A New Cylindrical Converging Shock Tube

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1 Introduction

Shock focusing is one of the most effective means to produce high pressure and high temperature at the center of convergence. For some decades now, much attention has been paid to the shock focusing phenomena due to the importance in study of the Richtmyer-Meshkov (RM) instability and extensive physical applications such as shock-wave lithotripsy, inertial confinement fusion, turbulent mixing in scramjet, collapse in supernova, and others. Specifically, it is of great interest to generate initially smooth converging shock waves and investigate their interaction with different flow configurations. The forerunner of research on converging shock was Guderley who obtained self-similar solutions of strong cylindrical and spherical shock waves in an ideal gas by theoretical analysis.[1] Experimentally, Perry and Kantrowitz were the first to produce cylindrical converging shock waves using a horizontal annular coaxial shock tube with a coaxial tear-drop-shaped inner core.[2] Takayama et al. established a horizontal annular coaxial shock tube and found that the converging shock waves visualized by the double-exposure holographic interferometry were inevitably disturbed by the struts supporting the inner core.[3] Subsequently, a vertical coaxial shock tube without diaphragm was built and later modified to produce a uniform cylindrical converging shock wave. Improved version of this shock tube could produce converging shock waves with minimum initial disturbances because of an independently self-supported structure. Then Hosseini and Takayama carried out an experimental study on the RM instability induced by cylindrical converging shocks interacting with a cylindrical interface in the improved shock tube.[4] Some other methods were also proposed to obtain the converging shock waves. Apazidis and Lesser produced polygonal shock waves in an essentially two-dimensional cavity.[5] A hemispherical implosion chamber was constructed by Glass and a hemispherical shock wave was successfully generated at its center and the temperature at an implosion focus was measured.[6] Dimotakis and Samtaney reported a gas lens technique in a two-dimensional wedge geometry to generate cylindrical converging shock waves where the fast-slow interface that refracts an incident shock into a cylindrical one must be carefully installed before each experiment.[7] In order to produce spherical shock waves, Hosseini and Takayama designed an aspheric lens-shaped transparent test section with an inner spherical cavity by explosion of silver azide pellets.[8] Many attempts have been made to generate converging shock waves.

While it is still limited to produce converging shock waves with initially smooth shape in laboratory environments. In order to solve this problem, an effective technique for generating cylindrical converging

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shock waves in an ordinary horizontal shock tube was proposed based on the shock dynamics theory in our previous work.[9]

However, there is no suitable facility that could produce shock waves strong enough to carry out high Much number experiments in laboratories. In this work, a new shock tube facility for generating a strong cylindrical converging shock wave is developed based on the shock dynamics theory similar to our previous work. This new shock tube aims to produce strong shock waves.

2 Design of the Shock Tube

The Chester–Chisnell–Whitham (CCW) relation is the basis of shock dynamics. When a shock wave moves through a tube, slowly varying in area, the shape of the shock will change due to the disturbances from the shock foot at the wall. The disturbances result in the change in the shock Mach number. The CCW relation describes how the shock Mach number M varies with the cross-sectional area A along a tube, which can be written as

$$\frac{2MdM}{(M^2-1)K(M)} + \frac{dA}{A} = 0 \tag{1}$$

Where

$$K(M) = 2(2\mu + 1 + 1/M^2)^{-1}\left(1 + \frac{2}{\gamma+1}\frac{1-\mu^2}{\mu}\right)^{-1} \tag{2}$$

$$\mu = \left(\frac{(\gamma-1)M^2+2}{2\gamma M^2-(\gamma-1)}\right)^{1/2} \tag{3}$$

γ is the specific heat ratio of the gas. For a wall with a given shape, the shape of the shock wave could be obtained by applying this relation.

