

# Starting Processes of a Supersonic Jet Issuing from a Circular Tube

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## ABSTRACT

The existence of a supersonic vortex ring with an embedded shock in the unsteady flow following the emission of a shock wave from a circular tube has been confirmed in a previous study (Baird, 1986). It was shown in that work that the vortex ring acts as a converging-diverging nozzle in the choked condition with a recovery shock analogous to that observed in supersonic nozzle flow. A description of the flow is given, followed by a comparison of flow features resulting from initial shocks with three different Mach numbers, 1.31, 1.46, 1.67.

## INTRODUCTION

In a previous study (Baird 1986) the unsteady flow processes which occur after the emission of a shock wave from a cylindrical tube open to the atmosphere was discussed. The central feature of such a flow is a persistent vortex ring which convects downstream after the establishment of the oblique shock pattern at the exit of the tube which is usually associated with a steady overexpanded jet. Under the conditions considered in this work (initial Mach numbers ranging from 1.31 to 1.67) a shock wave is embedded in the vortex ring which occurs because the toroidal vortex constricts the jet in the same way as a converging-diverging nozzle in the choked condition. The resulting recovery shock is seen as a rearward facing shock by an instrument in the laboratory frame. That is, a static pressure probe records a pressure drop as the shock passes (Phan and Stollery, 1982).

## EXPERIMENTAL ARRANGEMENT

The shock tube was similar to that used by Phan and Stollery. It consisted of a cylindrical tube with an internal diameter of 25 mm. The burst of the Mylar diaphragm was initiated manually with a needle, and this resulted in a shock propagating along the tube. The shock speed repeatability was better than 0.5%. A pressure transducer mounted near the exit of the tube triggered a delay unit which, in turn initiated the spark light source for the differential interferometer.

The differential interferometer was of the standard type (see Merzkirch 1974, p.117 for example) using Wollaston prisms with a beam separation angle of 2.5 minutes of arc in a direction perpendicular to the direction of the tube axis (Fig. 1). The mirrors were 150 mm diameter with a focal length of 1200 mm and the system was adjusted for finite white light fringes.

The method was chosen because it allowed clear visualization of the rearward facing shock by the shadowgraph effect while being insensitive to weaker density gradients in the axial direction of the tube. As a result the vortex core is only evident at its extremities and the vortex density gradients do not obscure the view of the rearward facing shock in the jet. A further advantage of this particular arrangement is that the oblique shock system at the exit is clearly visualized because of the fringe shifts caused

by the component of density gradient perpendicular to the tube axis.

## GENERAL FLOW DESCRIPTION

Figure 1 gives a schematic representation of the development of the supersonic jet as inferred by a series of interferograms taken at various intervals after the emergence of the initial shock from the open end of the tube.

As the initial shock emerges and begins to expand radially from the exit of the tube, the vortex ring also begins to form in the tube wall boundary layer adjacent to the tube exit (Fig. 1(a)). The radial expansion of the initial shock causes the shock to weaken and the resulting pressure reduction is communicated via expansion waves to the flow at the exit and thence upstream to the flow still in the tube. In this way a series of expansion waves moves upstream in the tube since the flow behind the initial shock is still subsonic. These expansion waves accelerate the flow in the tube until an oblique shock begins to form near the exit (Fig. 1(b)).

It should be noted that at this instant in the flow development the flow field at the tube exit is influenced by not only the wall boundary layer, but also by the presence of the vortex ring. Once the oblique shock system is closed across the tube (Fig. 1(c)), the flow at the tube exit upstream of the shock can no longer be affected by downstream influences.

The oblique shock reflection is then formed and the first signs of the rearward facing shock embedded in the vortex ring can be seen (Fig. 1(c)). The vortex ring has convected 0.5 of a diameter downstream by this time and is accelerating (see Fig. 4(c) of Phan and Stollery, 1983). The vortex ring with its attendant shock leaves the oblique shock structure (Fig. 1(d)), and continues downstream leaving the oblique shock structure characteristic of an overexpanded jet attached to the tube exit.

