Article ID: 1000-5773(2007)03-0253-06

An Improved of Experimental Hypervelocity Launcher and Simulation*

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Abstract: A numerical simulation method for calculation of the three-stage light-gas gun impacts on launch flier to hypervelocity is presented. Based on multi-fluid volume of fraction(VOF) and parabolic piecewise method(PPM), a multi-fluid parabolic piecewise method(MFPPM) shock wave physics code is developed to calculate the experimental hypervelocity launchers. To verify and validate our code of MFPPM, some experimental hypervelocity launchers from Sandia National Laboratories are simulated, and the numerical results of flier velocity are excellent in agreement with that experiment(the maximal relative error is 1.07%). Experiment and simulation results of our experiment on the three-stage light-gas gun are given(the maximal relative error is 1.04%). To satisfy well of the high-pressure equation of state(EOS) data measurement, an improved design model from the computation is presented.

Key words: hypervelocity launcher; multi-fluid parabolic piecewise method; simulations

CLC number: O411 **Document code**: A

1 Introduction

It is an important technique to launch flier plates in excess of 10 km/s in researching the high-pressure equation of state(EOS) of materials. Sandia National Laboratories had developed a shockless (i.e., a pressure ramp-up in time) hypervelocity launcher(HVL) in the nineties, and launched the flier plate to hypervelocity by using the graded-density impactor loadings[1-3]. Two configurations in Fig. 1 are used to realize the HVL. For the energy convergence, the right configuration in Fig. 1 may achieve much higher velocity than the left. The flier plate not only remains well flight attitude, small temperature increasing, but also has small distortions and without any fracture.

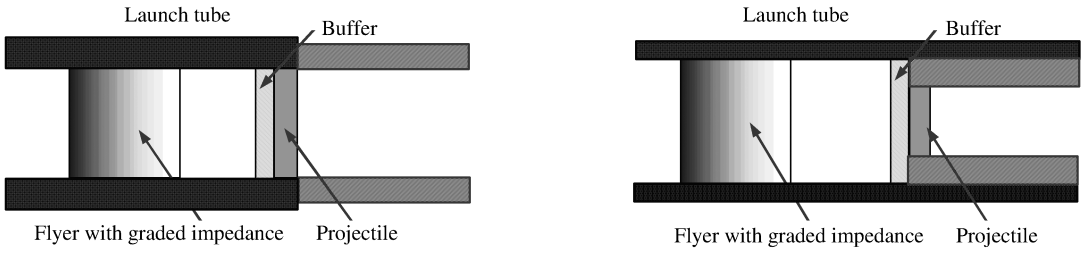


Fig. 1 Two configurations of the HVL

For complexity of the techniques, it is difficult to obtain the configuration parameters and optimization technique states only by experiment. Also, it would be difficult to understand the effects from

* **Received date**: 2006-08-25; **Revised date**: 2006-11-08

Foundation Item: Foundation of the Laboratory for Shock Wave and Detonation Physics Research (9140C6704010704); Foundation of CAEP (20050649)

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various factors to velocity, flight attitude and physical state of the flier plate. So, we must simulate the dynamic process of the flier plate under the graded-density impactor loading, and give some important parameters to the experiments. In this study, we develop multi-fluid parabolic piecewise method (MF-PPM) code to simulate the HVL. After verification and validation of this code, our experiment results and simulations are given. Finally, an improved design model from the computation is presented to satisfy two main requirements: The first is much more velocity of the flier plate, and the second, this loading must be nearly shockless and spatially uniform during the acceleration process.

