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by

A. G. Kurn

Aerodynamics Dept., R.A.E., Farnborough

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OBSERVATIONS OF THE FLOW FROM A RECTANGULAR NOZZLE

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SUMMARY

An experimental investigation is described of the flow from two rectangular nozzles, for the pressure ratio (H_j/p_∞) range up to 3, blowing into still air and into a stream flowing in the same direction as the jet and having a Mach number of 0.74. The jet stream was observed by taking schlieren photographs, from which the positions of the shock waves were measured and related to those from a circular nozzle. Measurements were made of the jet pressure profiles at several stations along the length of the jet stream, and it is shown that the general shape of these profiles can be observed at a light screen using smoke injected into the air supply pipe for the jet.

There was a substantial difference in the cross-sectional shape of the jet downstream of the nozzle for $M_\infty = 0$ and 0.74 which was associated with vortices formed by the interaction between the external stream and the jet flow diverging from the sides of the nozzle exit. Additional evidence from an elliptical nozzle confirmed the conclusion that for a practical engine design with any flattened nozzle exit vortices would be present in the flow with an external stream.

* Replaces RAE Technical Report 74043 - ARC 35451

CONTENTS

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1 INTRODUCTION

In the quest to reduce the exhaust noise from aircraft engines various modifications have been made to the conventional circular nozzle shape to obtain a high degree of mixing with the external stream at the nozzle exit. It has also been suggested that a flattened, oval or rectangular, shape might be beneficial, not only by giving some intrinsic reduction in jet noise, but also because noise shielding with an adjacent surface (e.g. wing or tailplane) might be increased by virtue of the possible reduction in the extent of the noise source. The present experiments were started in order to establish whether the jet flow from such nozzles had unusual features which might affect the aerodynamic interference with adjacent surfaces.

To obtain an understanding of the flow from flattened nozzles an investigation was made using two nozzles with almost rectangular exits. This work suggested that vortices were present when the jets from these nozzles exhausted into an external stream flowing in the same direction, and had a profound influence on the overall flow pattern. These observations led to confirmatory tests with an elliptical nozzle. All the tests were made on small nozzles in a wind tunnel, with a schlieren system to observe the jet stream. Pressure contours of the flow were obtained at several positions by traversing with a rake of pitot tubes, and the cross-sectional shape of the jet was made visible by smoke passing through a light screen. These two techniques gave results which agreed remarkably well, showing that in an external stream the flow from any practical nozzle with a flattened exit develops a characteristic cross-sectional shape.

2 THE TEST RIG

The work was carried out in the RAE 2ft × 1.5ft (0.61m × 0.46m) transonic wind tunnel where a rig exists for jet-blowing experiments. This rig consists of a coaxial pair of tubes cantilevered from a support in the tunnel settling chamber and positioned along the centre-line of the working section with a nozzle fitted to the end. Air at approximately tunnel temperature is fed to the nozzle along the inner tube, with the annular gap between the tubes used to remove by suction much of the very thick boundary layer that develops along the outside of the outer tube[1].

Most of the testing was done at tunnel Mach numbers of zero and 0.74* and a tunnel total pressure of 67 kN/m^2 which gave a Reynolds number of

* M_∞ = 0.74 was chosen only because earlier tests with a rectangular nozzle mounted on a wing upper surface had been made at this Mach number[2].

8.9×10^6 per metre at $M_\infty = 0.74$. However, when smoke was used to visualise the jet shape it was necessary to restrict the maximum total pressure of the jet to 96 kN/m^2; the tunnel pressure and the Reynolds number were consequently reduced by about 20% at the highest jet pressure ratio, H_j/p_∞, of 2.60: where H_j is the mean total pressure in the jet at the nozzle exit and p_∞ is the tunnel static pressure.

The range of jet pressures tested when using the smoke technique was from the free flow condition, with the jet total pressure equal to that of the free stream total pressure, to $H_j/p_\infty = 2.60$. For the schlieren observations H_j/p_∞ was varied over the range from about 1.9 to 3.0.

3 THE NOZZLES

Two almost rectangular nozzles were tested (Fig.1); these are identical in diameter where they attach to the coaxial tubes, and have almost identical ratios of width to height of 2.5 at their exits. It can be seen from Fig.1 that they are not quite rectangular at the exit: for ease of manufacture the nozzles were turned in a lathe, then two sections on opposite sides of the resulting conic frustum were removed and replaced by thin flat plates. The internal shape of the large nozzle, from 122mm upstream of the exit, diverges from a circular section of 1360 mm^2 to one of 1720 mm^2 over a distance of 40 mm. The flat plates, top and bottom, then reduce the cross-sectional area to 1271 mm^2 at the exit although the sides of the channel, being an extension of the upstream conical expansion, continue to diverge at a half-angle of about 3.6^o. The small nozzle has a simpler internal shape; the circular section remains constant at 1360 mm^2 until 72.5 mm from the exit where it is intersected by the plates which reduce the area to 677 mm^2 at the exit. The sides of the channel remain parallel in this case. The external shape of both models converges from a circular section 128mm upstream of the exits; the convergence is greater on the small nozzle due to the smaller exit. It was felt that if there were any significant effect of nozzle geometry on the flow field these two nozzles would be sufficiently different to make the change in flow apparent.

4 SCHLIEREN OBSERVATIONS

With sonic exit flow conditions a series of schlieren photographs was taken of the jet stream issuing from the two nozzles. The nozzles were rotated about their axes to obtain both plan and side views of the stream and the photographs are presented in Figs.2 to 5 for free stream Mach numbers of zero and 0.74.

There is no really outstanding difference in the flow from the two nozzles, except that with the free stream present ($M_\infty = 0.74$) it would seem that the geometry of the small nozzle gives rise to an increase in static pressure behind the nozzle so that the jet stream flow remains subsonic at $H_j/p_\infty = 1.95$ (Fig.5). There is, however, an appreciable effect on the jet flow from both nozzles due to the free stream. At $M_\infty = 0$ the entrainment and mixing of the jet with the external air is sufficiently great to destroy any visible shock structure beyond a distance of about 3 nozzle widths downstream from the nozzle exit, whereas this is not the case at $M_\infty = 0.74$.

Compared to a circular nozzle (Fig.6) a significant feature of the flow from both the rectangular nozzles is the divergence of the stream in plan view as it leaves the nozzle exit, which occurs with and without an external stream flowing and does not appear to vary much with jet pressure ratio (Figs.2 to 5). Measurements made from the schlieren photographs show this outflow angle to be about 11° for the large nozzle and 7° for the small nozzle. It is observed that the difference between these expansions in the stream flow corresponds roughly to the 3.6° difference in the internal angles of the two nozzles (section 3). The important feature of the divergence of the jet flow is that it continues for some considerable distance downstream with an accompanying increase in the span of the shock waves. For a circular nozzle on the other hand, although divergence initially occurs at the exit (and increases with jet pressure ratio) there is a corresponding contraction to the first normal shock which is nominally of the same diameter as the exit. This behaviour is repeated between successive shocks with a gradual decay due to mixing with the external stream. In fact the flow from the rectangular nozzles in side view is somewhat similar in behaviour to the flow from a circular nozzle.

From the photographs of Figs.2 to 5 the positions of the shock waves have been measured along the centre-line from the nozzle exit (ℓ). These distances have been non-dimensionalised by the nozzle height (h) and plotted against jet pressure ratio in Figs.7 and 8. It can be seen that there is very good agreement between the measurements made from the side and the plan view photographs. Except at the very low jet pressure ratios it is noticeable that there is a larger spacing between successive shocks from the small nozzle. This difference in the shock spacing may well be due to the different total pressure distributions across the exits of the nozzles (*cf.* Figs.10 and 13); that from the small nozzle is more uniform. It can also be seen, at the higher jet pressure ratios, that the movement of the shock waves downstream is linear with jet pressure ratio, which is in agreement with the flow development from a circular nozzle. For the very low jet pressure ratios the difference in the shape of the curves for the two nozzles depends more critically on the jet pressure ratios at which the streams become sonic. H_j/p_∞ is a somewhat artificial parameter in that H_j is the mean stagnation pressure in the flow at the nozzle exit, and the local external static pressure is different from p_∞ due to changes in the shape of the nozzle and the jet stream as mentioned earlier.

