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The structure of jets from notched nozzles

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Jets from notched nozzles are investigated by schlieren photography and pressure traverses. It is demonstrated that the dominant feature of the flow which determines the structure far downstream is the trailing vortices shed from the swept edges of the notches.

1. Introduction

When the nozzle configuration of the Olympus 593 engine for Concorde was changed from the prototype (Type A1) nozzle with an axisymmetric secondary shroud to the production (Type 28) nozzle with combined secondary shroud and thrust reverser buckets, considerable side-line noise reduction was achieved by leaving the buckets in a semi-closed position, thus effecting a squeezing of the jet in the horizontal plane (e.g. see Hawkins & Hoch 1971). This result led to a large number of mainly *ad hoc* experiments on the noise properties of so-called fishtail or notched nozzles obtained by cutting wedge-shaped notches in the originally conical nozzle.

In this paper we present the main results of a comprehensive study of the fluid mechanics of the jets from a wide range of such nozzles. We shall demonstrate that schlieren photographs, although interesting, give no clue to the most important feature of the flow mechanism, which is found to be associated with the persistence of the trailing vortices shed from the swept edges of the notches. An extremely simple mathematical model shows remarkable qualitative agreement with the observed flows, and it is hoped that the resulting better understanding of the flow structure can be combined with the rapidly advancing theories of noise shrouding and refraction to give some guide lines for the optimization of real engine nozzle configurations.

The text is arranged more or less in the order in which the work proceeded and is confined to a presentation and discussion of the results. The flows are so complicated that a proper theoretical treatment appears impossible at the moment. Indeed, the theoretical analyses have so far been of such a simple nature that we have not found it necessary to include any of the equations in the paper.

2. Experimental arrangement

The base nozzle used is shown in figure 1 (*a*). This is a modified Concorde-type primary nozzle with an extended conical part and exit diameter 1 cm. (We shall be quoting distances in cm, so that the unit of measurement is the nozzle exit

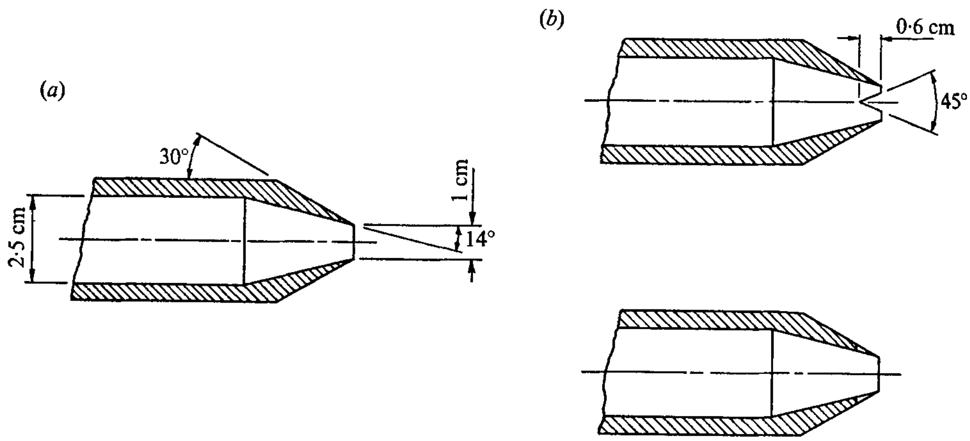


FIGURE 1. (*a*) Conical nozzle. (*b*) Nozzle with two notches.

diameter, and we still retain a clear indication of the actual scale of the flows.) Notched nozzles were obtained by cutting V-shaped notches of various depths and included angles in the base nozzle as shown in figure 1 (*b*) for the nozzle with 0·6 cm notches of 45° included angle, which was used for most of the results reported here. The 0·6 cm notches increased the mass flux through the nozzle by 26 %, but this cannot be translated directly into a change in mass-flux coefficient because we cannot define the effective exit area for a notched nozzle.

The nozzles were run continuously from a supply of unheated dry air at constant (but adjustable) stagnation pressure. Most experiments had a ratio of stagnation to atmospheric pressure of 3·128, corresponding to an isentropic jet surface Mach number of 1·40, which is close to the Concorde take-off condition.

Photographs were obtained by a conventional two-mirror schlieren system using either a continuous light source with exposure times of about 10^{-2} s or a spark source of effective duration about $0{\cdot}5 \times 10^{-6}$ s.

Pressure measurements were made with a 1 mm Pitot tube pointing upstream in the direction of the nozzle axis and with a yawmeter with six degrees of freedom.

3. Schlieren photographs

At first it was thought that the clue to the structure of jets from notched nozzles was to be found in the initial, supersonic part of the jet, which was expected to be greatly modified by the presence of the notches. Some 200 photographs were therefore taken with different notch configurations, light sources and knife-edge locations. However, although they show the interesting initial features of the flow, they do not really help us to understand what happens further downstream and we therefore present only a small sample. Figure 2 (plate 1) shows long and short duration pictures of the flow from the base nozzle and the nozzle with two 0·6 cm notches.

It is clear that in the plane perpendicular to the notch plane the flow is very similar to the flow from the unnotched nozzle although a certain initial contrac-

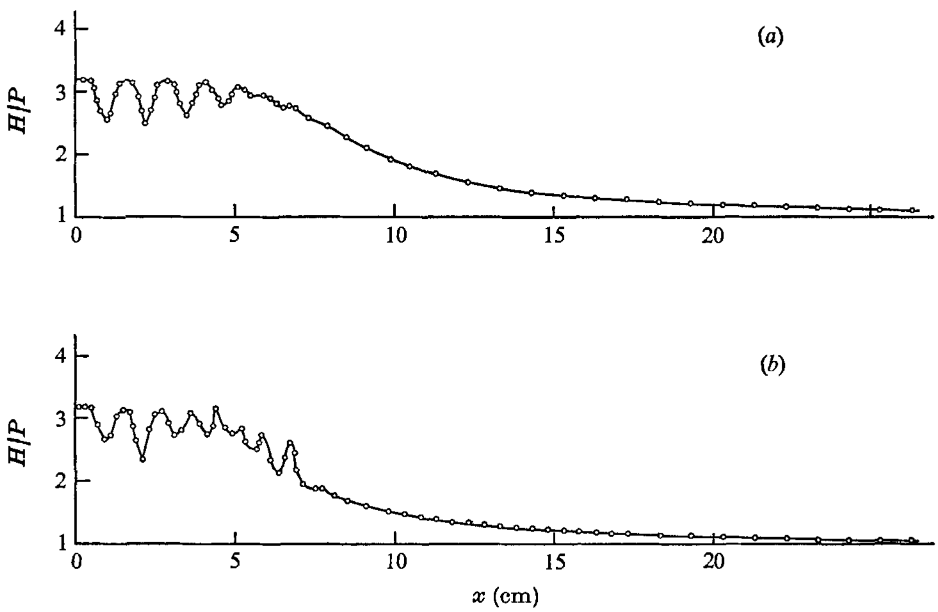


FIGURE 4. Axial pressure traverses. (a) Conical nozzle. (b) Notched nozzle.

