J. King Saud Univ., Vol. 6, *Eng. Sci.* (2), pp. 217–240 (A.H. 1414/1994)

MECHANICAL ENGINEERING

Effect of Nozzle Exit Geometry on the Development of Turbulent jets

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(Received 15/6/1991; accepted for publication 13/1/1993)

Abstract. Results are presented for some features of the structure of turbulent free jets issuing from an equilateral triangular nozzle and from a sharp-edged square nozzle with the same cross-sectional area. Comparison is made with a free jet issuing from a circular nozzle having the same area. Measurements cover mean flow parameters, velocity spectra and turbulence level. The results show that, although all jets become axisymmetric farther downstream, their development is substantially different. The development of the asymmetric jets is slower than that of the round jet, with the triangular being the slowest. Low wave-number eddies appear to dominate the flow along lines normal to the flat side of the asymmetric jets in the near field while small scale turbulent eddies are dominant along the vertices of these jets.

Nomenclature

A nozzle exit area

D diameter of circular nozzle

D_{eq} equivalent nozzle diameter; $D_{eq} = \sqrt{4A/\pi}$

D_h hydraulic diameter of nozzle; $D_h = A/\text{perimeter}$

f frequency, Hz

S_{uu} power spectral density of velocity component u

U mean (time averaged) velocity component in x-direction

U_j jet velocity (at the center of nozzle exit)

U_0 mean velocity along the jet centerline

u' fluctuating velocity component in x-direction

x axial coordinate measured from nozzle exit plane and normal to it

y lateral coordinate measured from jet axis and normal to it

$y_{0.5}$ half velocity width; y at the point with $U = 0.5\,U_0$

Introduction

Turbulent jets issuing from noncircular nozzles are important in many engineering applications, particularly in fluidics and thrust augmenting ejectors as well as in combustion chambers. The special features of three dimensional jets have drawn the attention of a number of investigators; however, previous work does not reflect its potential applications. The initial structure and development of such jets are markedly different from those issuing from axisymmetric nozzles. Hussain and Husain [1] studied experimentally incompressible elliptic jets of different aspect ratios. They pointed out that elliptic jets are quite different from plane and circular jets, owing mainly to the fact that the azimuthal curvature variation of a vortical structure causes its non-uniform self-induction and hence complex three-dimensional deformation. This deformation alters entrainment and other turbulence phenomena.

Sforza *et al.* [2] and Tsuchiya *et al.* [3] in their studies of three dimensional rectangular jets have shown that the flow field may be subdivided into three main regions which are a potential core region followed by a characteristic decay region and an axisymmetric decay region. They have also found that the flow field near the jet exit has a saddle-back velocity profile only on the spanwise axis, so that three dimensionality must be taken into account in this region. Koshigoe *et al.* [4] studied the flow field of an equilateral triangular jet and gave some results for spatial instability waves. They found that there is a large amplifiction rate of disturbances at the flat side compared with that at the vertex. In a later work [5], they tested two different triangular jets, one had a triangular orifice nozzle while the other discharges from a triangular pipe. They observed that axis switching occurs only in the case of the orifice jet and that the flat side is characterised by generation of large-scale coherent structures.

Quinn and Militzer [6] presented results of an experimental and numerical study of a turbulent free jet of air issuing from a sharp-edged square slot. Their experimental results revealed the existence of pronounced mean stream velocity off-center peaks in the very near field. Furthermore, they pointed out that there are no documented detailed measurements of mean velocity and turbulence structure available for turbulent square jets. Krothapalli *et al.* [7], Marsters [8] and Sfeir [9] investigated rectangular jets of different exit aspect ratios and Reynolds numbers. Their studies showed that the development of the jet depends on these two parameters.

The purpose of this paper is to provide experimental results showing some features of the structure of turbulent free jets issuing from an equilateral triangular nozzle and from a sharp-edged square nozzle with the same cross-sectional area. Comparison is made with a free jet issuing from a circular nozzle having the same cross-sectional area. It is worth noting that the circular nozzle has the least initial circumference among other three-dimensional shapes with the same cross-sectional area. For example, the circumference of square and triangular nozzles are 12.8% and 28.6% higher than that of a circular nozzle of equal area. The increase is of prime importance in the initial region of the jet in which maximum entrainment is expected to occur. The measurements cover both mean flow parameters and turbulence level. Emphasis is placed on the comparison of the velocity spectra of three-dimensional jets with the well-studied axisymmetric jet.

Experimental Set-up

The flow facility consisted of a constant speed centrifugal fan providing air to a plenum chamber of 0.26 m diameter and 0.28 m length which is fitted with gauge screens to ensure uniform flow through a smoothly contored 32:1 area ratio contraction nozzle. The shapes of the jet exits examined are shown in Fig. 1. Three types of jet exits with constant area (580 ± 0.5% mm^2) were fitted using 40 mm length carefully machined adapter pieces (Fig. 1) to transform the 36 mm diameter circular cross section to the required shapes. Jet exit shapes are: circular nozzle with 27.2 mm diameter, sharp-edged square nozzle with 24.1 mm height (positioned either normally or diagonally) and sharp-edged equilateral triangular nozzle with 31.7 mm height. The nominal Reynolds number based on jet exit velocity and the equivalent diameter was 6.35×10^4 for all jets and it varies within ± 13% if based on equivalent hydraulic diameter. The nominal mean streamwise velocity at the center of the nozzle exit plane was 35 m/sec. The streamwise turbulence intensity at the center of the nozzle exit plane was less than 0.5%

A linearized single hot wire anemometer system was used to measure the mean velocity and streamwise turbulence intensity. The velocity spectra were measured using a spectrum analyzer. The main purpose of the spectral analysis is to identify the dominant frequency peaks in the flow field.

Results and Discussions

Mean and turbulent velocity profiles

The mean streamwise velocities on the jet centerline and at positions off-center, corresponding to nozzle edges, are plotted versus the normalized distance measured from the nozzle exit (x/D_{eq}) in Fig. 2. Note that D_{eq} is the same for the three nozzles since it is defined as $\sqrt{4A/\pi}$ where A is the nozzle area. No attempt was made to study the jet spread rate and therefore the virtual origin was not determined. Mea-

