Experimental Study on a Heavy-Gas Cylinder Accelerated by Cylindrical Converging Shock Waves

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1 Introduction

When an initially perturbed interface separating two fluids with different properties is impulsively accelerated by a shock wave, the flow field will exhibit complex fluid dynamic phenomena due to the misalignment of the density and pressure gradients. It is often referred to as the Richtmyer-Meshkov (RM) instability [1, 2] and has been investigated within the past several decades due to its extensive physical applications such as inertial confinement fusion (ICF) [3], turbulent mixing in scram jet [4] and collapse in supernova [5]. Specifically, in most applications the shock waves maintain two-dimensional (e.g. cylindrical) or three-dimensional (e.g. spherical) converging shapes. Taking the ICF experiments, the thermonuclear fuel is contained in a small spherical solid capsule in advance and illuminated evenly by a number of well-designed laser beams. Simultaneously a spherical converging shock wave is generated and traverses the capsule. In the process even a tiny imperfection of the capsule surface can induce the RM instability and may destroy the fusion reaction [3]. It is therefore of fundamental interest and practical significance to explore the fluid dynamics of the flows in the interaction of interfaces with a converging shock wave.

The generation of converging shock waves in laboratory situations is a prerequisite in study of the RM instability experiments with respect to such shock waves. Perry and Kantrowitz [6] reported the design of a horizontal annular coaxial shock tube for the first time and visualized a cylindrical converging shock wave. Takayama et al. [7] established a horizontal converging shock tube and observed cylindrical shock waves with mode three or four instability generated by the struts supporting the inner core. Subsequently, a vertical coaxial diaphragmless shock tube was constructed [8] and later modified to produce a uniform cylindrical converging shock wave [9]. Besides the annular coaxial shock tube systems, recently Dimotakis and

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Samtaney [10] reported a gas lens technique in a two-dimensional wedge geometry to generate cylindrical shock waves and Hosseini and Takayama [11] designed an aspheric lens-shaped transparent test section to produce spherical shock waves by explosion of silver azide pellets.

Although attempts have been made for generating converging shock waves, most previous experimental works were conducted by studying the interaction of interfaces with a planar shock wave. Experimental study of the RM instability induced by converging shock waves is still limited [12]. The reason probably lies in the difficulty of the initial interface formation and the observation of flows [10, 12]. Recently, a simple but effective technique of generating the cylindrical converging shock waves based on shock dynamics theory was proposed by Zhai et al. in our laboratory [13]. A curved wall profile is designed in the shock tube test section and is capable of changing the incident planar shock waves directly into perfectly cylindrical ones. Experimental studies as well as further numerical and theoretical analyses have been performed to assess the influence of several parameters including the shock tube height, the converging angle and the incident planar shock Mach number on the wall profile and the resulting converging shock waves. The good agreement among them is achieved and verifies the method. Furthermore, the test section seems convenient for setting different types of interface and applying various diagnostic techniques for flow visualization. These include interfaces such as soap film bubbles, nitrocellulosic membranes, gas cylinders [14, 15] and gas curtains [16] and diagnostic techniques such as schlieren, shadowgraphy and laser sheet methods [14, 15, 16]. The present work is intended to investigate the interaction of the cylindrical shock waves with a heavy-gas (SF_6) cylinder in shock tube experiments. The originality lies in not only the cylindrical converging shock waves, but also the imaging method utilizing a high-power continuous laser (532 nm) combined with a high-speed video camera to capture the evolution of flow structures during a single test shot. The sequences of images based on the Mie scattering of the glycol droplets seeded in the gas cylinder obtained in a single run clearly show the development of the gas cylinder accelerated by converging shock waves.

2 Experimental Methods

The experiments were conducted in our 95 mm$\times$ 95 mm square cross section shock tube, whose total length is 9 m with a driver section of 2 m and a driven section of 7 m. Nitrogen was used as the driver gas and air as the driven gas. A planar shock wave with the Mach number M_0=1.2 was generated by the rupture of a polypropylene diaphragm initially separating the nitrogen and the driven air. For this investigation, the test section was fabricated with a well-designed wall profile based on the shock dynamics theory [13]. The gas cylinder flowing vertically through the test section was created in a careful procedure. In order to observe the development of the gas cylinder, planar imaging diagnostics were adopted. In particular, a continuous laser-sheet imaging method was developed to capture the evolution of the gas cylinder in a single run. The experimental and diagnostic details are documented below.