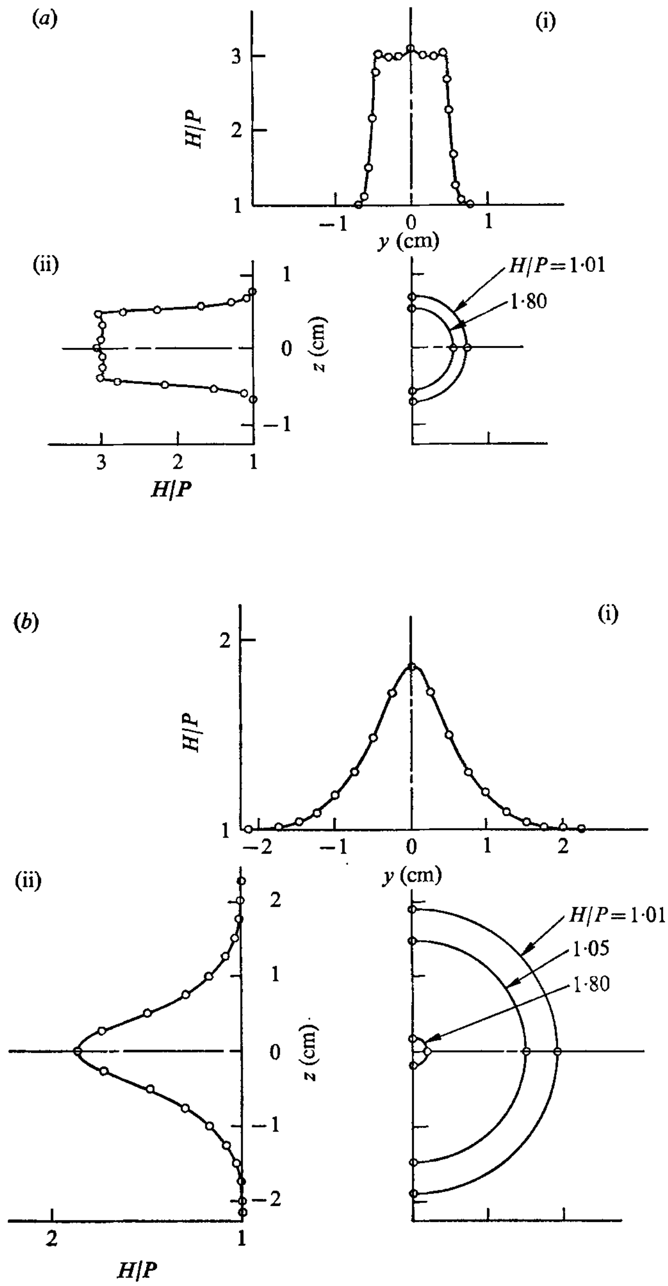
tion of the jet and a rather slower spreading downstream are evident. In the notch plane, however, there is a very marked fanning out of the outer part of the jet and a change in the shock cell structure. The turbulent structure of the initial part of the jet may be seen more clearly in figure 3 (plate 2), which shows the flow from a nozzle with 0·8 cm notches. Any attempt to derive detailed information from this type of photograph appeared unlikely to succeed.

4. Pitot-tube traverses

Much more information can be gained from Pitot traverses, and a lengthy programme was performed in which a number of jets were traversed along the centre-line and in great detail in planes normal to the axis at a number of stations. It is important to note that we are presenting *Pitot-tube readings* taken with the Pitot tube aligned in the direction of the nozzle axis. These cannot be translated directly into velocity, neither are they the true *Pitot pressure* where the flow is inclined to the tube as near the nozzle exit and in the outer parts of the jet. All absolute readings H are divided by the atmospheric pressure P.

Again we present only a small part of the total material, selected to bring out the main features. Figure 4 shows the axial traverses for the unnotched nozzle and the nozzle with two 0·6 cm notches. Initially the shock cell structure is only slightly modified by the notches, but towards the end of the supersonic region the number of shocks is increased. (Remember that in supersonic flow maxima in Pitot pressure correspond to minima in Mach number and vice versa.) The downstream decay is considerably accelerated by the notches.

Figures 5 and 6 show Pitot readings in the two planes of symmetry and



FIGURES 5 (*a*, *b*). For legend see facing page.

equal-Pitot-reading contours for the same two nozzles at different downstream stations x. As the jet from the unnotched nozzle is axisymmetric, the contours in it are circles. The contours in the notched jet speak for themselves. Not only do they show the much greater spread in the notch plane but they also demonstrate the tendency towards the formation of separate low speed side jets in the notch plane with intermediate regions of even lower velocity. This phenomenon persists

