

Shock Strength Gain and Transmitted Wave Attenuation in Focusing Contractions of Different Aspect Ratios

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SUMMARY To retain the focused collapse of shock waves but to reduce the wave attenuation in exit passages, contractions have been designed using different logarithmic spiral ray pairs. Experiments show that the higher aspect ratio spirals produce substantially less attenuation giving stronger downstream shocks but that the very high pressure pulse at the focus due to the implosion is also reduced.

1 INTRODUCTION

As is well known, the performance of a shock tube is essentially controlled by the ratio of the acoustic velocities of the driver and driven gases. Development of a number of different techniques has substantially raised this limitation and shock waves with velocity greater than 40 km/s are now achievable. Apart from the use of light driver gases, these techniques all heat the driver gas thereby increasing its acoustic velocity. Methods range from shock wave heating (i.e. double diaphragms, or lightweight high velocity pistons) and isentropic compression heating (heavy, low velocity pistons) to combustion, explosion and electrical discharge from large capacitor banks. Another alternative is to use an area contraction either at the diaphragm station or downstream in the driven section. The latter may be coupled to any of the previous driver techniques. Although different shaped area contractions have been shown to produce a wide range of shock strength gains (Bird, Ref. 1), a cylindrical or spherical implosion is known, in ideal theory, to produce an infinite strength at the implosion centre (Guderley, Ref. 2). The coupling of an implosion device to, for example, a high Mach number electric discharge tube has the potential for generation of the extremely high temperatures of about 10^6 K for a minimum of approximately 1 nanosecond required for controlled nuclear fusion experiments.

A study of implosions created by a focusing technique using an initially plane shock wave has been carried out by Milton and Archer (Refs. 3,4). A wall profile which is of logarithmic spiral shape has been shown to provide the appropriate collapse. The equation for this spiral in (ρ, θ) co-ordinates is

$$\rho = \frac{R}{\sin \chi} \exp\left(\frac{\chi - \theta}{\tan \chi}\right) \quad (1)$$

Figure 1 shows the appropriate nomenclature. During the implosion phase all reflections occur at infinitely small wall angles. Hence the loss factor in Mach reflection, η/M , (Milton, Ref. 5) that must be added to the Chester equation (Ref. 6) reduces to zero. This means that the logarithmic spiral is equivalent to a cylindrical collapse between neighbouring rays (see Fig. 1).

The imploded shock can be used to provide high enthalpy gas for a very short duration or to drive a much stronger shock down a passageway very much

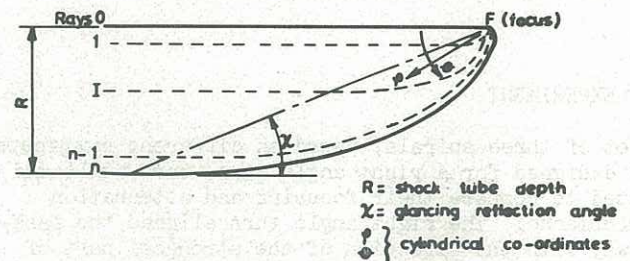


Figure 1 Shock Focusing Profiles

reduced in cross-sectional area. Attempts to recover a very high Mach number plane shock wave in such an outlet passage after implosion were reported in Ref. 7. However, although this wave was initially strong as expected, very high attenuation was experienced. Comparison with other contracting profiles (Ref. 8) which produced lower pressure rises at the contraction end, showed less attenuation. It was initially assumed that the direction of the outlet passage which was oriented in the shock tube direction in all cases resulted in greater disturbances with the logarithmic spiral where the strongest flow at implosion crossed the passage entrance at a larger angle (approximately 90°) than in the other contractions. Resulting turbulence and viscous losses were expected to be greater. Re-orientation of the passage showed that this effect, while of some significance, was insufficient to account for the major part of the attenuation. Further study comparing the pressure-time relationship just upstream of the passage showed that the large rate of change of area along the contraction near the focus of the logarithmic spiral resulted in an exploding wave returning upstream after implosion that decreased more rapidly in strength than the equivalent waves associated with the other contractions which exhibit less two-dimensional collapse. Thus the pressure in the contracting section driving the shock wave along the passage decreased rapidly for the logarithmic spiral with consequent high attenuation of the shock.

