangle$	conditionally averaged vorticity (s^{-1})
U_c	local centerline velocity (m/s)		

among the first to report that mixing transition occurs at a critical Reynolds number based on nozzle exit diameter (Re_D) of 25,000, which is of the same order as reported later by Dimotakis [9]. Tandalam et al. [11] studied the near-field of round jets emanating from a smooth contraction nozzle at three different Reynolds numbers (Re_D = 10,000, 30,000 and 55,000) using the PIV technique. They identified large-scale structures by applying proper orthogonal decomposition (POD) on the instantaneous velocity fields. Based on the POD analysis, a significant effect of Reynolds number on the near-field average vortex circulation was reported. Beyond five diameters, the average circulation profiles become independent of Reynolds number and collapsed onto each other. At higher Reynolds numbers, the vortices were found to appear closer to the nozzle exit.

Fellouah et al. [12] investigated the near and intermediate field of a round jet using stationary and flying hot-wire measurements. They found that very near the nozzle the streamwise velocity profiles were independent of Reynolds number. Conversely, streamwise turbulence intensity in the shear layer was found to increase with Reynolds number, and decreased in the central region of the jet. For Re_D = 6000, the mean velocity profile preserves the initial jet condition for a longer distance. In other words, it takes a shorter distance for the flow at Re_D = 10,000 and 30,000 to develop from initial top-hat profile to a Gaussian profile. From two to five diameters, the streamwise turbulence intensity was found to be the lowest at the higher Re_D = 30,000, while farther downstream, a Reynolds number independence was noticed. For the same axial range, the streamwise velocity profiles were shown to be Re independent. A close match of the velocity profiles at low Re_D = 6000 and 10,000 was noted, falling below the limit proposed by Dimotakis [9]. Investigation of the velocity spectra showed the appearance of the inertial sub-range at Reynolds numbers above $\sim$20,000, which was considered by Fellouah et al. [12] as onset of mixing transition. Kwon and Seo [13] studied the Reynolds number effect on the behavior of round jets using PIV. Exploring a range of low Reynolds numbers (Re_D = 177–5142), they found that the length of the zone of flow establishment decreased with increasing Re_D and the centerline velocity decayed more rapidly. They also found that the Reynolds shear stresses increased with Reynolds number.

Large eddy simulation (LES) of round jets has been carried out by Bogey and Bailly [14] to study the effect of Reynolds number ($1.7 \times 10^3 \leqslant Re_D \leqslant 4 \times 10^5$). In their LES simulations, the influence of the Reynolds number on the jet development was investigated by keeping identical initial conditions (shear-layer thickness, inflow forcing), except for the jet diameter. Based on the vorticity contours, a transitional zone was located immediately after the potential core. In the transitional zone, a large range of scales was observed at a higher $Re_D = 4 \times 10^5$, whereas at $Re_D = 1.7 \times 10^3$, the fine turbulent scales were rarely present. Further, as Reynolds number increases, the generation of the vortical structures in the shear layer was found to occur closer to the nozzle.

Flow characteristics of square jets have been studied by Grinstein et al. [15], Grinstein and DeVore [16], Quinn and Militzer [17], Sankar et al. [18], Tsuchiya et al. [19] and more recently by Ghasemi et al. [21] using numerical simulations and experiments. It is well established that the fundamental difference between square and round jets lies in the initial vortex structures. In square jets, the presence of sharp corners deforms the vortex structures which break down into smaller scales. The process of vortex self-induction initiates a complex interaction between azimuthal and streamwise vorticity leading to the axis-switching phenomenon [20]. Axis-switching is believed to be responsible for the higher entrainment [8] and enhanced mixing in square jets compared to round jets.

In the case of square jets, very few studies provide data for the effect of the Reynolds number on the flow and entrainment characteristics. Ai et al. [22] performed planar laser induced fluorescence measurements to study starting square jets at three different Reynolds numbers Re_D = 2360, 3560 and 4716. At these flow conditions, the jets do not go through the mixing transition as discussed by Dimotakis [9].

Recently, Xu et al. [23] studied the Reynolds number effect in a jet issuing from a long square pipe. The main difference between jets emanating from a long pipe and from a smooth contraction nozzle is the presence of secondary flows. In the case of a jet from a long pipe, the secondary flows change the flow features in the near exit of the jet, which eliminates the potential core region. In addition to the secondary flows, presence of the thick shear layer at the exit of the long pipe eliminates the axis-switching mechanism. The mixing transition at Re_D > 30,000 was reported by examining the centerline velocity decay rate, centerline streamwise turbulence intensity and spectra. The critical Reynolds number reported in [23] was $Re_D \sim$ 30,000 which is higher than the critical Reynolds numbers reported by Dimotakis [9], Ricou and Spalding [10] and Fellouah et al. [12].

All of the studies discussed above indicate the need to further research on the effect of the Reynolds number on flow characteristics of square jets. Of particular interest is the influence of the near-field turbulence on the downstream development of the jet. In this paper, flow and turbulence statistics in the near-field of a square jet that emanates from a smooth square contraction nozzle is