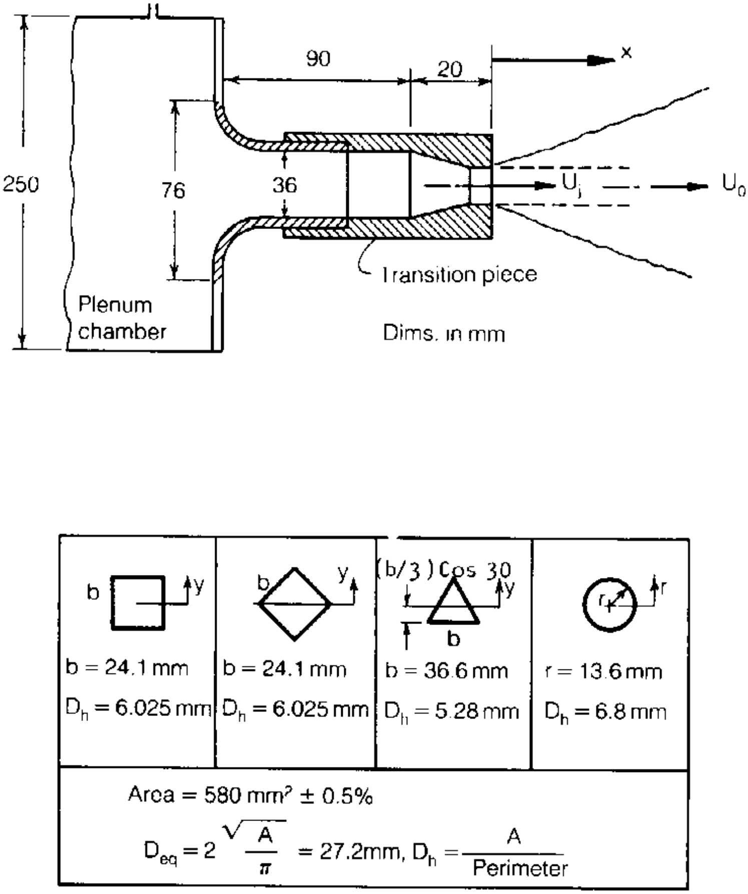


Fig. 1. Geometry of nozzle exits. (N.T.S.).

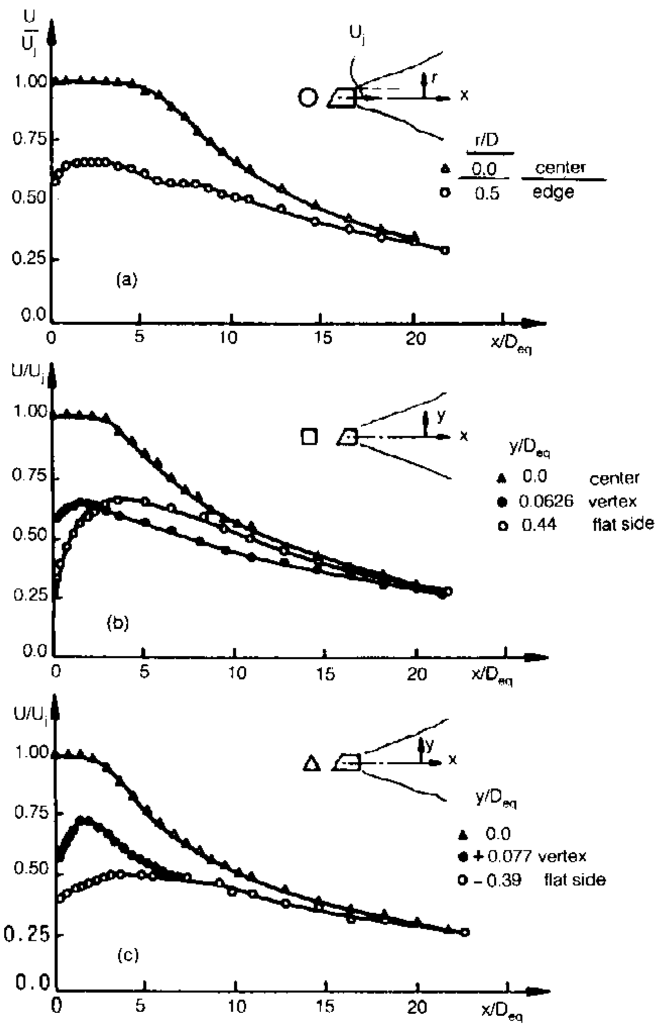


Fig. 2. Mean stream-wise velocities at jet centerline and along nozzle edges.

a) : Round nozzle, b): Square nozzle, c): Triangular nozzle.

surement of x from the virtual origin is important when studying jet self-similarity but this was not among the objectives of the present investigation.

Figure 2a indicates that the potential core for the round jet extends as expected to 4D while Figs. 2b and 2c indicate that centerline velocity stays constant up to 2.7D for the square jet and up to about 1.4 D_{eq} for the triangular jet. The uncertainity in determining these numbers is within the experimental uncertainity in measuring U. The differences in the extent of the potential cores are attributed to the differences in the structural behavior of jet flows in the mixing region where additional shear strains exist in the case of 3-dimensional jets; namely those issuing from the square and triangular nozzles. These extra strains tend to enhance mixing within the shear layers and therefore shorten the potential core.

The decay of the centerline mean velocity downstream of potential core based on a log-log plot (not shown) reflects the above discussion in the sense that the decay is faster for the three dimensional jets as compared to the x^{-1} decay for the round jet [10]. The profiles show that there is distinct difference between the streamwise velocities along the vertex line and the flat-side line for 3-dimensional jets. However, the difference diminishes within 7.3 D_{eq} for the triangular jet while it takes upto about 20 D_{eq} for the square jet to diminish. It is worth noting that the velocity has a relatively sharp peak along the vertex line of triangular jet at $x/D_{eq} = 1.65$; on the other hand the velocity along the flat side changes in a very mild fashion for the same jet. Similar behavior but not as distinct is observed in the case of the square jet. This can be attributed to the fact that the vertex of triangular jet exit (nozzle) is at smaller angle than that of the quare jet which is expected to cause stronger interaction between the boundary layers at the vertex of the triangular jets.

Figure 3 shows the mean velocity profiles at nozzle exit ($x = 0$) and at $x/D_{eq} = 11$ for the three jets. The results show that the flow was uniform at nozzle exits and that the three jets have attained bell shape profile at the downstream station which indicates that the jets may have lost the memory of their initial states. Furthermore, the data in Fig. 3b show that the mean velocity profile for the jet issuing from the square nozzle appears to be axisymmetric. On the other hand the tail of the velocity profile of the triangular jet (Fig. 3c) does not tend to zero within the shown data, indicating very slow decay in the lateral direction compared with the round jet. It should be noted that the half-velocity width $y_{0.5}$ at this axial location is largest for the round jet followed by the square and triangular jets, respectively.

