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On the Influence of Initial Conditions on a Turbulent Plane Jet

– The Role of Nozzle Exit Area –

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Abstract

The dependence of statistical flow properties of a turbulent plane jet on the nozzle-exit area was investigated experimentally. Jet flows from three plane nozzles were measured using hot wire anemometry at an identical Reynolds number ($Re = U_{co}\ H\ /\ \nu$) of 9,000 and nozzle aspect ratio of 36, but with nozzle-exit areas of A = 900 mm^2, 3600 mm^2 and 14400 mm^2, whereby $U_{o,c}$ was the mean exit velocity, ν was the kinematic viscosity of air, and H was the slot opening width. Results demonstrated a longer potential core and a higher decay rate for the case with a larger nozzle-exit area. The centerline turbulence intensity (u^*) showed a strong dependence on A in the near field but this dependence weakened progressively as the jet propagated downstream. The jet flow from the nozzle with a larger exit area produced a relatively higher near field turbulence intensity, indicating a significant dependence of near field vortical structures on the nozzle-exit area. The centerline turbulence intensity profiles became self-similar, collapsing on a single curve only for $x/H \geq 10$. Overall, the dependence of the mean and turbulent velocity field on nozzle-exit area was significant, confirming the influence of initial and boundary conditions.

Introduction

Turbulent plane jets have received significant research attention since Schlichting [1]. One reason for this was because of their two-dimensional nature. This offers great advantages in reducing time consumption in numerical modelling, applications in areas of heat and mass transfer, air curtain designs and ventilation or air-conditioning systems [2, 3]. In laboratory experiments, a plane jet is produced by a slender rectangular slot of dimensions $w \times H$, where $w \geq H$. The plane nozzle is supported by two parallel plates known as sidewalls, attached to the slot's short sides [4]. This configuration ensures the mean jet propagation in streamwise (x) direction, spreading in lateral (y) direction and negligible entrainment in the span wise (z) direction. Hence the nozzle produces a statistically 2-D jet over a reasonably large downstream distance which is precisely governed by the nozzle aspect ratio, AR = w/H [5].

Published literature demonstrates that a smoothly contoured plane nozzle produce a ‘‘top-hat’’ mean velocity profile and a laminar flow state at the nozzle exit while a sharp-edged orifice-plate produces saddle-backed velocity profile [5, 6]. Although the impacts of initial conditions on downstream flows are becoming well-known [5-9], there are limited studies which have investigated jets from plane jet nozzles of different geometry in identical flow facilities. To address this need, this article reports statistical behaviour of a turbulent plane jet of different nozzle-exit areas, where $A = w \times H$.

Mi et al. [6] found the highest mean scalar decay and highest frequency of primary vortex formation from a sharp-edged orifice-plate followed by a smoothly contoured nozzle and the lowest for a pipe-jet. Antonia and Zhao [10] and Hussain and Zedan [11] investigated smoothly contracting axisymmetric nozzles and pipe-jets, and arrived at similar conclusions. Mi et al. [12] measured jet flows from nine nozzle configurations comprising of a smoothly contoured circular, an elliptical, a triangular, a square, a rectangular, a cross-shaped and a star-shaped exit. Their results revealed that, relative to a circular jet, the centerline mean velocity of a non-circular jet decayed more rapidly, implying an increased entrainment of ambient fluid. Hence their investigation found a significant influence of geometric profile on jets from differently configured nozzles.

From measurements in a plane jet, Hussain and Clark [13] found that a jet with an initially laminar boundary layer results in a higher rate of change of mass flux and attains asymptotic state closer to the exit plane. In a similar investigation Chambers et al. [14] found more organized and symmetric large-scale shear-layer structures dominant in a laminar compared to a turbulent jet. Goldschmidt and Bradshaw [15] studied the effect of exit centerline turbulence intensity on flow field of a plane jet, concluding a larger spreading angle for a jet with higher exit turbulence intensity. Hussain [16] noted a dependence of vortex formation frequency on nozzle geometry, while Russ and Strykowski [17] found that, as the boundary layer thickness at the exit plane was increased, vortex shedding/pairing occurred further downstream. Eaton and Johston [18] provided an evidence of the influence of initial boundary layer thickness on downstream development of free shear flows. A study conducted by Ali and Foss [19] found that the geometric design of plane nozzles produces an influence on the discharge properties of submerged plane jets. Hence it is apparent that different nozzle geometries produce different downstream flows but the choice of each configuration often depends on the application.