In order to relate the shock waves in the supersonic jet flow from one nozzle to those from another with the same exit shape it is necessary to scale the measurements made by some nozzle dimension. When the exits of the two nozzles are different in shape the problem of comparing the jet streams becomes more difficult. However, by using the hydraulic diameter (D_h)* as a unit of measurement excellent correlation has been obtained in the positioning of the first normal shock from a circular nozzle and the first normal shocks from the two rectangular nozzles. This suggests that the effect of using D_h is to provide a unit of measurement common to the jet structure from both nozzle shapes, thereby matching the lengths of the first cells in the jet streams. This is shown in Fig.9 where the shock positions from a circular nozzle are compared to those from the small rectangular nozzle. The circular nozzle results were obtained from tests in the same tunnel at the same Reynolds number. In Fig.9 the normal shocks in the jet streams are numbered downstream from the nozzles (i.e. shock No.1 in Fig.9 ≡ 1st shock in Figs.7 and 8). As these two nozzles are so different in shape it is suggested that the dimension D_h may be appropriate for comparing the flow from nozzles of any shape. The conversion to hydraulic diameter for the two rectangular nozzles is given by $D_h = 1.46$ h.

From Fig.9 it can be seen that at $M_\infty = 0$ the jet length containing a regular shock structure from the circular nozzle extends appreciably further downstream than it does from the rectangular nozzle (see also Fig.6). It is probable that the reduced height of the rectangular nozzle allows the mixing process to reach the centre of the jet stream within a shorter distance. With an external stream flowing, results from the circular nozzle are given at $M_\infty = 0.50$ and 0.80, and for the rectangular nozzle at $M_\infty = 0.74$. For both nozzles the cellular shock pattern extended out of sight beyond the downstream edge of the tunnel schlieren window so it was not possible to determine the position at which the shock structure broke down, although Fig.5 suggests that

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* The 'hydraulic diameter' D_h of a non-circular pipe or nozzle is defined as (4X cross-sectional area/perimeter).

for the rectangular nozzle this is just downstream of the window*. Fig.9 shows that the spacing of the shock waves from the circular nozzle at $M_\infty = 0.80$ is uniform within the length of stream observed, which indicates that the mixing process is insufficient to affect the cellular structure of the jet stream. On the other hand, successive shock waves from the rectangular nozzle at $M_\infty = 0.74$ progressively become closer together with distance downstream, and the jet flow decays nearly as rapidly as the flow from the circular nozzle discharging into still air.

5 JET STREAM PROFILES

5.1 Pitot traverses

Total pressure distributions across the jet streams were measured by means of a rake of pitot tubes traversed across the exits of the two nozzles and at 152mm and 229mm downstream of the exits**. The profiles obtained are presented in Figs.10 to 12 for the large nozzle and in Figs.13 to 15 for the small nozzle. They are shown as contour lines of constant $\Delta H/H_\infty$, where ΔH is the increment in pressure above the total pressure of the external stream, H_∞ †. Thus the boundary of the jet stream is where $\Delta H/H_\infty \to 0$, but due to entrainment producing an asymptotic tendency the position of this boundary is difficult to define and has been omitted.

It can be seen that with the jet blowing into still air the exit flow from the small nozzle, with the greater internal contraction, is more uniform (Fig.13) than the flow from the large nozzle (Fig.10). As the jet moves downstream from the large nozzle there is a progressive widening of the stream, but very little increase in depth (Figs.11 and 12). The flow from the small nozzle does not broaden as rapidly as that from the large nozzle, but there is an appreciable increase in height giving a 'diamond' shape to the jet (Figs.14 and 15).

With the free stream flowing ($M_\infty = 0.74$) it can be shown, if the $\Delta H/H_\infty$ values are converted to $(H_\infty + \Delta H)/p_\infty$, that the exit flows for the two nozzles

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* For the rectangular nozzle the distance from the nozzle exit to the end of the schlieren window was about 220 mm.

** In a supersonic stream the pitot tube reading is less than the total pressure but at these jet pressure ratios the difference is a maximum of only about 2% at the centre of the nozzle exit which is insignificant in the present context.

† At $M_\infty = 0$, $H_\infty = p_\infty$.

are the same as for $M_\infty = 0$ (i.e. the contours of $(H_\infty + \Delta H)/p_\infty = (H_j/p_\infty)_{local}$ are identical for $M_\infty = 0$ and 0.74). Part of the boundary layer from the support tube is shown in Fig.13, which suggests that it was possibly thicker beneath the nozzle where no traverse was made*. Downstream from the exit the flow from both nozzles takes on a 'dumb-bell' shape with an indication that the flow is dividing into two cores at opposite ends of the major axis (Figs.12 and 15).

It is possible to deduce the approximate extent of the central supersonic region from these total head contours if it is assumed that everywhere the static pressure is equal to that in the free stream. For $M_\infty = 0$ the sonic boundary is given by $\Delta H/H_\infty \triangleq 0.9$, and for $M_\infty = 0.74$ by $\Delta H/H_\infty \triangleq 0.3$; so that at the station furthest from the nozzles (Figs.12 and 15) it can be seen that the jet streams at $M_\infty = 0$ are completely subsonic.

5.2 Jet stream smoke visualisation

To determine the contour shape of a jet stream by a pitot traverse can take an appreciable time, so an attempt was made to show the general outline indicated by the traverses through the use of smoke, although no previous successful use of the technique in supersonic flow was known. A tube from a smoke generator was connected to the jet air supply pipe, and a 1kW strip light was positioned vertically to shine through the tunnel schlieren windows. The light beam was restricted to pass through two vertical slits in series so that a sheet of light about 13mm thick crossed the tunnel working section. The lighting system was mounted on a carriage so that the sheet of light could be traversed along the jet stream. A camera, positioned at an oblique angle to the jet tube, was focussed on a square grid (with sides of 25.4 mm) in the plane of the light screen. The grid was photographed through the glass wall of the tunnel, and then superimposed on subsequent photographs of the smoke passing through the light screen, to give a scale which shows the distortion due to the angular position of the camera and the refraction due to the glass. After a certain amount of experimenting with the quantity of smoke and the film exposure the photographs of Fig.16 were taken. By tracing around the outside of the nozzle onto the grid board held against the nozzle exit the outline shown in the photographs was obtained. It is, of course, slightly larger than the actual nozzle exit but helps to give an idea of how the area of the smoke relates to the nozzle. Unfortunately, the camera was inadvertently moved so that the exit

* The suggestion of asymmetry in the boundary layer is probably due to small cross-flows in the tunnel over the long length of tube supporting the nozzles. It probably exists in Fig.10 although measurements were not made.

at $M_\infty = 0.74$ is displaced slightly to one side. When these photographs are compared to the total pressure contours of Fig.15, and an allowance made for distortion, it can be seen that they are remarkably similar. Measurements made of the shape of the smoke in Fig.16 at $M_\infty = 0.74$ show that the boundary of the smoke coincides approximately to the $\Delta H/H_\infty = 0.1$ contour of Fig.15. At $M_\infty = 0$, due to the greater diffusion of the smoke, the boundary is less clearly defined.

The confidence inspired by the success of the smoke technique at this stage led to a wider investigation with the small rectangular nozzle, when both jet pressure and free stream Mach number were varied. No great change in jet stream shape occurred for free stream Mach numbers between 0.5* and 0.9. More noticeable was the change when jet pressure ratio was varied, the 'dumb-bell' shape becoming more pronounced as the jet pressure ratio decreased (see Fig.17b)**. This occurred in a progressive and continuous manner with no abrupt change as the jet stream became subsonic. Moving the light screen progressively from the nozzle to the end of the schlieren window†, the flow leaving the rectangular exit immediately began to change to the characteristic 'dumb-bell' shape. The 'dumb-bell' appeared to develop slowly downstream with only a slight change in shape discernible from about 200mm downstream of the nozzle exit to the end of the schlieren window. The effect of the thickness of the boundary layer on the afterbody was investigated by turning off the suction system which normally operates when a free stream is flowing (section 2). This was found to have a negligible effect on the shape of the jet.

Confirmation that with an axi-symmetric nozzle the external stream does not alter the jet stream shape is given in Fig.17a where two photographs are presented at the same Mach numbers as for the rectangular nozzle in Fig.16. The double coaxial nozzle in this case is typical of the design used on engines of present day transport aircraft, with a long gas generator and a fan duct. The photographs show that the two circular jet streams are identical in size.

