A Semi-annular Cylindrically Converging Shock Tube for Richtmyer-Meshkov Instability Studies

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Introduction

The Richtmyer-Meshkov (RM) instability occurs when an initially perturbed interface separating two different fluids is impulsively accelerated by a shock wave [1, 2]. The amplitude of initial perturbation on the interface will be amplified following the refraction of the shock. Subsequently second instabilities (such as Kelvin-Helmholtz instability) develop, and finally the flow will transit to turbulence if the initial shock is strong enough. The primary mechanism for the presence of these complex phenomena is the baroclinic vorticity resulting from the misalignment of the density gradient across the interface and the pressure gradient of the shock.

The RM instability has received increasing attention in the last several decades due to its important role in various fields, including inertial confinement fusion (ICF), combustion and astrophysics [3]. Most previous experimental studies only cared about the planar shock induced RM instability [4–6]. However, the RM instability existing in ICF or other practical applications is the converging shock wave impacting a disturbed interface. The converging RM instability largely differs from its planar counterpart for the appearance of many new flow characteristics, involving the nonuniformity of the flow in radial direction after initial shock and reflected shocks, the geometry convergence in circular direction, extremely high pressure in converging center and the secondary impact by the reflected shock from the converging center. Experimental investigations on converging RM instability are necessary under the stimulation of academic interests and practical application requirements in ICF. However, only few experiments were conducted on this subject so far due to the great challenge in producing converging waves in laboratory conditions and in forming density interfaces in a converging geometry [7, 8].

The first converging shock tube was designed and manufactured by Perry and Kantrowitz [9]. In their experiments, the light from the centre of the test section was observed as the converging shock wave approached the focal point, indicating that a considerably high temperature was achieved in the converging center. Following their basic principle, a horizontal coaxial annular shock tube was constructed by Takayama et al. [10], and it was found that the converging shock waves were inevitably disturbed by the struts supporting the inner core. In order to overcome this disadvantage, a vertical coaxial diaphragmless shock tube was established and later modified to produce cylindrical converging shock waves with minimum initial disturbance using an independently self-supported structure [11]. An experimental study on interaction of the cylindrical converging shock wave with a cylindrical interface was carried out in the improved shock tube [7]. Besides the coaxial structure, a gas lens technique [12] was adopted to generate cylindrical converging shock waves in a two-dimensional wedge geometry where a fast-slow interface refracting an incident shock into a cylindrical one must be carefully installed before each experiment. Subsequently, the theory was extended to the three-dimensional spherical geometry for both fast-slow and slow-fast gas interfaces [13]. Recently, the shock dynamics theory was employed to design a curved wall profile of the test section to transform a planar shock wave to a cylindrical one, and the interaction of the shock with various interfaces including gas bubbles and gas cylinders was also performed [14–16].

For the purpose of generating converging shock waves with minimum disturbance and easily forming density interfaces for RM instability studies, a new semi-annular converging shock tube is developed in this work. The structure of the shock tube and the device used to form interfaces are described specifically. Then pressure histories are reported to verify the feasibility and reliability of the facility.

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Finally, the evolution of a single-mode interface accelerated by a converging shock is studied.
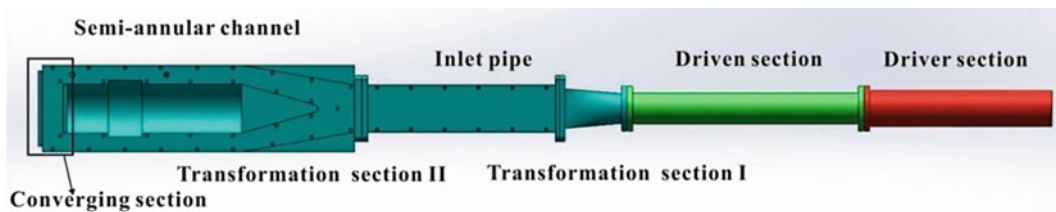
The Semi-Annular Shock Tube

A drawing of the present facility is shown in Fig. 1. A 1.2 m long driver section and a 1 m long driven section are separated by a rupturable polypropylene diaphragm. A transformation section I, an inlet pipe, a transformation section II, a semi-annular section and a test section are connected to the driven section in sequence. The inner and outer radii of the semi-annular section are 85 and 95 mm, respectively. The test section, located at the end of the shock tube, is half a cylinder with an inner height of 5 mm. All these parts are assembled, aligned and sealed in a self-strutted way. A planar shock wave is generated by a sudden rupture of the diaphragm. After the shock wave passes through transformation section I and propagates in semi-circular inlet pipe, the profile of the shock front is changed to be semi-circular. Subsequently, after the shock traverses the transformation section II, the semi-circular-shaped shock will be transformed to be one with semi-annular configuration. Finally, a cylindrical converging shock wave is generated after a 90° turn and then reflects from the focal point, propagating in the test section.

