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Experimental Investigations of the Effect of Reynolds Number on a Plane Jet

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Abstract

The effect of Reynolds number, $\mathrm{Re} = U_{o,c}H/\mu$, where $U_{o,c}$ is the nozzle exit centreline velocity, H is the slot-opening width and n is the kinematic viscosity of air) on the velocity field of a turbulent plane jet from a radially contoured nozzle of aspect ratio 60 is investigated. Measurements are conducted using a single wire anemometer over an axial distance of 160*h*. The Reynolds number is varied between 1,500 and 16,500. Results show that the Re affects various flow properties such as the velocity decay rate, half-width and turbulence intensity. The significant dependence on Re of the mean flow field persists till Re = 16,500, while the Re effect on the turbulent properties becomes weaker above Re = 10,000. The present investigation also suggests that an increase in Re leads to a higher rate of mixing in the near field but a lower rate in the far field.

Introduction

A true plane jet issues from a rectangular nozzle of high aspect ratio, *w/H* (where *w* is the short side and *H* is the long side of the rectangular nozzle). The jet is confined within two parallel side walls, attached to the short sides of the nozzle. This configuration enables the jet to spread in the lateral (*y*) direction only. Some applications of a plane jet include engineering environments, e.g. in propulsion units and lift-producing devices, Quinn [1], air curtains and some combustion applications.

It is well established experimentally that, at sufficiently high Reynolds number, the normalized mean velocity profiles and the spreading rates of a round jet are almost independent of Reynolds number (Panchapakesan and Lumley [1], Hussain et al. [3]). The visualizations of Mungal and Hollingsworth [4] for their jet at very high Reynolds number (Re ~ 2 × 10^8) showed that its spreading rates and normalized mean velocity profiles are close to those of a laminar jet. In contrast, at low Reynolds numbers, both the mean and turbulent flow fields depend significantly on Re. This is evident, from Oosthuizen [5] for round jet, measured at moderate Re. Likewise, both Lemieux and Oosthuizen [6] and Namar and Otugen [7], studied the effect of Reynolds number in a plane free jet, over the Re ranges of 700 – 4200 and 1000 – 7000, revealed that Re influenced the entire mixing field.

When Lofdahl et al. [8] investigated a plane wall jet, they found the jet spreading rates to remain variable even up to Re = 20,000. An investigation by Stanley et al [9] and Klein et al [10] at Re = 3,000 and Re ~ 6,000, respectively, was conducted only in the near and transition fields (*x/H* ≤ 15 and *x/H* ≤ 20) even though Klein et al [10] claimed they covered the far field.

Clearly, wide range of different conditions makes it impossible to isolate the effect of Reynolds number from that of other variables. Hence conclusive quantitative data describing the Re dependence of a plane jet is not available. To address this issue, we have carried out an experimental investigation into a plane jet at Re between 1,500 and Re = 16,500, using a radial contraction nozzle with aspect ratio of *w/H* = 60, bounded by side walls, over a wider Re-range, and flow region up to *x/H* = 160.

Experimental Details

The overall jet facility, shown in Figure 1, has been described in detail in Deo [11].

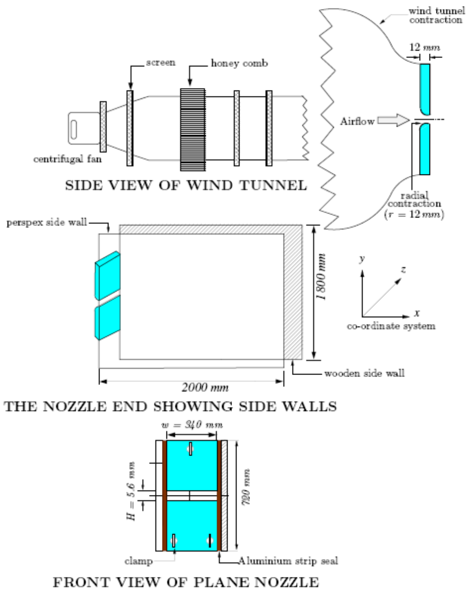

Figure 1: Schematic diagrams of the plane jet facility, showing the wind tunnel, plane nozzle arrangement and side-walls.