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* $M_\infty = 0.5$ is the lowest Mach number obtainable in the 2ft × 1.5ft tunnel under normal operating conditions unless an attempt is made to choke the diffuser.

** As in Fig.16 ($M_\infty = 0.74$) the nozzle exit on the photograph is displaced to one side.

† For the smoke tests the jet tube was shortened to provide a visual traversing length of about 320 mm from the nozzle exit.

In contrast, a nozzle with a flattened exit of elliptical shape was tested. Pressure contours from this nozzle had been obtained during an experiment some years previously[2], and they are presented with the nozzle shape in Fig.18. It can be seen from these contours that the flow from this nozzle also forms into a 'dumb-bell' shape, albeit with the ends somewhat distorted. The smoke shapes however, over the same range of free stream speed and jet pressure ratio as for the rectangular nozzle, did not reveal this distortion, and it is thought that there was possibly some asymmetry in the pitot traversing gear which interfered with the flow. A photograph of the smoke at a low jet pressure ratio is given in Fig.17c to compare with that from the rectangular nozzle (Fig.17b); the similarity is apparent. Alteration of the exit pressure profile by fitting a wire mesh screen inside the nozzle at the end of the circular section made no significant difference to the jet shape. When blowing into still air, however, the flow, as for the rectangular nozzle, was entirely different from that with an external stream flowing. The jet diverged appreciably in the vertical direction and the smoke diffused so much that the photographs taken did not clearly define the outline and are not worth presenting.

6 DISCUSSION

The smoke distributions for the flattened nozzles, particularly that of Fig.17c, indicate that a pair of contra-rotating vortices exist in the external stream on each side of the jet, with the upper right-hand vortex circulating in an anti-clockwise direction and the upper vortex of the opposite pair rotating clockwise. The surface flow on the outside of both the elliptical and rectangular nozzles, as shown by an oil flow technique, gave no obvious indication that the vortices were directly due to the external shape of the nozzles. However, schlieren observations of the flow leaving the nozzles revealed an appreciable divergence of the jet stream in plan view, and it is possible that the vortices are formed by the interaction of the external stream with the diverging flow in the plane of the jet exit.

The lateral divergence of the jet from a particular flattened nozzle remains effectively constant irrespective of free stream velocity or jet pressure ratio (Figs.2 to 5), which suggests that the divergence is determined primarily by the internal geometry of the nozzle. However, when jet pressure ratio is reduced the cross section of the jet indicates an apparently more pronounced vortex system (*cf.* Fig.16 for $M_\infty = 0.74$, and Fig.17b). This may be because the constant lateral divergence of the jet gives rise to a vortex system which has a relatively more dominant effect on the weakened jet flow.

A change in nozzle geometry to increase the divergence of the jet stream is shown also to make the vortex system more pronounced. Evidence of this is given by the smoke patterns of Figs.17b and c, which indicate that the vortices are strongest from the elliptical exit where the divergence is greatest. Similarly, Figs.2 to 5 show that the large rectangular nozzle has a greater jet divergence than the small nozzle. The pressure contours for the jet streams from these two nozzles (Figs.11, 12, 14 and 15) show a correspondingly more prominent 'dumb-bell' shape for the large nozzle, suggesting that this nozzle has the stronger vortex system.

It is not clear whether the outer shape of the nozzle has an important influence on the development of the vortices, but it seems likely that to some extent the thinning of the jet in the vertical direction is induced by the inward component of flow along the top and bottom surfaces. However, as the general character of the flow is so similar for the three nozzles, it seems reasonable to expect similar flow from any nozzle broadly comparable in shape to those tested here. In particular, it seems likely that any practical nacelle shape for a turbofan engine which incorporated a transition from the basically circular shape around the fan to a flattened exit would produce this sort of jet shape.

It is natural to expect that mixing between the jet and free stream will be enhanced by the presence of vortices as illustrated by these tests. It is also reasonable to expect that the noise sources in the distorted jets will be different in magnitude and location; from this it may be deduced that it will be difficult to relate the noise produced by a jet from a non-circular nozzle in a moving stream to that produced by the jet from the same nozzle exhausting into still air. Discrepancies have in fact been noted in such tests (e.g. Ref.3).

7 CONCLUSIONS

(1) It appears that the shock cell pattern of the supersonic jet flow from a nozzle can be compared to that from another nozzle with a different exit shape if the cell lengths are scaled by the hydraulic diameter.

(2) The jet stream can be made visible by mixing smoke with the air supply and observing a cross-section as it passes through a thin sheet of light shining across the tunnel. By traversing the screen of light along the jet stream the

behaviour of the jet can be determined far more rapidly than by the tedious pitot traverse method.

(3) It seems likely that for any asymmetrical nozzle the jet stream leaving the nozzle exit will diverge more in one plane than another. This is apparent, in particular, for an internal circular section changing to a flattened exit (rectangular or elliptical) where the flow divergence is greatest in the plane of flattening. It has been shown that the cross-sectional shapes of the jet streams exhausting into still air, from two nozzles with similar rectangular exits but different internal geometries, become appreciably different as they progress downstream.

(4) The degree of lateral divergence of the jet flow from a flattened nozzle exit does not appear to be strongly influenced by an external stream flowing in the same direction as the jet. This initial divergence of the jet flow remains effectively constant irrespective of free stream velocity or jet pressure ratio, and appears to be dependent only on the internal geometry of the nozzle. The external stream gives rise to two pairs of contra-rotating vortices situated one on either side of the flattened jet. It is thought that these vortices are formed by the interaction of the external stream with the diverging part of the jet flow, with an increase in divergence apparently strengthening the vortices. This vortex system appreciably changes the cross-sectional shape of the jet, giving an outline which is thought likely to be characteristic of all flattened nozzles. It would therefore be imprudent to carry out model tests representative of an aircraft with an asymmetric nozzle in flight by testing in still air. In particular noise generation processes may be significantly different in the deformed jet with an external stream.

SYMBOLS

A	nozzle exit area
C	nozzle exit perimeter length
D	nozzle exit diameter
D_h	nozzle exit hydraulic diameter (= 4A/C)
H_j	mean total pressure in the jet at the nozzle exit
H_∞	free (or external) stream total pressure
h	nozzle exit height
ℓ	distance measured downstream from the nozzle exit along the nozzle centre-line
M_∞	free stream Mach number
p_∞	free stream static pressure
ΔH	local total pressure in the jet stream - H_∞