Comparing with previous annular shock tubes [9–11], this semi-annular shock tube provides an open inner core. Therefore, the diagnostic system can be equipped nearly in the same way as in the planar ones. Moreover, the open test section provides us great convenience for interface formation, which will be introduced in detail hereinafter.

Characteristics of the Shock Tube

To capture the propagation of converging and diverging shock waves, a high-speed schlieren photography system used in our group [14] is modified to match with the semi-annular shock tube. Two parallel planar mirrors are added in the commonly used Z-type schlieren system, which includes two concave mirrors, two convex lenses, a blade and a slit. One planar mirror is placed within the open core of the semi-annular channel with an oblique angle of 45°, and the other one is placed face-to-face away from the first mirror to change the light path. In order to clearly track the shock front in the test section, the frame rate of the camera is set to be 65,100 f.p.s. corresponding to a time interval between two consecutive frames of about 15.4 μs, and the shutter of the camera is adjusted to be 1 μs. Figure 2 shows the propagation of the converging shock wave and the reflected wave. It can be seen that the semi-cylindrical shock has steeped in the

Fig. 1 Structure of the cylindrically converging shock tube

Fig. 2 Sequence of schlieren pictures showing the propagation of the shock
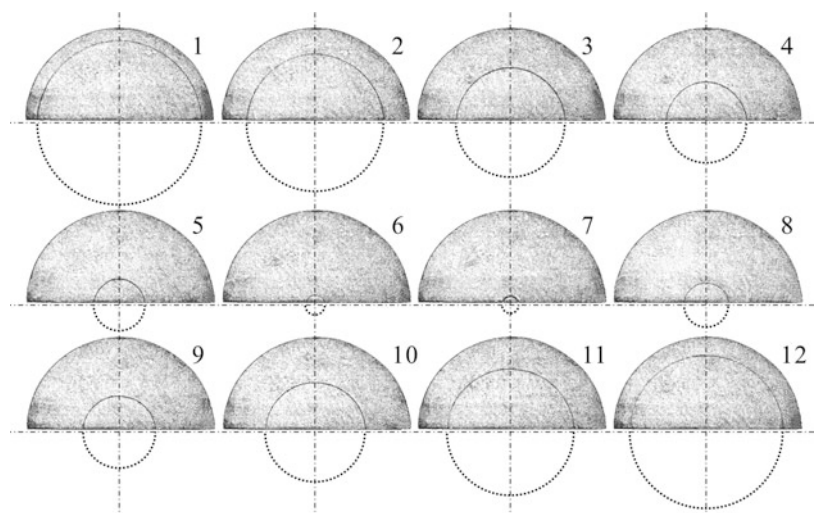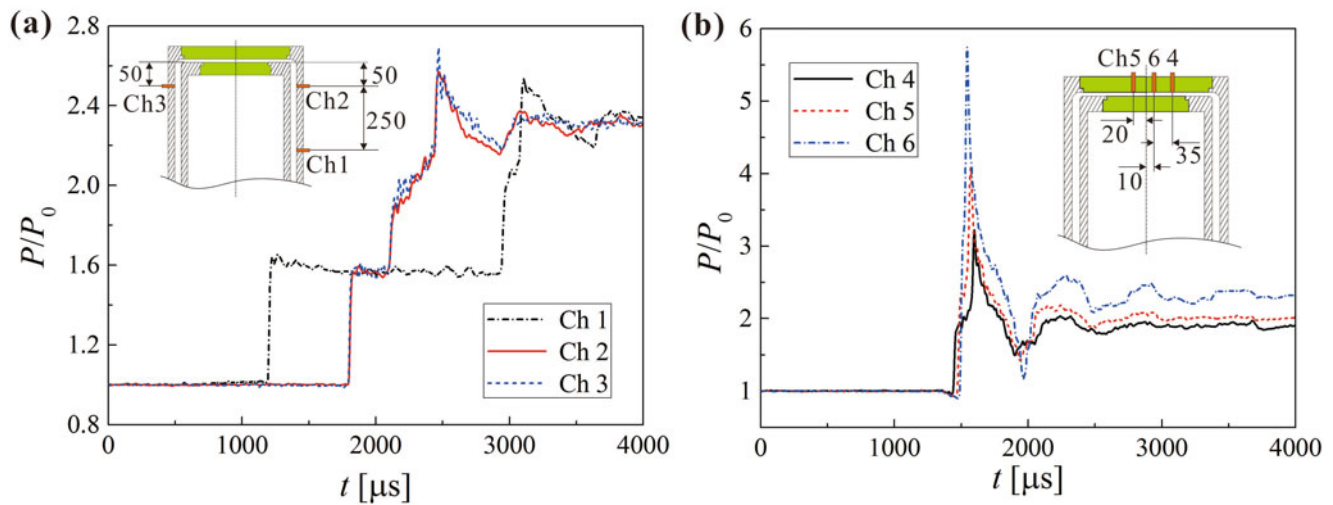
Fig. 3 Pressure histories corresponding to Ch1–Ch3 transducers mounted on the semi-annular section (**a**) and Ch4–Ch6 transducers mounted on the test section (**b**)