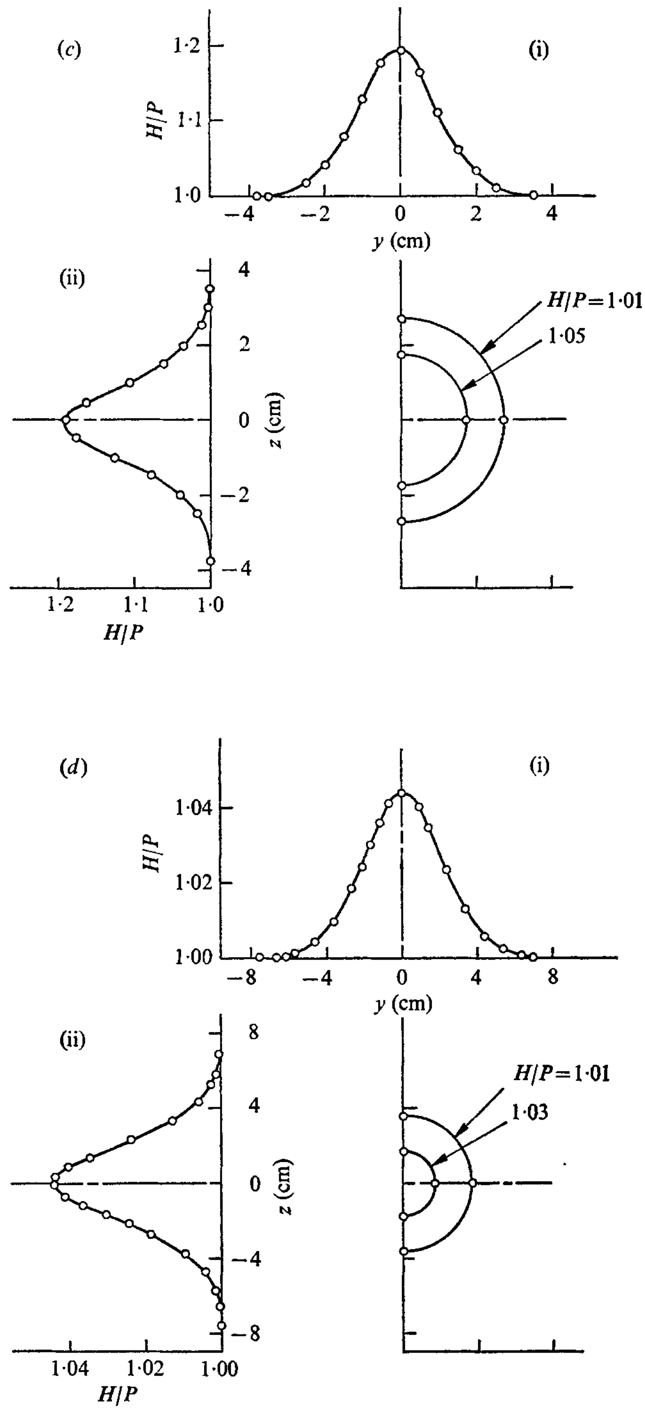
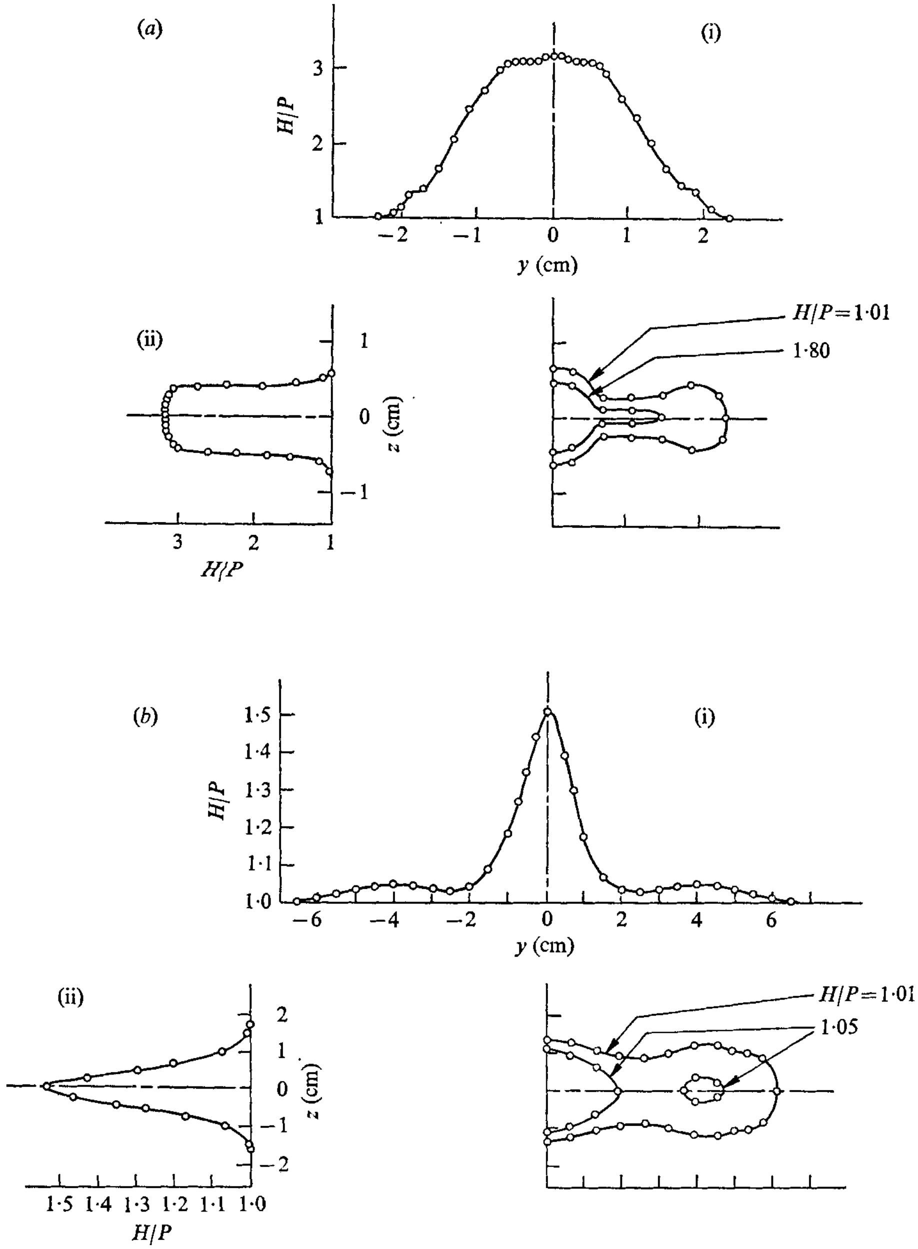


FIGURE 5. Pitot pressure traverses and contours for jet from conical nozzle at (*a*) $x = 1{\cdot}15$ cm, (*b*) $x = 10$ cm, (*c*) $x = 20$ cm and (*d*) $x = 40$ cm. (i) Horizontal plane. (ii) Vertical plane.



FIGURES 6 (a, b). For legend see facing page.

well beyond 20 exit diameters, so that it is present in the whole of the noise-producing region of the jet.

The same general pattern was found for a large number of different configurations and was present also in low speed air jets and in submerged water jets from notched nozzles. A particularly pronounced example is that of the flow from a nozzle with a single notch shown in figure 7.