To overcome this problem new shapes were required which would still maximise the implosion effect by keeping all Mach reflections during the shock magnification process to angles approaching zero but which would be more gradual in shape near the implosion centre. In other words, they would have a higher 'aspect' ratio; i.e. ratio of the overall length of the contraction to the height of its opening. Appropriate shapes have been constructed using rays of the existing logarithmic spiral. The

closer the initial ray grouping near the curved wall of the spiral, the higher is this aspect ratio. Thus a series of logarithmic spiral ray profiles can be produced having different aspect ratios. These allow focusing, pressure rise and attenuation in appropriate outlet passages to be compared. The equation for the rays forming the walls of these spirals is

$$\rho_i = \frac{i}{n} \frac{R}{\sin \chi} \exp \left(\frac{\chi - \theta}{\tan \chi} \right) \quad (2)$$

where n is the selected total number of rays in the original logarithmic spiral contraction (Fig. 1) and $n-i$ is the ray pair chosen for the new contraction. The major questions regarding these shapes are

- do they achieve the same potential at the contraction end or focus as the full logarithmic spiral collapse?
- do they satisfactorily reduce shock wave attenuation in the outlet passages?

2 EXPERIMENT

A set of three spirals, based on different ray groups and designed for a right angle turn, were built and tested to compare their focusing and attenuation performance. The right angle turn aligned the passageway with the direction of the strongest part of the collapsing shock thereby reducing as much as possible any effect from the corner. The original spiral of Fig. 1 [walls (0) and (3) of Fig. 2], which had been designed to fit a simple air-air shock tube of channel depth $R = 44.45$ mm, was supplemented by two new inner walls [walls (1) and (2) of Fig. 2] at i/n of $2/3$ and $1/3$ respectively. This gave channels with initial openings of 14.82 mm and 29.63 mm. To obtain an acceptable exit channel width for flow visualisation in the small shock tube available, the profiles of the upper walls were slightly displaced from the focus to allow the width of the exit channels to be 1.00 mm, 2.00 mm and 3.0 mm for the small, intermediate and large spirals respectively. This gave a contraction area ratio for all three shapes of 14.82:1. Thus the shock movement in the reforming section just upstream of the focus (see Fig. 2) which is designed to straighten the shock wave at the start of the passage is slightly modified. However, the focusing behaviour upstream of this section for all the spirals is not altered and any overall detrimental effect on shock strength magnification should not occur. When the area ratio is 14.82:1 the theoretical, Chisnell (Ref. 9) magnification of a wave with initial Mach number $M_0 = 2.3$ is 1.6, giving a transmitted shock wave $M_T = 3.7$. This is equivalent to the Guderley (Ref. 2) values for imploding cylindrical shocks. Both theories, it should be noted, assume a constant property fluid with isentropic index, $\gamma = 1.4$. If the outlet passage walls had been retained at the focus and at the log spiral 90° point the area ratio would have been 44.4:1 (Ref. 7). The incoming shock Mach number would then have theoretically increased from, say $M_0 = 2.3$ to $M_T = 4.6$.

The three contractions were tested for a range of incoming shock Mach numbers from $M_0 = 1.95$ to $M_0 = 2.50$. Shadowgraph photographs were taken to examine

- whether additional shocks were formed in the contracting section during the implosion phase, or
- whether major differences in flow disturbances in the exit passageways existed.

These photographs are shown on Figures 3, 4, 5 and 6. Pressure measurements were taken in the exit tube at four different positions at similar length to passage depth ratios for each shape ($l/d = 0, 2, 6$ and 14), as shown on Fig. 7. A graphical presentation of results is also shown on this figure.

3 RESULTS

As each shape has a different length to depth ratio in the contracting section, the boundary layer will attenuate the shock more in the smaller spiral than in the large one. Corrections have thus been carried out for all shapes using Mirel's formula (Ref. 10) for a fully turbulent boundary layer. The final results are given as Mach numbers calculated from the measured pressure ratios with the correction for viscous attenuation added. Hence the comparison of both implosion gain and attenuation in the passageway is based only on the effects due to the contraction shape. Results are given in Table 1. Values tabulated are the mean of a number of tests, approximately 20 in each case at $l/d = 0$ and 8 tests at $l/d = 2, 6$ and 14 respectively. Standard deviations are given on the table and for clarity are marked only at $l/d = 0$ and 14 on Fig. 7. It should be noted that they are greater at these points than at $l/d = 2$ and 6 . They are also greater for all positions on the small spiral than on the other two.

