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An Investigation of the Influence of Nozzle Aspect Ratio on the Velocity Field of Turbulent Plane Jet

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Abstract

The effect of nozzle aspect ratio (w/H) (major axis to minor axis ratio) on the velocity field of a turbulent plane jet is investigated using a hot-wire anemometer. The aspect ratios investigated were in the range $10 \leq w/H \leq 60$. The initial turbulence intensity profiles exhibit a lower intensity at higher aspect ratios although this is probably caused by the nozzle whose profiles change with aspect ratio. The length of the potential core and the normalized mean and rms velocities are all found to be a function of w/H, in both the near and far field. Lower aspect ratio leads to faster decay of the mean velocity. Most investigations on aspect ratio effects have been on rectangular jets, hence this work is unique in its own right. Overall, the dependence of the current plane jet on aspect ratio is quite significant.

Introduction

Plane jets are a class of fundamental turbulent shear flow that have been a subject of research interest mainly due to their relative simplicity. An ideal plane jet is a statistically two-dimensional flow, with a dominant mean flow in the axial (x) direction, jet spread along the lateral (y) direction and zero entrainment in the transverse (z) direction. Side walls, placed in the x-y plane are necessary to achieve this. Plane jets have received much attention, both experimental and modelling investigations.

Plane jets can exhaust from rectangular nozzles, either into the ambience or into a controlled co-flow. While many studies have indicated the importance of initial conditions (jet exit Reynolds number, nozzle aspect ratio, exit velocity profiles, nozzle geometry, presence or absence of co-flow and presence or absence of side walls), very few of these initial conditions have been systematically assessed. Previous work has tested to some degree, the effect of nozzle geometry [1], effect of nozzle exit turbulence on jet spreading [2], effect of presence/absence of sidewalls [3] and effect of jet exit Reynolds number [4, 5, 6] . However, the influence of nozzle aspect ratio for a plane jet has yet to be studied systematically.

Nozzle aspect ratio, w/H, is defined from the exit dimensions of the rectangular nozzle, where w and H are the dimensions of the short and long sides of the nozzle respectively. [7] assessed the influence of slot aspect ratio over the limited range, $3.4 \leq w/H \leq 12$). They used total head tubes and hot-wire anemometry, and suggested that their smallest aspect ratio jet exhibits quite different behavior to the larger aspect ratios. Later, [8] studied the aspect ratio dependence of unconfined rectangular jets between $2 \leq w/H \leq 20$ using hot-wire anemometry. He found that the rate of near field mixing increases with increased three-dimensionality and hence with increasing aspect ratio up to $w/H = 20$. Their work also suggested that the shortest potential core, highest shear layer turbulent kinetic energy, highest Reynolds shear stresses and largest turbulent transport of Reynolds stresses, were found with the largest aspect ratio.

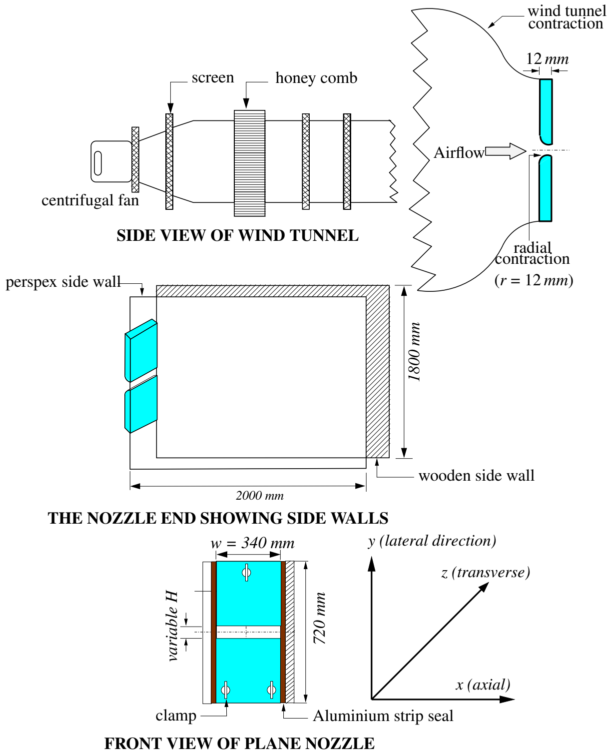

Figure 1: Schematic of the plane jet facility.