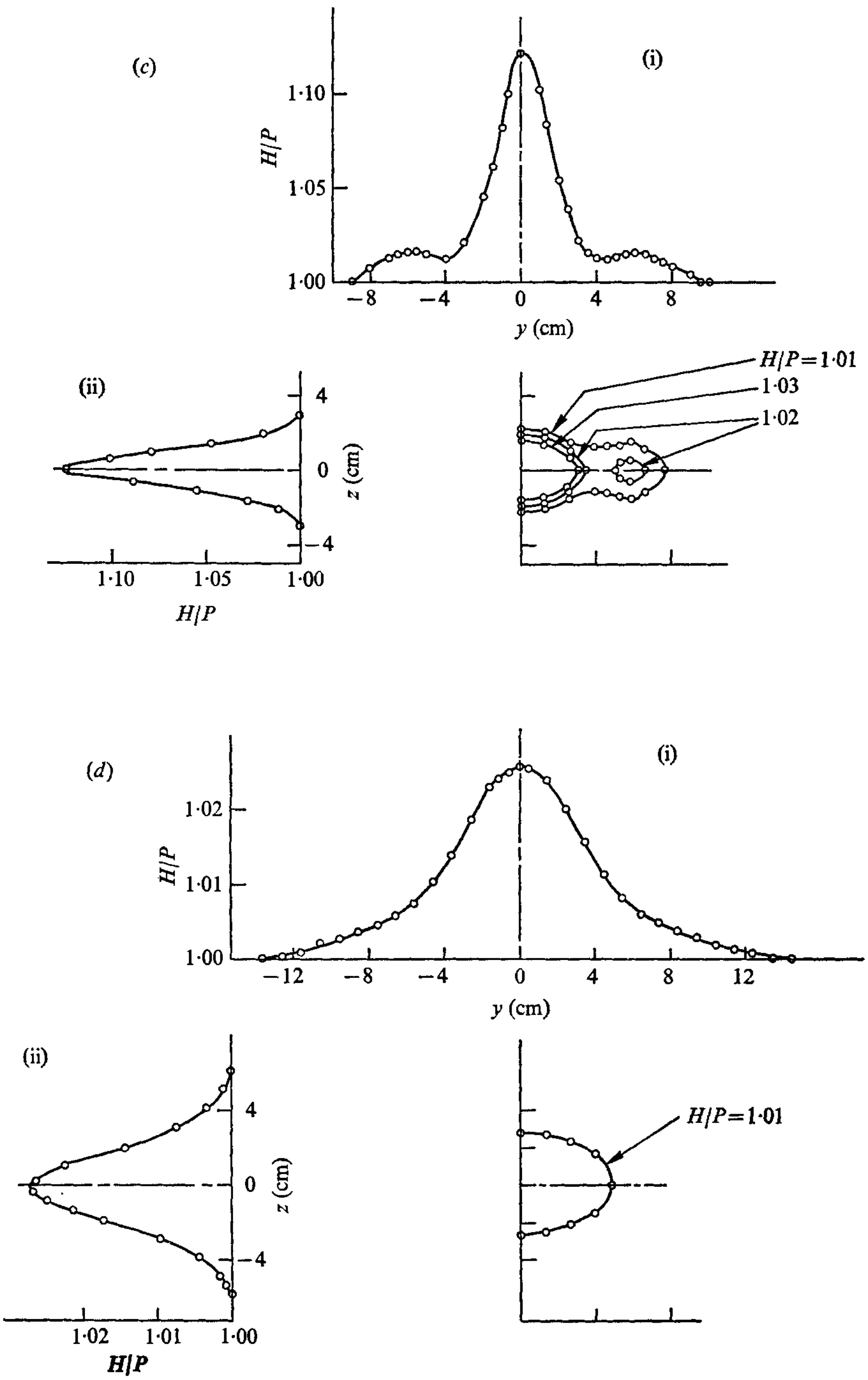


FIGURE 6. Pitot pressure traverses and contours for jet from notched nozzle at (a) $x = 1{\cdot}15$ cm, (b) $x = 10$ cm, (c) $x = 20$ cm and (d) $x = 40$ cm. (i) Notch plane. (ii) Perpendicular plane.

