Simulation and Modeling Investigation into Shock Wave Characteristics by Gas-Filled Pressure Vessels under Hypervelocity Impact

FangfangGai[1*], BaojunPang[2], LiyanYu[1], JitaoZhao[1] and YueminYu[1]

[1]*College of Sciences, Heilongjiang University of Science and Technology, Harbin, 150022, China*
[2]*Hypervelocity Impact Research Center, HIT Aerospace Laboratory, Harbin, 150080, China*
fang19811119@163.com

Abstract

Based on the characteristics of shock wave which are produced by spherical projectiles hypervelocity impact on nitrogen-filled pressure vessels, apply ingone-dimensional shock wave theory and numerical simulation method, at the condition of the debris clouds is completely ablated, the process of shock wave propagation in the gas is analyzed, and model of shock wave propagation is built. The law of shock wave propagation, the pressure of shock wave and the pressure pulse duration are obtained. The result shows that at the same impact velocity, the pressure of shock wave is increasing with gas pressure and projectile diameter. Fracture of pressure vessels impacted by hypervelocity projectiles with a diameter less than 3mm is governed by inflation pressure for projectile impact velocities of 7 km/s.

Keywords: hypervelocity impact; gas shock wave; shock wave theory; pressure vessels; numerical simulation

1. Introduction

Spacecraft often employ pressure vessels to contain gases and liquids (e.g. for breathing gases, propellant storage, *etc.*). A pressure vessel subjected to hypervelocity impact by meteoroids and space debris can represent a significant hazard to a space vehicle because of the energy stored within the vessel. Impact damage modes for pressure vessels include leakage, cracking and catastrophic rupture. Catastrophic rupture of the vessel can send high-velocity fragments in all directions and secondary damage becomes a serious threat to the spacecraft [1-4].Experimental results [5-9]show that some pressure vessel fracture from the rear wall, but leaving no or few impact traces at the vessel's rear wall. During hypervelocity impact the projectile perforates the front wall, generating a debris cloud. The expanding debris cloud propagates to the vessels rear wall. It is subject to a strong interaction with the gas, a strong gas shock wave is generated. The debris clouds are completely ablated on the distance from the vessels front wall to the rear wall if gas pressures exceeded a few bars. The shock wave reaches the rear wall, reflects, travels to front wall and produces a pressure pulse there. The amplitude of this wave will, in certain conditions, be high enough to cause initiation and propagation of cracks from the rim of the front wall impact hole. It is therefore necessary to explore propagation process of shock wave in pressure vessels. In the paper the propagation process of shock wave in pressure vessels is studied by numerical simulation method and theoretical analysis method, and the model of shock wave propagation is built.

2. Simulation of Propagation of Shock Wave

In the following the numerical simulation is performed to analyze the propagation process of shock wave which is produced by spherical projectiles hypervelocity impact on nitrogen-filled pressure vessels. Figure1 shows the initial geometry model which is built by the AUTODYN-2D is in axial symmetry (due to axial symmetry, only half of the projectile and vessel is established). Considered for this paper, the cylindrical pressure vessels are made of A1 2024 alloy, and the projectiles are made of aluminum. The vessel casing off the penetration zone is described using shell elements. For the penetrated front wall SPH particles are applied. In the case of simulation 10 SPH particles are set across the vessel thickness. Johnson-Cook strength model and Tillotson EOS are used, and nitrogen is described via an ideal gas EOS.