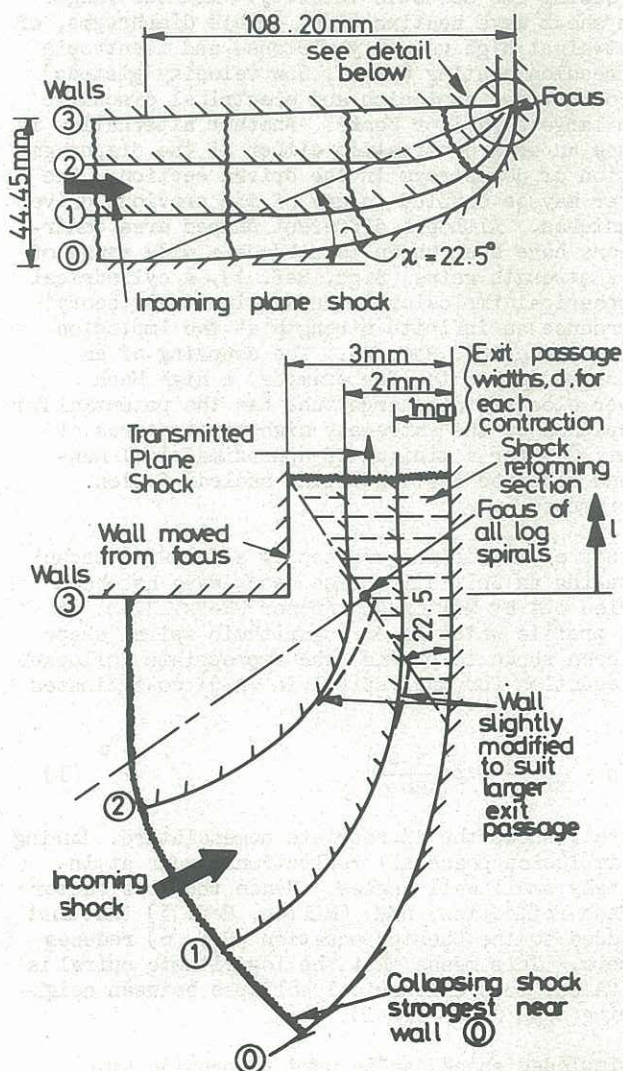


Figure 2 Self Similar Log Spiral Channels For 90° Turning Angle

TABLE 1

| Spiral | Mach number at position l/d | | | | | | | | | | | |
|--------|-------------------------------|-------|-------|------------|-------|-------|------------|-------|-------|------------|-------|-------|
| | 0 | | | 2 | | | 4 | | | 8 | | |
| | ΔM | M_T | S | ΔM | M_T | S | ΔM | M_T | S | ΔM | M_T | S |
| Large | 0.017 | 2.159 | 0.061 | 0.024 | 1.818 | 0.040 | 0.036 | 1.660 | 0.039 | 0.057 | 1.604 | 0.039 |
| Medium | 0.033 | 2.040 | 0.055 | 0.040 | 1.928 | 0.023 | 0.053 | 1.696 | 0.038 | 0.076 | 1.675 | 0.046 |
| Small | 0.017 | 1.883 | 0.112 | 0.079 | 1.827 | 0.075 | 0.093 | 1.772 | 0.070 | 0.118 | 1.807 | 0.080 |

Note: $M_T = M_{\text{measured}} + \Delta M$

where ΔM = viscous attenuation effect

S = standard deviation

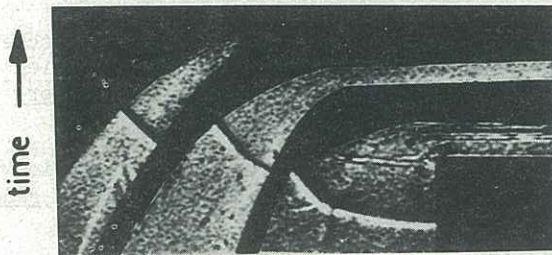


Figure 3 Focusing Action of 3 Self Similar Spirals

4 DISCUSSION

The focusing action of the three spirals is compared in Fig. 3 and a more detailed view of the implosion in the smallest spiral is shown on Fig. 4. In all cases no reflected shocks can be seen and the only disturbance is the collapsing main front. That is, the main shock is focused. Figure 5 shows a sequence of events for the medium sized spiral. Again, no upstream disturbances are visible before the collapse phase has ended. As the main shock front passes into the exit passage, the beginning of a reflected shock wave is now visible. The following motion of the front down the passage then produced a series of disturbances which are unavoidable in all contractions.



Figure 4 Focusing Action of Small Spiral

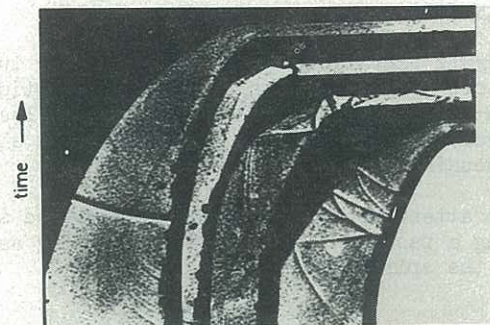


Figure 5 Implosion and Subsequent Action-Medium Spiral

Comparison with the large spiral of Fig. 6 shows that the size of these disturbances, for example the expansion fan at the corner, is smaller for the higher aspect ratio shape. Of more importance is the fact that, for this shape, the reflected waves progressing back upstream are divided into a number of weak shocks rather than the single exploding shock of the full size spiral. These photographs therefore show that focusing is also achieved with the higher aspect ratio spirals and indicate that the decay in the driving pressure for the flow in the passage will decrease with increasing aspect ratio because of the weaker exploding shock structure.