2 Basic Algorithm

Based on volume of fraction(VOF) model[4], we combine the PPM method[5] with the interface tracking to apply to Euler hydrodynamic equations, and involve to a two-step Lagrange/Remap algorithm to solve multi-fluid problems. The first step is Lagrangian step in which the computation cells distort to follow the material motion, and the second step is Remap step where the distorted cells are mapped back to the Eulerian mesh. The 1D Euler control equations can be written as

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+\dfrac{\partial(\rho u)}{\partial x}=0 \\ \dfrac{\partial(\rho u)}{\partial t}+\dfrac{\partial(\rho u^2+p)}{\partial x}=0 \\ \dfrac{\partial(\rho E)}{\partial t}+\dfrac{\partial[(\rho E+p)u]}{\partial x}=0 \\ \dfrac{\partial Y^{(i)}}{\partial t}+u\dfrac{\partial Y^{(i)}}{\partial x}=0, \qquad i=1,\cdots,N-1 \end{cases} \tag{1}$$

where ρ is the density, u is the velocity, p is the pressure, E is the total energy of a unit mass, N is the kind of materials and $Y^{(i)}$ is VOF for i'th material. In a mixed-cell containing N materials, the volume of fraction satisfies

$$\begin{aligned} &\rho=\sum_{i=1}^{N}Y^{(i)}\rho^{(i)}, \qquad \rho u=\sum_{i=1}^{N}Y^{(i)}\rho^{(i)}u^{(i)} \\ &\rho E=\sum_{i=1}^{N}\left(Y^{(i)}\rho^{(i)}e^{(i)}+\frac{1}{2}Y^{(i)}\rho^{(i)}u^2\right), \quad \sum\nolimits_1^N Y^{(i)}=1 \end{aligned} \tag{2}$$

The total energy of a unit mass is given by $E=e+u^2/2$, e is the specific energy. A simplified Gruneisen EOS is used in this paper $p=(\gamma-1)\rho e+c_0^2(\rho-\rho_0)$, γ is the constant of material, ρ_0 and c_0 are the density and sound speed under the normality, respectively. To effectively capture interfaces of the materials, the two-step Lagrange/Remap algorithm to Eq. (1) can be divided into a four-step calculation: ① the piecewise parabolic interpolation of physical quantities, ② approximately solving Riemann problems, ③ evolution of the Lagrange equations and ④ mapping the physical quantities back onto the Euler mesh.

(1) Lagrange Step

Lagrange equation in 1D for multi-fluid can be written as

$$\begin{cases} \dfrac{\partial \tau}{\partial t}-\dfrac{\partial(r^\alpha u)}{\partial m}=0 \\ \dfrac{\partial u}{\partial t}+r^\alpha\dfrac{\partial p}{\partial m}=0 \\ \dfrac{\partial E}{\partial t}+\dfrac{\partial(r^\alpha u p)}{\partial m}=0 \\ \dfrac{\partial Y^{(i)}}{\partial t}=0 \end{cases} \tag{3}$$

where τ is the specific volume, α is 0, 1, 2 corresponding to plane, axial symmetry and spherical symmetry problems, r is the spatial coordinate, m is the mass coordinate, $m=\int_{r_0}^{r}\rho r^{\alpha}\mathrm{d}r$.

(2) Remap Step

In Lagrange step, the computation cells distort to follow the material motion, and in Remap step, the distorted cells are mapped back to the Euler mesh. The piecewise parabolic interpolation and integral methods in this step are same as in Lagrange step. After Remap step, we update the physical quantities in Euler mesh as $(\rho_{\mathrm{Euler}})_j^{n+1}$, $(u_{\mathrm{Euler}})_j^{n+1}$, $(E_{\mathrm{Euler}})_j^{n+1}$, $[(Y^{(i)})_{\mathrm{Euler}}]_j^{n+1}$. This process can be extended to 2D and 3D easily according to the spatial operator-split algorithm.