Figure 2 shows that during the interaction of the hypervelocity debris cloud with the gas, a strong gas shock wave is generated. And shock wave propagate along with the leading edge of the debris cloud. Shock wave front in pressure gas is formed of conical due to deceleration of debris clouds (Ref.10, 11).
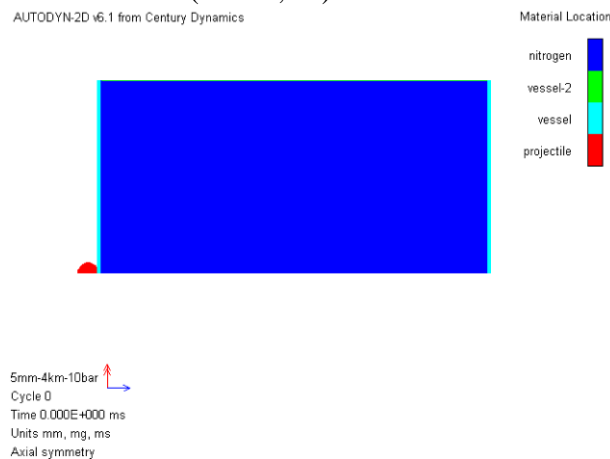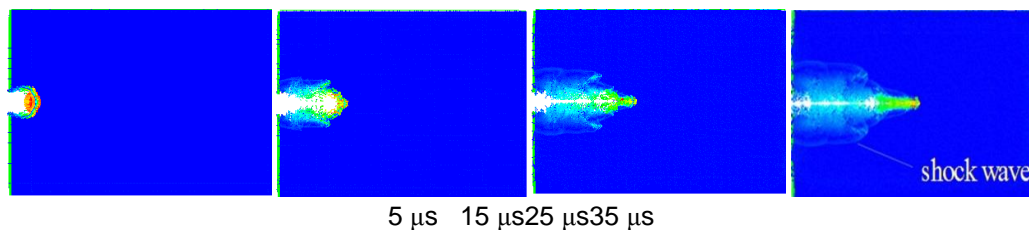

Figure 1. Initial Geometry Model

5 μs   15 μs 25 μs 35 μs

Figure 2. Numerical Results of Shock Wave Propagation (Impact Velocity 4.0km/s, Projectile Diameter 6.0mm, Gas Pressure 4.0MPa)

3. Analysis of Propagation Process of Shock Wave

3.1. Simplified Model of Pressure Vessel

In the study, curvature of vessels is not considered to influence propagation process of shock wave because the projectile (millimeters level) is much smaller than vessel, simplified model of pressure vessel shown in Figure 3. Assumptions in model are as follows: the vessel wall is considered plate, plate thickness of the model is equal to wall thickness of vessel, the distance between the two plates is equal to vessel diameter, and the space between the two plates is filled with pressure gas.

3.2. Computation of Shock Wave Pressure

When the debris cloud are completely ablated in pressure gas, the action of a debris cloud to gas inside a pressure vessel is modeled by a impulsive load, which is in correspondence with experimental observations for pressures exceeding a few atmospheres (Ref. 5). A pressure pulse (impulsive load) of short duration is applied to the external surface of the gas. The pressure pulse duration is determined from the assumption that the complete initial momentum and energy of the debris cloud are transferred to the gas in time by deceleration of the debris cloud. Figure 4showsthatpressure acting on the surface of the gas which drops sufficiently rapidly with time.
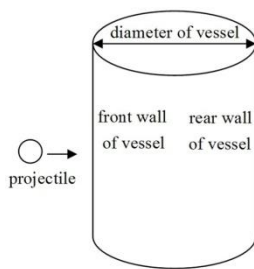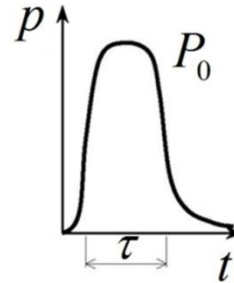

Figure 3. Simple Model of Pressure Vessel   **Figure 4. Shapes of Pressure Pulses**

Figure 5 showsinitialshape of debris cloud ($v_{ar}$is radial velocity of the debris cloud, $v_c$is axial velocity of the debris cloud). In a short time interval τan expanding planarpiston is pushed into the gas with a velocity v_c. The impact creates a shock wave inthe gas, which propagates with a velocity close to v_c. To basic relations of one-dimensional shock waves the initial pressure of the shock wave P_0can be evaluated as follows[12]:

$$P_0 = \frac{2}{\gamma + 1} \rho_0 v_c^2 \qquad (1)$$

Where: γ -specific heat ratio, for a diatomic gas (nitrogen) ,$\gamma = 1.4$, ρ_0 - initial gas density.

By Ref.12,13thepressure amplitude of the shock wave just before the reflection from the rear wall can be written as

$$p \approx P_0 \frac{m_0}{M} \qquad (2)$$

Where:m_0-the initial pressure pulse encompasses a gas mass in the time interval τ, M-the shock wave encompasses a gas mass in the time interval t .

