Experimental Studies of the Production of Converging Cylindrical Shock Waves

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Abstract

An improved experimental technique for the production of cylindrical converging shock waves is presented. This is accomplished with an annular shock tube fitted with an axisymmetric area contraction which redirects an annular incident shock into a cylindrical implosion chamber. The contraction profile is designed in accordance with Whitham's ray-shock theory, and a three-element profile is found to provide the best overall performance on the basis of two-dimensional tests. Experiments with a three-element conical contraction demonstrate that highly symmetrical cylindrical implosions may be achieved by this method, and that the cylindrical shock amplification is well predicted by the Chester-Chisnell-Whitham (CCW) area Mach No. rule.

Contents

Converging cylindrical shocks were first generated in 1951[1] by employing a "tear-drop" centerbody in a shock tube to turn and force a planar incident shock to implode. However, despite great success, the guideline for designing the centerbody is not clearly defined. The present study examines an alternate device which employs an annular shock tube containing segmented axisymmetric area contractions which turn an annular incident shock through 90 deg.

The contraction profile design is illustrated in Fig. 1, which shows a plane incident shock approaching three-element contraction of initial width h_0 containing compression corners D, E, and F in the lower wall. For corner angles that are small enough, a Mach reflection occurs at each so that a shock-shock[3] follows a linear path across the channel, arriving, respectively, at expansion corners A, B, and C in succession. Now, if the upper wall is broken at A and made parallel to DE, the ray-shock theory[2] implies that the Mach stem propagates uniformly; that is, the shock-shock is eliminated. Since the Mach stem becomes the incident shock for each succeeding element, expansion corners B and C are located in a similar way. Compression corners E and F have been shifted downstream for the practical considerations of providing a parallel channel for Mach stem stabilization and also allowing for possible exit passage enlargement. Advantages of this design are that any combination of compression corner angles can be used and that the transmitted shock is likely to be relatively uniform. Furthermore, 90 deg corner angles for expansion can be avoided so that flow separation and strong pressure gradients behind the transmitted shock can be eliminated. In the axisymmetric case the shock-shock will follow a curved path, so the three-dimensional ray-shock theory[3] must be used to determine the upper wall corner locations numerically, once the lower corner angles are selected. The axisymmetric contraction cone as well as the centerbody are then developed by rotation.

Two-dimensional tests were carried out for three cases: 1) a logarithmic spiral, 2) a five-element contraction, and 3) a three-element contraction. They were performed in a 5.08-cm^2 air-to-air shock tube. Owing to the limited shock tube dimensions, the design exit passage width h became unacceptably small for photographic studies and boundary-layer considerations. Hence, most of the tests were carried out in an "off-design" mode (passage width $h' > h$). In addition, the three-element profile was modified by cutting into segment D′B′ (Fig. 1) so that only the first element operates as designed. For this modified three-element contraction ($h' = 3.18$ mm, $h = 0.81$ mm, and $h_0 = 50.8$ mm), Schlieren photographs were individually taken at $M_0 = 1.80$. They are presented in Fig. 2 and show the motion of Mach stem and the shock front in the exit passage. Next, pressure measurements with a single transducer in the exit passage indicate that all three profiles achieve essentially equal shock amplification at $M_0 = 1.80$, and that only the modified three-element contraction exhibits an absence of pressure attenuation with time at the point of measurement. Furthermore, a wave diagram analysis of the shock motion in the exit passage by the ray-shock method is found to adequately describe both the coalescence of shock-shocks and the asymptotic approach to a uniform shock front. Shock front perturbations ϵ measured from the diagram exhibit a power decay law with distance x for $\epsilon \sim x^{-n}$. The present experimental results give $n = 0.85$ and 1.08 for x/h_0 less and larger than 10, respectively. It is in fair agreement with theoretical values[3] $n = 0.5$ and 1.5.

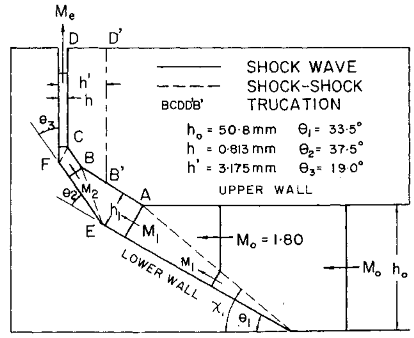

Fig. 1 Schematic of two-dimensional three-element contraction design.

