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RT instability in cylindrical implosion of jelly ring*

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The interfacial RT instability experiments on imploding jelly liners in cylindrically convergent geometry have been performed. The liner's instability growth was observed clearly with a high-speed framing camera. Jelly liners have different initial perturbation forms on their inner and outer interfaces, being either smooth or sinusoidal. The initial perturbations also have different magnitudes and spatial frequencies (for example, mode n=5, 10, 20). The experimental results show that the growth and coupling of perturbations on inner and outer surfaces are remarkably different.

Meanwhile, the relevant 2-D numerical simulation of hydrodynamics combined with Level Set method has been performed. Using the numerical code, we can design the parameters of imploding jelly liner, and predict the experimental results. The results of simulation are demonstrated to be in good agreement with the measured data in a series of experiments.

Keywords: hydrodynamic instability, perturbation, jelly ring
PACC: 4720, 4725, 5235P

1. Introduction

Hydrodynamic instability and turbulent mixing have been challenging problems up to now. There are three main kinds of traditional interfacial instability. RT (Rayleigh–Taylor) instability occurs when an interface between materials having different density is affected by acceleration whose vector is perpendicular to the interface and directed from the lower density material to the higher density one. RM (Richtmyer–Meshkov) instability occurs when an interface is affected by a stationary shock wave. KH (Kelvin–Helmholtz) instability occurs when there is a discontinuity in the tangential component of the flow. The interfacial instability is widely encountered in Inertial Confinement Fusion (ICF), detonation physics, electromagnetic implosion and other fields. It is one of keys to achieving high energy density in the laboratory.[1–3]

Three stages are included in interfacial instability in general: exponential increase of small perturbations, nonlinear growth and turbulent mixture. The theoretical and experimental studies on the first linear stage are comparatively less sophisticated. However, there are many difficulties to be overcome for the study of the latter stages. A primary question is how to distinguish different fluids and to form the initial perturbation in experiments. Many techniques have been developed since 1940, such as thin organic film, plane fast-removable partition plate, gas curtain and so on. But there are some disadvantages in those methods: in particular, they cannot well model the situation of cylindrical or spherical implosion of the fluid interface.[4,5]

The jelly liner (ring) driven by imploding gas detonation is a new experimental technique used in this paper to study the nonlinear growth process of interfacial perturbation and turbulent mixture in a cylindrical geometry.[6] In addition, various initial perturbations can be easily set up owing to the jelly ring's plasticity. The evolutions of the ring's inner and outer surfaces are clearly observed by high speed framing photography, including perturbation growth, rebound of inner surface and turbulent mixing. The numerical simulation was based on a 2-D hydrodynamic code with a Total Variation Diminishing (TVD) scheme and in cooperation with the level set method to treat the interface properly, and well reproduces the experimental observations for different initial perturbations.

2. Experimental setup

The scheme of the experimental device is shown

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in Fig.1. A jelly ring with outer diameter of 110mm, inner diameter of 80mm, and thickness of 10mm was sandwiched between two 20mm thick PMMA plates which were transparently polished. There is a steel ring backing the PMMA plates to ensure that they do not expand in experiments. The experimental implosion chamber is shown in Fig.2. There is air at 1 atm pressure inside the jelly ring; the outside volume is filled with oxygen/acetylene mixture at 1 atm, the volume radio being 2.5 : 1. There is an array consisting of 36 spark gaps to ignite the gas mixture synchronously when these gaps break down by a high voltage pulse.

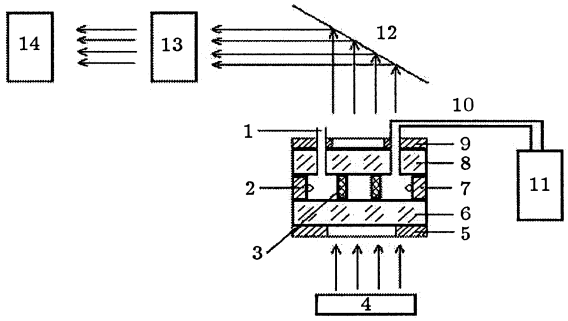


Fig.1. Scheme of experimental setup. 1,10: gas in and exit; 2: spark gaps; 3: jelly ring; 4: light source; 5,7,9: steel rings; 6,8: PMMA plates; 11: mixture gas can; 12: mirror; 13: optical system; 14: high speed camera.