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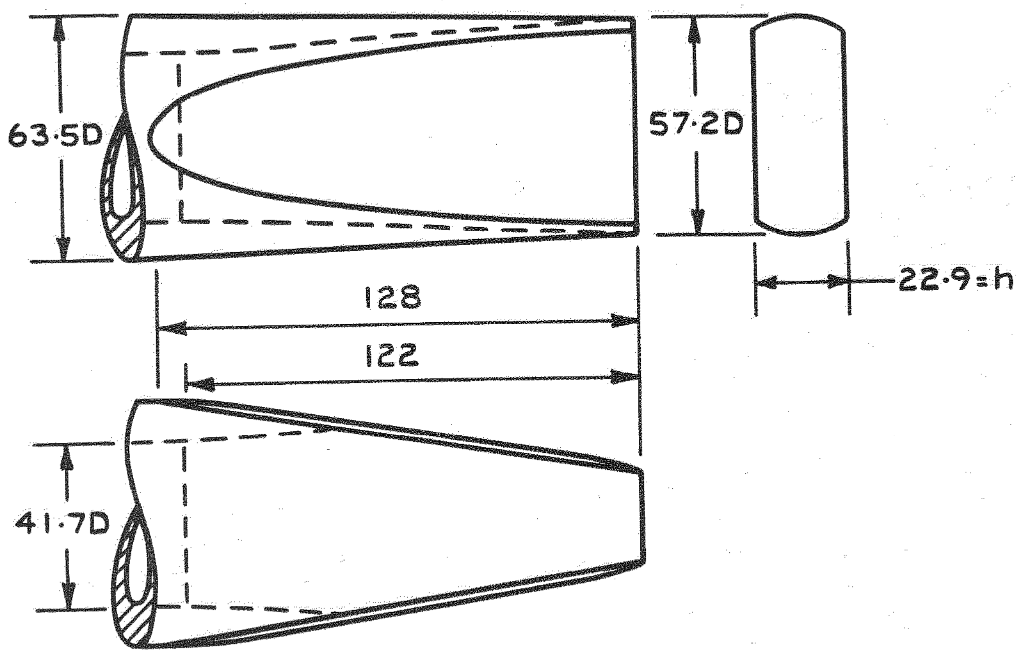
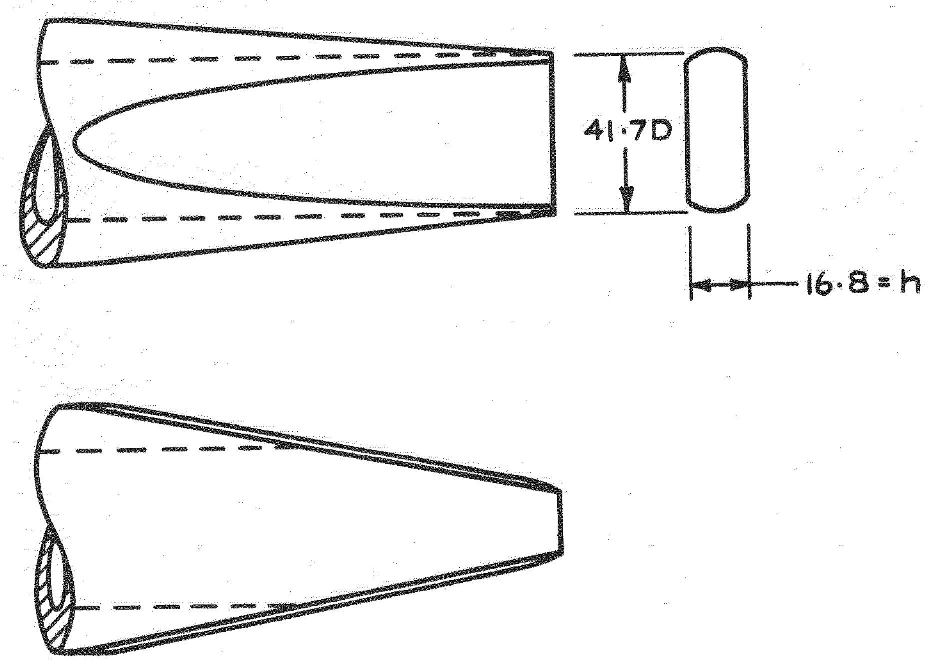
Dimensions in millimetres