The test section of the shock tube consists of a uniform zone (ZHBP), a simple-wave zone (PBQ), a double-wave zone (BQD), and a converging part (DOQ) as sketched in figure 1. The simple-wave zone and double-wave zone compose the transferring zone. The parameters (the coordinates, θ and M) of point Q in figure 1 could first be determined. According to design, the cylindrical shock focuses along the converging part, the ray angle of point Q (θ_Q) should exactly equal to the converging angle θ_0, and can be expressed as

$$\theta_Q = \theta_0 = \int_{M_0}^{M_Q} \frac{dM}{cA} \tag{4}$$

Where

$$cA = \sqrt{(M^2-1)\,K(M)/2} \tag{5}$$

c is the speed of nonlinear disturbance wave on the shock front. From the expression (4), the Mach number at point Q (M_Q) can be obtained. The coordinates of point Q can be obtained using the CCW relation and the geometrical relation.

From point O, a circle with a radius of the distance between points O and Q can be drawn, which intersects with the straight line OH at point D. The circular arc QD is the desired shock front and the Mach numbers of any point on it are M_Q. If the arc QD is divided into many small equal parts, the coordinates of ith point (x_i, y_i) and θ_i can be calculated from the geometrical relationship. Then characteristics method could be used to calculate the parameters of any point in the region BQD, and the parameters of any point on the curved line BQ are obtained immediately.

For the region PBQ is a simple-wave region, the characteristic line is straight for each point along the line BQ, and θ_i and M_i are constant along the characteristic line. The intersecting points of these characteristic lines with PQ form the curved line PQ. The first point P where the wall starts to bend can be easily determined. Then the iteration method can be adopted to determine all the coordinates of these intersecting points.

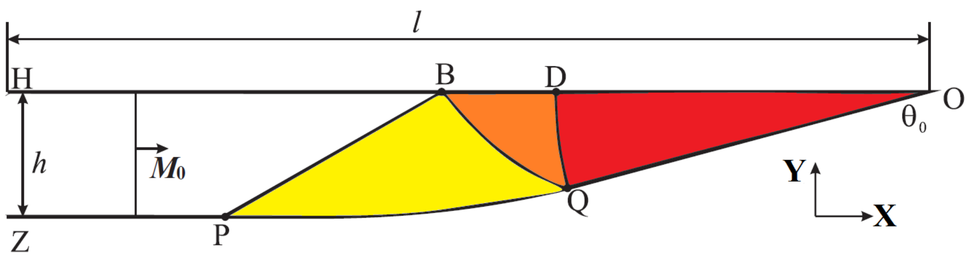

Figure 1. The schematic of the wall profile. h: the shock tube height; M_0: the Mach number of the incident planar shock;θ_0: the converging angle; l: the distance between the point O and H; ZHBP: uniform zone; PBQ: simple-wave zone; BQD: double-wave zone; DOQ: converging part

3 Implementation

In this work, the test section with a height of 1820 mm is manufactured. The initial parameters of the test section are: l = 9330 mm, θ_0 = 25°, h = 1495 mm, and M_0 = 2. An observation window with the dimension of 500 × 600 mm^2 is mounted in the test section for the flow-field visualization. The details of the test section are schematically given in figure 2. The strength of the shock when it enters the converging part, namely, the shock Mach number at point Q, is 2.5 calculated from the CCW relation. When the shock enters the converging part, the relation of Mach number M and R, the distance between shock position and O is shown in figure 3. Figure 3 shows that the Mach number will get to around 8 near the center area. In an atmospheric air environment, the temperature will rise to around 4000K after the shock wave whose Mach number reaches 8. The vibrational energy of molecule will be excited and oxygen dissociation reaction occurs.

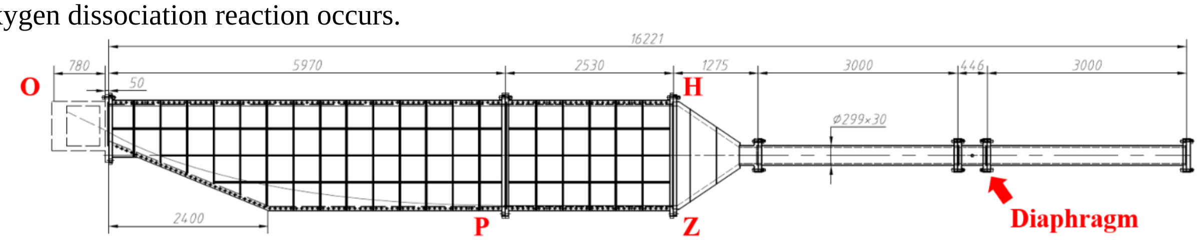

Figure 2. The detailed design diagram (Unit in graph: mm)