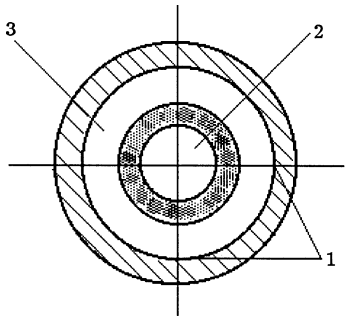


Fig.2. Cylindrical imploding chamber. 1: spark gap array; 2: air; 3: oxygen/acetylene gas mixture.

The preparation of jelly is simple; the initial perturbations on both surfaces are determined by the shape of the model. Sinusoidal patterns were used in the experiments. Owning to the transparency of the PMMA plates, the high speed rotating mirror framing camera (results recorded by film) with Schlieren technology has been utilized to record the flow pattern. The framing rate is 6.25×10^4f/s, the time interval between two frames is 16μs and the exposure time for each frame is 0.5μs.

3. Numerical simulation

3.1. 1-D implosion of incompressible fluid[7]

There are two assumptions in the numerical simulation; the first one is that the jelly ring is incompressible when

$$P_{\rm CJ}/K \ll 1, \tag{1}$$

where $P_{\rm CJ}$=4.5MPa is the Chapman–Jouguet detonating pressure of O_2-C_2H_2, and K is the volume modulus (≈2.2GPa) of water. The second assumption is

$$(n^2G)/(\rho u_{\rm p}^2) \ll 1, \tag{2}$$

where n is the modular number of initial azimuthal perturbation, the shear modulus of jelly G=7.0kPa, and density of jelly $\rho=10^3$kg/m^3. $u_{\rm p}$ denotes $\sqrt{na}$, a is the outer surface acceleration of jelly ring. Equation (2) means that the azimuthal velocity can be neglected in comparison with the radial one. Consequently, the movement of jelly ring can be reasonably predicted with 1-D hydrodynamics.

The gas detonation process can be ignored in calculation because it takes a very short time relative to the ring converging process. The polytropic index and pressure parameters of detonation products are determined by calibrating the 1-D calculation with the experimental data; therefore we obtain γ=2.5, P=1.8MPa.

Figures 3–5 show the results of 1-D calculation and experimental measurements.

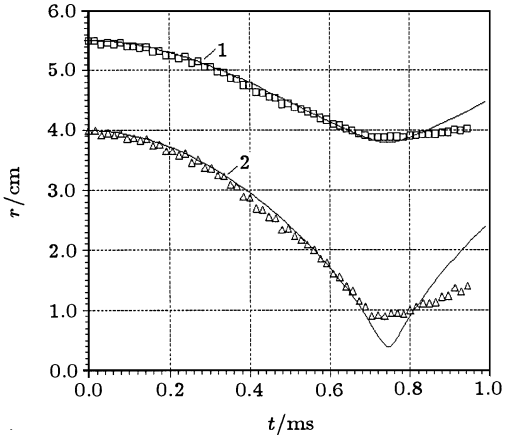


Fig.3. r-t diagram of collapsing jelly ring. 1: outer boundary; 2: inner boundary; □ △: relative experimental results.

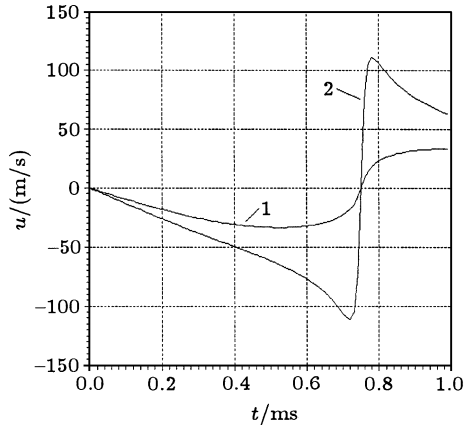


Fig.4. Calculated outer (1) and inner (2) boundary velocity.