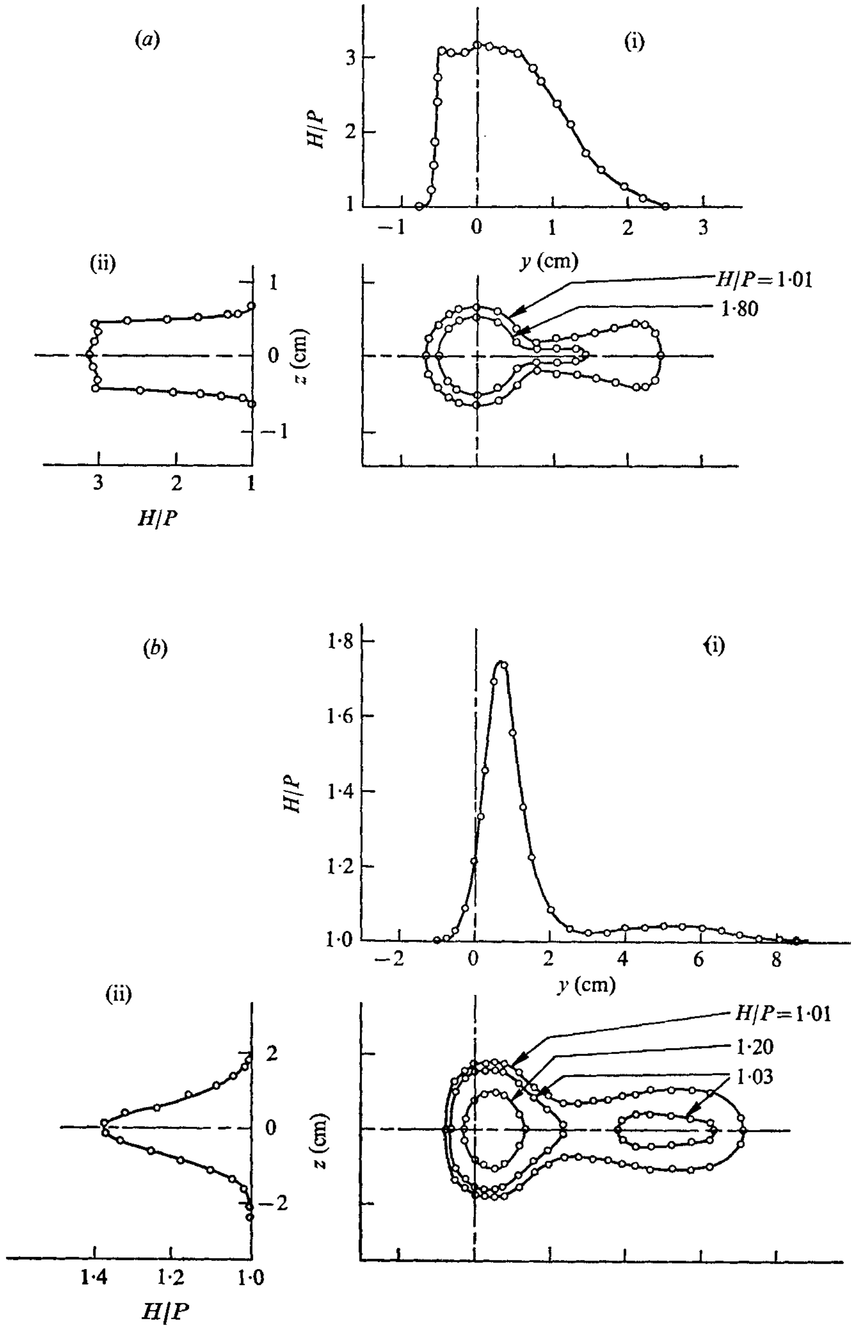


FIGURE 7. Pitot pressure traverses and contours for jet from nozzle with single notch at (a) $x = 1{\cdot}15$ cm and (b) $x = 10$ cm. (i) Notch plane. (ii) Perpendicular plane.

This clearly suggests that we should look for a new process of lateral momentum transport in such jets, as the outer low speed regions would decay very rapidly if they were supplied only by higher momentum air by the usual process of turbulent mixing. The primary effect of the notches is therefore not so much to change

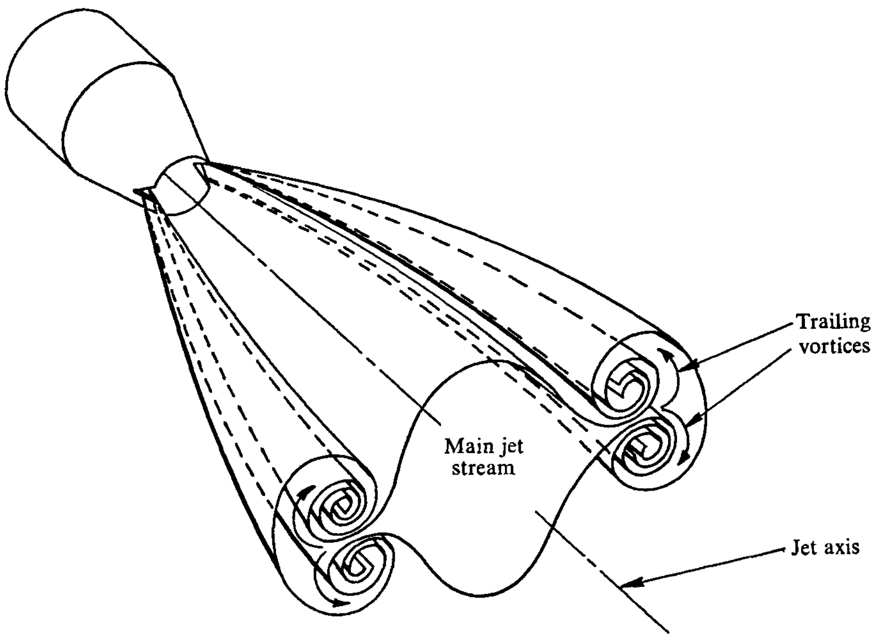


FIGURE 8. Sketch of jet structure.

the rate of mixing in different planes of the jet, but rather to introduce such a new mechanism. Remembering the well-known production of longitudinal vortices from the leading edges of delta wings at incidence it is not difficult to see the qualitative similarity, which suggests that each swept notch edge sheds vorticity in the downstream direction and that this vorticity rolls up into four discrete vortices.

This also explains why the phenomenon persists so far downstream; indeed aircraft trailing vortices persist for literally miles after the longitudinal momentum flux of the jets has disappeared. An attempt to show the main features of the flow is given in figure 8.

5. A crude mathematical model

In this model the transverse flow in any cross-section is replaced by an incompressible, two-dimensional potential flow due to four vortices of equal strength, placed symmetrically with respect to the axis of the jet, and the development of the jet with distance from the nozzle exit is then hopefully represented by the variation with time of the shape of the jet contour in the two-dimensional flow. At first sight such a model might appear to be too crude to have any merits, but it should be recalled that potential flow theory has been remarkably successful in representing flows due to *vortices* in many other fluid-mechanics applications.

Initially the four vortices are located on a unit circle at $(y, z) = (a, \pm b)$ and $(-a, \pm b)$, where the configuration can be characterized by the single parameter $\theta = \tan^{-1} b/a$. Using standard complex potential theory it is then possible to write down the instantaneous velocity field due to the vortices assuming that this is