a Large nozzle



b Small nozzle

Fig. 1a & b Nozzle geometry

H_j/p_∞

1.93

2.13

2.32

2.51

2.70

2.90

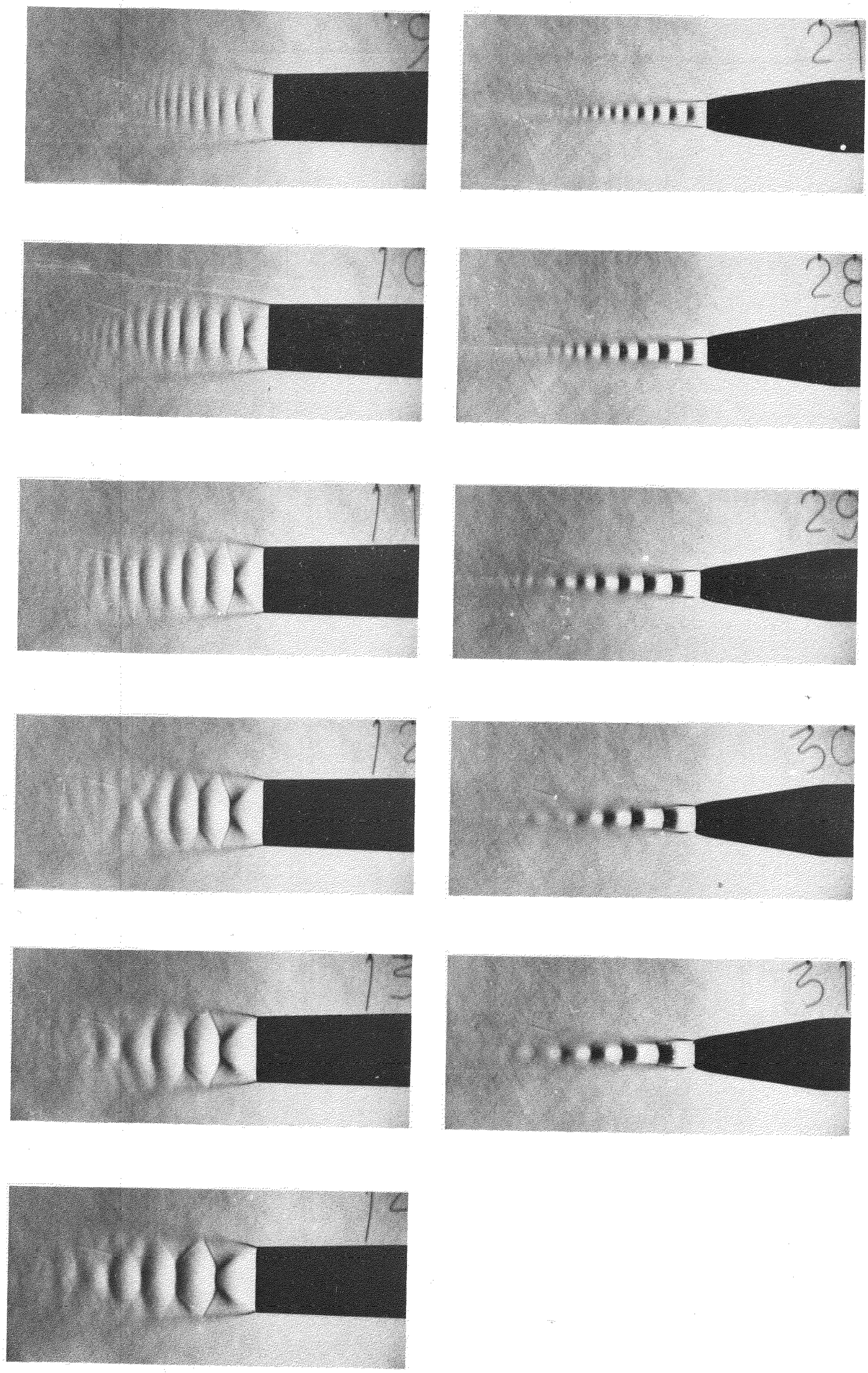


Fig.2 Jet stream flow from the large nozzle, $M_\infty = 0$

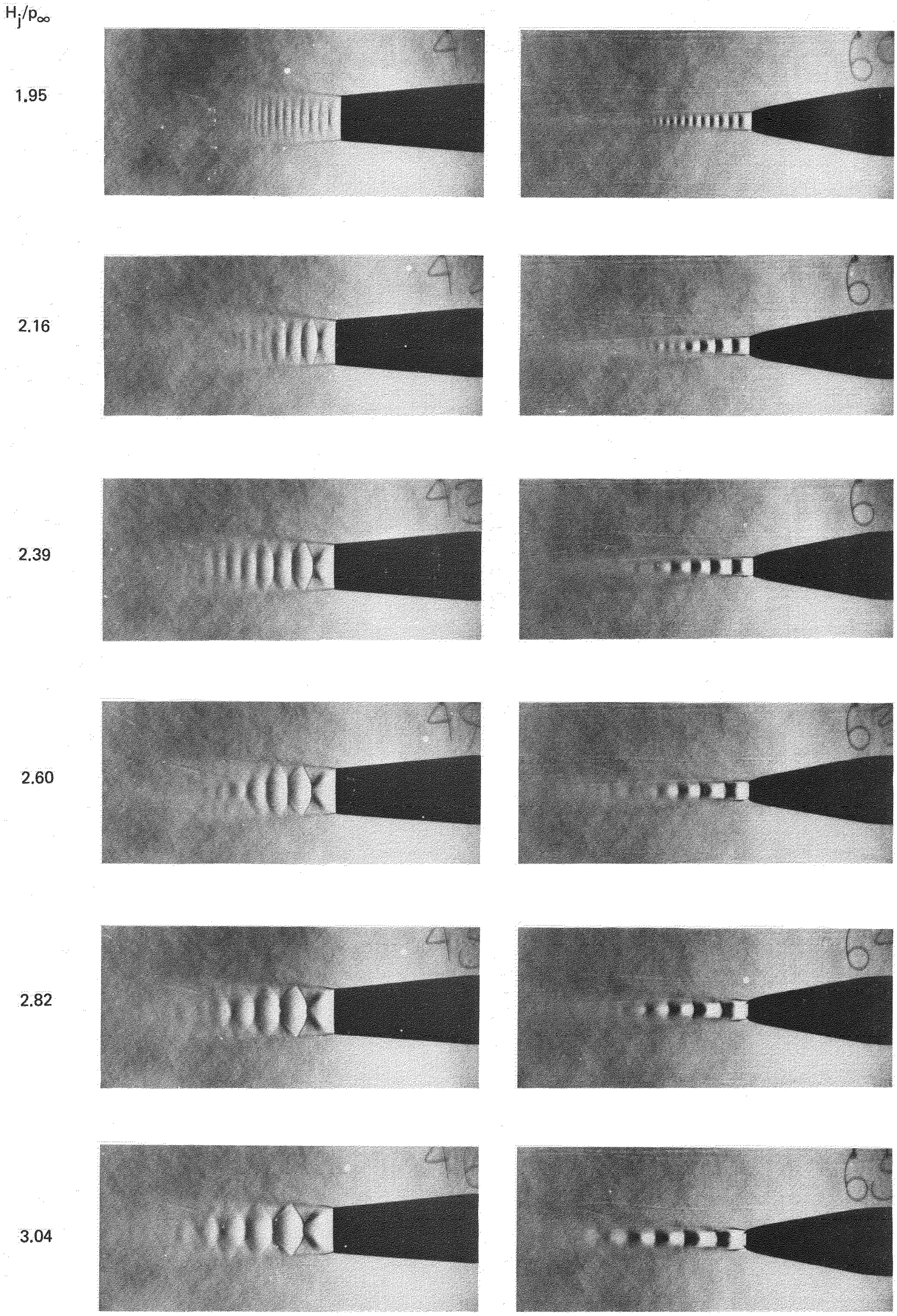