In the following m_0, M andτ are evaluated. Figure 5 shows that gas mass $m_0$bounded by the surface of cone with a radius $v_{ar}\tau$, and height $v_c\tau$. Thus m_0 can be written as

$$m_0 = \frac{1}{3} \rho_0 \pi \left(v_{ar}\tau \right)^2 \left(v_c \tau \right) \qquad (3)$$

Energy conservation in impact process is considered. Thus impact energy of projectile is equal to energy of initial pressure pulse, pressure pulse duration$\tau$is:

$$\frac{1}{2} m_p v_p^2 = \frac{1}{2} \rho_0 \left[\frac{1}{3} \pi \left(v_{ar}\tau \right)^2 v_c\tau \right] v_c^2 \Rightarrow \tau = \frac{1}{v_c} \sqrt[3]{\frac{3}{\pi} \frac{m_p}{\rho_0} \left(\frac{v_p}{v_{ar}} \right)^2} \qquad (4)$$

Where: m_p-projectile mass, v_p-impact velocity of projectile.

3.3. Propagation of Shock Wave from the Front Wall to the Rearwall

Pictures of shock wave propagation from numerical simulation is presented in Figure 6. According to a characteristic of bound of shock wave, it is assumed that the shock front propagates in a bounded region of a space inside pressure vessel (in a hypothetical channel). This hypothetical channel is bounded by a conical surface. It may be possible at this point to draw the some analogy to the conical surface bounding the path of fragment at outer edge of the debris cloud. Figure 6 shows that gas mass M bounded by the surface of cone with a radius r_s, and height l_s. Thus M can be written as

$$M = \frac{1}{3} \rho_0 \pi r_s^2 l_s \qquad (5)$$

When the shock wave reach rear wall of pressure vessel ($l_s = D_v$, $r_s = r_0$), the shock wave encompasses a gas mass M_1 can be written as

$$M_1 = \frac{1}{3} \rho_0 \pi r_0^2 D_v \qquad (6)$$

Where: D_v-diameter of pressure vessel.

Thus the pressure amplitude of the shock wave just before the reflection fromthe rear wall is

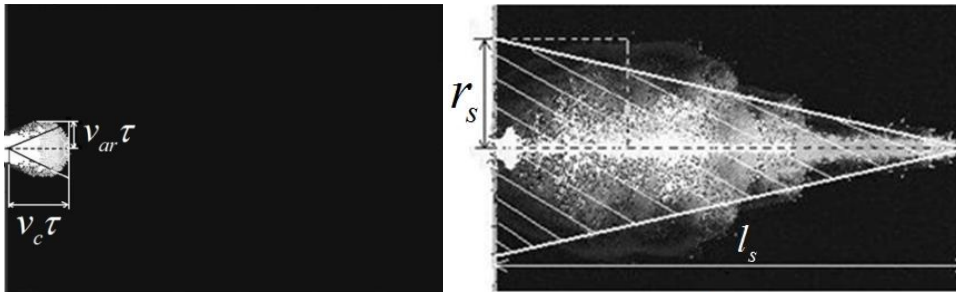$$p_1 \approx P_0 \frac{m_0}{M_1} \qquad (7)$$

Figure 5. Initial Shape of Debris Cloud   Figure 6. Bound of Shock Wave

3.4. Propagation of Shock Wave From the Rear Wall to the Front Wall

In the following the reflection of the shock wave from the pressure vessel's rear wall is considered. Goal is the calculation of pressure pulse amplitude enhancement upon reflection from the rear wall and estimation of the pressure pulse duration. The rear wall is considered absolutely rigid. When arrival of the shock wave at the rear wall, it is reflected. The reflected shock travels back to the front wall. Let a pressure pulse of short duration be applied to the surface of the gas. In a short time interval τ_{r1}impulsive is pushed into the gas, creating a pressure p_{r1}.Relation between the pressure of incident shock wave and the pressure of reflected shock wave can be written as

$$p_{r1} = K_{r1} p_1 \qquad (8)$$

Where:K_{r1} - the shock wave reflection coefficient, $K_{r1} = \dfrac{(3\gamma - 1)\, p_1 - (\gamma - 1)\, p_0}{(\gamma - 1)\, p_1 + (\gamma + 1)\, p_0}$ (by Ref.14).