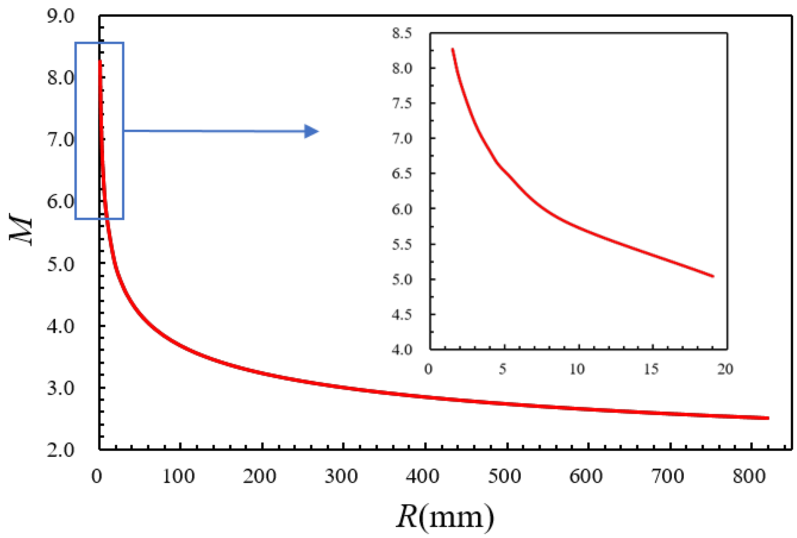

Figure 3. The numerical results of *M*-*R* relation

Experimentally, an aluminum diaphragm is initially placed between the driver and driven sections to separate the gases with different pressures. Once the diaphragm is ruptured, a planar shock wave is generated and propagates in the driven section. The shock strength is measured by three piezoelectric pressure transducers (KISTLER Type601CAA) mounted in the shock tube wall of the driven section. Rarefaction waves are generated simultaneously but travel to the driver section. When the planar shock wave enters the transferring zone, it is converted to the cylindrical shock gradually and it speeds up a little. The shock speed is further increased in the converging part. The photograph of the shock tube is given in figure 4.

Figure 4. Photograph of the shock tube

4 Test results

In early test experiments we measure the initial Mach number by choosing suitable aluminum diaphragms with symmetrical cross grooves (see figure 5).

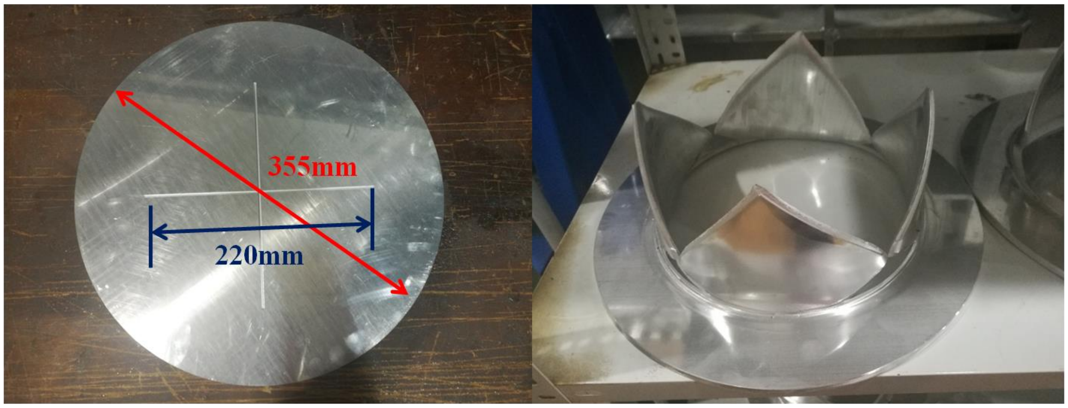

Figure 5. Left: initial diaphragm; right: ruptured diaphragm

And table 1 gives the initial Mach number of the last four experiments. We can see that the initial Mach number is very stable and meets the experimental requirements.