3 Verification and Validation

To verify and validate our code of MFPPM, the Sandia's hypervelocity experimental impactor of the configuration in Fig. 2 is selected to calculate. The three-stage light-gas gun used in these studies had a bore diameter of 29 mm. As indicated in this figure, a three-stage light-gas gun projectile faced with a graded-density impactor is mad to impact a thin flier plate located at the muzzle end of the barrel. We select three experimental models by using the MFPPM to calculate and compare with that experiment. The graded-density impactor is consisted of six layered materials, which include TPX plastic, magnesium, aluminum, titanium, copper and tantalum according to impedance from low to high respectively. The flier plate materials used in this study consisted of titanium (Ti-6-Al-4V), aluminum. Table 1 shows the thickness of each material, the initial velocity of the graded-density impactor, the results of Sandia's experiment and the calculation results by MFPPM in this work. Numerical results are indicated in Fig. 3, the flier velocities in the three experiments are excellent in agreement with Sandia's experiments.

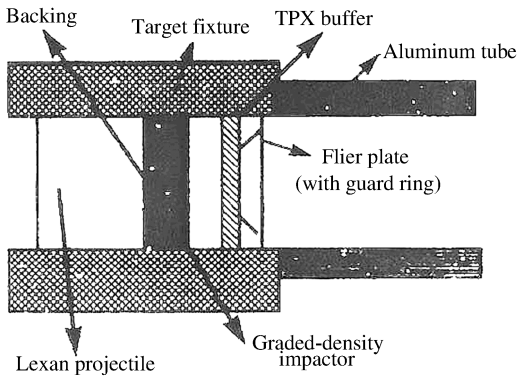


Fig. 2　Schematic of a graded-density

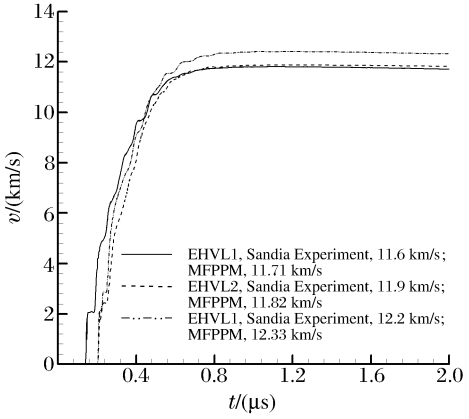


Fig. 3　Axial velocity curves of the flier plate

Table 1　Comparison with the flier plate velocity between Sandia experiment and MFPPM numerical method

Experiment No.	Multi-ply assembly by thickness/(mm)	Buffer/Flier-plate thickness/(mm)	Impact velocity /(km/s)	Flier-plate material/ Velocity/(km/s)	MFPPM velocity result/ Error/(km/s)
EHVL1	0.64/0.33/0.28/ 0.31/0.19/0.52	0.81/0.41	7.2	Al/11.6	11.71/0.95%
EHVL2	0.61/0.30/0.24/ 0.32/0.20/0.44	1.21/0.43	7.35	Ti6/11.9	11.82/0.67%
EHVL3	0.62/0.30/0.23/ 0.33/0.19/0.44	1.25/0.42	7.35	Al/12.2	12.33/1.07%

4 Our Experiment Simulations and Improvement

Next, we list our experimental and numerical results, as well as an improved model from the computation. This is an experimental model for hypervelocity launch on our three-stage light-gas gun, the configuration is indicated in Fig. 4. The graded-density impactor consists of six layered materials: tungsten, copper, titanium, aluminum, magnesium-aluminum alloy and lexan. The thickness/diameter of each material is 2.068 mm/32 mm, 0.311 mm/32 mm, 0.436 mm/32 mm, 0.516 mm/32 mm, 0.599 mm/32 mm and 1.5 mm/32 mm, respectively. The initiall velocity of the layered impactor in our design model is 5.42 km/s. The flier plate with a thickness/diameter of 1.2 mm/32 mm is titanium, the buffer layer material is lexan with a thickness/diameter of 1.0 mm/39 mm and the barrel materials are tungsten, steel and aluminum. The flier velocity measured in our experiment is 8.4 km/s. Fig. 5 shows the result of the axial flier velocity history, the flier velocity nearly stablize at 8.488 km/s in our simulation and the maximal relative error is 1.04%. In Fig. 6 we show the calculated configuration of density and X-ray image in our experiment at the same time. It is clear that the axial flier velocity is excellent in agreement with our experiment, and the diameter of the flier keeping flat almost achieve 20 mm which is basically satisfied with the require of impact in EOS measurement.