Given the distinctions in the velocity field of rectangular jets with different aspect ratios [8, 7], the velocity field of a plane jet may also depend on the aspect ratio. To verify our postulate, a preliminary investigation has been carried out using hot wire anemometry. We have used four aspect ratios for the investigation, which are w/H = 10, 20, 30 and 60. It has been also proposed that the nozzle aspect ratio has to be large - typically 50 to achieve a flow that is statistically 2-dimensional and free from end effects as stated in [9]. However, this hypothesis has not been tested experimentally. For these reasons, the current nozzle was designed to provide higher nozzle aspect ratios than previously studied (i.e. > 20) and also higher than that proposed in [9] (i.e > 50).

Length w (mm)	340	340	340	340
Width H (mm)	34	17	11.33	5.6
Aspect Ratio w/H	10	20	30	60
r/H	0.353	0.706	1.059	2.143
Range of x/H	30	100	100	160

Table 1: Nozzle geometric parameters.

Experimental Details

The plane jet facility, illustrated in Figure 1, is described in detail elsewhere ([4]). Briefly, the nozzle has a 90^o radial contraction machined into two plates of 12 mm thickness ($r = 12$ mm), separated by gap width, H, which is adjusted to allow the variation of the nozzle aspect ratio. Table 1 lists the nozzle geometric parameters and the nozzle aspect ratios selected. The nozzle aspect ratios were selected by studying previous measurements of rectangular jets by [7, 8] who showed that their three-dimensional flows are still show significant differences, even at their highest aspect ratios (i.e. $w/H = 20$).

The plane jet, emerges from the radial contraction shown in Figure 1, into ambient air. Hot-wire anemometry was used to measure the axial (x) centerline and lateral (y) instantaneous velocities. Data were sampled at 18.4 kHz and 400,000 samples, were collected at every axial location. A three-dimensional traversing system, controlled via a tri-axial driven control switch, was mounted below the plane nozzle to enable measurements along all the 3-axes to an accuracy of $\pm$ 0.5 mm in all three directions. The extent of measurements along the axial direction are shown in Table 1 for each aspect ratio. The Reynolds number $Re = U_{co}H/\nu$, where H is the nozzle slot opening, U_{co} the jet exit velocity on the centerline and ν the kinematic viscosity of air, was about 1.65×10^4.

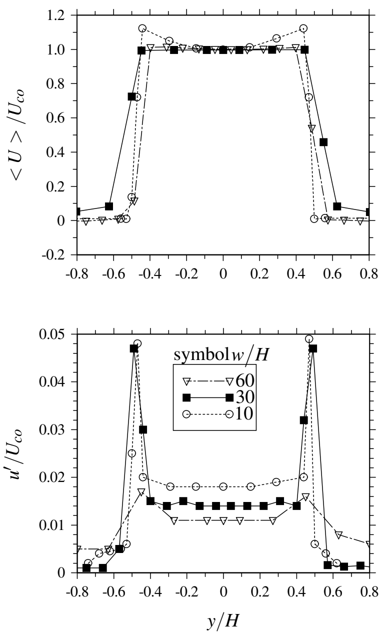

Figure 2: The normalized mean velocity profiles (top) and turbulence intensity fields (bottom), at different nozzle aspect ratios, at the nozzle exit plane.

Results

Figure 2(top) presents the normalized initial velocity and turbulence intensity profiles, measured at $x/H \approx 0.5$, for the nozzle aspect ratios, w/H = 10, 30 and 60. Here, $< U >$ is the mean velocity and u' is the rms velocity. The mean profiles are *top-hat* for w/H = 30 and 60, and *saddle-backed* for w/H = 10. The top-hat profiles are typical of that from a smooth-contraction nozzle (e.g. [5], [1]) while the saddle-backed profile is a characteristic of a sharp-edged orifice type nozzle (e.g. [8]). The mean profile is uniform ($< U > /U_o \approx 1$) over the range -0.46 $\leq y/H \leq$ 0.46 for w/H = 30 and over the range -0.4 $\leq y/H \leq$ 0.4 for w/H = 60. The figure shows that the initial velocity profiles also change with aspect ratio because r/H changes with w/H. The saddle-backed profiles for w/H = 10 are caused by the relatively small radius of the exit plates i.e. r/H = 0.353, because in this case, the nozzle tends to be of an orifice type.