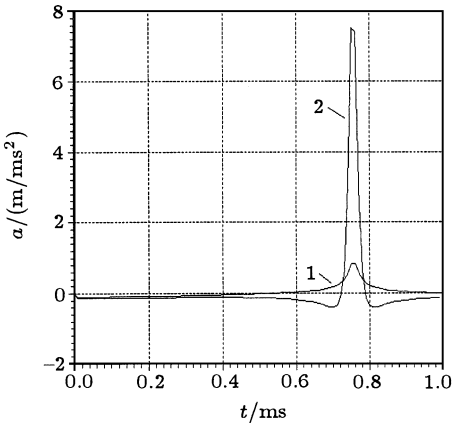


Fig.5. Calculated outer (1) and inner (2) boundary acceleration.

3.2. 2-D compressible hydrodynamic simulation[8]

In order to study the interfacial perturbation effectively, it is useful to express the equations of conservation in cylindrical coordinates. In general, the equations can be written as

$$\frac{\partial \bar{U}}{\partial t} + \frac{\partial \bar{F}}{\partial \xi} + \frac{\partial \bar{G}}{\partial \eta} = 0, \tag{3}$$

where

$$\bar{U} = U/J,$$
$$\bar{F} = (y_\eta F - x_\eta G) = (\xi_x F + \xi_y G)/J,$$
$$\bar{G} = (-y_\xi F + x_\eta G) = (\eta_x F + \eta_y G)/J.$$

For the considered problem, we have the following form:

$$\xi_x = \cos\theta,\ \xi_y = \sin\theta,\ \eta_x = -\frac{\sin\theta}{r},\ \eta_y = \frac{\cos\theta}{r},$$

$$J = \frac{1}{r}. \tag{4}$$

On the other hand, a high-order TVD scheme is used in the numerical code. The equation of state (EOS) of a perfect gas is used for the detonation products and air:

$$p = (\gamma - 1)\rho\left[e - \frac{1}{2}(u^2 + v^2)\right], \tag{5}$$

where γ=1.4, P_0=1 atm, ρ=1.23kg/m^3 for air. Those for the denotation products are determined in a 1-D calculation. It is assumed that the EOS of the jelly is the same as that of water:

$$p = (\gamma - 1)\left[\rho e - \frac{1}{2}\rho(u^2 + v^2) - B\right] - B, \tag{6}$$

where γ=7.0, B=300MPa, ρ=1000kg/m^3.

The initial value of level set is defined by

$$\psi = \begin{cases} 1 & \text{jelly zone,} \\ 0 & \text{air or detonation products zone.} \end{cases} \tag{7}$$

So in the whole flow field, the EOS can be taken as

$$p = [\gamma(\psi) - 1][\rho e - 0.5\rho(u^2 + v^2)] \tag{8}$$

and

$$\gamma(\psi) = \begin{cases} \psi\gamma_2 + (1 - \psi)\gamma_1, \\ \psi\gamma_2 + (1 - \psi)\gamma_3, \end{cases} \tag{9}$$

where γ_1 is of detonation product, γ_2 is of jelly ring, and γ_3 is of air.

The MAC (Marker and Cell) method is used in the numerical simulation, and only 1/4 circle needs to be solved because of the azimuthal symmetry.

4. Experimental and calculated results

In our experiments, the jelly rings had different initial perturbation forms with different magnitudes and different spatial frequencies: for example, azimuthal mode number n=0–20, perturbation magnitude 0–2mm. When the initial perturbations on both outer and inner boundaries have the same mode number, there are still alternations of matches of them: peak to peak, or peak to bottom. Of course, spark gap number corresponded to the mode number in the experiments.