Fig.3 Jet stream flow from the small nozzle, $M_\infty = 0$

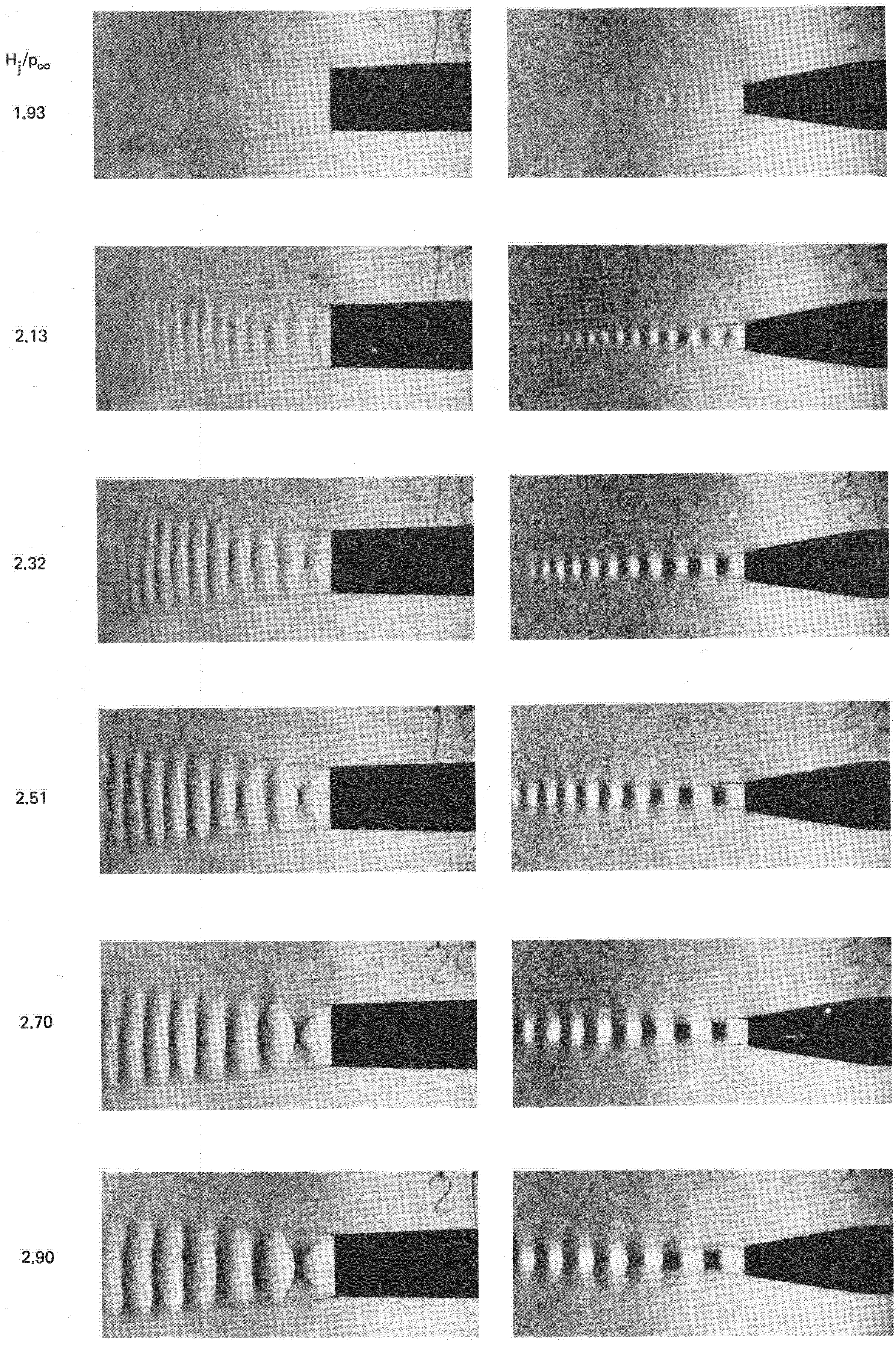


Fig.4 Jet stream flow from the large nozzle, M_∞ = 0.74

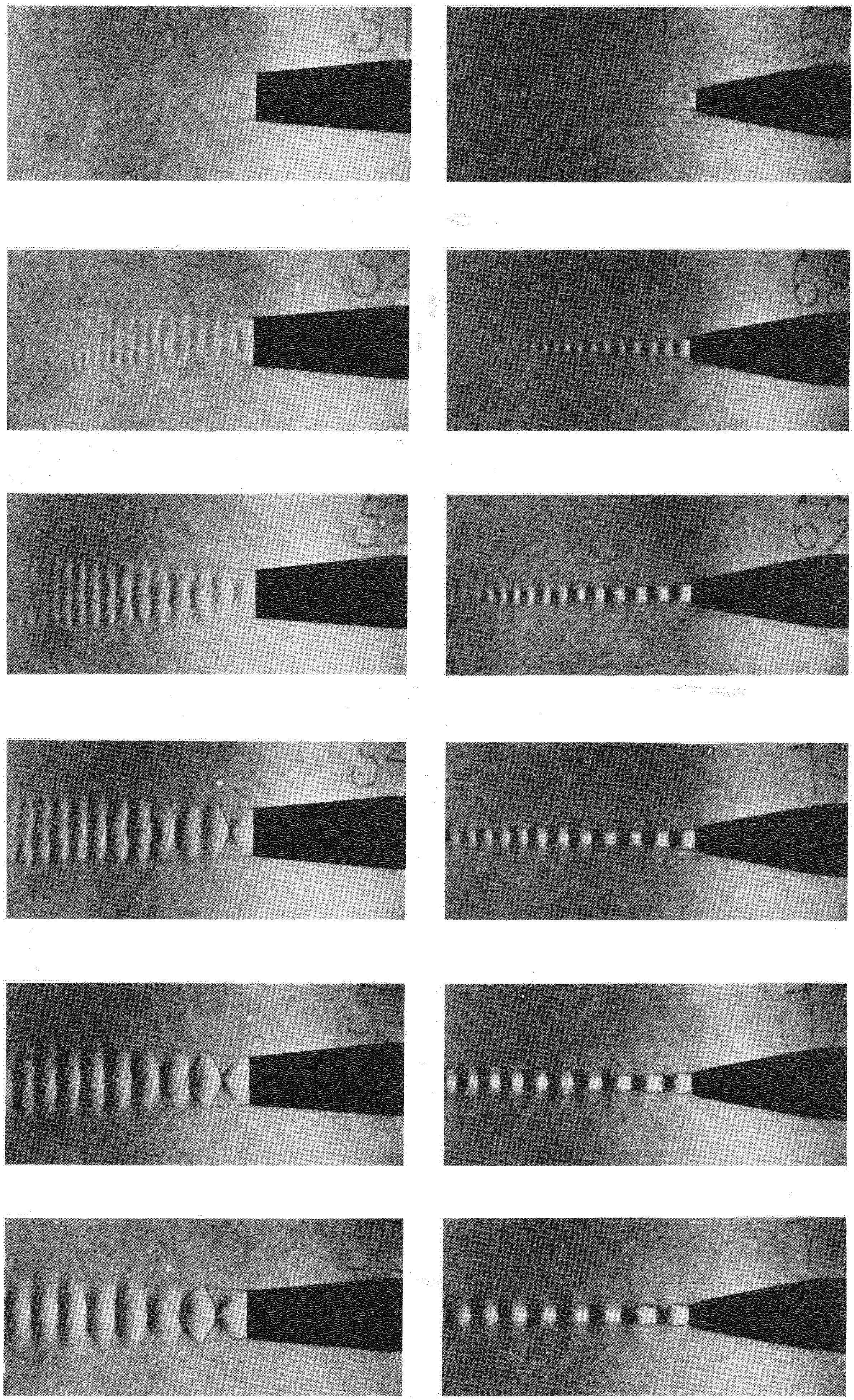
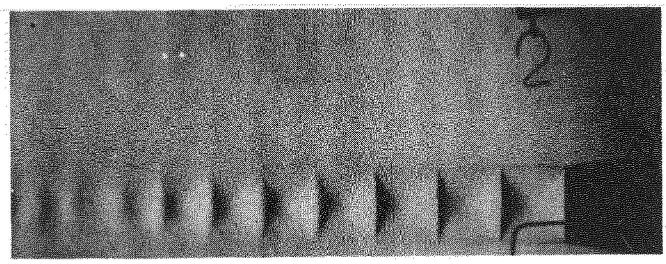
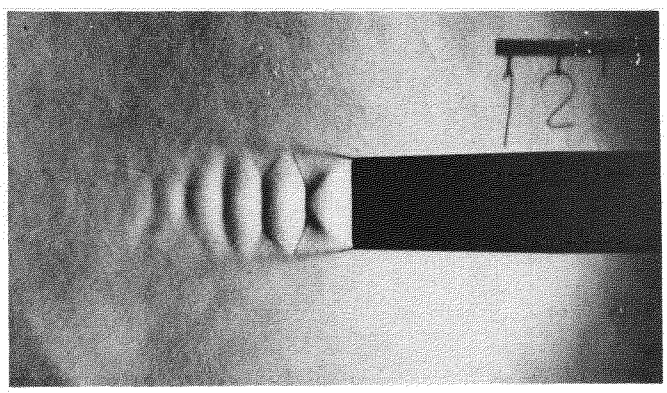