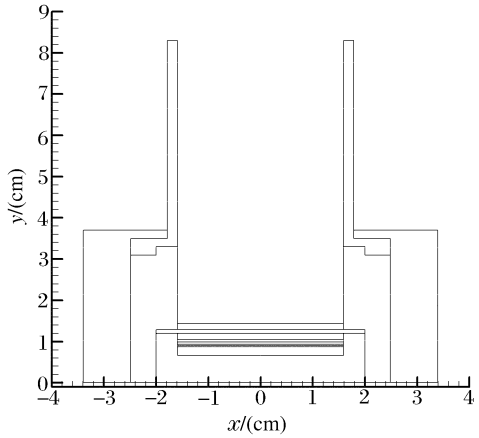


Fig. 4 Experimental configuration

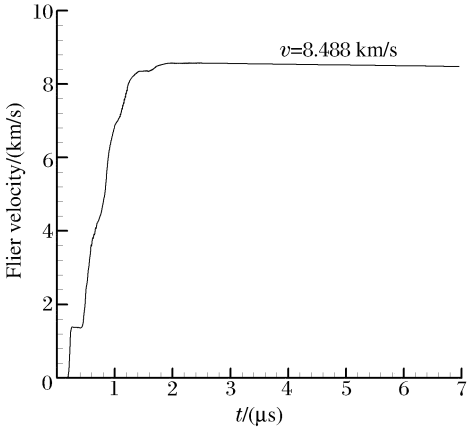


Fig. 5 Result of the axial flier velocity history

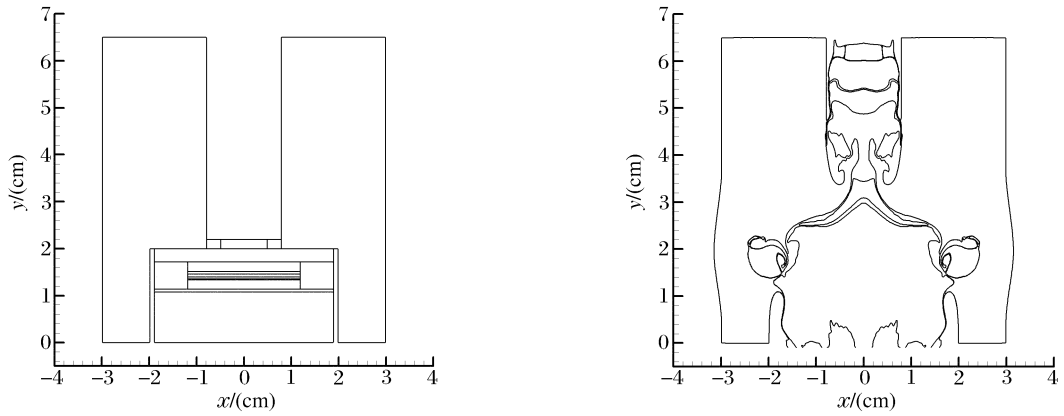


(a) Numerical method (b) Experiment

Fig. 6 Comparison of the images between numerical method and experiment

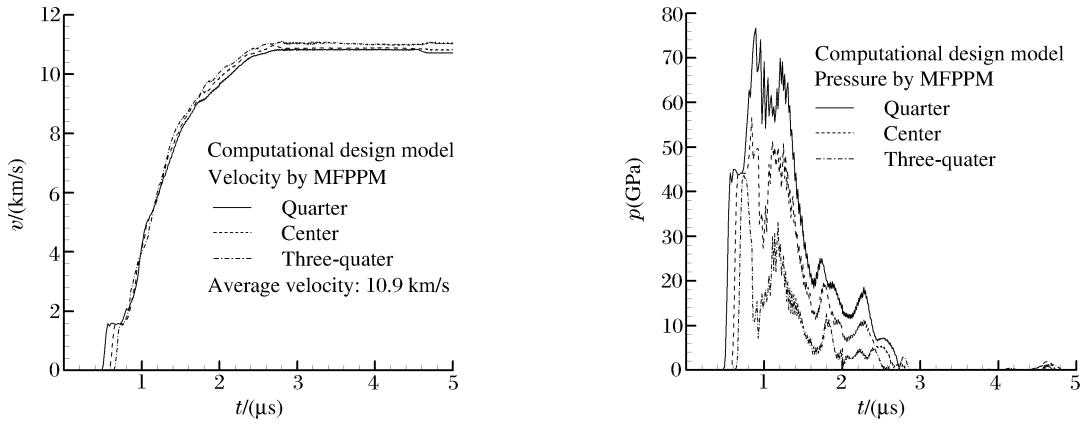
Following the launch, to obtain the high-pressure EOS data the flier must be intact, flat, and the velocity must also be known for use in planar impact experiment. The flier impact velocity is crucial

for obtaining accurate EOS measurements. So another improved design model from the computation is given, in which the barrel must be stepped down to enhance impactor momentum and kinetic energy transfered to the central flier. This means that the downstream barrel diameter is an important parameter. Fig. 7(a) is the configuration of the design model. The graded-density impactor consists of seven layered materials: titanium, tungsten, copper, titanium, aluminum, magnesium-aluminum alloy and lexan. The thickness/diameter of each material is 0.5 mm/38 mm, 2.0 mm/24 mm, 0.3 mm/24 mm, 0.4 mm/24 mm, 0.5 mm/24 mm, 0.6 mm/24 mm and 2.0 mm/24 mm, respectively. The initiall velocity of the layered impactor is 6.0 km/s. The flier plate with a thickness/diameter of 2.0 mm/16 mm is of titanium, the buffer layer material is lexan with a thickness/diameter of 2.9 mm/38 mm and the barrel material is tungsten alloy. We present the interfacial positions of the materials at $t=5.0$ μs in Fig. 7(b). The axial velocities and pressure histories at the quarter, center