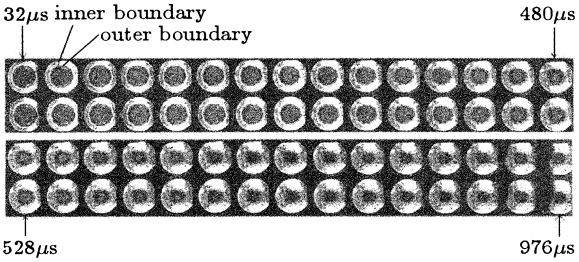


Fig.6. Framing photograms of shot No. 19 with initial perturbation n=10 and amplitude 1mm.

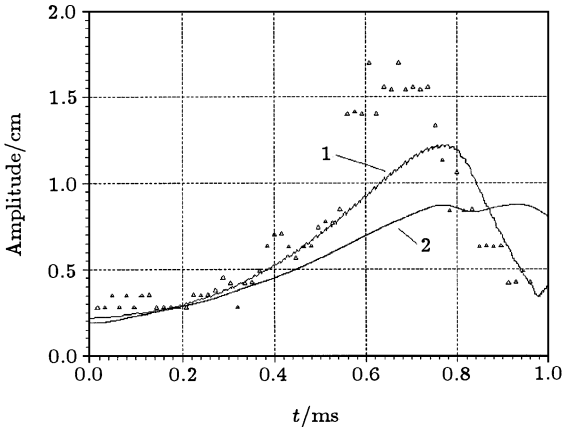
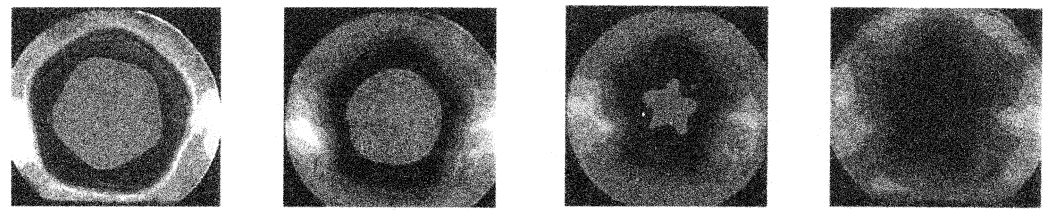
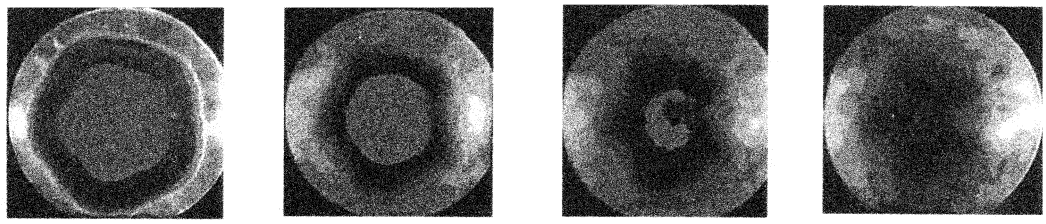


Fig.7. Numerical simulation and experimental measurement of perturbation on outer boundary in shot No.19. Calculated: 1, incompressible model; 2, compressible model. Measured: Δ.

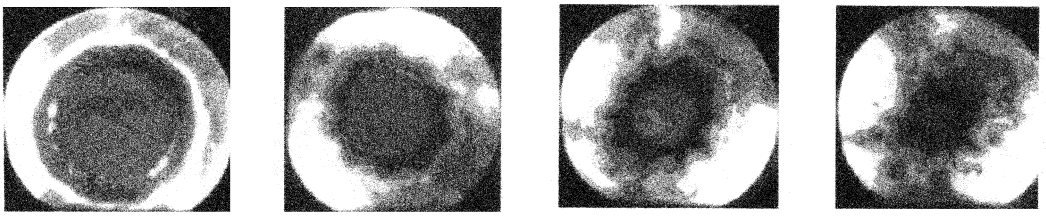
Figure 6 shows a typical experimental result. The outer boundary of jelly ring bears a sinusoidal perturbation of n=10 and amplitude 1mm. The inner boundary is smooth. It can be concluded that the outer boundary is accelerated toward the central axis until 520 μs from the beginning of the initiating detonation. In this stage, the outer surface is unstable and the inner one stable. From 520μs to 720μs, the outer surface is still accelerating toward the central axis, but the inner one rebounds, both of them being stable. After 720μs, both the outer and the inner surface are accelerated against the axis. Then the inner surface becomes unstable and the outer one stable. The calculated results confirm those issues. The perturbation growth obtained from the compressible or incompressible model is in accord with the experimental results (see Fig.7).