The axial variations of the longitudinal component of turbulence intensities along the centerline and at positions off-center, corresponding to nozzle edges (in the shear layer) are shown in Fig. 4. It is evident that the turbulence intensities are fairly higher

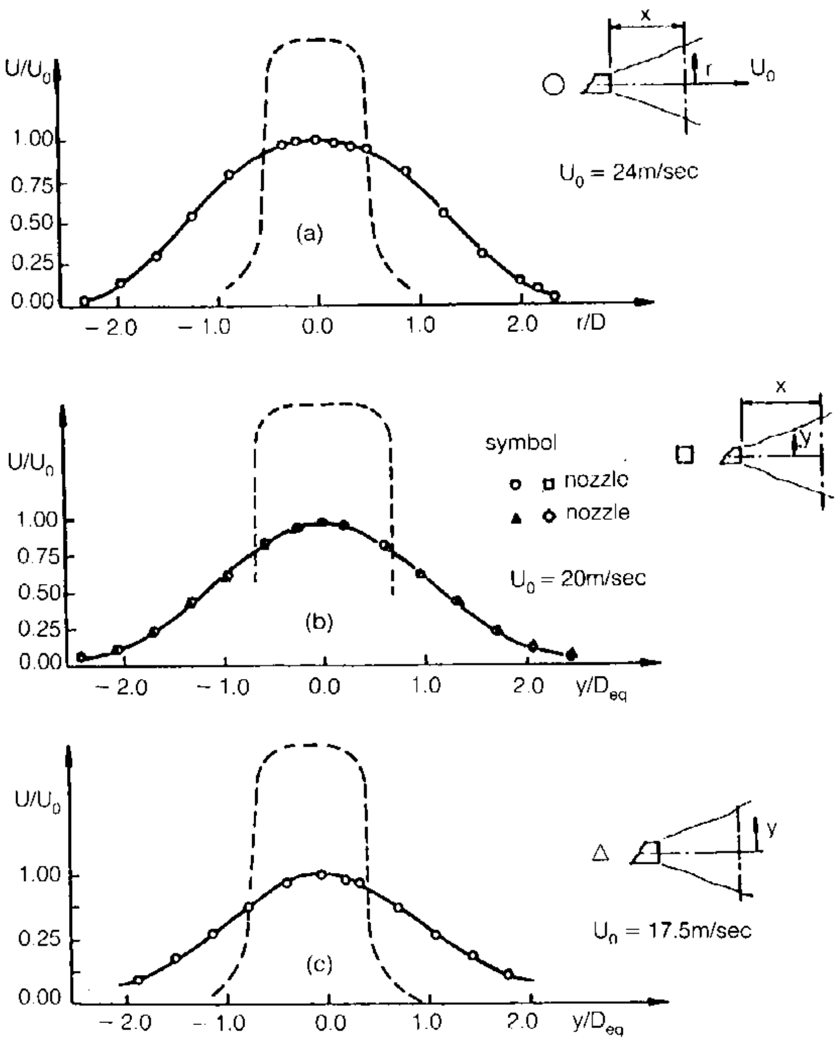


Fig. 3. Mean streamwise velocity profiles at x/D_{eq} = 11

a) Round nozzle, b): Square nozzle,

c) Triangular nozzle.

--- exit profile for each case

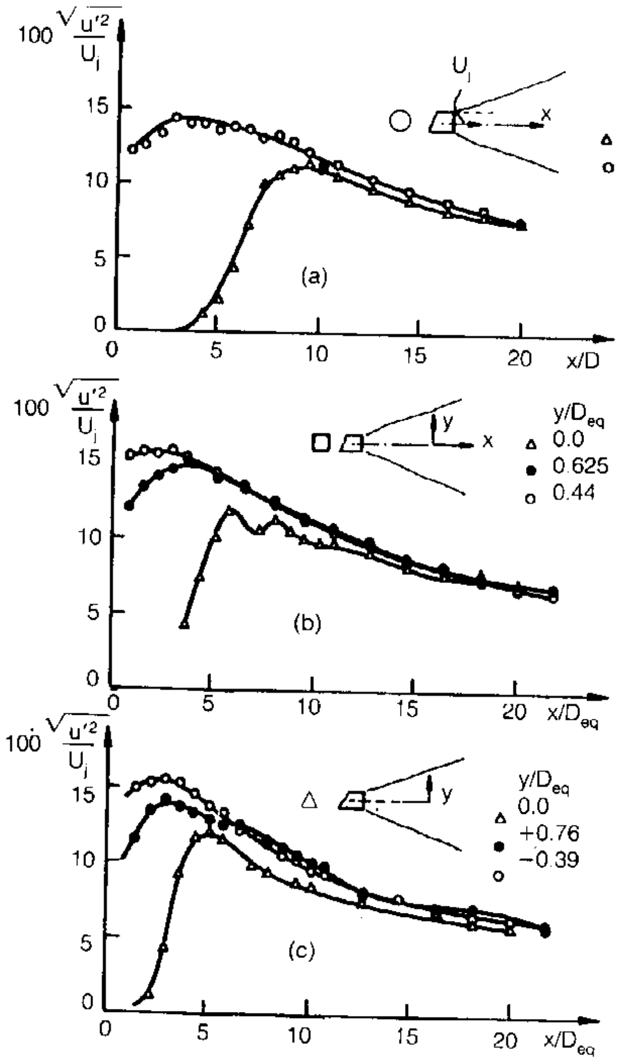


Fig. 4. Longitudinal component of turbulence intensity at jet centerline and along nozzle edges. a): Round nozzle, b): Square nozzle, c): Triangular nozzle

in the shear layer than at the centerline for the three jets in the initial region; which is expected because of the presence of the potential core. At the end of the potential core, the turbulence intensity along the centerline increases very rapidly to reach a maximum before dropping slowly near the outer edge. It is interesting to note that there are two adjacent peaks in the case of the square jet; possibly due to vortex pairing in this developing region. The variation of the turbulence intensity measured along lines perpenedicular to the nozzle at the vertex and the flat side in the initial region of the three-dimensional jets is markedly different. In both cases the turbulence level is higher along the flat-side line compared with the vertex line. This also was observed by previous investigators [4,5]. They attributed this behavior to the dominant effect of large scale structures generated along the flat side compared with the fine scale turbulence dominating the flow emanating from the vertex. This hypothesis is supported by the present data as will be shown later when discussing the spectral development associated with velocity fluctuations in these jets.

Figure 5 shows the longitudinal turbulence intensity profiles at nozzle exit ($x = 0$) and at $x/D_{eq} = 11$ for the three jets which correspond to the mean profiles shown in Fig. 3. The results indicate that the turbulence level is very low at the center of the nozzle and increases towards its wall for all jets. Further we observe that the turbulence field of the jet emanating from the square nozzle (Fig. 5b) is not yet axisymmetric as indicated by the mean field (Fig. 3b). As for the triangular jet, the data in Fig. 5c show that the jet is definitely not axisymmetric yet.

Velocity spectra

Power spectral analysis has been carried out at selected locations for each of the three jets investigated in order to identify any preferred frequencies; these frequencies in the velocity signal are usually associated with large scale vortical structures. This was achieved by feeding the linearized output of the hot wire into a spectrum analyzer that employs fast Fourier transform. The velocity spectra presented here are averages of 64 ensembles. Since our main objective here is to compare the frequency content, the gain in the signal can be arbitrary.