Fig.5 Jet stream flow from the small nozzle, M_∞ = 0.74



Circular nozzle. Diameter = 47 mm. $H_j/p_\infty = 2.47$



Large rectangular nozzle. Plan view. $H_j/p_\infty = 2.51$

Fig.6 Flow from a circular and a rectangular nozzle into still air

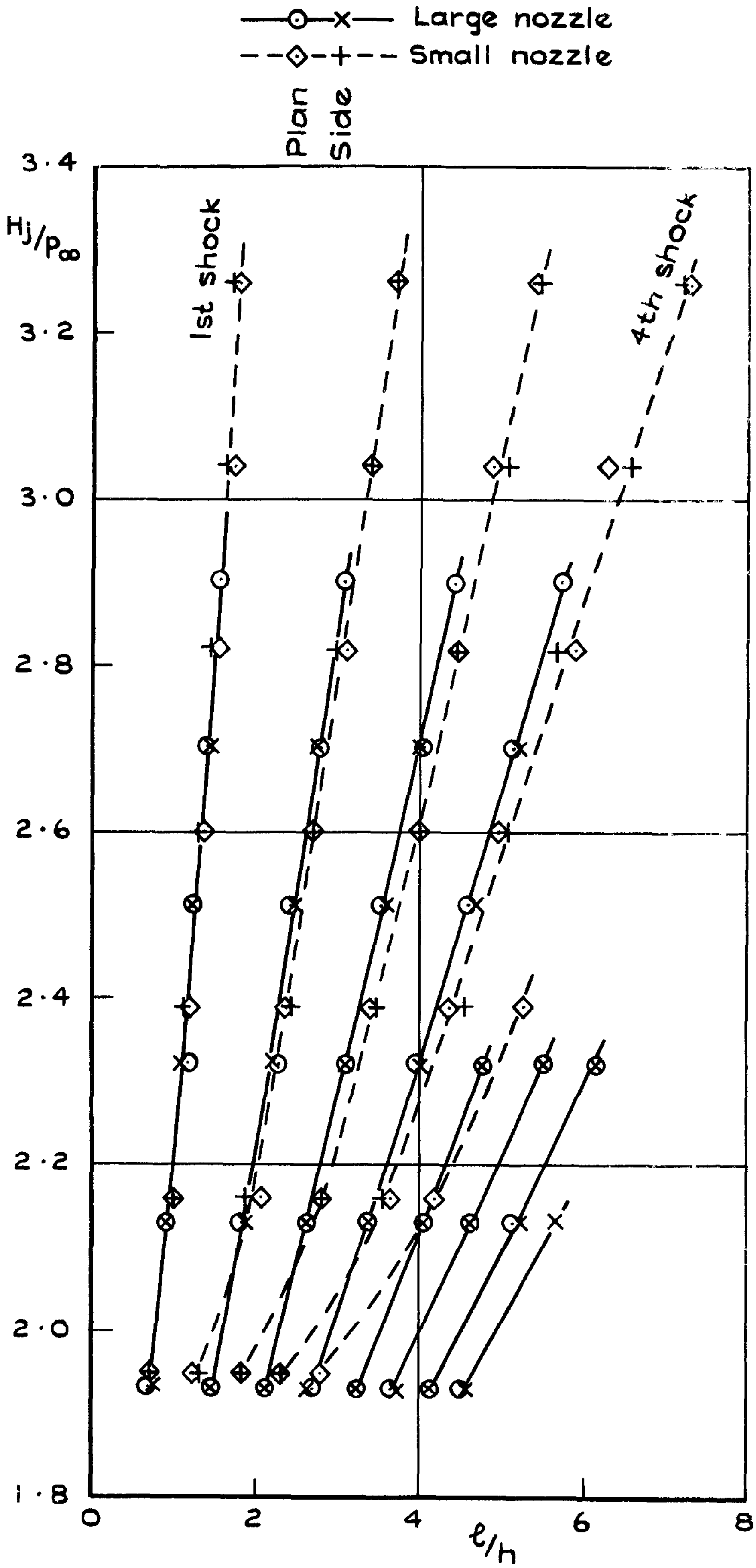


Fig.7 Jet stream development from the nozzles at $M_\infty = 0$

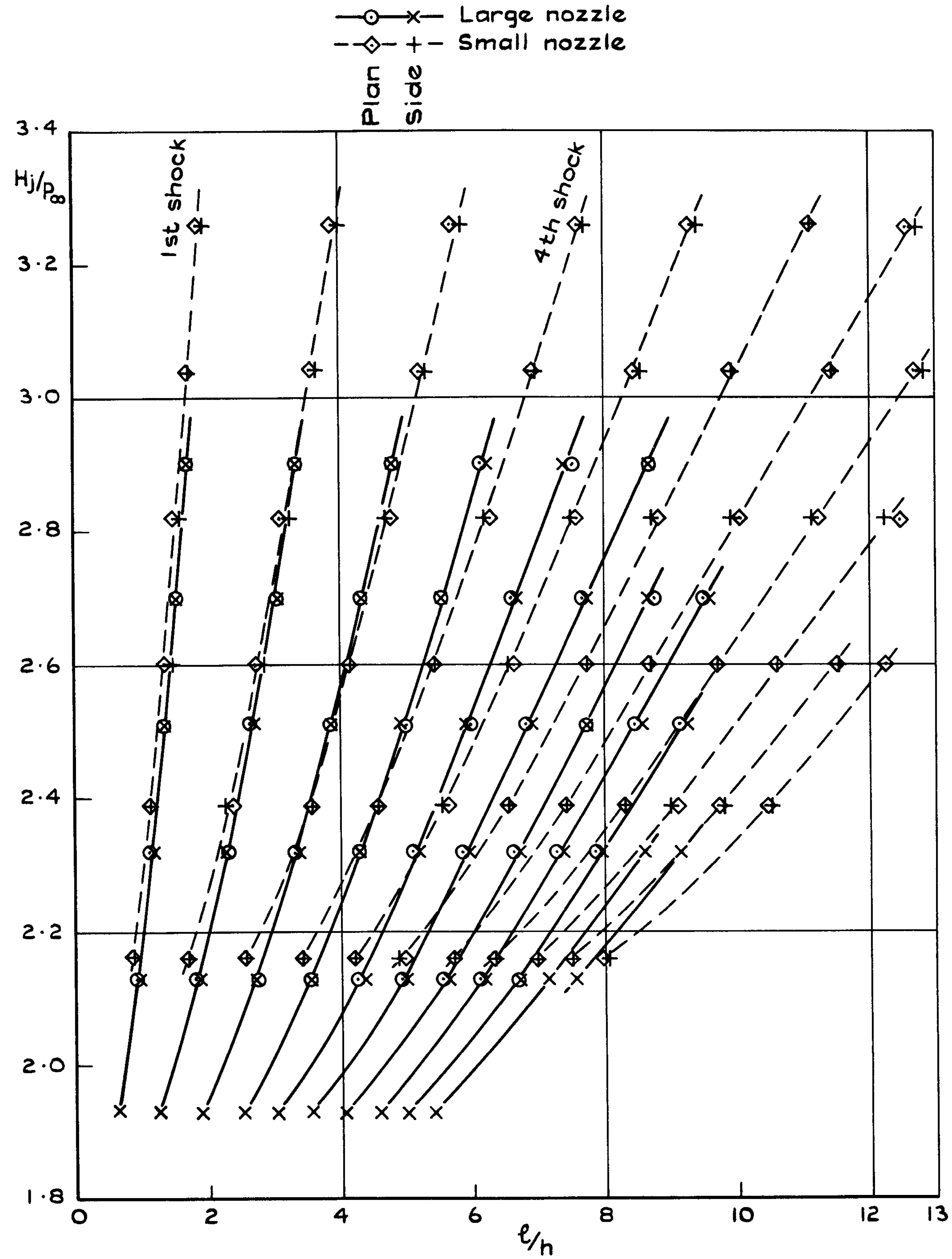


Fig.8 Jet stream development from the nozzles at $M_\infty = 0{\cdot}74$

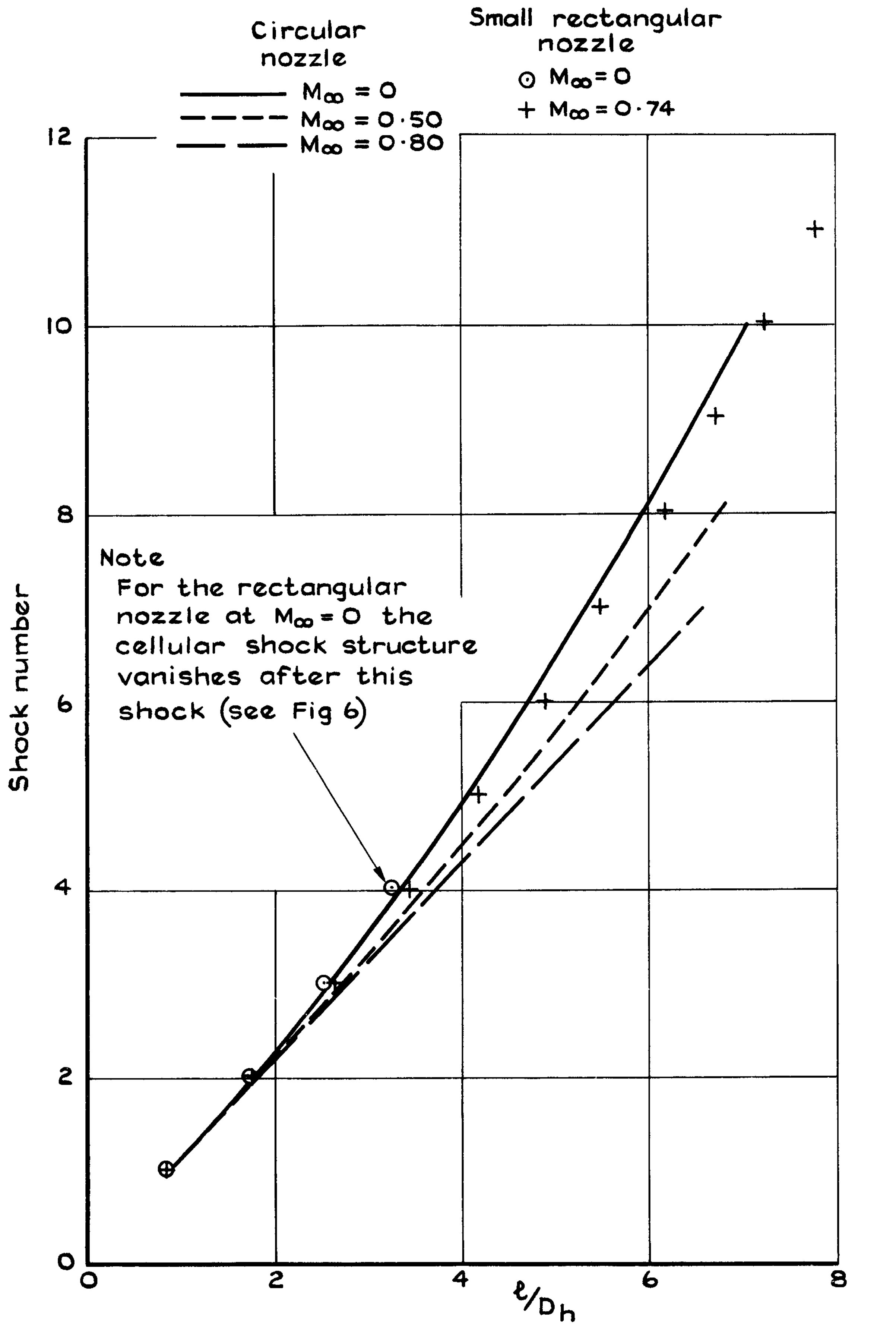
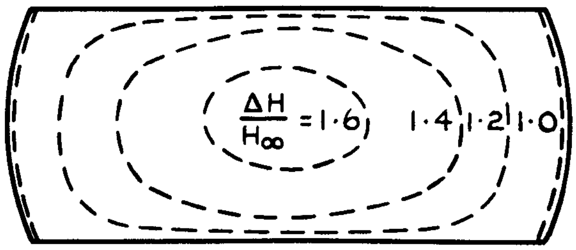
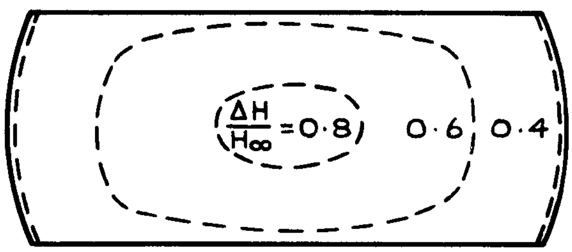


Fig. 9 Flow comparison between a circular and a rectangular nozzle at $Hj/p_\infty = 2 \cdot 50$