The normalized initial turbulence intensity profiles (Figure 2 (bottom)) also show a significant variation on nozzle aspect ratio and r/H. Again, the central region has a nearly uniform turbulence intensity, ranging from 1 % to 1.8 %. It is evident that the initial turbulence intensity is lower ($\approx$ 1 %) for w/H = 60 and higher ($\approx$ 1.8 %) for w/H = 10. The shear layers show peak turbulence intensities, which is the largest for w/H = 10 and smallest for w/H = 60. Reduced central region and shear layer intensities are lower at higher aspect ratios, possibly due to reduced near field mixing (as shown later) for these case. Less interactive activity of the jet keeps the turbulence levels low. The dependence of the initial turbulence intensity on the nozzle aspect ratio suggests that this parameter is likely to influence both the near and far field characteristics of the plane jet flow. Hence the present assessment of the effect of aspect ratio is somewhat complicated by a secondary influence of the effect of different initial conditions.

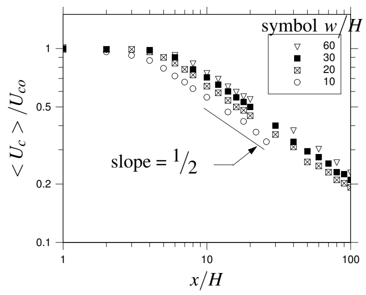

Figure 3: Evolution of the normalized mean streamwise velocity decay on the jet centerline, measured at different nozzle aspect ratios.

Figure 3 shows the normalized centerline velocity decay at various aspect ratios. (Note that $< U_c >$ is the mean velocity on the jet centerline). The plot reveals some interesting features. A strong dependence of the velocity decay on aspect ratio is evident. The length of potential core increases with the aspect ratio, even at w/H as high as 60. An opposite dependence was noted by [8] and [7] for their three-dimensional rectangular jet. The discrepancy is most likely to be an effect of nozzle type, rectangular for theirs verses planar for ours. However, their dependence suggests that current variations are not solely due to the different r/H, since this parameter was constant in their experiments. Potential core lengths have also been assessed for plane jets, but only at relatively low Reynolds numbers and for single aspect ratios. [10] studied plane jet at Re = 4200, w/H = 5.8, [1] at Re = 32,550, 61,400 and w/H = 44 and [5] at 1,000 $\leq Re \leq$ 7,000, w/H = 44. These investigators presented near field data of centerline velocity decay which shows the length of the potential core. Table 2 compares the potential core lengths obtained in past and present measurements. Overall, the measurements in the literature compare well with current findings, although there are some interesting differences, especially between those of rectangular jet investigations and plane jets. The trends of the unconfined rectangular jets in [8] are opposite to those for the present plane jet, with him measuring a decrease in potential core length with increasing aspect ratio.

The far field centerline velocity decay exhibits the usual inverse-square relationship for a plane jet

$$\left[\frac{U_{co}}{\langle U_c \rangle}\right]^2 = K_u \left[\frac{x}{H}\right] + \frac{x_o}{H} \quad (1)$$

where K_u and x_o are constants determined by experiments. The values of the K_u are used to compare the effect of aspect ratio on the far field flow (Table 2). It is evident that the decay rate varies significantly with the nozzle aspect ratio. The highest decay is found for w/H = 10 (with largest value of K_u) and the lowest for w/H = 60 (with smallest K_u). The general trends of the centerline decay are presented in Figure 4.

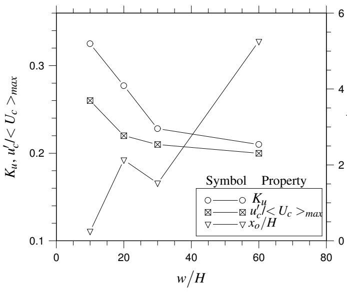

Figure 4: The dependence of some flow parameters on nozzle aspect ratio.