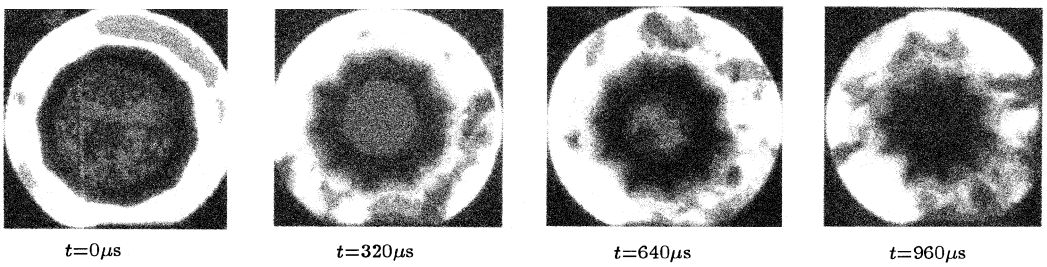
(a) Shot No. 27 with initial unmatched perturbations of n=5 on both outer and inner boundaries.



(b) Shot No. 26 with initial matched perturbations of n=5 on both outer and inner boundaries.

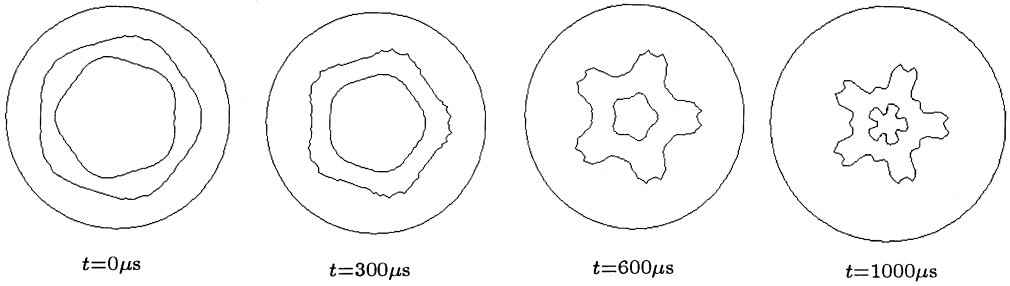


(c) Shot No. 21 with initial unmatched perturbations of n=10 on both outer and inner boundaries.

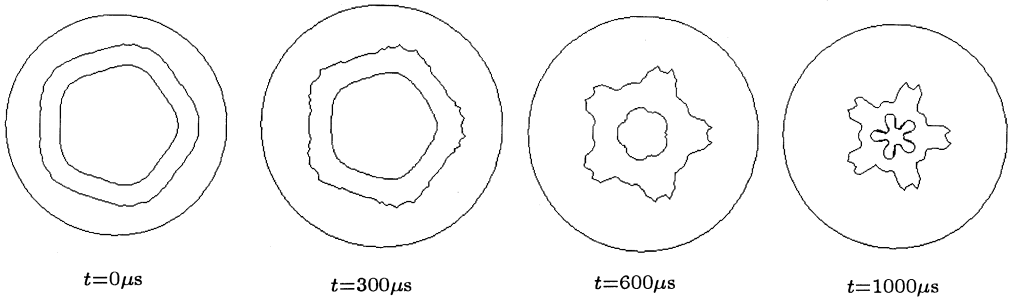


(d) Shot No. 31 with initial matched perturbations of n=10 on both outer and inner boundaries.