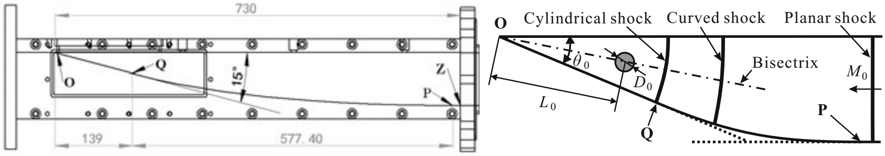

Fig. 1 Drawing of the test section (left) and schematic of initial conditions (right).

Fig. 1 presents the drawing of the test section which is designed by the shock dynamics theory and schematic of the initial conditions. The lower curved wall manufactured accurately by the linear cutting technique can be divided into three parts: the oblique line (from end point O to point Q) for focusing the cylindrical shock wave, the horizontal line (from point P to point Z) for connecting the shock tube and the middle curved line (from point Q to point P) for transferring the planar shock wave into the cylindrical one. In this study, the known parameters are chosen as the incident planar Mach number M_0=1.2, the converging angle θ_0=15^0, the test section height h=95 mm and length l=730 mm. Then the Mach number of Q can be calculated as M_Q=1.29, and the length of $\overline{OQ}$ is R_Q=143.87 mm.

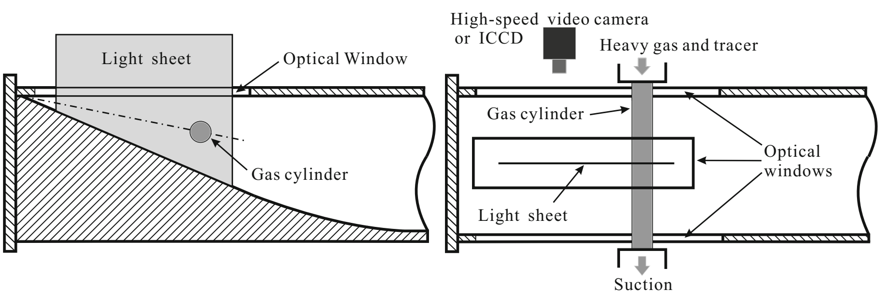

Fig. 2 Schematic of top view (left) and side view (right) of the test section.

Fig. 2 presents the detailed schematic of the test section showing the planar imaging diagnostics such as Mie scattering. The heavy-gas (SF_6) cylinder flows under gravity into the test section through a single, round nozzle of diameter D_0=5 mm mounted along the bisectrix of the converging angle on the top wall and is sucked mildly through a plenum on the bottom wall by a vacuum pump. The distance from the gas cylinder axis to the center of the curvature (i.e. the end point O in Fig. 1) is L_0=181.55 mm (Note that here L_0 is a little longer than R_Q, which means that the gas cylinder is not positioned within the converging section. That's why the evolution of the gas cylinder shown in Fig. 4 is asymmetric. More experiments will be performed and presented elsewhere.). Optical windows are located in top, bottom and side walls of the test section. The light sheet with thickness of less than 1 mm illuminates the flow through the center of the optical window horizontally. In our early experiments, the flow was illuminated by a 1 Hz pulsed Nd:YAG laser operating at 532 nm and the scattering light of glycol droplets mixed with the heavy gas was captured by a 1024x1024 intensified charge coupled device (ICCD) (DH734i-18F-03). The triggering of the laser and ICCD was controlled by the pressure transducers and the timings after shock impact were controlled by a four channel delay generator (DG645). It is noting that the facility is analogical to the PLIF widely used in the previous works [14, 15, 16]. In such situations, however, numerous experiments must be performed to obtain the evolution process and the same initial conditions must be confirmed prior to each run again and again. In order to avoid the imperfect repeatability of the experiment, a continuous laser-sheet imaging method utilizing a high-power continuous laser (SDL-532-15000T, 15 W, 532 nm) combined with a high-speed video camera (FASTCAM SA5) is introduced in our current experiments. In particular, the evolution of flow structures can be captured during a single test shot. The success of this method lies in finding the equilibrium between the shutter speed of the camera and the brightness of the resulting images.