On the balance of scientific evidence from literature, it becomes clear that the nozzle-exit shape, as well as the geometry has a profound influence on the initial boundary layer characteristics of the jet to such an extent that it produces significant differences in downstream flow properties. In this study, we have measured flows from three plane jets using hot wire anemometry, at the same Reynolds number ($Re = U_{co}H/\nu$) of 9,000, a nozzle aspect ratio (AR) of 36, but with different exit areas of A = 900 mm^2, 3600 mm^2 and 14400 mm^2 respectively. Our aim was to investigate the impact of nozzle-exit areas on otherwise identical plane jets in the same flow facility.

Experimental Details

The experimental set-up has been described in detail elsewhere [4, 5, 7, 20]. The planar nozzle facility consisted of an open circuit wind tunnel with flow straightening elements and a smooth contraction exit, whose dimensions were 720 × 340 mm^2. Attached to the wind tunnel exit was a radially contoured planar nozzle, that consists of two 12-mm thick perspex plates, mounted vertically but with a horizontal gap of width H = 5 mm in the centre, to produce a large aspect ratio radially contoured nozzle (w/H = 36). The contoured radius r =12 mm (r/H = 1.8 which produced a top-hat exit velocity profile). Three nozzle exit area (A) were selected, with A = 900, 3600 and 14400 mm^2 (Table 1). Other initial/boundary conditions were kept constant during the course of the experiment.

Sidewalls were placed in the x-y plane to enhance two-dimensionality. Three-dimensional traverse was used to undertake measurements to accuracy of ± 0.5 mm. The extent of measurements covered $0 \le x/H \le 40$, primarily focussing on the near and transition field flow. A constant temperature anemometer, in conjunction with a PCF-30 data acquisition system was employed to undertake measurements. Before each experiment, the hot wire probe was calibrated in the jet's potential core with a turbulence intensity < 0.5%. The wind tunnel fan was operated at a Reynolds number, Re = 9,000. The instantaneous axial centerline velocity was recorded at a *Nyquist* frequency of 18.4 *Hz*, for duration of 22 s per sample.

w	*H*	*r*	*w/H*	*r/H*	*A*
180	5	9.0	36	1.8	900
360	10	18.0	36	1.8	3600
720	20	36.0	36	1.8	14400

Table 1: The nozzle design parameters used in the present investigation.

Results and Discussion

Figure 1a presents the near field mean velocity (U_c) normalized the exit centreline mean velocity ($U_{o,c}$). It is demonstrated that the length of the jet's potential core (x_p) containing pure jet fluid, and estimated by the maximum axial (x) distance at which $U_c(x) = 0.98U_{o,c}$, is a function of nozzle-exit area, A. Evidently, as A was increased from 900 mm^2 to 14400 mm^2, x_p decreased from 5H to 3H. It is worth mentioning that neither the shape of the exit velocity profiles nor the exit turbulence intensity values changed. Hence the decrease in length of the potential cores with an increase in nozzle-exit area indicate that near field entrainment, and the mixing rate of jet fluid with the ambient is enhanced by increasing the nozzle exit area.

The normalized mean centerline velocity for A = 900, 3600 and 14400 mm^2 are represented by Figure 1b. The profiles changed as nozzle-exit area was varied and became self-similar only when $x/H \ge 10$. The velocity decay rates are well represented by the following relation

$$\left[\frac{U}{U_{co}}\right]^2 = K_U\left[\frac{x}{h}\right] + \frac{x_0}{h} \quad \ldots [1]$$

where U_{co} is the mean centerline velocity at the nozzle exit, and K_U, x_0 are some experimental constants. K_U is usually the nominal measure of the velocity decay rates.

