Experiments in Fluids 28 (2000) 93–94 © Springer-Verlag 2000

Centreline mixing characteristics of jets from nine differently shaped nozzles

J. Mi, G. J. Nathan, R. E. Luxton

Abstract The centreline mixing characteristics of jets from nozzles with nine different cross-sectional shapes are compared. It is shown that the breakdown of axisymmetry of the initial jet configuration generally results in increased mean-velocity decay and increased RMS fluctuations.

1 Introduction

Previous studies of jet flows related predominantly to those from circular nozzles. Recently, attention to three-dimensional non-circular jets has risen significantly, due to their potential to provide increased mixing rates relative to the circular jet (see, e.g., Ho and Gutmark 1987; Gutmark et al. 1989; Hussain and Husain 1989; Quinn 1989; Miller et al. 1985). However, these previous investigations do not allow proper comparison of the turbulent mixing characteristics of different non-circular jets for three reasons. First, no previous study has examined a wide range of different nozzle shapes. Second, the jet facilities and measurement techniques employed in different previous studies are different. Third, the mixing characteristics of jets have been shown by Husain and Hussain (1989) and Dowling and Dimotakis (1990), for example, to be apparatus-dependent. To establish the true influence of jet exit shape, we have measured the centreline velocity in nine jets issuing from differently shaped nozzles using identical facilities and nominally identical experimental conditions.

2 Brief description of experiments

The nine nozzle shapes investigated include a smooth circular contraction, used as a reference, and eight differently shaped orifices (Fig. 1). The aspect ratio (AR) for the triangular orifices refers to the ratio of the side length to the base. The corners in the non-circular shapes were rounded to a small radius 1.5 mm, which differs from the sharp corners tested in previous investigations. The Reynolds number (Re_d), based on the exit mean velocity U_{exit} and equivalent diameter D_e (the diameter of an equivalent circular nozzle with the same exit area) is approximately 15000 for all the cases.

In the present measurements, a 5 μm tungsten wire ($\sim$1 mm in length) was used. The wire was operated by an in-house constant temperature circuit at an overheat ratio of 1.7. The wire calibration was done against a standard pitot tube at the exit with low turbulence intensity ($<0.5\%$) from a smooth contraction nozzle.

3 Results

Figures 2(a) and 2(b) show the centreline ratios $U_{\max}/U_{cl}$ and u'_{cl}/U_{cl} for all jets. Here, U_{cl} and u'_{cl} are the centreline mean and RMS of the axial velocity, while $U_{\max}$ denotes the maximum of U_{cl}, which for most of the nozzles occurs downstream from the exit because of the vena contracta. For comparison, also included in Fig. 2(a) are Quinn's (1989) data for three different jets at $Re \approx 200000$. Several observations can be made:

(1) The average length of the jet potential core (L_{pc}) is generally shorter in jets from the non-circular orifices ($L_{pc} \approx 1.0 \sim 3.5D_e$) than in those from the circular orifice ($L_{pc} \approx 4.0D_e$). In particular, $L_{pc} \approx 1.0D_e$ is shortest in the jet with an initial shape of isosceles triangle. Furthermore, when comparing the length L_{pc} from the circular orifice with that from the smooth contraction, a significant reduction is apparent: $L_{pc} \approx 4.0D_e$ (orifice) and $L_{pc} \approx 5.0D_e$ (contraction).

(2) In the near field ($x/D_e < 10$), the decay rate of U_{cl} is greater for each of the non-circular jets than for the circular jet and is greatest of all for the isosceles triangle case. However, when $x/D_e \geqslant 10$, the square, cross- and star-shaped jets have nearly the same decay rate as the circular jet (orifice).

(3) In the intermediate and far-field regions ($x/D_e \geqslant 10$), $U_{\max}/U_{cl}$ asymptotes to a linear dependence on x in all the jets, consistent with previous investigations (e.g. Hussain and Husain 1989; Quinn 1989).

(4) For the same shaped jets, the present data do not match closely with those of Quinn (1989). Clearly, the decay rates of

Received: *23 February 1999*/*Accepted*: *7 May 1999*

J. Mi, G. J. Nathan, R. E. Luxton
Department of Mechanical Engineering
University of Adelaide
SA 5005, Australia

Correspondence to: Dr J. Mi

The support of the Australian Research Council is greatfully acknowledged.

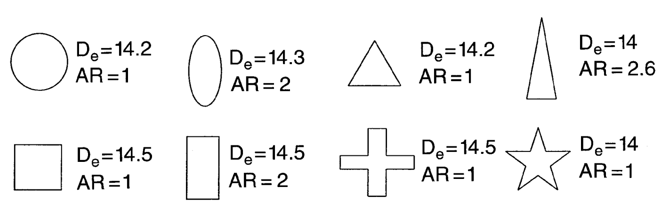

Fig. 1. Different orifice shapes with their equivalent diameter D_e (mm) and aspect ratio AR