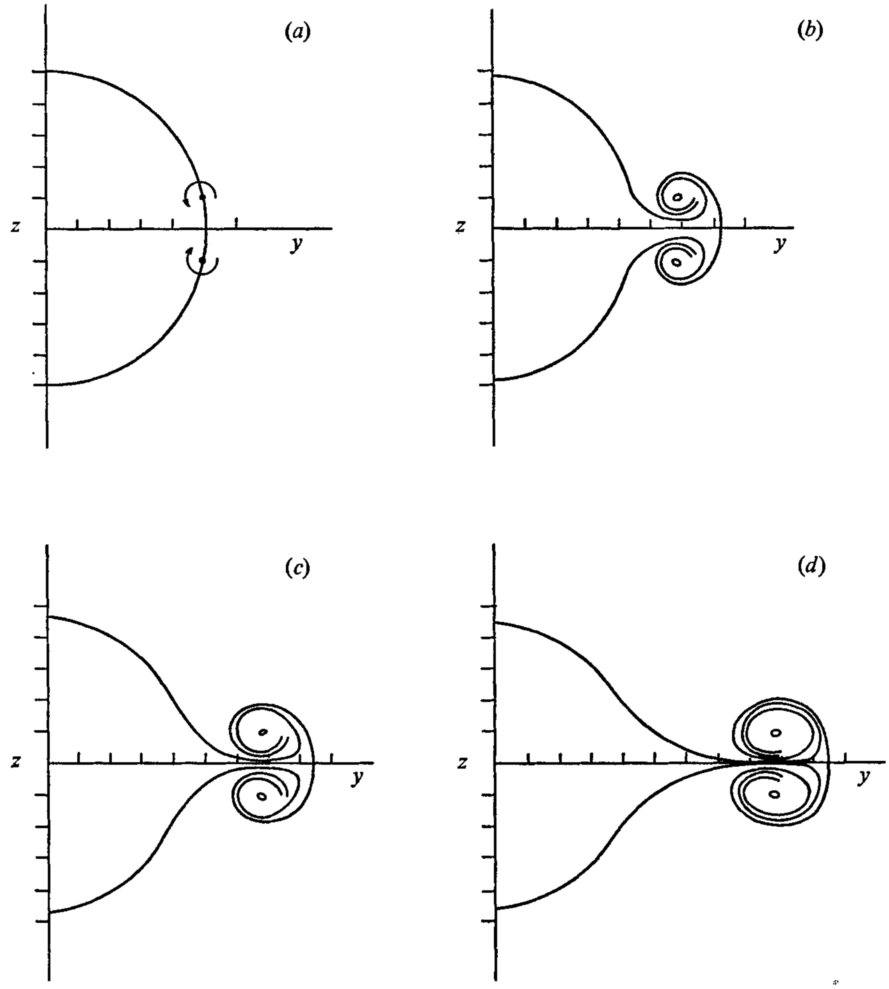
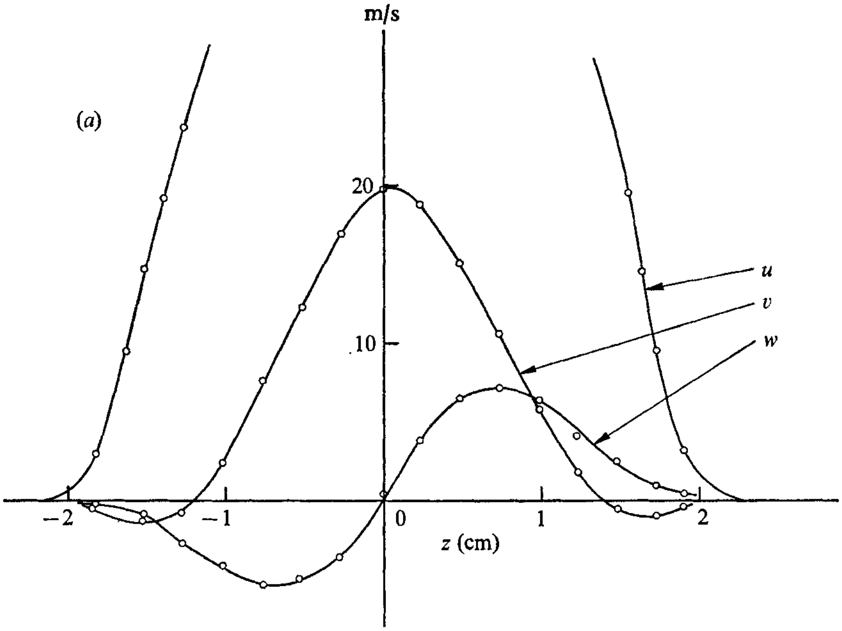


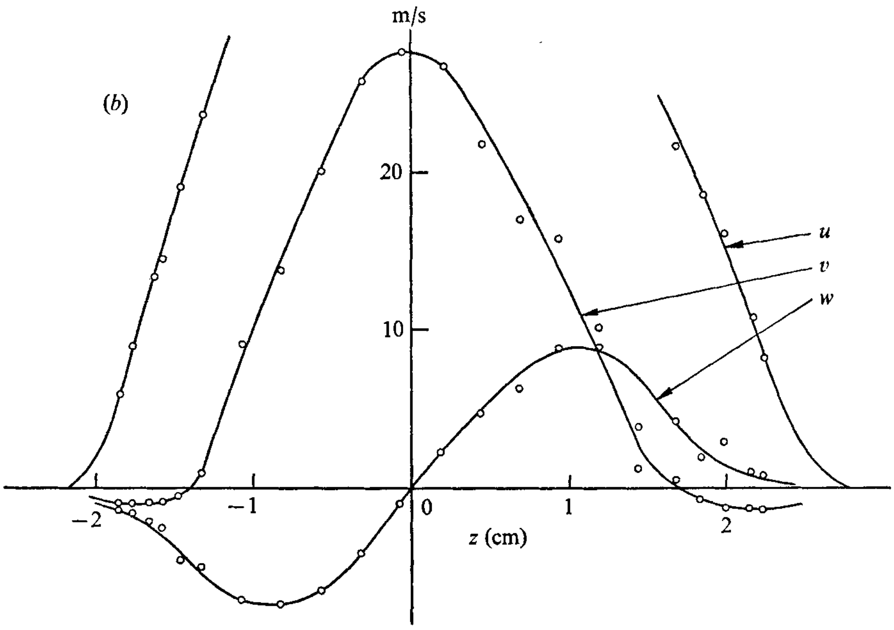
FIGURE 9. Distortion of unit circle at (a) $Kt = 0$, (b) $Kt = 0{\cdot}25$, (c) $Kt = 0{\cdot}5$ and (d) $Kt = 1{\cdot}0$.

everywhere due to all four vortices except at the position of any one vortex, where the velocity is assumed to be that induced by the remaining three vortices. The algebra is straightforward and need not be repeated here. The equations were integrated numerically on the University of Manchester 1906A computer. The computations were lengthy but did not involve any difficulties as long as one did not want details too close to the centre of the vortices. In this part of the flow theoretical results are not significant anyway, as viscous effects will dominate in the real flow.

The results of just one calculation are given in figure 9 as distorted shapes of the originally circular jet boundary for different values of the parameter Kt, where K is the vortex strength and t the time, for the case $\theta = 11{\cdot}5°$.

The general similarity with the observed flows is obvious although it is hardly reasonable to look for quantitative agreement. Numerical calculations showed that the development of the distorted jet shape is extremely sensitive to the





FIGURES 10 (a, b). For legend see next page.