Development of the spectrum along the centerline

The development of the centerline longitudinal velocity spectrum is shown for the three jets in Figs. 6,7 and 8. In all figures, sharp peaks appear at 600 and 1200 Hz. Upstream influence may be responsible for these exact tones, but most probably not for the energy content around them.

Figures 6(a) and 6(b) show the spectral development of the axisymmetric jet in near and far fields, respectively. It is observed that considerable energy content is

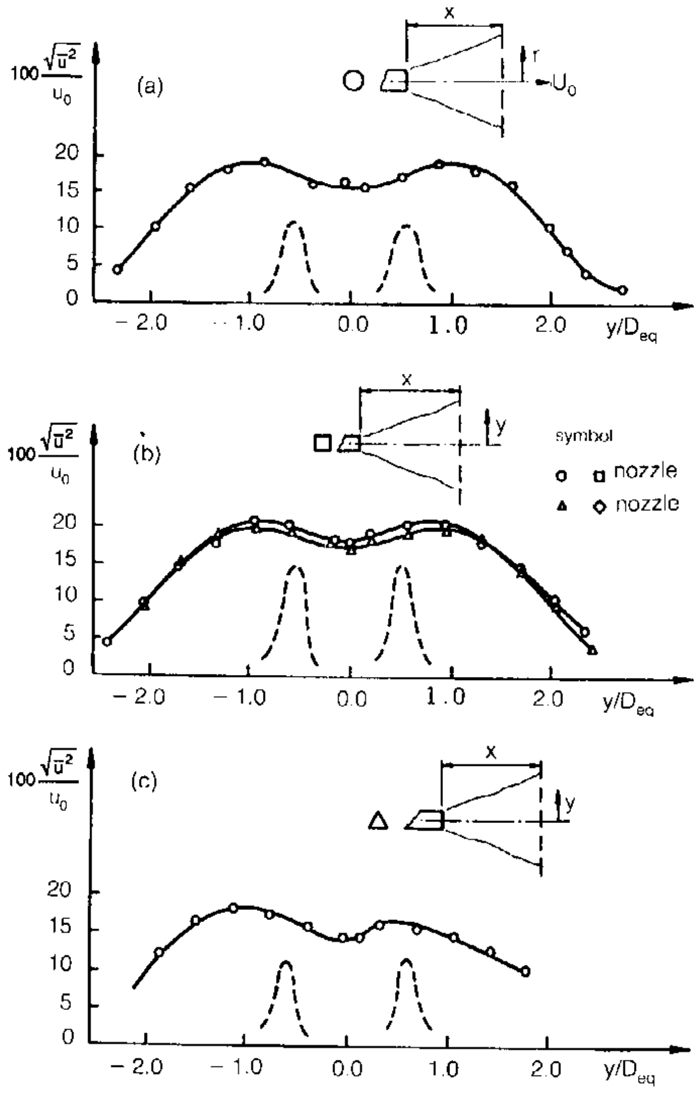


Fig. 5. Longitudinal component of turbulence intensity at $x/D_{eq} = 11$

a) Round nozzle, b) Square nozzle, c) Triangular nozzle, ---- exit profile for each case.

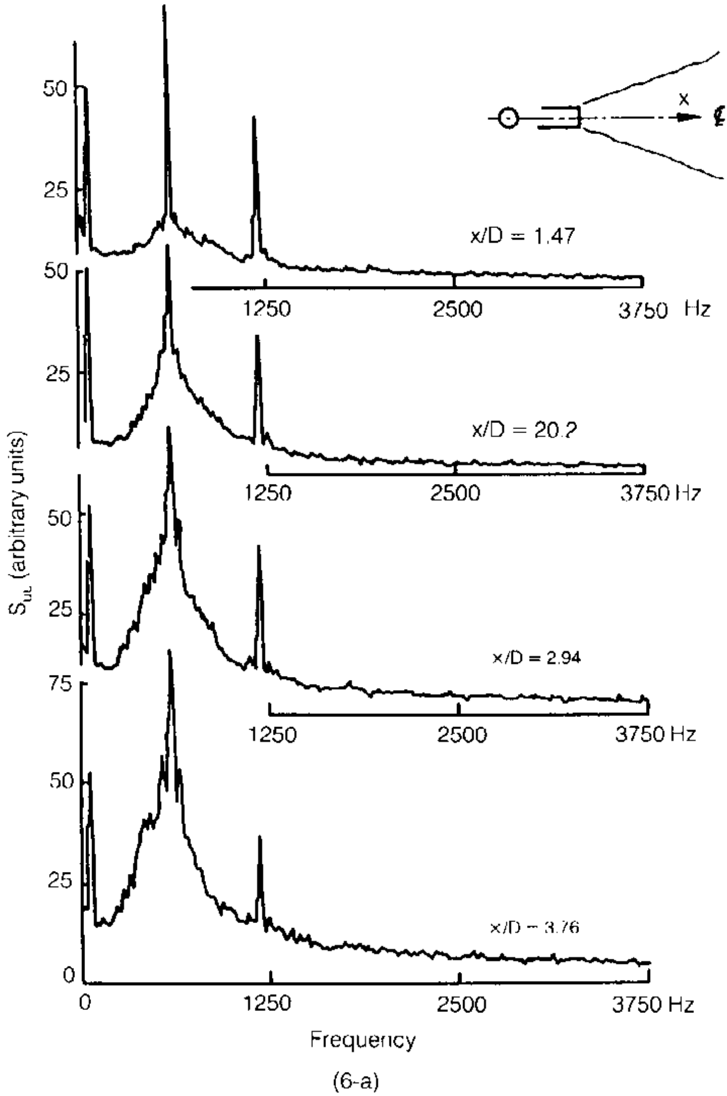


Fig. 6(a). Velocity spectra along jet centerline: Near field.