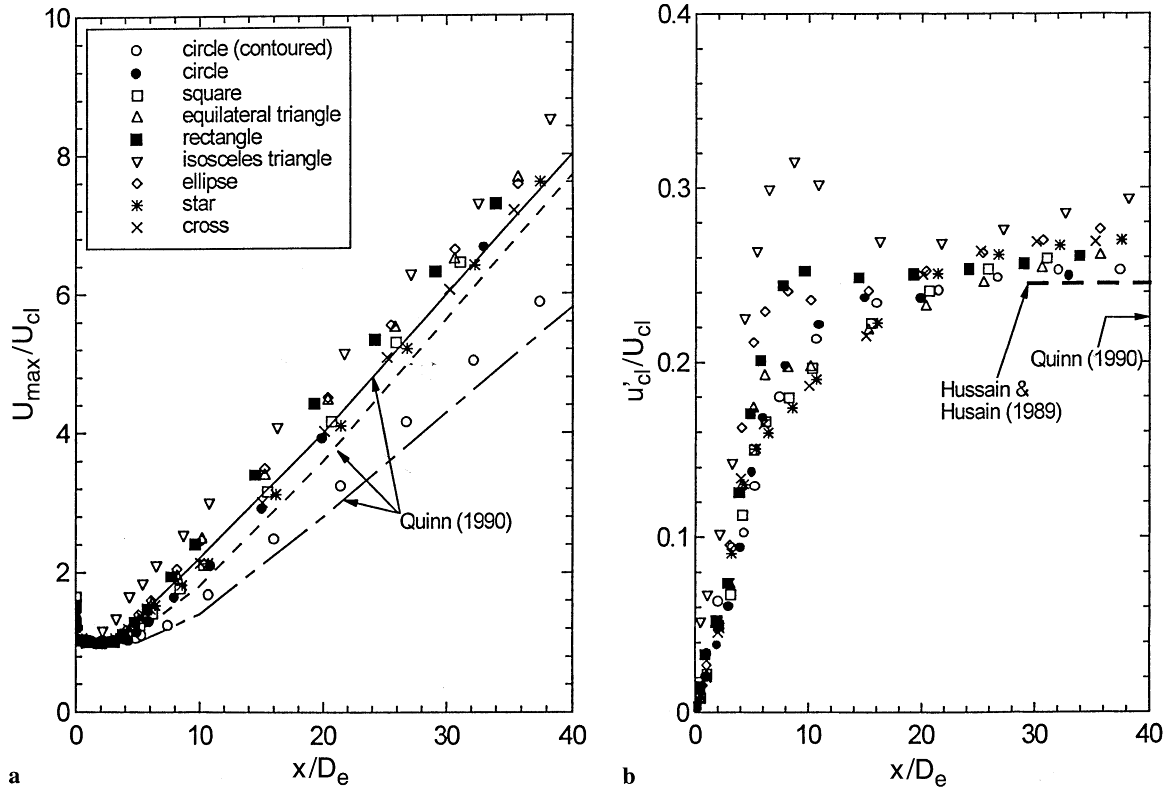

Fig. 2. Centreline variations of U_{max}/U_{cl} and u'_{cl}/U_{cl} in nine different jets. Symbols for present data are indicated on the plots. Quinn (1989): — - —, circular contraction; - - - -, circular orifice; ——, elliptic orifice ($AR=5$)

U_{cl} and the levels of u'_{cl}/U_{cl} are both higher for the present case. This difference may be attributed to the difference in Re_d since Quinn's data were obtained at $Re_d \approx 200000$ which is much higher than the present $Re_d \approx 15000$. This is supported by Malmstrom et al. (1997) who showed that the decay rate of U_{cl} decreases as Re_d increases until a critical value is reached.

(5) While no hump occurs in the near-field variation of u'_{cl}/U_{cl} in the circular, square, cross- and star-shaped jets, a hump is discernible in the data from the elliptic, rectangular and triangular jets. Direct numerical simulations of several non-circular jets ($x/D_e \leqslant 9$) by Miller et al. (1995) have indicated that axis-switching occurs in an elliptic ($AR=2$) jet, a rectangular ($AR=2$) jet and two triangular ($AR=1$, 2) jets, but *not* in a square jet. This phenomenon has also been observed experimentally in the comparable non-circular jets (e.g. Ho and Gutmark 1987; Gutmark et al., 1989; Hussain and Husain 1989). Accordingly, it is postulated that the hump is associated with the axis-switching phenomenon, which does not occur in the square, cross- and star-shaped jets investigated.

4
Conclusions

A comparison has been made of the centreline mean flow and turbulence characteristics in nine differently shaped jets. In general, relative to the circular jet, the centreline mean velocity of the non-circular jets decays more rapidly, implying increased entrainment of ambient fluid. Of particular interest is the jet with an initial shape of an isosceles triangle ($AR=2.6$) which appears to produce the greatest mixing rates among all the jets investigated. Moreover, the square, star- and cross-shaped jets do not promote significant changes in the far-field mixing rates relative to their circular counterpart.

References

Dowling DR; Dimotakis PE (1990) Similarity of the concentration field of gas-phase turbulent jets. J Fluid Mech 218: 109–141

Gutmark E; Schadow KC; Parr TP; Hanson-Parr DM; Wilson KJ (1989) Noncircular jets in combustion systems. Exp Fluids 7: 248–258

Ho CM; Gutmark E (1987) Vortex induction and mass entrainment in a small-aspect-ratio elliptic jet. J Fluid Mech 179: 383–405

Hussain F; Husain HS (1989) Elliptic jets. Part 1. Characteristics of unexcited and excited jets. J Fluid Mech 208: 257–320

Malmström TG; Kirkpatrick AT; Christensen B; Knappmiller KD (1997) centreline velocity decay measurements in low-velocity axisymmetric jets. J Fluid Mech 346: 363–377

Miller RS; Madnia CK; Givi P (1995) Numerical simulation of non-circular jets. Comput Fluids 24: 1–25

Quinn WR (1989) On mixing in an elliptic turbulent free jet. Phys Fluids A1: 1716–1722