and three-quarter points in the flier are plotted in Fig. 8. The average axial velocity of the flier achieved 10.9 km/s, and the maximal pressure at the position of the quarter is about 76.8 GPa. It is obvious that the velocity has a jump (weak shockless) at the beginning, then increases slowly, and finally achieves an almost stable state. After 3.0 μs, the pressure of the flier is almost zero(intact) and the flier not only remains flight attitude well, but also has small distortions.



(a) Interface at $t=0$　　(b) Interface at $t=5.0$ μs

Fig. 7　Configurations of the interfaces



(a) Axial velocity　　(b) Pressure

Fig. 8　Axial velocities and pressures of the flier at quarter, center and three-quarter points

5 Summary

Based on multi-fluid PPM method, the MFPPM code was developed to simulate the HVL problems. For verification and validation, the experimental hypervelocity launcher of Sandia's was selected. The main results of our HVL experiment and simulation are given, and obtained the numerical results are consistent with our experimental. Finally, an improved design model from the computation is presented. We expect the next experiment to verify and validate our numerical results in the future.

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一种超高速发射实验装置的改进及其数值模拟

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摘要: 以流体比容方法和三阶PPM方法为基础, 给出了适用于三级气炮超高速发射过程数值模拟的多流计算方法和计算代码MFPPM。利用Sandia实验室一系列的实验装置及其结果对计算代码进行了验证和确认, 获得了较好的数值模拟结果(其中最大相对误差为1.07%), 同时对冲击波物理与爆轰物理实验室设计的实验装置进行了数值模拟, 计算结果与实验结果相差1.04%。为了更好地满足超高压下材料状态方程的测量, 提出了一种带汇聚型的改进装置设计, 并给出了相应的数值模拟结果。

关键词: 超高速发射; 多流体计算方法; 数值模拟

中图分类号: O411 **文献标识码:** A