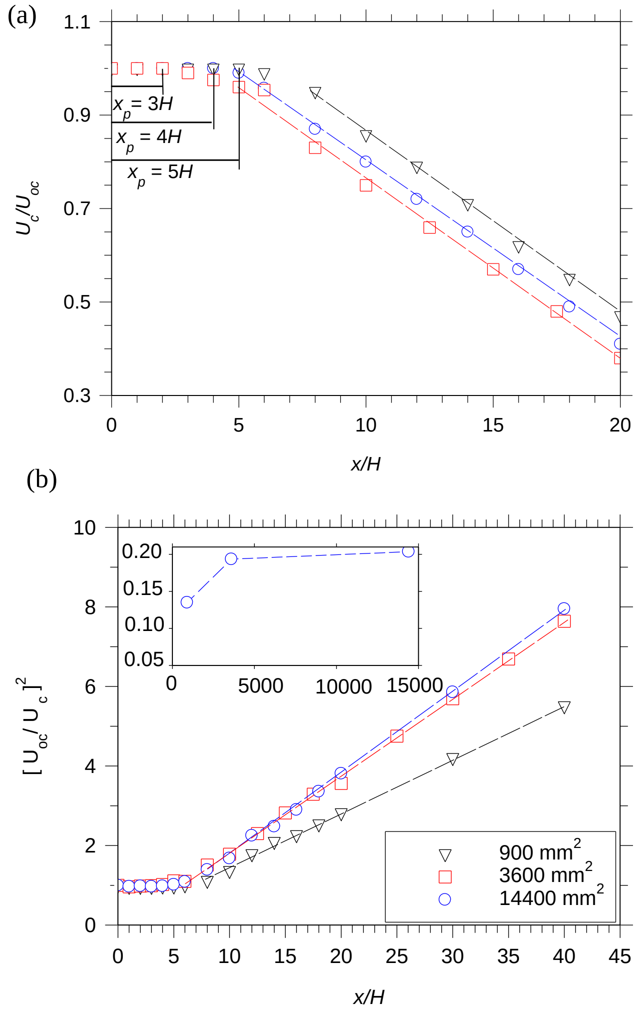

Figure 1: The normalized mean velocity decay (a) in the near field (b) in the far field.

Figure 1(b) demonstrates a strong dependence of K_u on A. It is noticeable that a larger exit area produces a higher decay rate of mean centerline velocity, with numerically similar K_U values for A = 3600 and 14400 mm^2 nozzles. In their work, Malmstrom [8] investigated the effects of nozzle-exit area on K_U for in round jets. Their results also suggested an increase in K_U for larger nozzles. For the present experiment, a larger decay rate with an increase in exit area suggests that there is a feedback of the larger initial entrainment, on the decay of mean velocity. Hence a more rapid far field entrainment of ambient causes the jet to decay faster. This suggests that the nozzle exit area not only affect the near field, but also the far field.

Based on the decay rates of jets of different nozzle exit size, we note that the virtual origins (x_0) take significantly different values. That is, the nozzle with largest exit size has the smallest (most negative) values of x_0. Literature shows a clear dependence of nozzle geometry on jet virtual origins [Gouldin et al. 21]. Flora and Goldschmidt [22] noted that their virtual origin moved upstream with a relatively modest increase in exit turbulence intensity from 1.06% to 1.28%. Similarly, Deo et al. [20] tested nozzle of different-exit geometries and found that an increase in exit turbulence intensity from ~1.7% to 2.3% was associated with a shift in virtual origin from x_0 = 3.9 to 0.4 and x_0 = 4.7 to 2.0. Uddina and Pollard [24] used round and plane jets with coflows to show that x_0 could be dependent on boundary layer thickness. However, their conclusion, that it is unlikely that turbulence intensity played a role in x_o, is at odds with Deo et al. [20] and Flora and Goldschmidt [22]. This is perhaps due to the use of a co-flow which is yet another initial condition imposed on the jet [Gouldin et al. 21]. Nevertheless, their analysis did demonstrate an influence of boundary-layer thickness on x_o which is in agreement with Deo et al. [20].