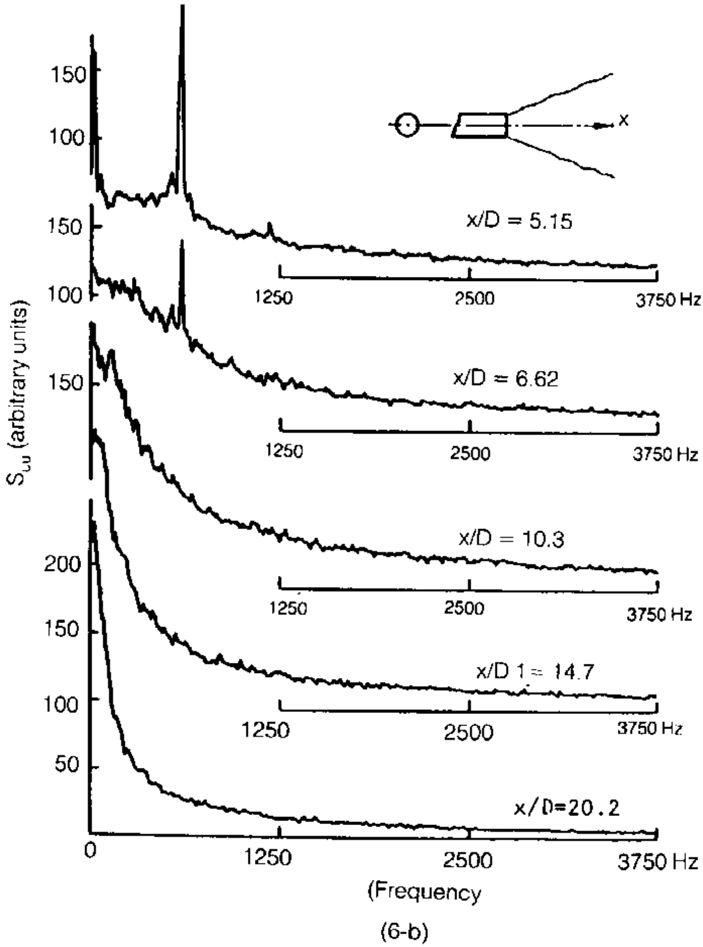


Fig. 6(b). Velocity spectra along jet centerline: Far field.

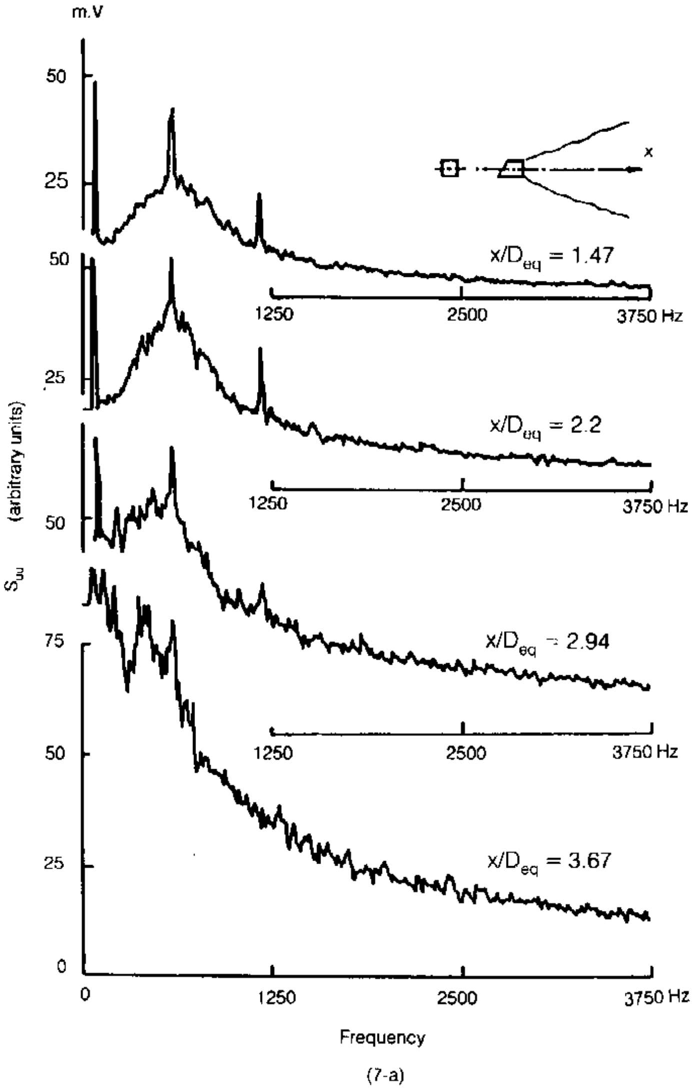
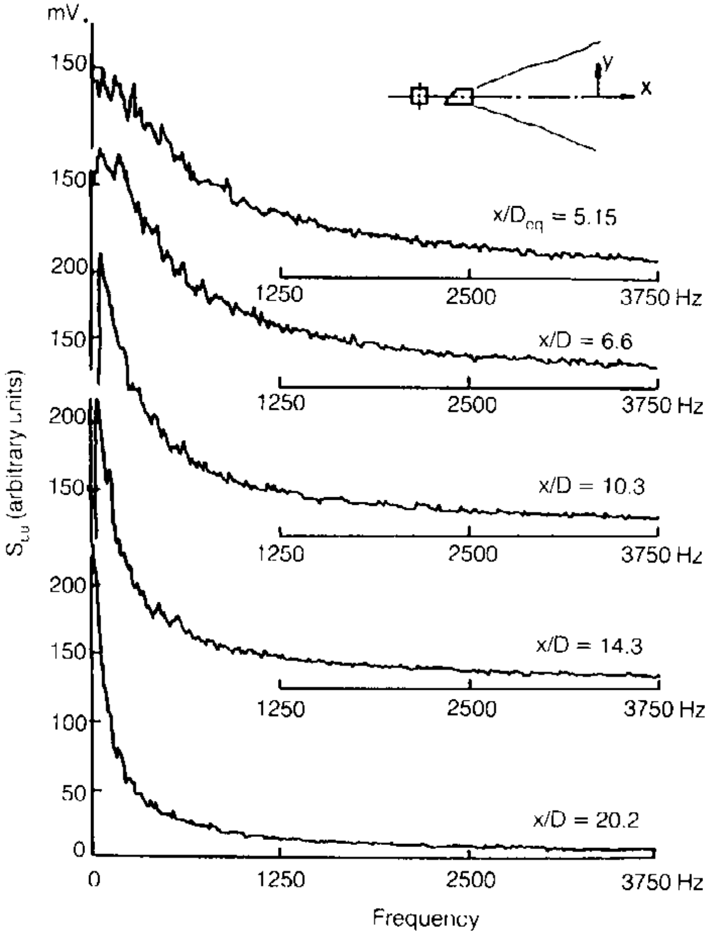


Fig. 7(a). Velocity spectra along square jet centerline: Near field.



(7-b)

Fig. 7(b). Velocity spectra along square jet centerline: Far field.