The present plane nozzle is referred to as a radial contraction nozzle *r/H* ≈ 2.14, where *r* is the nozzle exit radius), to differentiate it from the smooth contraction nozzles used in most previous investigations (e.g. Gutmark and Wyngnanski [11], Namar and Otugen [7], Bradbury [13] and Antonia et al [14]). For a comprehensive description of the radially contoured nozzle, see Deo [11] and Deo et al [15]. A constant temperature hot-wire anemometer (CTA) was employed to undertake measurements. A copper plated tungsten single hot wire probe, length l_w ~ 1 mm and diameter d_w ~ 5 μm was mounted parallel to the *z*-axis of the traverse. Hot wire calibration was performed in the jet potential core (turbulence intensity ~ 0.5%. Control of the jet Reynolds number, $\mathrm{Re} = U_{o,c}H/\mu$, was achieved by varying the speed of the wind tunnel fan. The maximum achievable Reynolds number was 16,500, without reducing the nozzle aspect ratio. The range of Reynolds numbers was selected to be 1,500 ≤ Re ≤ 16,500. The extent of measurements along the axial direction was 0 ≤ *x/H* ≤ 160, to include the near, transition and far fields.

Results and Discussion

Figure 2 shows the normalized profiles of mean velocity and turbulence intensity obtained at x ≈ 0.5H for Re = 3,000, 10,000 and 16,500.

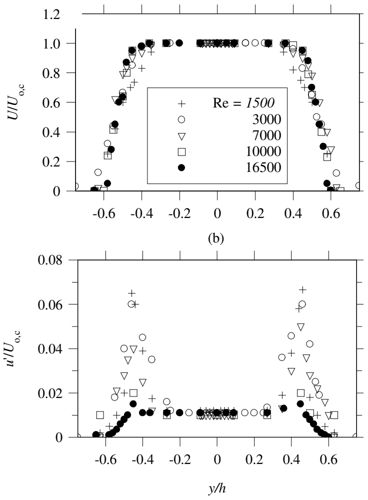

Figure 2: Lateral profiles of (a) normalized mean velocity and (b) turbulence intensity obtained at $x/H \approx 0.5$.

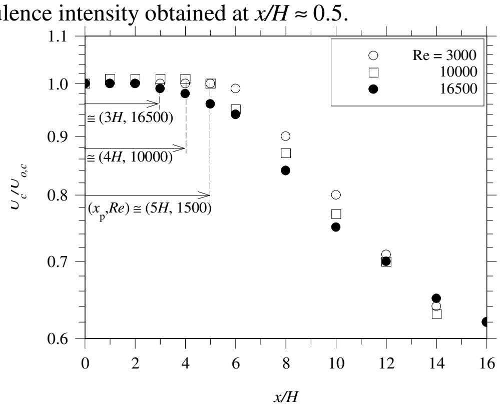

Figure 3 The near-field mean velocity variation along the centerline and potential core length for different Re.

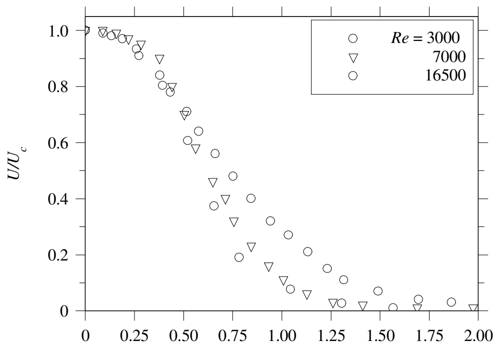

Figure 4: Lateral profiles of U/U_c at $x/H = 5$.

A dependence of the normalized exit velocity and turbulence intensity profiles on Re is noticeable. However, they become nearly identical when Re ≈ 10,000. Dependence of exit velocity profiles on Re were also noted by Namar and Otugen [7] for their `plane' jet without side walls, however, their velocity profiles did not become identical even at Re = 7,000. The present turbulence intensities in the central region ($|y/H| \leq 0.3$ - 0.4) are below 1.0% for all Re. The peak values of turbulence intensity occur in the mixing layers and their magnitudes decrease as Reynolds number increases. Furthermore, over the range $|y/H| \leq 0.30$ - 0.4, the mean velocity is uniform (i.e. $U/U_{o,c} \sim 1$), indicating that the present radial contraction nozzle can produce a similar exit velocity profile to that from the conventional smooth contraction nozzle.

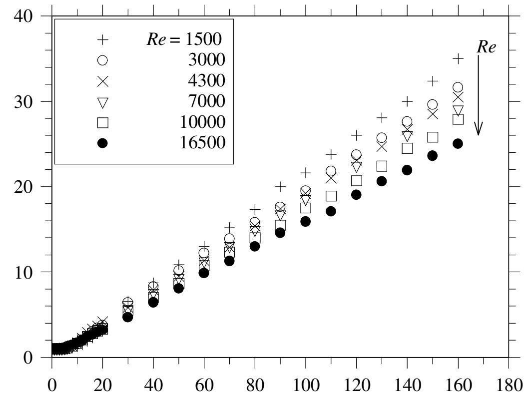

Figure 5: Centerline variation of the mean velocity decay.