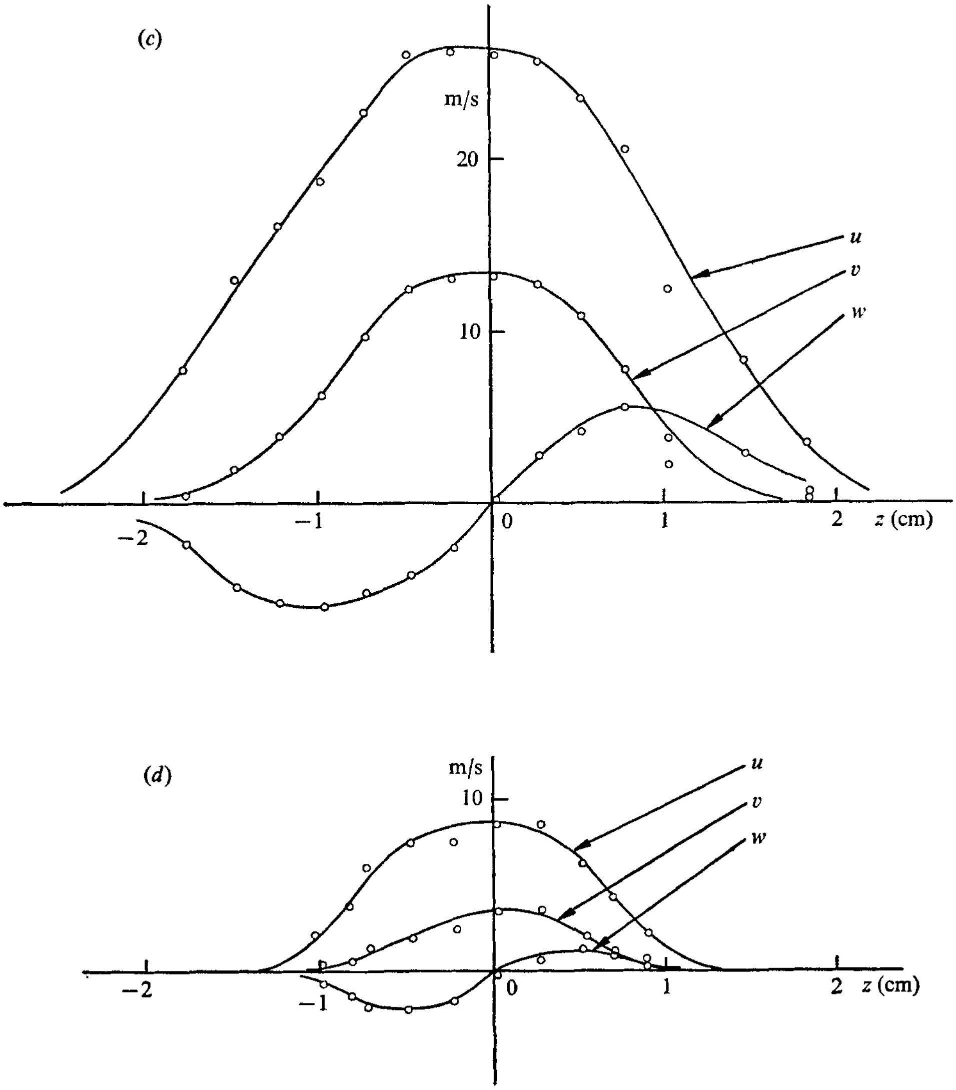


FIGURE 10. Velocity components at $x = 10$ cm and (*a*) $y = 3{\cdot}5$ cm, (*b*) $y = 5{\cdot}8$ cm, (*c*) $y = 7{\cdot}2$ cm and (*d*) $y = 8{\cdot}0$ cm.

location of the vortices, i.e. to the value of the angle θ, and one would therefore expect great sensitivity to notch shape and location. This was found to be the case in a number of experiments which will not be reported here.

6. Yawmeter traverses

A complete three-dimensional exploration of the jet is of course extremely laborious, but to demonstrate that it is possible we concluded the experiments by exploring the complete velocity field in the outer part of a plane 10 diameters downstream of the exit of the nozzle with 0·6 cm notches. Figure 10 shows sample

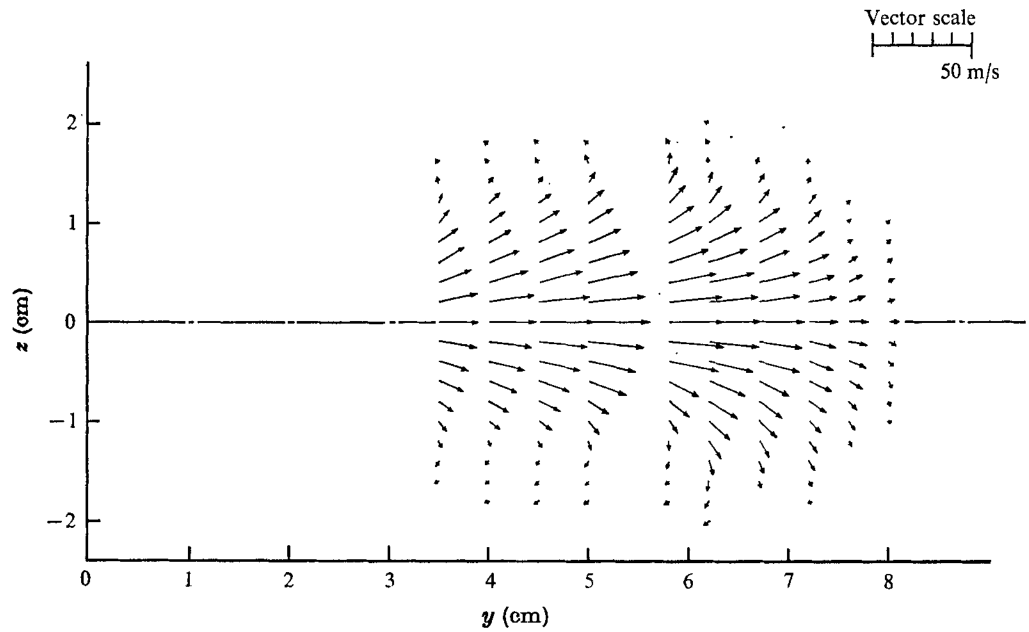


FIGURE 11. Velocity vector diagram at $x = 10$ cm.

curves of the velocity components in the direction of the axis (u), in the notch plane (v) and in the perpendicular plane (w). Figure 11 is a complete vector diagram of the velocity field in the y, z plane.

Although we have no doubts about the vortex model as a correct description of the basic mechanism, this is of course in the real flow greatly obscured by the large axial component of the velocity and by the turbulent mixing and entrainment. It was not found possible to determine the precise location of the vortex centres, nor have we been able to deduce a realistic value for the vortex strength.

7. Conclusions

We have shown how a detailed exploration of the structure of jets from notched nozzles leads to a physical explanation of the mechanism of such flows. We have also gone some way towards defining the main parameters of the flow. It is clear that notches are effective silencers not so much because they reduce the maximum shear in the jet and thereby the strength of the noise sources, but rather because they cause the sources to be surrounded by a broad region of low speed turbulent flow.

It is hoped that the recent improvement in the understanding of the shrouding and refracting effects of such regions (see Crighton 1975) will enable the acousticians to prescribe optimum flow configurations which can then be produced by a suitable location and shape of the notches.