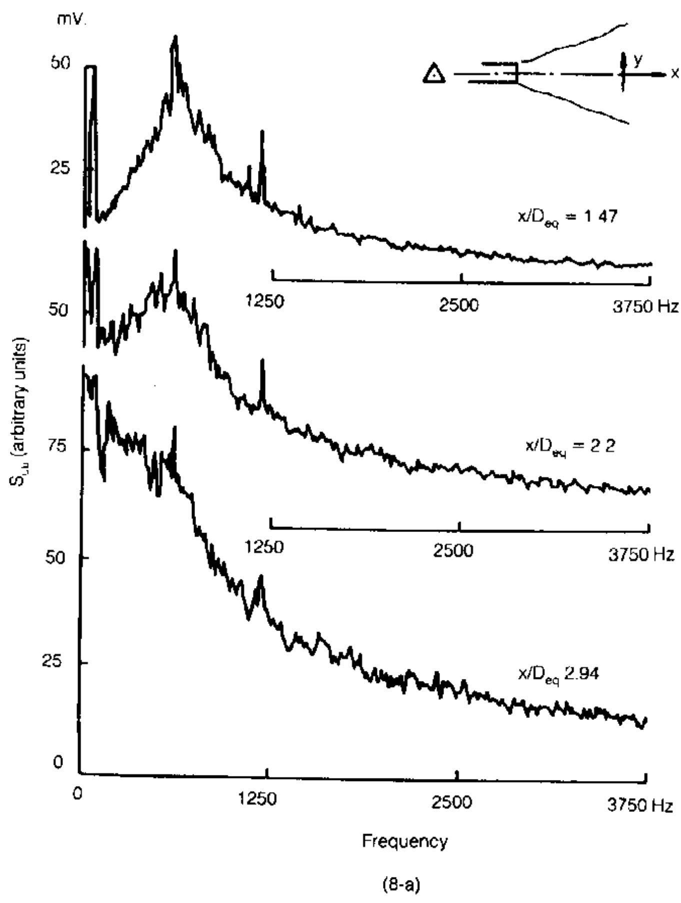


Fig. 8(a). Velocity spectra along triangular jet centerline: Near field.

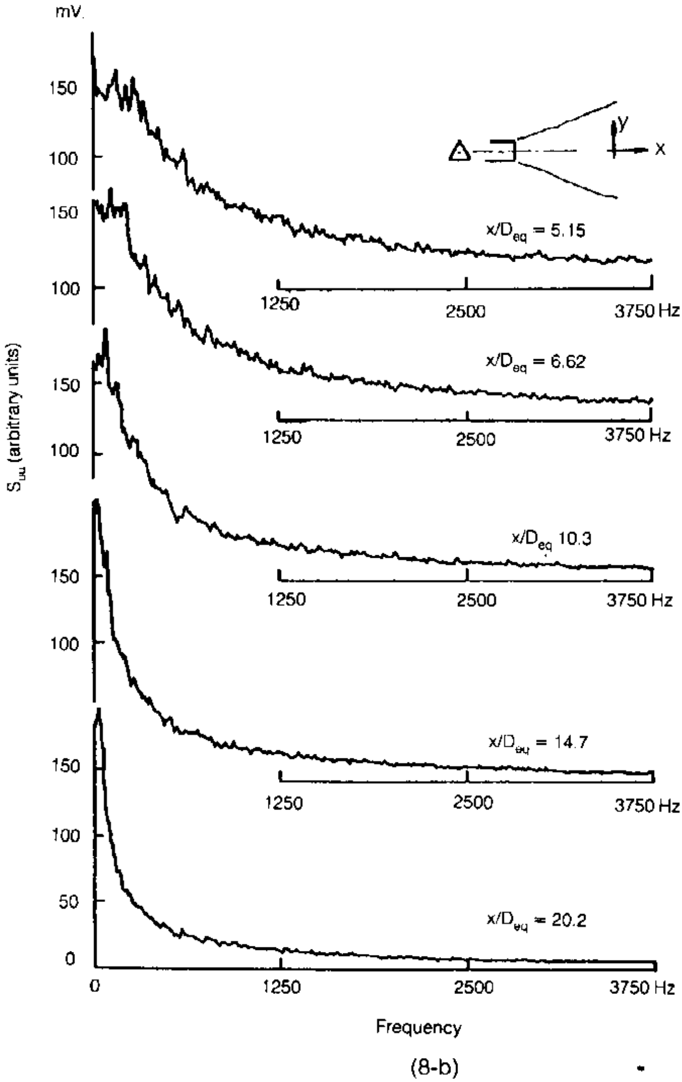


Fig. 8(b). Velocity spectra along triangular jet centerline: Far field.

present around the peak at 600 Hz and covers frequencies from 200 Hz to 1000 Hz. This peak survives until $x/D \simeq 5$. Starting around $x/D = 6.6$ the main bulk of the energy content shifts towards lower frequencies. It appears that a spectrum of the turbulence-type is obtained at $x/D = 10.3$ and develops to a typical turbulence spectrum further downstream.

Figures 7(a) and 7(b) show the spectral development for the square jet at same locations presented in Fig. 6. Similar to the case of the axisymmetric jet a broad peak exists around 600 Hz; however this peak survives only up to $x/D_{eq} \simeq 2.2$. At x/D_{eq} equal 2.9 a build up of low frequency fluctuations starts to appear. This is due to the developing shear layers and it also indicates that the potential core ends around this location; which is earlier than the case of the round jet. It is interesting to note that this is consistent with the result of Fig. 2. At $x/D_{eq} \geqslant 3.67$, the results indicate that the development towards fully developed turbulence is slower than the case of the round jet which may be attributed to the lack of axial symmetry in the initial region.

Figures 8(a) and 8(b) show the corresponding results for the triangular jet. Notice that measurements were made along an axis that passes through the centroid of the nozzle section. Here, it is clear that the broadening of the peak around 600 Hz towards lower frequencies starts at $x/D_{eq} = 2.2$ which is earlier than in previous jets. Also it is observed that the peak has been overshadowed by the buildup of low frequency fluctuations at $x/D_{eq} = 2.94$. As for the far field, the development towards fully developed turbulence appears to be even slower than the case of square jet due to the more severe three-dimensionality.

Off-center spectra

Figures 9 and 10 show velocity spectra at y-locations corresponding to the vertices and the flat side of the triangular and square nozzles as well as the edge of the round nozzle.

The results of Fig. 9 show that there is a marked difference between the spectra at the flat side and the vertex side for the square and triangular jets close to the nozzle exit ($x/D_{eq} = 0.735$). In general there is more energy content at low frequencies in the flow emanating from the flat side compared with that emanating from the vertex. This has been observed also in Ref. [4] and was attributed to the presence of a large scale coherent structure generated at the flat side as compared with the fine scale turbulence dominating the flow along the vertex line.