Figure 3 presents the near-field mean velocity along the centerline. As demonstrated, the length (x_p) of the potential core, where the mean velocity is approximately constant and equal to $U_{o,c}$ is a function of Re. For example, $x_p/H \approx 5$ for Re = 3,000 and $x_p/H \approx 3$ for Re = 16,500. Namely, x_p/H decreases with Re. Correspondingly, the jet spreads more rapidly for higher Re, which is verified by lateral profiles of U/U_c in Figure 4. These together imply that the relative entrainment, thus mixing, of the jet is enhanced by increasing the Re in the near field.

Investigation	Re	Decay		Spread	
		K_u	x_{01}/H	K_y	x_{02}/H
Jenkins & Goldschmidt [17]	14000	0.160	0.40	0.093	-8.20
Hitchman et al. [16]	7000	0.147	8.05	0.108	-1.94
Browne et al. [18]	7700	0.147	8.05	0.112	-1.94
Gutmark & Wyngnanski [12]	30000	0.174	-0.7	0.099	-3.21

Table 1: A summary of plane jet decay and spreading of jets with side walls

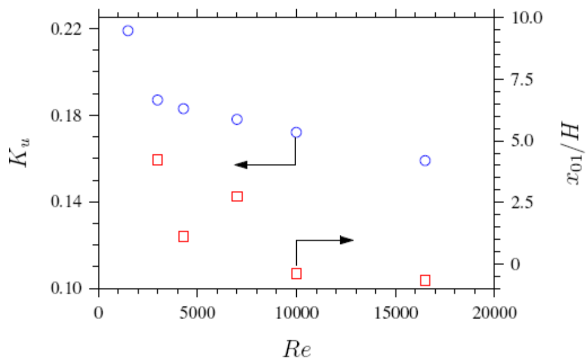

Figure 6: Dependence of K_u and x_{01} on Re_h

The mean velocity decay is shown in Figure 4. The data conform to the well-known inverse square relationship expressed by

$$\left[\frac{U_{o,c}}{U_c}\right]^2 = K_u\left[\frac{x}{H}+\frac{x_{01}}{H}\right]$$

where K_u is the slope and x_{01} is the x-location of the virtual origin of the profiles.

Figure 5 demonstrates that the velocity decay rates for Re_h = 7,000 and 16,500 agree well with Hitchman et al. [16] for Re = 7,000 and Jenkins and Goldschmidt [17] for Re = 14,000, providing confidence in our measurements. Further, the velocity decay rate can be measured by the magnitudes of K_u.

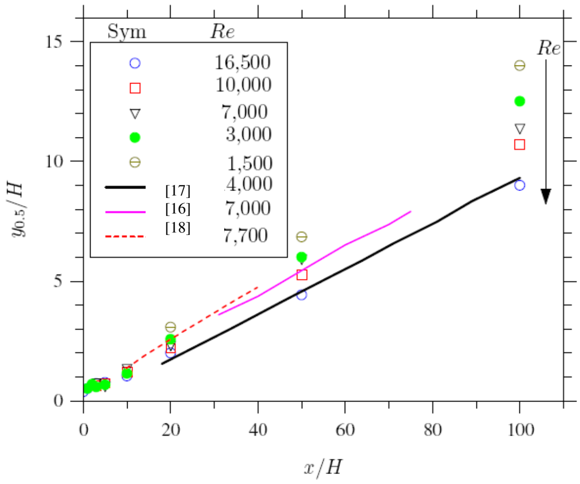

Figure 8: Dependence of K_y on the Re.

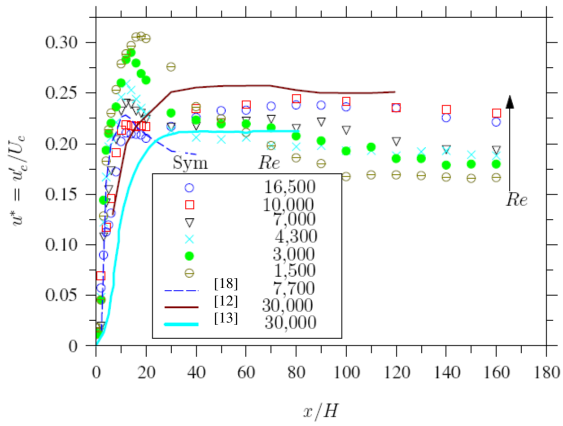

Figure 9: Evolutions of the centerline turbulence intensity.

Figure 6 shows the dependence of K_u on *Re*. As demonstrated, K_u decreases monotonically with an increase in *Re* and that K_u does not approach to an asymptotic value, even at to *Re* = 16,500. This suggests that the Re continues to affect the mean velocity field even at *Re* = 16,500. In addition, it appears from Figure 6 that the virtual origin x_{01} is smaller at higher Reynolds number.