Table 1: Test results of the initial Mach number

Diaphragm thickness (mm)	Groove depth (mm)	Pressure of rupturing diaphragm (MPa)	Temperature (℃)	Mach number-M_0
8	1.5	5.11	20	2.020
8	1.5	5.17	21	2.015
8	1.5	5.15	21	2.003
8	1.5	5.03	20	1.990

Figure 6 shows the Mach numbers of test experiment on the converging part (see figure 1: DOQ) of the facility by four piezoelectric pressure transducers (KISTLER Type601CAA) mounted in the bottom of the converging part. The experimental data is in good agreement with the theoretical calculation results.

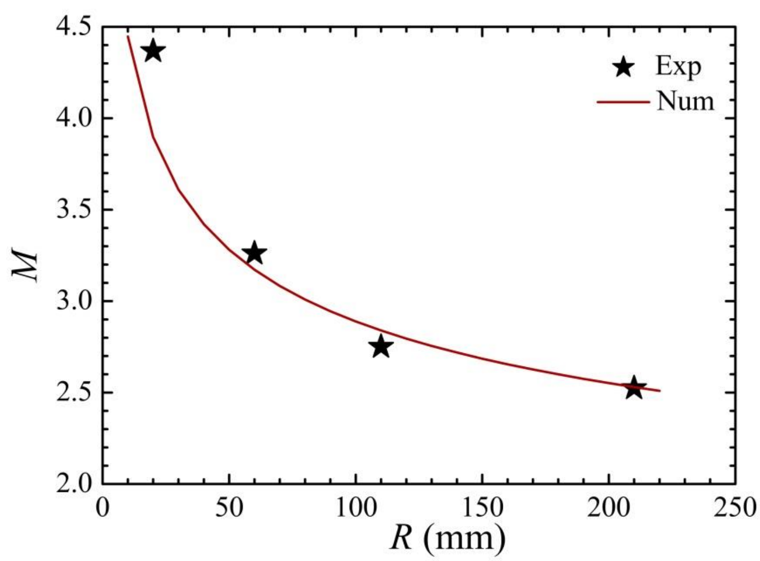

Figure 6. Numerical results (Num) compared with experiment results (Exp) of M-R relation in the converging part

References

[1] G. Guderley. (1942). Starke kugelige und zylindrische Verdichtungssto¨ße in der Na¨he des Kugelmittepunktes bzw. der Zylinderachse. Luftfahrtforschung. 19: 302.

[2] R. W. Perry, and A. Kantrowitz. (1951). The production and stability of converging shock waves. J. Appl. Phys. 22: 878.

[3] K. Takayama, H. Kleine, and H. Gronig. (1987). An experimental investigation of the stability of converging cylindrical shock waves in air. Exps. Fluids. 5: 315.

[4] S. H. R. Hosseini, and K. Takayama. (2005). Experimental study of Richtmyer-Meshkov instability induced by cylindrical shock waves. Phys. Fluids. 17: 084101.

[5] N. Apazidis, M. B. Lesser, N. Tillmark, and B. Johansson. (2002). An experimental study of converging polygonal shock waves. Shock Waves. 12: 39.

[6] T. Saito, and I. I. Glass. (1982). Temperature measurements at an implosion focus. Proc. R. Soc. London, Ser. A. 384: 217.

[7] P. E. Dimotakis, and R. Samtaney. (2006). Planar shock cylindrical focusing by a perfect-gas lens. Phys. Fluids. 18: 031705.

[8] S. H. R. Hosseini, and K. Takayama. (2005). Implosion of a spherical shock wave reflected from a spherical wall. J. Fluid Mech. 530: 223.

[9] Z. G. Zhai, C. L. Liu, F. H. Qin, J. M. Yang, and X. S. Luo. (2010). Generation of cylindrical converging shock waves based on shock dynamics theory. Phys. Fluids. 22: 041701.