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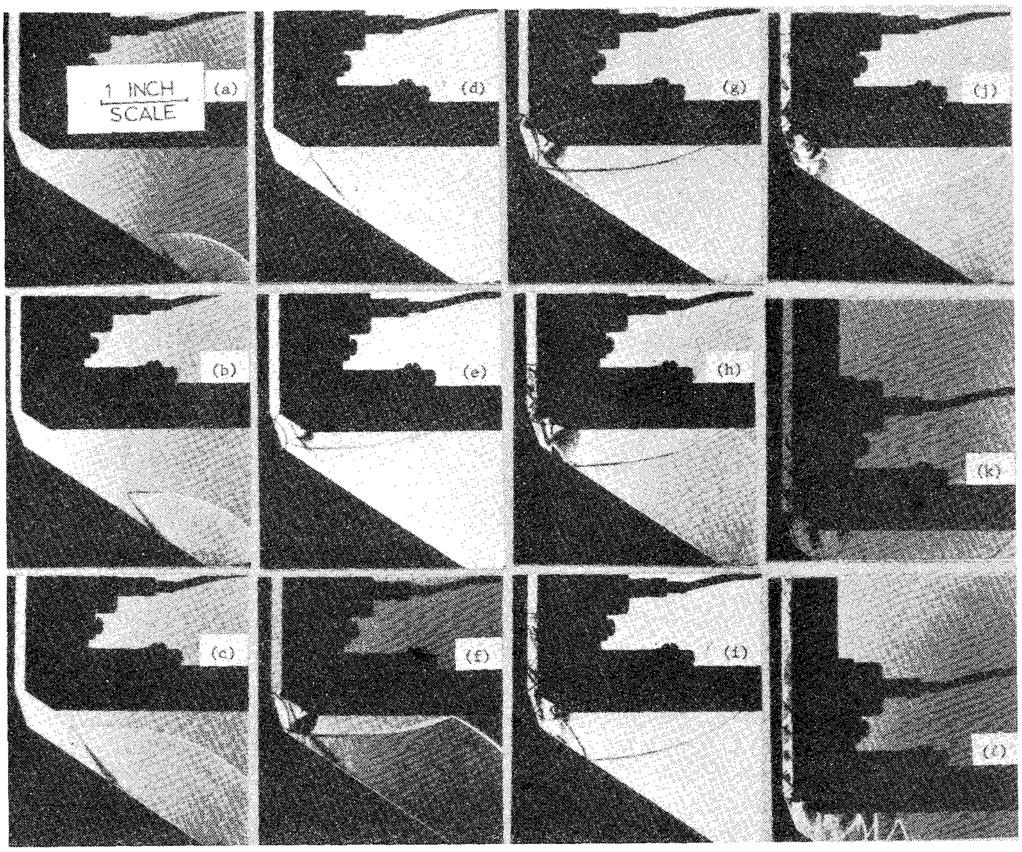

Fig. 2 Schlieren photograph of two-dimensional modified three-element contraction.

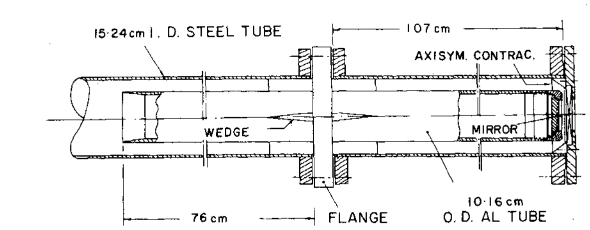

Fig. 3 Schematic of shock tube design for converging cylindrical shock.

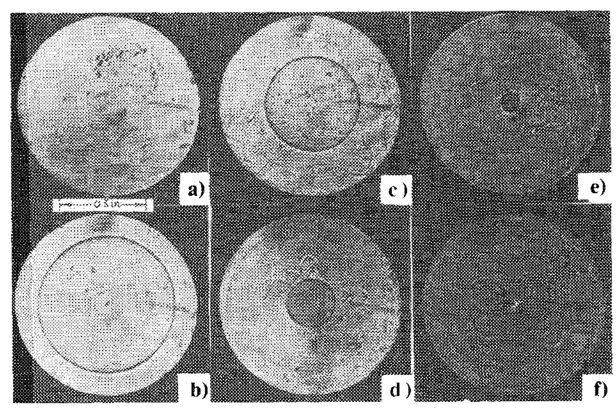

Fig. 4 Shadowgraphs showing converging cylindrical shock waves: a) Noflow, b) −5.8 μs, c) −3.7, d) −1.7, e) −0.5, f) 0.

A schematic of the annular shock tube is shown in Fig. 3. The end walls of the inner and outer tubes form the cylindrical implosion chamber which is connected to the annular passage by a three-element axisymmetric contraction. The enlarged cylindrical chamber width is $h' = 2.46$ mm (design $h = 0.52$ mm) and $h_0 = 2.54$ cm. Shadowgraphs of the shock motion in the cylindrical chamber were individually taken as presented in Fig. 4 for $M_0 = 2.00$. Figure 4a shows small anomalies, which are oil droplets from the driver gas and scratches on the window. Figures 4b and c show that the cylindrical shock has a high degree of circular symmetry at large radii. In Fig. 4d, e, and f, the supersonic flow behind the converging shock is seen to be perturbed by the oil droplets. At smaller radii, the resulting wave angles become smaller, suggesting significant shock amplification. Figure 4 illustrates that although the imploding shock collapses into a very small region, an ultimate breakdown in shock front curvature occurs indicating an eventual instability. Shock Mach number measurements with a single-pressure transducer mounted in the implosion chamber wall at various radii indicate that the cylindrical shock amplification there is predicted quite close by the CCW area Mach number relation, except at a small radius less than 6 mm where experimental error is large.

It is concluded from these results, that highly symmetrical cylindrical converging shock can be produced by the present method, despite the fact that the modified three-element contraction is designed for partial shock-shock cancelation. An eventual breakdown in shock front curvature is noted at small radii. It is noteworthy that a contraction operated at the full design condition by increasing h_0 is likely to be even more successful.

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References

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