3 Results and Discussion

The shape of the shock waves moving in the converging part without any interfaces has been proven to be of cylindrical shapes experimentally and numerically [13]. Thus the detailed validation is neglected here and we mainly focus on the RM instability characteristics of the gas cylinder.

As mentioned above, our experiments were carried out using different planar imaging diagnostics. In the early stage, Mie scattering was implemented using the pulsed Nd:YAG laser and ICCD. In each test run the incident Mach number was checked according to the pressure transducer signals and the generation of the gas cylinder was operated carefully. Fig. 3 presents an example of the distorted interfaces captured by this Mie scattering system. It is shown that the gas cylinder is distorted and the change with time of the interface can be observed. However, it is a heavy work to obtain quantitative results and moreover, the precision is suspectable owing to the imperfect repeatability of the experiment. In the current stage, the continuous laser-sheet imaging method is utilized and the evolution of the gas cylinder can be observed in a single test run. Fig. 4 gives the evolution of the gas cylinder when the shock wave propagates towards and reflects from the end point. The time interval between two consecutive frames is 50 μs and the shutter of the camera is settled 1/153,000 s to ensure that the images with no superposition are visible.

As the shock passes by, the gas cylinder develops a crescent shape and then forms a vortex pair due to the vorticity that is initially deposited on the boundary of the gas cylinder (frames 1 to 11). The interface in bottom position of the frames (named bottom interface hereinafter) forms an arch and the boundary of the top interface is spreading, which is different from that accelerated by a planar wave in the previous studies [14, 15]. About 600 μs after the shock passage, the interface stops moving and is further compressed due to the reflected shock from the end point (frame 12). Then the bottom interface grows with a round shape, while the top interface

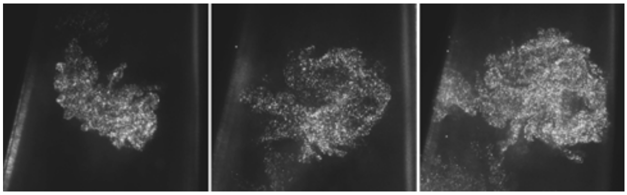

Fig. 3 Images of the distorted interface captured one per run by Mie scattering at different times with time interval of 1,000 μs and 200 μs, respectively.

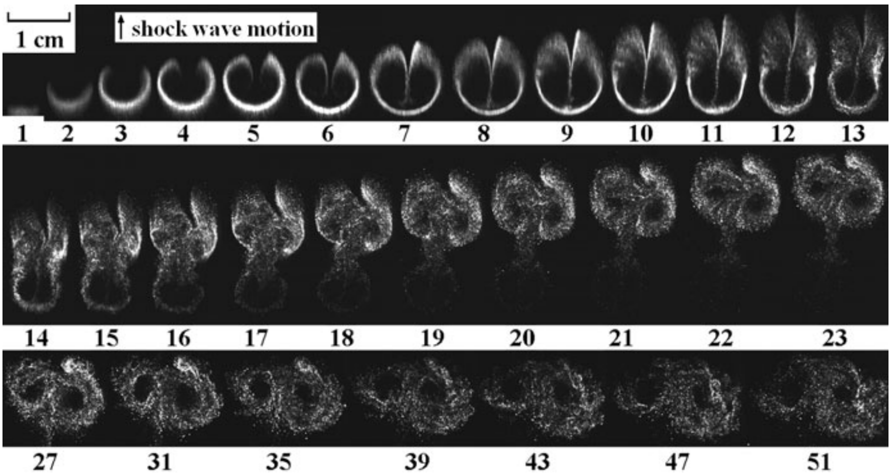

Fig. 4 The evolution of the heavy-gas cylinder. The frame rate is 20,000 fps and the shutter is 1/153,000 s.

develops into another vortex pair because of the formation of additional vorticity (frames 13 to 20). The results indicate that the vortical direction of the second vortex pair is opposite to that of the original one. At late times, the bottom interface diffuses and the second vortex pair develops due to its induced velocity and small scale disturbances are amplified (frames 21 to 51).