propagation process, and the shock fronts match well with the circular arcs of the same centre.

The position of shock fronts is measured and compared with the self-similarity solution. In this experiment, the initial radius $r_0 = 43.6$ mm is taken as the radius of the outmost shock front, and the value of $t_0 = 83.0$ μs is calculated from the experimental data using the fitting of least squares. A self-similarity constant of 0.83 ± 0.01 fitted from the experimental data agrees well with previous experimental and analytical studies [17], which further verifies the reliability of the semi-annular shock tube.

Pressure histories measured by six transducers are plotted in Fig. 3, in which the data is normalized by the atmospheric pressure $P_0 = 1.017 \times 10^5$ Pa at room temperature. The locations of these transducers are also indicated. The pressure variations in Fig. 3(a) indicate that the pressure has a sharp jump when the incident shock arrives at the transducers and the post shock pressure keeps nearly constant at each transducer. The good coincidence between Ch2 and Ch3 signals verifies the uniformly annular shock waves as the shock wave passes over the Ch2 and Ch3 transducers simultaneously. The pressure variations with time in converging test section are shown in Fig. 3(b). The incident shock passes through each transducer in quick succession, resulting in a pressure jump in each position of the transducers. The post shock pressure increases as the shock propagates toward the centre. When the reflected shock passes by, there is another pressure jump, and the post shock pressure decreases gradually with some fluctuations at each position of the transducers.

## Application for Converging RM Instability

In order to get rid of the geometry constraint, an interface formation device which can be inserted to the test section after the generation of the interface, as shown in Fig. 4 (b), is designed to generate density interfaces with soap film technique [18]. The device is made of two semi-circular plexiglass plates fixed on a rectangular block, with radii of 50 and 80 mm, respectively. The microchannels curved in opposite surfaces of two plates have a design of single-mode shape with a width of 0.5 mm and a depth of 1.5 mm. Two corresponding plexiglass single-mode filaments with a width of 0.4 mm and a depth of 1.7 mm are embedded separately in the microchannels to form two small cusps for constraining the soap film. A soap film bubble is blown between the two plates until the soap film connects the cusps and becomes perpendicular to the plates. After the formation of the single-mode interface, the device is carefully inserted to the test section and then equipped with the optical windows in the test section.

As a demonstration, here, a single-mode air/SF_6 interface is formed, which is described in the form of $r = R_0 + a_0 \cos(n\theta)$ in the polar coordinate system. The corresponding perturbation with the amplitude of $a_0 = 2$ mm and the wave number of $n = 6$ is imposed on the unperturbed interface $R_0 = 25$ mm. The processes of the interface deformation and shock propagation after the shock-interface interaction are vividly shown in Fig. 5, and the time interval between two consecutive images is about 23 μs. At the beginning, an incident shock forms and converges to the initial interface