In Figure 1(d) numbers refer to various regions of the flow. Region 1 is that region upstream unaffected by the expansion wave, region 2 is at the exit of the tube where the flow has become supersonic as a result of the expansion. Region 3 is just downstream of the first oblique shock, while region 4 represents the eventual free jet. Region 5 is the 'throat' of the vortex ring, while 6 is the flow region supersonic in the vortex frame of reference. 7 is the region downstream of the shock.

Figure 2 is a pressure trace recorded by Phan (1982) using a static pressure probe placed 2 diameters from the tube exit. Since the probe is stationary in the laboratory frame regions 5, 6, and 7 are reversed. On the figure the pressure measurements corresponding to regions 5, 6, and 7 are marked.

## EFFECT OF MACH NUMBER

The description given above refers to the flow resulting from an initial Mach number of approximately 1.5. Figures 3, 4, and 5 are differential



Figure 1: Diagram depicting essential features of the flow development. The numbers marked in (d) refer to regions described in the text.

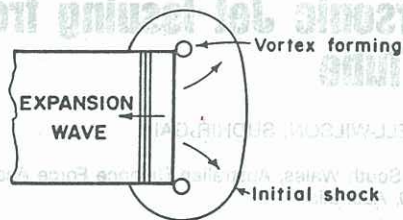


FIGURE 1(a)

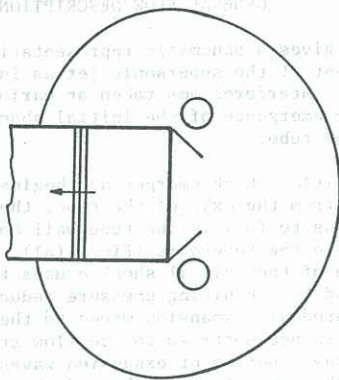


FIGURE 1(b)

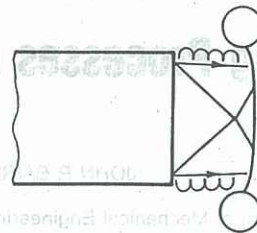


FIGURE 1(c)

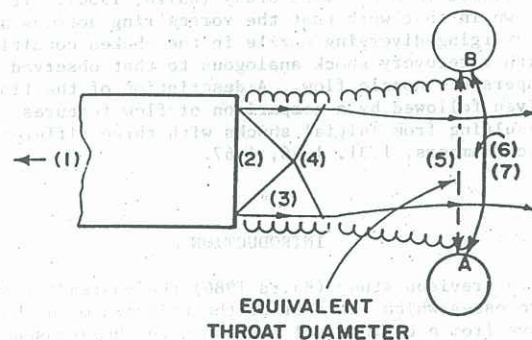


FIGURE 1(d)

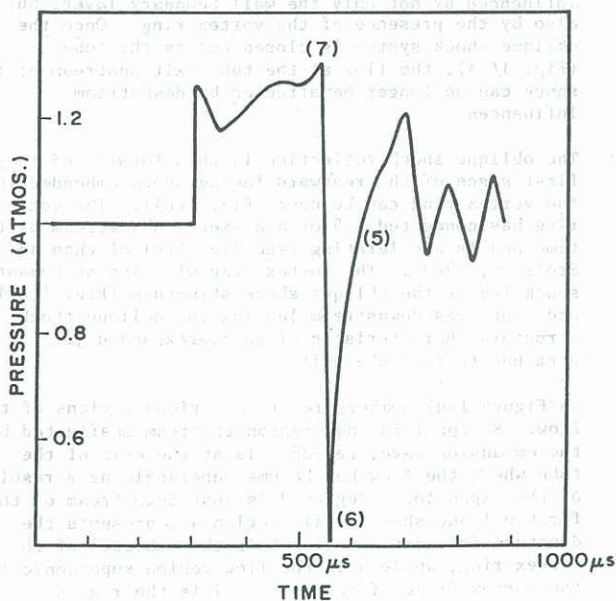


FIGURE 2

Figure 2: Pressure trace on the centreline of the tube at 2 diameters from the exit measured by Phan (1982). The numbers refer to regions of Figure 1(d).

interferograms of the vortex rings resulting from initial Mach numbers of 1.31, 1.46, and 1.67 respectively.