Although the evolving interfaces are asymmetric because of the nonuniform initial conditions (i.e. L_0 is longer than R_Q), the results obtained by the continuous laser-sheet imaging method still show the complete evolution process of the gas cylinder, which provides the possibility for further precious measurements and will be helpful for numerical validation and theoretical modeling.

4 Conclusion

The interaction of a heavy-gas (SF_6) cylinder with cylindrical converging shock waves was investigated experimentally in our well-designed shock tube. The flow features were obtained by the Mie scattering. The ICCD combined with the 1 Hz pulsed laser captured the images only one per run, while the high-speed video camera combined with a high-power continuous laser was able to capture the evolution process in a single run. The RM instability characteristics of the gas cylinder accelerated by converging shock waves were presented. More improved experiments and corresponding quantitative analysis will be performed in the future.

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References

1. Richtmyer, R.D.: Taylor instability in shock acceleration of compressible fluids. Commun. Pure Appl. Math. 13, 297–319 (1960)
2. Meshkov, E.E.: Instability of the interface of two gases accelerated by a shock wave. Transl. of Izv. Acad. Sci. USSR Fluid Dyn. 4, 151–157 (1969)
3. Lindl, J.D., McCrory, R.L., Campball, E.M.: Progress toward ignition and burn propagation in inertial confinement fusion. Phys. Today 45(9), 32–50 (1992)
4. Yang, J., Kubota, T., Zukoski, E.E.: Applications of shock-induced mixing to supersonic combustion. AIAA J. 35(31), 854–862 (1993)
5. Arnett, W.D., Bahcall, J.N., Kirshner, R.P., Woosley, S.E.: Supernova 1987A. Annu. Rev. Astron. Astrophys. 27, 629–700 (1989)
6. Perry, R.W., Kantrowitz, A.: The production and stability of converging shock waves. J. Appl. Phys. 22, 878–886 (1951)
7. Takayama, K., Kleine, H., Gronig, H.: An experimental investigation of the stability of converging cylindrical shock waves in air. Exps. Fluids 5, 315–322 (1987)
8. Watanabe, M., Onodera, O., Takayama, K.: Shock wave focusing in a vertical annular shock tube. In: Brun, R., Dumitrescu, L.Z. (eds.) Shock Waves at Marseille IV, pp. 99–104. Springer (1995)
9. Hosseini, S.H.R., Onodera, O., Takayama, K.: Characteristics of an annular vertical diaphragmless shock tube. Shock Waves 10, 151–158 (2000)
10. Dimotakis, P.E., Samtaney, R.: Planar shock cylindrical focusing by a perfect-gas lens. Phys. Fluids 18, 031705 (2005)
11. Hosseini, S.H.R., Takayama, K.: Implosion of a spherical shock wave reflected from a spherical wall. J. Fluid Mech. 530, 223–239 (2005)
12. Hosseini, S.H.R., Takayama, K.: Experimental study of Richtmyer-Meshkov instability induced by cylindrical shock waves. Phys. Fluids 17, 084101 (2005)
13. Zhai, Z.G., Liu, C.L., Qin, F.H., Yang, J.M., Luo, X.S.: Generation of cylindrical converging shock waves based on shock dynamics theory. Phys. Fluids 22, 041701 (2010)
14. Jacobs, J.W.: The dynamics of shock accelerated light and heavy gas cylinders. Phys. Fluids A 5, 2239–2247 (1993)
15. Tomkins, C.D., Kumar, S., Orlicz, G.C., Prestridge, K.P.: An experimental investigation of mixing mechanisms in shock-accelerated flow. J. Fluid Mech. 611, 131–150 (2008)
16. Orlicz, G.C., Balakumar, B.J., Tomkins, C.D., Prestridge, K.P.: A Mach number study of the Richtmyer-Meshkov instability in a varicose, heavy-gas curtain. Phys. Fluids 21, 064102 (2009)