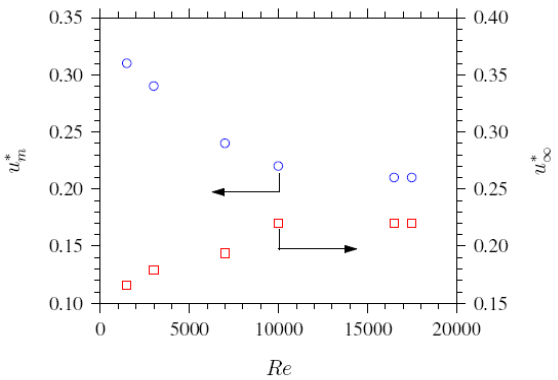

Figure 10: Reynolds number effect on u^*_m and u^*_∞ .

Figure 7 shows the stream wise variations of the velocity half-width $y_{0.5}$ at different Reynolds numbers. Note that $y_{0.5}$ is the lateral distance from the centerline at which the local mean velocity is half the centerline value. The values of $y_{0.5}$ were derived from the lateral velocity measurements (not presented here).

As expected, the data conform to the following far-field relation:

$$\frac{y_{0.5}}{h} = K_y \left[\frac{x}{h} + \frac{x_{02}}{h} \right]$$

where constants K_y and x_{02} are determined by experiments.

When Re changes from 1,500 to 16,500, the half-width spreads out at different rates. This is better illustrated in Figure 8 by the Re-dependence of K_y, a measure of the spreading rate. Clearly, the spreading rate decreases with an increase in *Re* which is consistent with the trend in the decay of U_c (Fig. 5). This together proves that, different from the near-field case, the far-field entrainment rate is reduced by increasing Re.

Figure 9 shows the centerline turbulence intensities (normalized rms, $u^* = u'_c/U_c$) for the different Re values. The development of u^* is similar to that of Browne et al. [13] for a plane jet (w/H = 20 and Re = 7,700). However, the near-field local maximum in the intensity (u^*_m) is slightly different. Their local maximum occurs at x/H = 12 and has a magnitude of 0.23 while ours for Re = 7,000 occurs at x/H = 11 and has a magnitude of 0.24. This difference could be due to the big difference in the aspect ratio (our w/H = 60 versus w/H = 20 in Browne et al. [18]). Thomas and Goldschmidt [19] found yet another value of the maximum for Re = 6,000, which occurs at x/H = 11, with a magnitude of 0.27. The discrepancies observed are likely due to differences in jet initial conditions, consistent with Mi et al. [20], that the occurrence of the pronounced local maximum in scalar intensity of a round jet depends upon exit conditions.

Further, as Re increases from 1,500 to 16,500, the magnitudes of u^*_m decreases from 0.31 to 0.22 (Fig. 10). The values of u^*_m are nearly identical for Re ≥ 10,000. The occurrence of higher u^*_m for lower Re suggests that the underlying large-scale structures are initially more coherent and organized for low Reynolds numbers. In these cases, the intermittent incursion of induced low velocity ambient fluid across the jet produces higher fluctuation amplitudes and lower mean values of the local velocity, and thus higher relative turbulence intensities. When Re is increased, the underlying structures become more three-dimensional and less coherent, and consequently the magnitude of u^*_m is reduced. Figure 10 also indicates that u^* converges to a single curve for Re = 10,000 and 16,500. It appears as well that in both cases u^* reaches an asymptotic value of u^*_∞ = 0.22 at x/H > 60. However, for Re < 10,000, the intensity and its evolution trend are both strongly dependent on the Re. Over 100 ≤ x/H ≤ 160, u^* asymptotes to different values of u^*_∞ for different Re for Re < 10,000, see Fig. 10. Clearly, u^*_∞ increases with increasing Re.

Conclusion

The measurements revealed that Re affect various flow properties (mean velocity decay rate, half-width and turbulence intensity). The dependence on Re of the mean flow field appears to persist at Re = 16,500, while the Re effect on the turbulent properties is eliminated above Re ≈ 10,000. Our measurements also suggest that increasing Re leads the jet to mix its surroundings at a higher rate in the near field but less rapidly in the far field.

Specifically, the findings from present work are as follows.

- Our radially contoured nozzle, of r/H ≈ 2.14, generates a quasi-top hat mean exit velocity profile. The uniform part of the profile widens as the Re increases. For Re ≥ 10,000, the profiles become independent of Re.
- The length of jets' potential core decreases with Re. The jet decay and spread rates downstream of the potential core

decrease with increasing Re, and this trend persists even at Re = 16,500.

- The centerline turbulence intensity shows a local maximum in the near-field. Below Re = 10,000, its magnitude and axial location decrease as Re is increased.

Acknowledgments

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