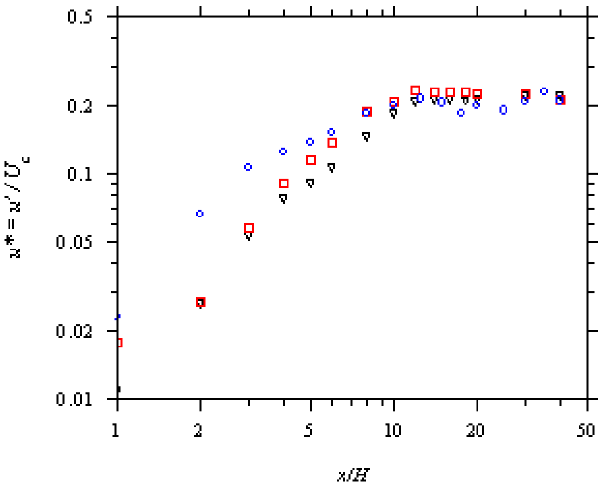

Figure 2: The centerline turbulence intensity field for the three cases. The definitions of the symbols are identical to those in Figure 1.

Our measurements show that nozzle exit size has an influence on the jet's potential core, with an increase in length for a larger nozzle exit area. Our previous measurements [20] showed that an increase in the initial turbulence intensity from ~1.7% to 2.3% was associated with a translation of the virtual origins from x_o/H = 3.9 to 0.4. Clearly, similar observations can be made with the case of nozzle exit size, thus confirming that the flows from configurations of different nozzle exit size are statistically different.

Figure 2 shows the normalized rms $u^* = u_c / U_c$ on the jet centerline. Clear trends are evident, especially in the near field. Between the downstream distances over the range $0 \le x/H \le 10$, larger nozzle exit area leads to relatively higher turbulence intensities. The trend is more visible when A = 14400 mm^2. The increase in turbulence intensities are likely to be linked to the evolving large-scale structures within the shear layers. In these cases, it is possible that the faster acceleration of the vortex cores produce the larger variances of the instantaneous velocity from the mean. The clear distinction between A = 14400 mm^2 and the other two cases are significant to ascertain that relatively large differences in their vortex development exist.

The different shape in the evolution of u* for jets of different nozzle exit size implies differences in the underlying large-scale structures of these jets. The rapid rise in u^* is probably associated with stronger intermittent incursions of low-velocity, predominantly ambient, fluid at these near field locations, causing higher velocity fluctuations relative to the mean values. When $x/H > 10$, the intensities asymptote, and collapse onto a single curve. Their asymptotic values of u^* is around 0.2.

The initial rapid increase of u* is a distinct feature of all plane jets, reflecting the streamwise growth of the shear-layer instability [25] due to the large-scale structures, perhaps similar to those evidenced from the plane jet flow visualizations of Gordeyev and Thomas [25] and Shlien and Hussain [26]. It is these large-scale structures which are responsible for large-scale engulfment of the ambient fluid, higher velocity fluctuations and higher decay of mean velocity, and thus high turbulence intensity. It can be also deduced from previous work that the far-field flow is influenced by propagation of these structures [27], and the dominance of large-scale structures diminish as it convects further downstream due to the generation of a broader range of smaller eddies.

Conclusions

The present work has shown that the centerline velocity field is sensitive to nozzle exit area, with a larger area producing faster decay of mean velocity both in the near and far field. The dependence on turbulence intensity is also significant, suggesting that large-scale structures develop differently when the exit area is varied. Even though the initial velocity profiles (not shown here) were similar for the three nozzle cases, mean and the turbulence fields are different. This suggests that the change in nozzle area affects the development of the shear-layer characteristics. The potential core lengths were also found to be dependent on the nozzle exit area.

The results of present investigation together with the analytical hypothesis of George [9], experimental work of George and Davidson [28] and recent measurements of Deo [4] confirm that the downstream development of any plane jet is dependent upon its exit boundary (in this case the nozzle exit area) and the upstream conditions such as initial turbulence intensity. In other words, even in the fully-developed state, a plane jet does not 'forget' its origin. Therefore, the classical theory, which argues that all jets should become asymptotically independent of source conditions and that the jet properties will depend only on the rate at which momentum is added and the distance from its source, is not valid for a plane jet.

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