It is evident that the dependence of K_u on aspect ratio seems to be asymptotic as expected, with the difference at w/H = 30 and w/H = 60 being small. However, the present results are different to the measurements of [8], who did not use side walls. For example K_u = 0.277 at w/H = 20 for the present jet at while for his results K_u = 0.240 at w/H = 20. Similarly, K_u = 0.325 at w/H = 10 for plane jet at while for his results K_u = 0.220 at w/H = 10. This is probably attributable to the difference between rectangular and plane jets although a difference in Reynolds number may also play a small role. The results of [11] for w/H = 20 and Re = 7,700 for their smooth contraction plane nozzle show a lower decay rate at the same aspect ratio. This difference is probably due to the combined effect of lower Reynolds number and a different shaped radial contraction nozzle as stipulated in [4]. A similar explanation can be offered for the discrepancy in K_u for [5] and [1]. The results of [12] are consistently higher than those of current measurements for their plane jet at w/H = 120 and Re = 34,000. This is consistent with a sharp-edged orifice, having a higher rate of decay than a smooth contraction. Overall, the constant, K_u in the measured range of w/H compares better with [8] and [12] for their orifice type nozzles rather than the smooth contraction nozzles of [5], [11] or [1]. This implies that our initial conditions are similar to that of a orifice type nozzle rather than a smooth contraction, even though the current nozzle is radially contoured. The dependence of the virtual origin x_o/H is clearly demonstrated in Figure 4. The figure also shows that x_o/H is not asymptotic even at w/H = 60, suggesting aspect ratio effect still dominates even at aspect ratio as high as 60. The dependence of centerline velocity decay rate K_u on the exit turbulence intensities cannot be conclusively evaluated from the current data, due to the combined influence of both r/H and w/H. However, the currently observed higher turbulence intensities correlate well with the corresponding higher decay rates, at smaller aspect ratios and vice versa for higher aspect ratios. This agrees totally with [2], who also observed faster decay and spreading rates when exit intensities were larger.
1

INVESTIGATION			PROPERTIES		
author(s)	Re_H $\times 10^3$	w/H	x_p $\times H$	K_u	$u_c'/ < U_c >$ max
current	16.5	10	2.0	0.33	0.26
	16.5	20	3.0	0.28	0.22
	16.5	30	4.0	0.23	0.21
	16.5	60	5.0	0.20	0.20
[8]	36.7	5	4.0	0.20	0.15
[8]	36.7	10	3.1	0.22	0.17
[8]	36.7	20	2.6	0.24	0.20
[11]	7.70	20	3.0	0.14	0.23
[5]	7.00	44	2.0	0.18	0.22
[1]	32.5	44	4.0	0.11	0.17
[12]	34.0	132	N/M	0.27	N/M

Table 2: Summary of current and literature work.[1]

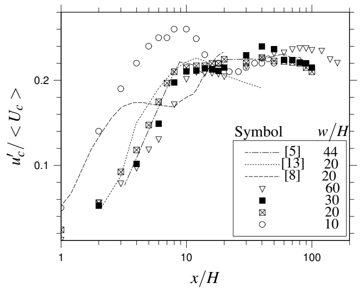

Figure 5: The axial centerline normalized rms at different nozzle aspect ratios.

Figure 5 shows the axial centerline normalized rms velocity. Clear trends are evident - the lowest aspect ratio jet (w/H = 10) shows a dramatic transition in the rms in the immediate near field when compared with the higher aspect ratios. This is quite unexpected because the effect of nozzle aspect ratio is thought to be small in the near field and only to be significant in the transition and far fields. It is not possible to isolate the effects of initial conditions (Figure 2) and aspect ratio from the present data alone, and more data is required to determine whether this is a genuine effect of the aspect ratio. It is possible that both are contributing to the near field effect. The value of r/H (stated in Table 1) are quite small and this suggests that the flow emerging from the smallest aspect ratio nozzle is more like an orifice type plane nozzle rather than a smooth contraction nozzle. This makes the lowest aspect ratio jet quite different in the initial field, hence the rms are different in the near field. At x/H = 10, there are distinct peaks in the rms for all aspect ratios, with the highest aspect ratio having the smallest peak value. For verification, the peak values in rms at x/H = 10 are listed Table 2 and also plotted in Figure 4. It is observable that the peak values in rms also seem to approach an asymptotic value at higher aspect ratios. It means that the rms is approaching its self-similar state faster when nozzle aspect ratio are larger, which is quite expected. The occurrence of a bigger peak for w/H = 10 shows that the large-scale vortices are more coherent and organized than for w/H = 60 for which

[1] Jet types - [8] rectangular jet sharp-edged orifice exit, [11] plane jet smooth contraction exit, [5] rectangular jet smooth contraction exit, [1] rectangular jet smooth contraction exit and [12] plane jet sharp-edged orifice exit

the near field peak is reduced.

Initial conditions are not expected to have a significant influence on the far field values of normalized rms. However, according to Figure 5, differences seem to persist even at $x/H > 10$. This means that the nozzle aspect ratio effect is maintained, even in the far field.