In the case of Figure 3 there are no oblique shocks at the tube exit of the tube, indicating close pressure matching between the exit pressure and the pressure external to the tube. A strong vortex ring is still present, with the notable feature being a patterned structure at its centre plane. This is the position where the rearward facing shock is observed at higher initial Mach numbers, and it is speculated that the pattern effect may have been caused by a weak normal shock perturbed by the turbulent jet.

Figure 4 was taken with an initial Mach number of 1.46 and the oblique shocks at the tube exit are clearly evident. The vortex ring and rearward facing shock are also present as described in the previous section. For Figure 5 the initial shock had a Mach number of 1.67 and the oblique shocks at the exit reflect an increased Mach number at the exit (region 2). The flow has more turbulent structure, but the vortex ring and embedded shock can still be seen. The reduction in the larger scale turbulent eddies due to the favourable pressure gradient is also a feature.

#### CONCLUSION

The unsteady flow following the emergence of a shock wave from a circular tube has been described in detail for one case, and a comparison made with the flow resulting from initial shocks at three different Mach numbers. An interesting feature of this flow is the termination of the shock in a strong viscous shear in the absence of a solid boundary.

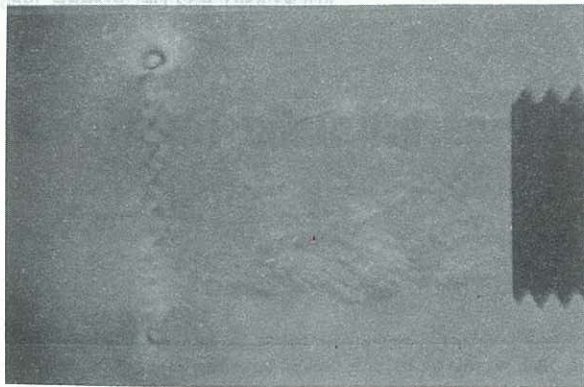


Figure 3: A differential interferogram of the flow resulting from an initial Mach number of 1.31, taken with the vortex ring approximately 2 diameters from the exit of the tube.

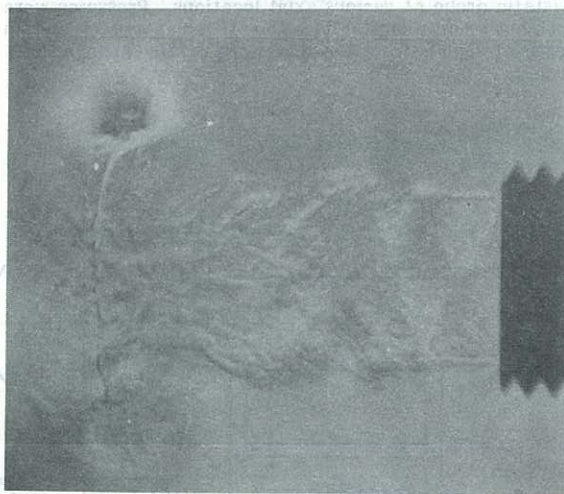


Figure 4: A differential interferogram of the flow resulting from an initial Mach number of 1.46, taken with the vortex ring approximately 2 diameters from the exit of the tube.

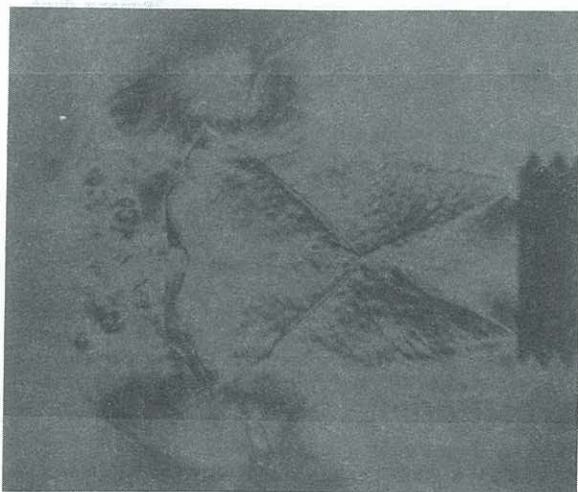


Figure 5: A differential interferogram of the flow resulting from an initial Mach number of 1.67, taken with the vortex ring approximately 2 diameters from the exit of the tube.

## REFERENCES

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