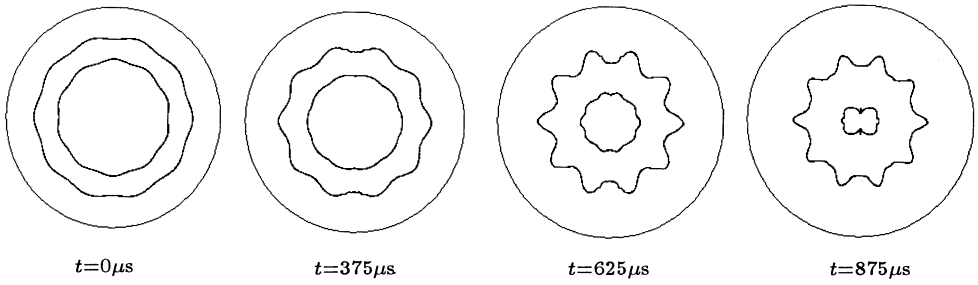
Fig.8. Framing photograms of interactions of disturbance on both boundaries.



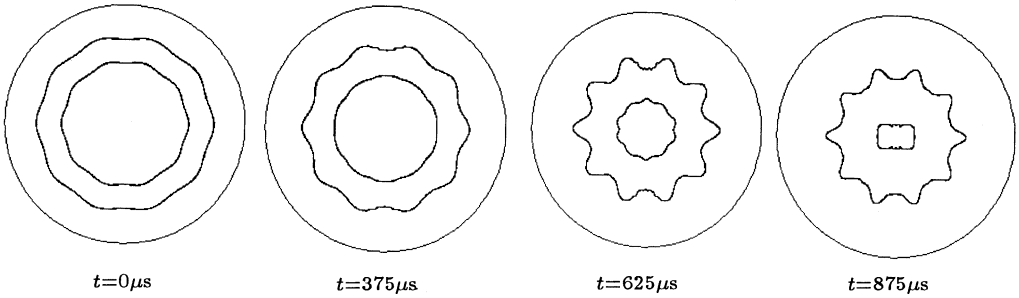
(a) 2-D simulation of shot No. 27.



(b) 2-D simulation of shot No. 26.



(c) 2-D simulation of shot No. 21.



(d) 2-D simulation of shot No. 31.

Fig.9. Numerical simulation of interactions of disturbance on both boundaries.

A feature of the experiments is the investigation of interaction between perturbations on the outer and inner boundaries. Two kinds of experiments have been designed for this purpose, in which both initial perturbations on outer and inner boundaries have the same mode number $n(5,10)$ and amplitude, but differ in the spatial matching of them; the two initial perturbations match in the form of 'peak to peak' (phase matching) for the first kind, and 'peak to bottom' (unmatched phase) for the second kind. The results of

these experiments and related simulations are shown in Fig.8(a,b,c,d) and Fig.9(a,b,c,d). It is found that the phase of inner interfacial perturbation becomes the opposite one during jelly ring implosion. Meanwhile, that of the outer one is still the same. Consequently, the liner with phase matching is more easily destroyed than the unmatched one. In fact, the matched liner broke down, but the unmatched liner remained intact after the experiment. The numerical simulation reproduces correctly these interesting phenomena. Though the accurate reason of this phenomenon is unknown now, it may be related to the interaction between disturbances on both surfaces, and the phase change of the inner surface results in the turbulence mixing in the interior area and in finally breaking the jelly ring.

5. Conclusion

The jelly technique has distinctive advantages in 2-D hydrodynamic instability studies, especially for converging implosion. It can be used to verify the theoretical models and numerical codes quantitatively.

The 2-D numerical simulation can reproduce correctly the complicated experimental process. Its results accord with the experiment quantitatively for the linear stage, and qualitatively for the nonlinear stages. In the experiments on the interaction of perturbations on outer and inner boundaries, an interesting phase reversal of inner perturbation has been observed.

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