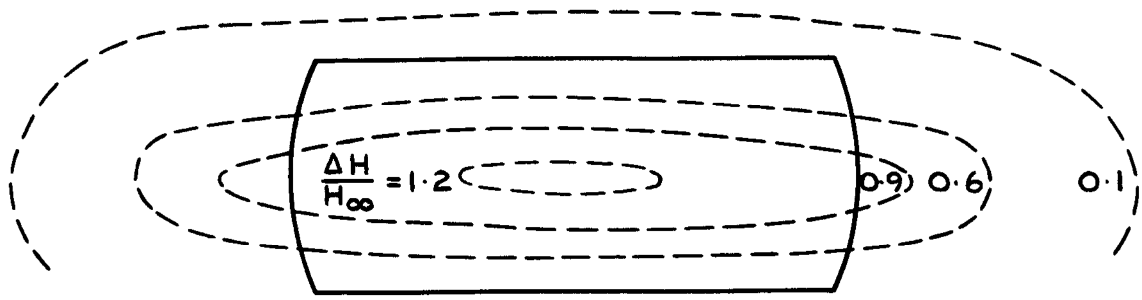
$M_\infty = 0$



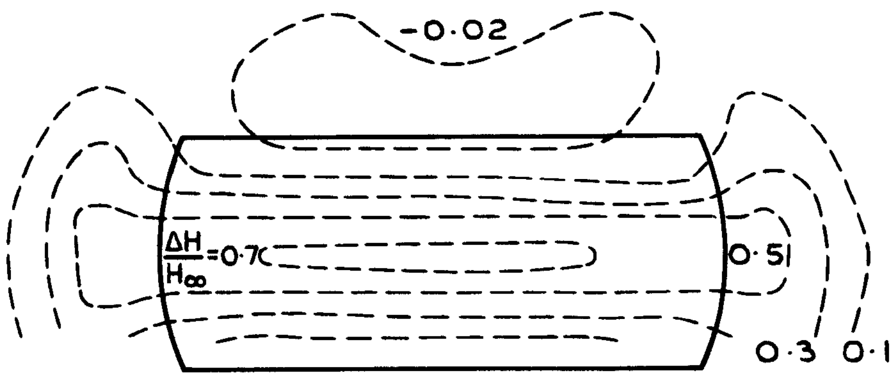
$M_\infty = 0 \cdot 74$

Large nozzle. $H_j/p_\infty = 2 \cdot 32$

Fig. 10 Total pressure profiles at nozzle exit



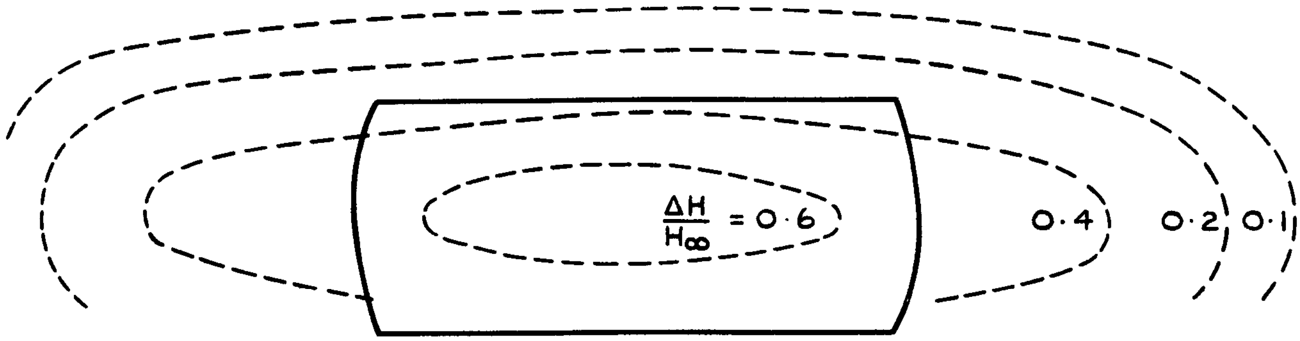
$M_\infty = 0$



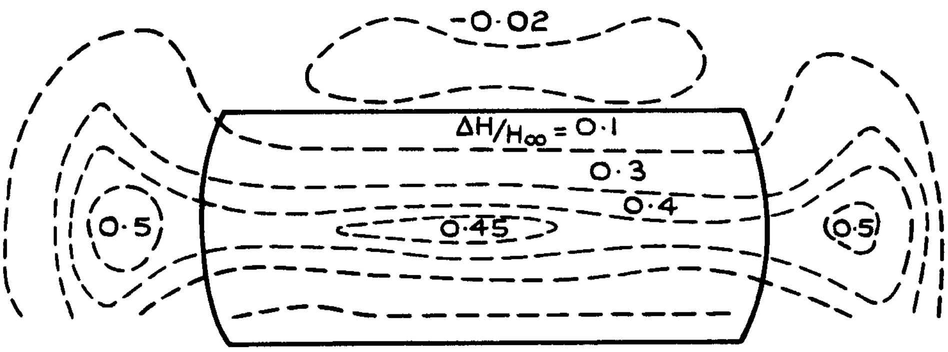
$M_\infty = 0{\cdot}74$

Large nozzle. $H_j/p_\infty = 2{\cdot}32$

Fig.11 Total pressure profiles 152 mm ($\ell/h = 6{\cdot}7$) downstream from nozzle exit



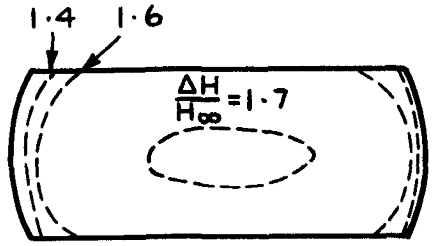
$M_\infty = 0$



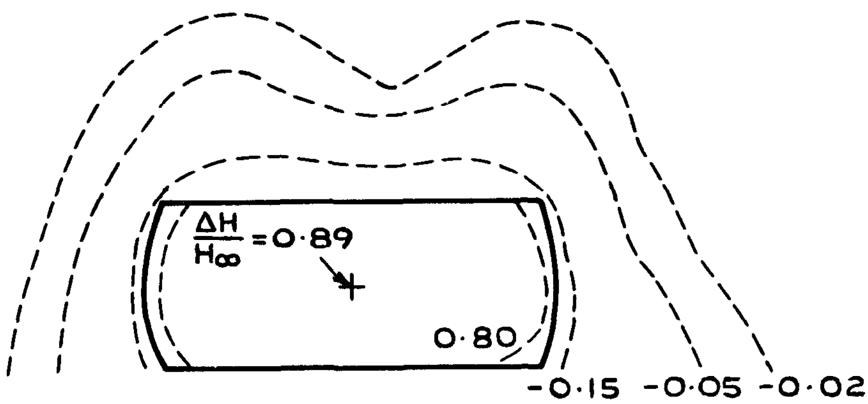
$M_\infty = 0 \cdot 74$

Large nozzle. $H_j / p_\infty = 2 \cdot 32$

Fig. 12 Total pressure profiles 229 mm $(\ell / h = 10)$ downstream from nozzle exit



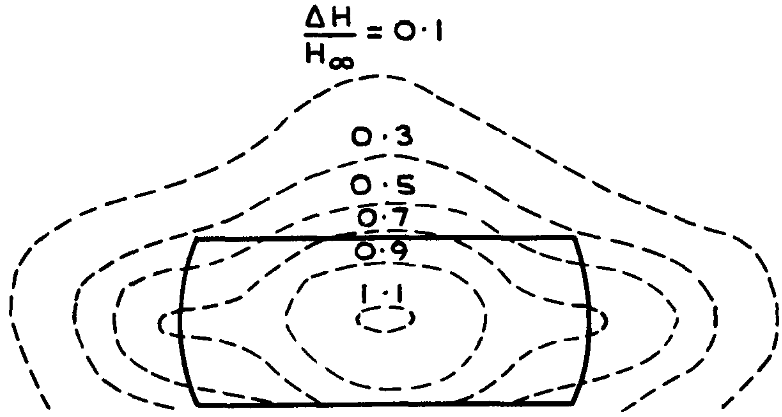
$M_\infty = 0$



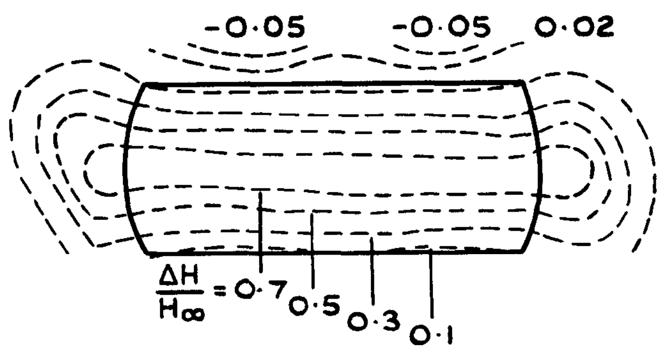
$M_\infty = 0\cdot74$

Small nozzle. $H_j/p_\infty = 2\cdot60$

Fig.13 Total pressure profiles at nozzle exit



$M_\infty = 0$



$M_\infty = 0 \cdot 74$

Small nozzle $Hj/p_\infty = 2 \cdot 60$

Fig. 14 Total pressure profiles 152mm ($\ell/h = 9 \cdot 1$) downstream from nozzle exit

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