Fig. 4 Drawing of the interface formation device equipped with the top and bottom windows (**a**) and a real device for forming single-mode interfaces (**b**)
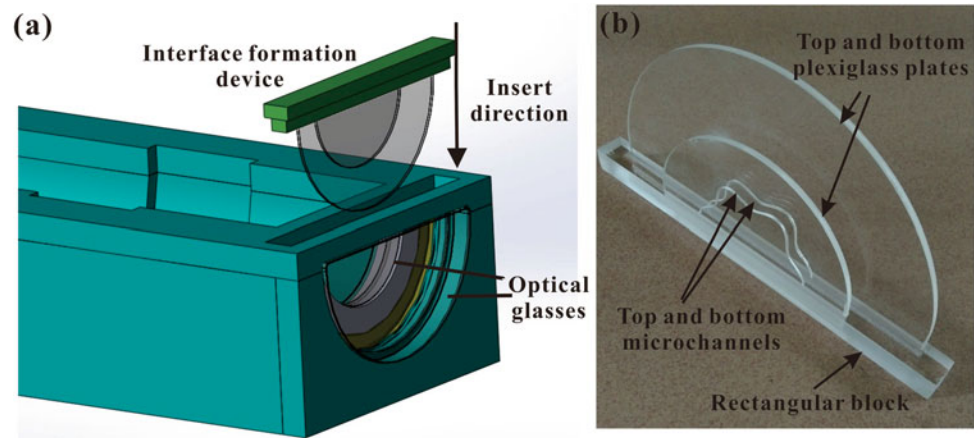
Fig. 5 Schlieren picture sequences of the evolution of a cylindrical single-mode interface accelerated by a cylindrically converging shock
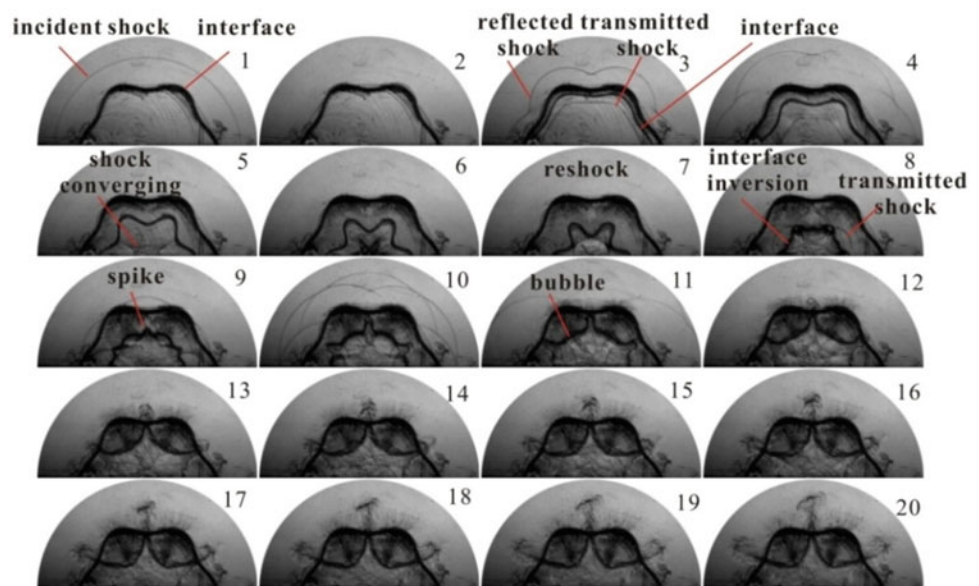
(frame 1). After the interaction of the incident shock and the initial interface (frame 2), both outward-moving reflected shock and inward-moving transmitted shock are formed (frame 3), and their shapes change gradually (frames 3–5). Then the initial shock reflects back from the focal point and impacts the deformed interface again (referred to as reshock, frames 6–8). Subsequently, after the reflected shock passes through the deforming interface, complex shock patterns arise due to the refraction and reflection of the shock waves, and new flow structures, including spike and bubble, emerge due to the effect of additionally deposited baroclinic vorticity (frames 9–12). Finally, the amplitude of the perturbation increases gradually under the effect of total baroclinic vorticity together with the complex waves in the flow field. The rich phenomena existing in converging RM instability are different from those in planar shock cases, exhibiting great potential of this facility for study of the converging RM instability.

Conclusion

A semi-annular cylindrical converging shock tube is designed and constructed in the present work for performing experiments of the converging RM instability. The new self-strutted facility provides great convenience for interface formation and flow observation. The schlieren pictures of the shock in the test section indicate that the facility is capable of generating converging cylindrical shock waves with good stability. The converging effect of the shock wave is revealed by the pressure variations with time at different locations. A self-similarity constant of 0.83 ± 0.01 fitted from the experimental data agrees well with previous experimental and analytical studies, verifying the reliability of the semi-annular shock tube. Finally, a single-mode interface is formed in the test section, and the evolution of the interface accelerated by a

converging shock wave is captured by the high-speed schlieren imaging system. Rich phenomena observed from the present results are of benefit for exploring underlying physics of the converging RM instability.

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