Further downstream at $x/D_{eq} = 2.94$, Fig. 10 shows the velocity spectra corresponding to those presented in Fig. 9. It is observed that the spectra at the vertex and

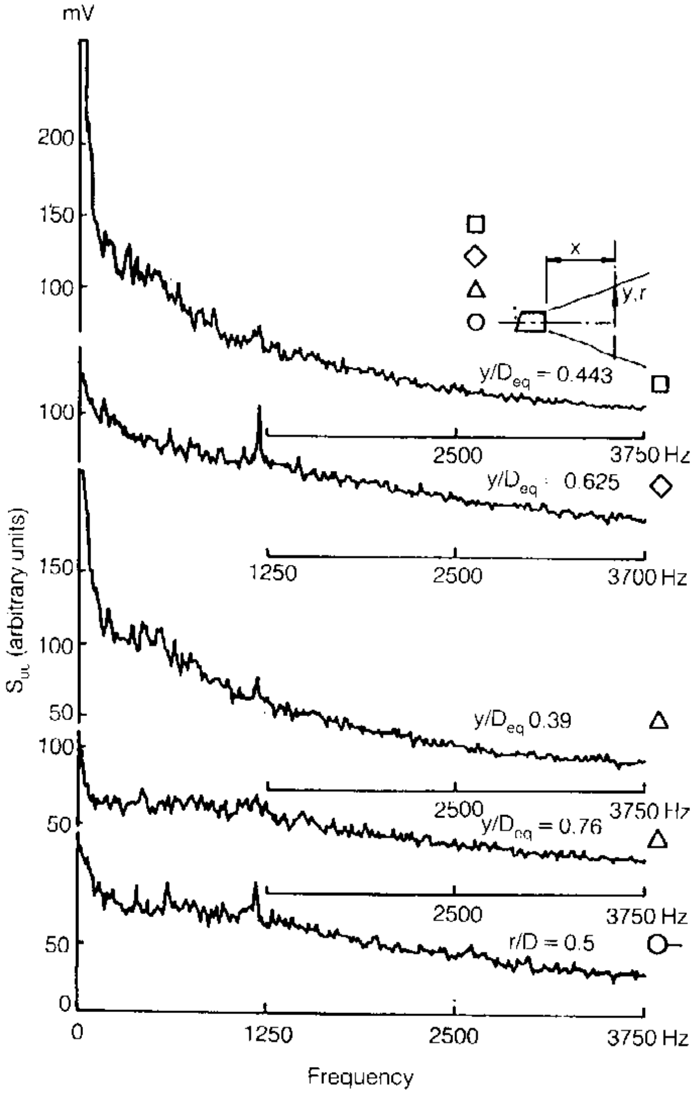


Fig. 9. Comparison of velocity spectra at the edge of the round jet and at the flat side and vertex for the square and triangular jets at x/D_{eq} = 0.735.

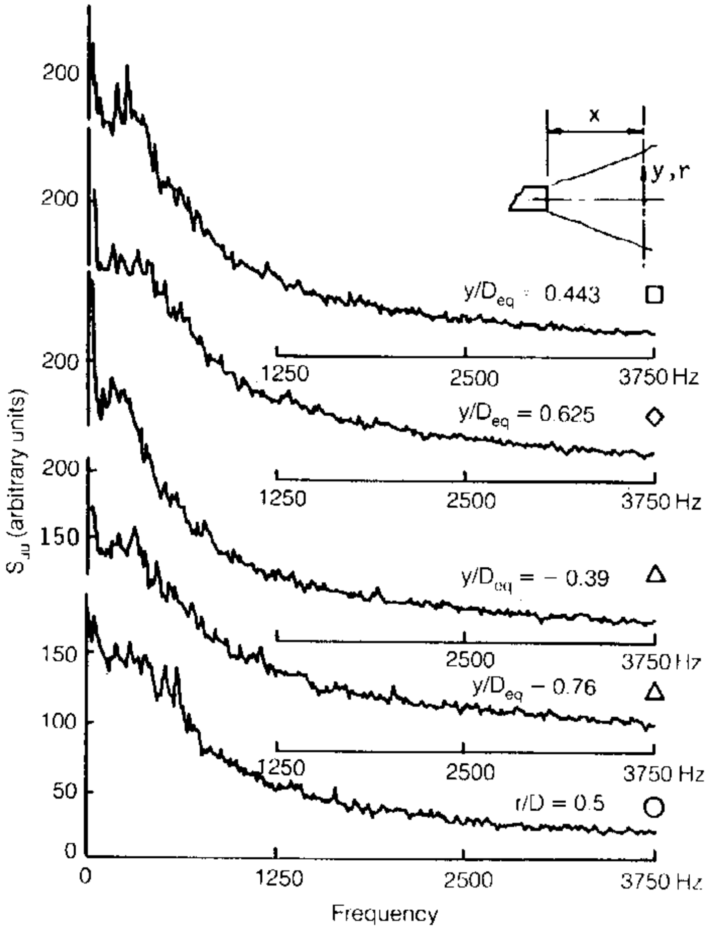


Fig. 10. Comparison of velocity spectra at the edge of the round jet and at the flat side and vertex for the square and triangular jets at $x/D_{eq} = 2.94$.

flat side become fairly close for the three dimensional jets and are even comparable to the spectrum at the edge of the round nozzle.

The time histories for signals measured along the vertex line and flat side for the three dimensional jets at x/D_{eq} = 0.18 and 0.735 are shown in Figs. 11 and 12. These results indicated that the large scale eddies at the flat side are less organized although stronger compared with smaller scale eddies along the vertex lines.

Summary and Conclusions

Limited results on the development of 3-D jets issuing from triangular and square nozzles were obtained experimentally. The results were compared with those of an axisymmetric jet with equal nozzle area. Hot-wire measurements were made along the centerline of the jets and along axial lines emanating from the edges of each nozzle. Mean streamwise velocity and turbulence intensity profiles were obtained at a limited number of stations. Also the power spectral density was measured at selected locations in the flow field. The main conclusions of the study are:

1. Three-dimensional jets eventually become axisymmetric far downstream of the nozzle exit. The triangular jet was the slowest to approach axial symmetry, followed by the square jet.

2. The variation of the centerline velocity and its decay along the jet axis is strongly dependent on nozzle geometry. Present data showed that the potential core extends to x/D_{eq} = 1.4 for the triangular jet, to x/D_{eq} = 2.7 for the square jet and to x/D = 4 (as expected) for the found jet.

3. Spectral measurements in the nearfield showed the presence of a broad but dominant peak around 600 Hz along an axial line normal to the flat side of each of the triangular and square nozzles, indicating that the flow is dominated by large scale vortical structures along these lines. This is supported by large values of turbulence intensity there. In contrast, small scale turbulence is dominant along lines emanating from the vertices of the nozzles.

4. The turbulence intensity along the centerline grows rapidly following the end of the potential core to a maximum then drops slowly with x/D_{eq} in all three jets. However, two peaks at x/D_{eq} = 5.8, 8.2 were observed in the square jet case. The reason for these peaks is not exactly known.