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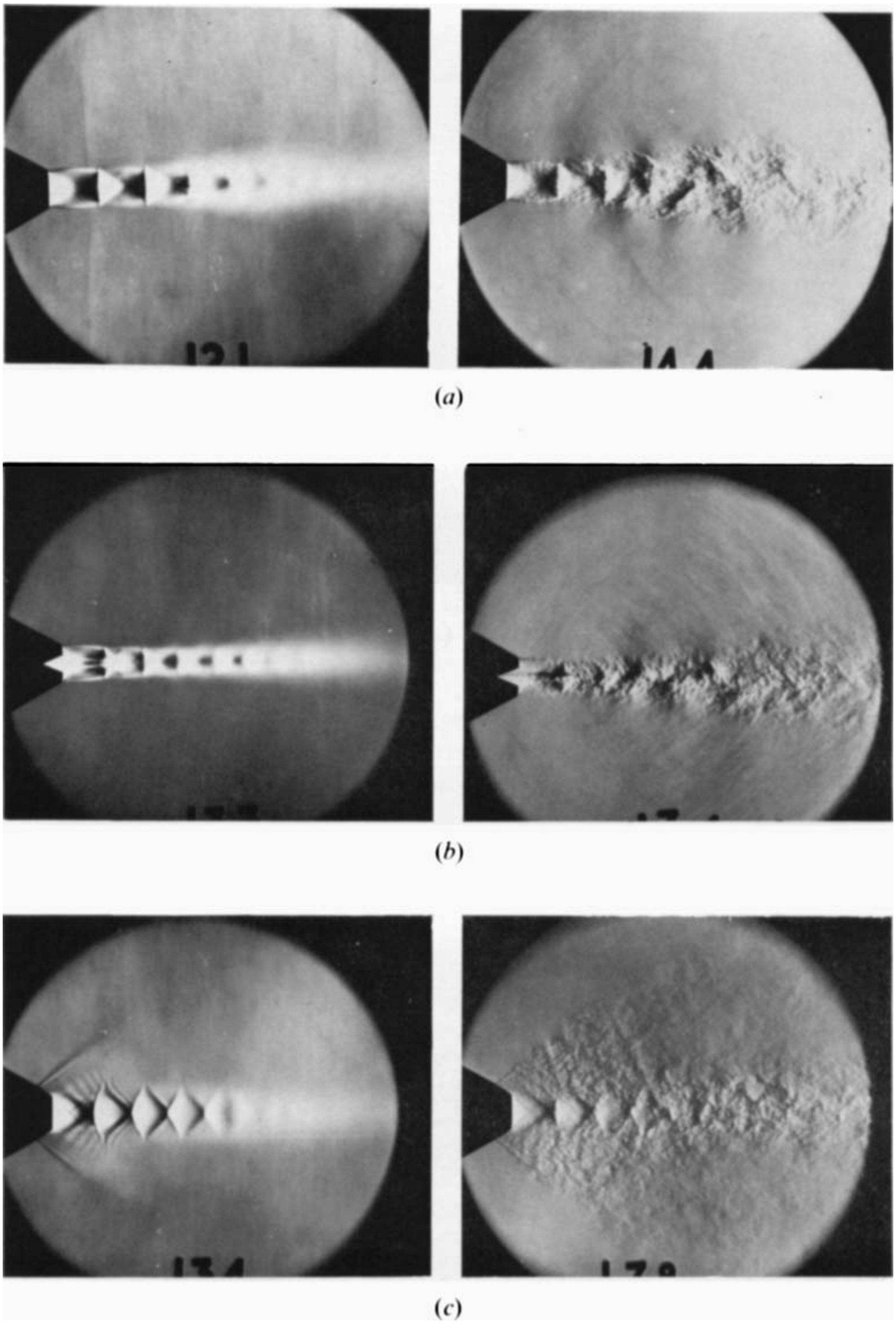
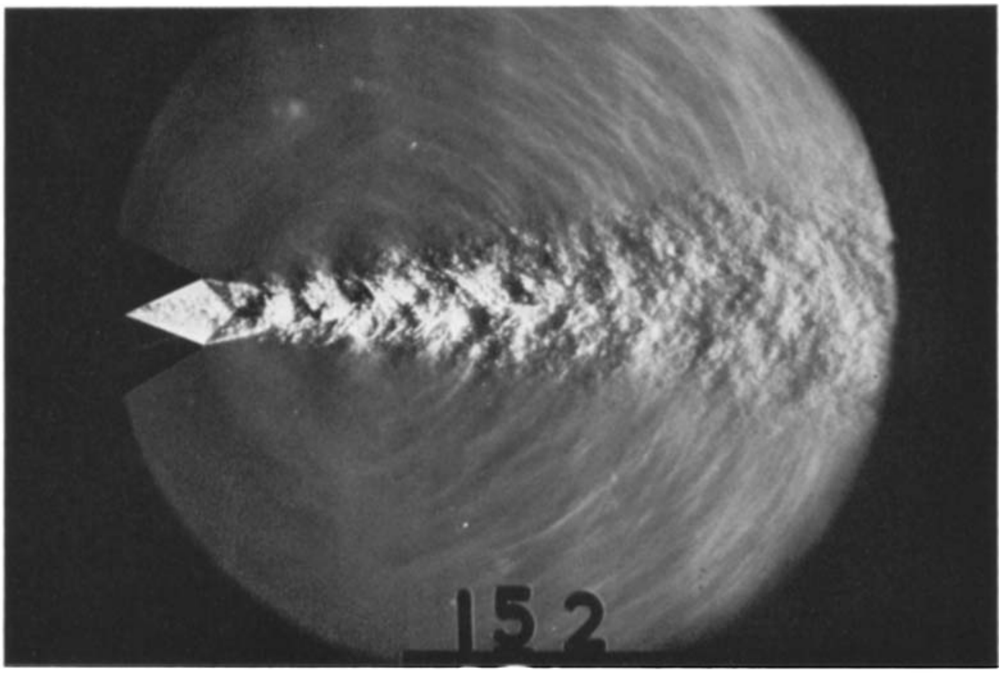


FIGURE 2. Schlieren photographs. (*a*) Conical nozzle. (*b*) Notched nozzle viewed in notch plane. (*c*) Notched nozzle viewed in perpendicular plane.



(*a*)

(*b*)

FIGURE 3. Schlieren photographs of jets from nozzle with 0·8 cm notches. (*a*) Notch plane. (*b*) Perpendicular plane.