Conclusions

A preliminary study has been carried out, to assess the effect of aspect ratio on a plane jet. The variation of w/H was achieved by varying the gap between two radially curved plates, which also cause a change in r/H, hence some changes in the initial conditions. At this point, it is not possible to separate the two influences, but the effects are significant enough to provide indicative trends of the effect of aspect ratio. Key results are:

1. It has been found that the normalized initial velocity profiles and turbulence intensity profiles are different when varying w/H. This, however, could be a direct effect of varying r/H for the nozzles rather than an influence of the aspect ratio. The normalized turbulence intensities in the central region (i.e. $|y/H| \approx 0.5$) are 1 % for $w/H = 60$ and increased up to 1.8 % when $w/H = 10$.

2. The length of the jet potential core is smaller at lower nozzle aspect ratio. This suggests that the rate at which ambient fluid is drawn into the jet (i.e. the mixing rate) in the near field, is greater when the nozzle has a smaller aspect ratio.

3. The rate of centerline velocity decay decreases with increasing aspect ratio. For example, for $w/H = 10$, $K_u = 0.325$ but for $w/H = 60$, K_u decreases to 0.2. An aspect ratio dependence of the jet virtual origin, x_o/H has also been noted.

4. The centerline normalized rms are also sensitive to aspect ratio. In the near field, peak rms is found at $x/H = 10$, indicating a maximum deviation of the instantaneous centerline velocity from the mean. This means higher instabilities are likely to be caused by smaller nozzle aspect ratio in the near field. This is consistent with the above finding that rapid mixing in the near field occurs for lowest aspect ratio jet, hence faster engulfment of the ambient fluid into the jet causes biggest fluctuations of the instantaneous signal from its mean. It is also possible that a faster acceleration of large-scale coherent vortices occur at this location. In the far field, the normalized rms have not become asymptotic at the current range of measurements, although they approach it. The absolute magnitude also different.

The present findings are not conclusive because of the combined influences at different initial conditions (r/H) and aspect ratio (w/H). Nevertheless, the influences are of sufficient magnitude to warrant a more complete investigation where aspect ratio is varied for fixed initial conditions. Both, independent investigations on, r/H and w/H are now complete and the preliminary assessment of results suggest that the influence of r/H is even greater than w/H. Full documentation of the independent investigation on aspect ratio dependence, will be presented in near future.

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References

[1] Hussain A K M F and Clark A R . Upstream influence on the near field of a planar turbulent jet. *Phys. Fluids*, **20** (9):1100-1112, 1977.

[2] Goldschmidth V W and Bradshaw P . Effect of nozzle exit turbulence on the spreading (or widening) rate of plane free jets. In Proc. *Joint Eng., Fluid Eng. and Appl. Mech. Conference*, ASME, 1–7, Boulder, Colarado, June 22-24 1981.

[3] Hitchman G J , Strong A B , Slawson P R , and Ray G . Turbulent planar jet with and without confining walls. *AIAA J.*, **28**(10):1699-1700, 1990.

[4] Deo R C , Mi J , and Nathan G J . An investigation of the effects of reynolds number on a turbulent plane jet. *J. Turbulence*, Under Review, 2004.

[5] Namar I and Ötügen M V . Velocity measurements in a planar turbulent air jet at moderate reynolds numbers. *Exp. Fluids*, **6**:387–399, 1988.

[6] Löfdahl L , H Abrahamsson , B Johansson , and T Hadzianagnostakis . On the reynolds number dependence of a plane two-dimensional wall-jet. *Doktorsavhandlingar vid Chalmers Tekniska Hogskol*, **1292**:8pp, 1997.

[7] Marsters G F and Fotheringham J . The influence of aspect ratio on incompressible turbulent flows from rectangular slots. *Aeronaut. Quart*, XXXI, **4**:285–305, 1980.

[8] Quinn W R . Turbulent free jet flows issueing from sharp-edged rectangular slots: The influence of slot aspect ratio. *Exp. Thermal. Fluid Sc.*, **5**:203–215, 1992.

[9] Pope S B . *Turbulent Flows*. Cambrige University Press, UK, 2002.

[10] Lemieux G P and Oosthuizen P H . Experimental study of behaviour of planar turbulent jets at low reynolds numbers. *AIAA J.*, **23**(12):1845-1846, 1985.

[11] Brown L W B , Antonia R A , and Chambers A J . The interaction region of a turbulent planar jet. *J. Fluid Mech.*, **149**:355–373, 1984.

[12] Heskestad G . Hot-wire measurements in a plane turbulent jet. *Trans. ASME, J. Appl. Mech.*, **32**:721-734, 1965.

[13] Brown L W B , Antonia R A , Rajagopalan S , and Chambers A J . Structure of complex turbulent shear flows. In Proc. *IUTAM Symposium*, 411–419, Marcseille, 1982.