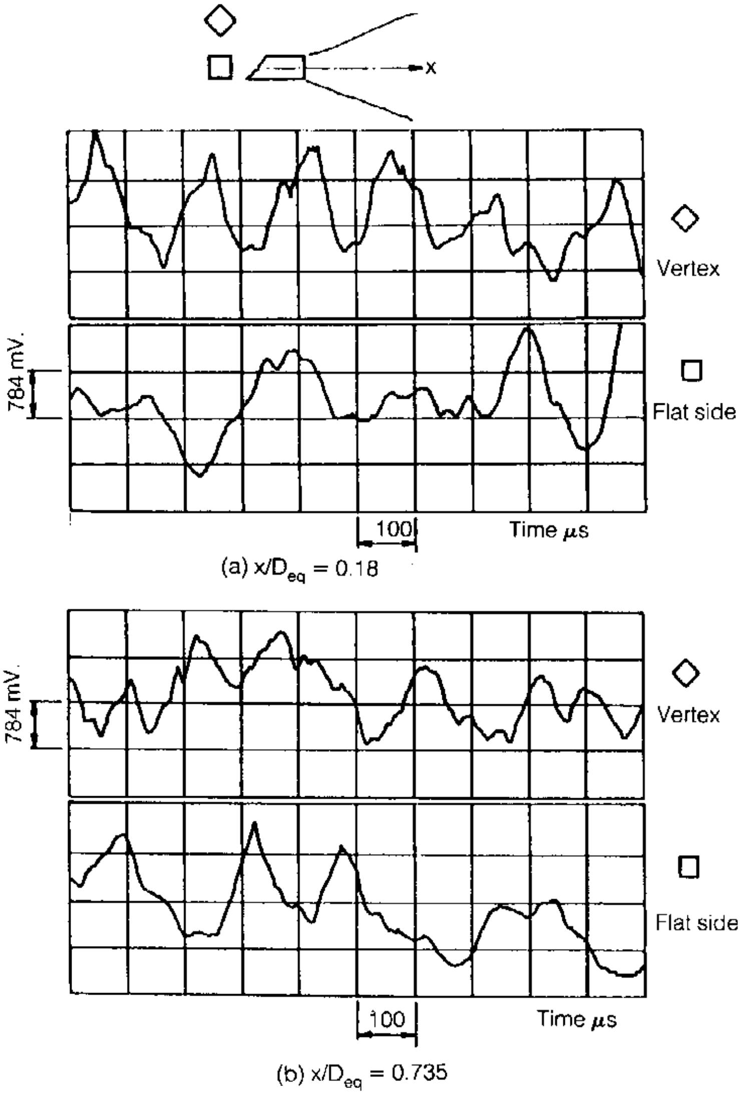


Fig. 11. Time history for signals along the vertex line and flat side for square jet. (a) $x/D_{eq} = 0.18$, (b) $x/D_{eq} = 0.735$

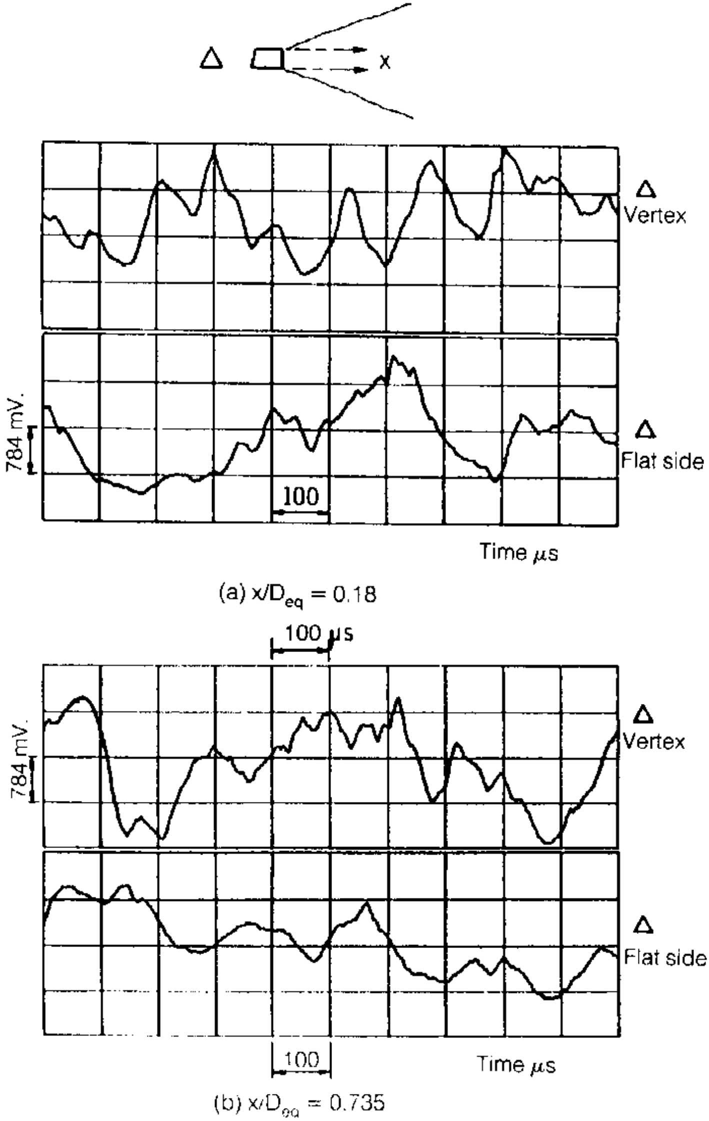


Fig. 12. Time history for signals along the vertex line and flat side for triangular jet. (a): x/D_{eq} = 0.18, (b) x/D_{eq} = 0.735

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تأثير شكل مخرج المنفث على تَطوّر النَفّاث المضطرب

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(استُلم في ١٥/٦/١٩٩١م؛ قُبل للنشر في ١٣/١/١٩٩٣م)

ملخص البحث. تعطي هذه الورقة نتائج لبعض الملامح الخاصة بعدة نفّاثات حرة مضطربة خارجة من مُنَفِّثْ ذو مقطع ثلاثي متساوي الأضلاع ومن مُنَفِّثْ مربع الشكل له مساحة المقطع نفسها. كما تعطي مقارنة مع نَفَّاث آخر حُرّ مضطرب خارج من مُنَفِّثْ دائري له مساحة مقطع الأشكال السابقة نفسها. وقد شملت القياسات السرعة المتوسطة والتحليل الطيفي للسرعة ومستوى الاضطراب. وتُبيّن النتائج أنه بالرغم من أن كل النفاثات تصبح في النهاية متماثلة حول المحور إلا أن تطوّرها مختلف تمامًا. فالنفّاثات الخارجة من مقطع غير دائري تتطوّر بمعدّل بطيء وعلى الأخص النَفَّاث الخارج من المقطع الثلاثي. كما توضح النتائج أن الدّوامات ذات الرقم الموجي المنخفض على طول الخط العمودي على الجانب المستوي لمخرج النَفّاث غير المحوري تكون غالبة في بداية السريان بينما تتغلب الدوّامات المضطربة الصغيرة على طول الخط الموازي للمحور والذي يبدأ في نقطة تقاطع السطحين المستويين لمخرج هذه النفّاثات.