The graph of Figure 7 showing the output pressures confirms this latter observation. For the highest aspect ratio spiral, the Mach number ratio M_T/M_0 degenerates from 1.88 at $l/d = 0$ to 1.80 at $l/d = 14$, a drop of 4%. Equivalent drops for the medium and

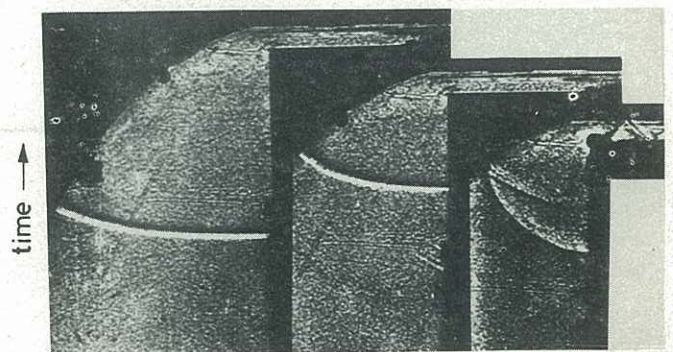


Figure 6 Implosion and Subsequent Action-Large Spiral

large spiral are 18% and 26% respectively. The highest aspect ratio spiral gives higher shock strengths than the ordinary logarithmic spiral from $l/d = 1.8$ onwards.

The gain due to the focusing action itself is poorer with the higher aspect ratio. For the transducer nearest the implosion centre ($l/d = 0$), the large spiral experiences a Mach number ratio 15% higher than the smallest spiral while the medium spiral ratio is 8% higher. In all cases the value of M_T/M_0 is greater than that given by Chisnell. This may be due to pressure variation across the passageway caused by the greater gain on the lower wall of the contraction. The reduction in gain near the focus with the higher aspect ratio spirals indicates a less effective implosion as the flow becomes less cylindrical.

5 CONCLUSIONS

(a) Spirals constructed from groups of ray tubes from the original logarithmic spiral contraction produce a collapsing shock front without reflected shock waves forming upstream. That is, they all have a focusing action.

(b) The attenuation rate of the transmitted shock wave along a passage reduces with increasing aspect ratio of the spiral.

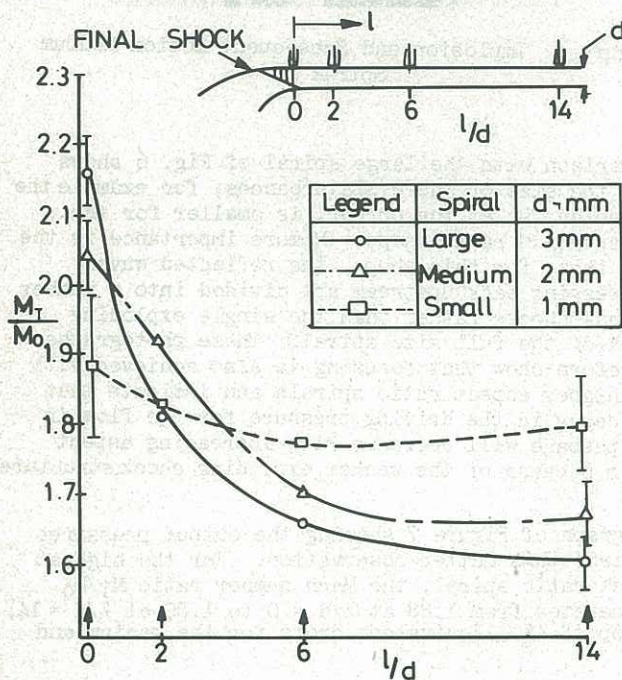


Figure 7 Attenuation in Outlet Channel

(c) The focused pressure rise also decreases as aspect ratio increases. If a small, rapidly pulsed volume of high enthalpy gas is required, the conventional logarithmic spiral is still more efficient with its cylindrical implosion effect. The inference is that even greater gain would be available from spherical implosions and would thus justify the design and development of axisymmetric profiles to produce them. Studies of axisymmetric Mach reflection are now being completed for this purpose.

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