For the calculation of the duration of the reflected pressure pulse it is assumed that the gas mass that has been encompassed by the reflected pressure pulse is equal encompasses a gas mass M_1, and radius of action of reflected pressure pulse is equal r_0(Figure 7). Hence it follows

$$\tau_{r1} = \frac{M_1}{D_1 \rho_1 \pi r_0^2} \qquad (9)$$

Where: ρ_1 - density of incident wave front, $\rho_1 = \frac{(\gamma + 1) p_1 + (\gamma - 1) p_0}{(\gamma - 1) p_1 + (\gamma + 1) p_0} \rho_0$,

D_1 - velocity of incident wave front, $D_1 = \sqrt{\frac{\gamma + 1}{2} \frac{p_1}{\rho_0}}$ (by Ref.14).

Velocity of reflected wave front is as follows[14]:

$$D_{r1} = \sqrt{\frac{\gamma + 1}{2} \frac{p_{r1}}{\rho_0}} \qquad (10)$$

In the time interval τ_{r1} the reflected pressure pulse encompasses a gas mass m_{r0}, bounded by the surface of a cylinder. Figure 7 shows that gas mass m_{r0} bounded by the surface of cylinder with a radius r_0, and height $D_{r1}\tau_{r1}$.

$$m_{r0} = \rho_0 \pi r_0^2 (D_{r1}\tau_{r1}) \qquad (11)$$
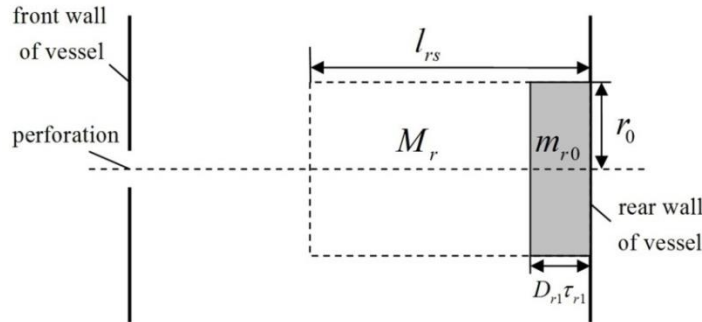

Figure 7. Bound of Reflection Shock Wave

Based on the above-mentioned analysis of shock wave Propagation, the process of shock wave propagation from the rear wall to the front wall is analyzed.

The reflected shock front propagates in a bounded region of a space inside pressure vessel is assumed. This hypothetical channel is bounded by a cylindrical surface. The reflected shock encompasses a gas mass M_r. Figure 7 shows that gas mass M_r bounded by the surface of cylinder with a radius r_0, and height l_{rs}.

$$M_r = \rho_0 \pi r_0^2 l_{rs} \qquad (12)$$

When the shock wave reach from wall of pressure vessel($l_{rs} = D_v$), the reflected shock encompasses a gas mass M_{r1} can be written as

$$M_{r1} = \frac{1}{3} \rho_0 \pi r_0^2 D_v \qquad (13)$$

Thus the pressure amplitude of the shock wave p_2 just before the reflection from the from wall is

$$p_2 = p_{r1} \frac{m_{r0}}{M_{r1}} = p_{r1} \frac{D_{r1}\tau_{r1}}{D_v} \qquad (14)$$

When the reflected shock reaches to the front wall, it can produce a pressure pulse there. The front wall is considered absolutely rigid. For the evaluation of the pressure amplitude that is reflected from the front wall the approach described above is used. Front wall failure occurs when initial gas pressure and an additional shock wave pressure that is reflected from the front wall, exceeds a certain critical limit.

4. Validation of the Model and Analysis of Calculation Result

4.1. Validation of the Model

The hypervelocity experiment in Ref. [5] is selected as references model for the propagation of shock wave. The test samples are cylindrical vessels, with a wall thickness (t_v) of about1 mm and a diameter(D_v) of 150 mm, made of Al 5754. All projectiles are aluminium spheres, impacting at normal incidence in the center of the vessels cylinder wall. The projectile diameters(d_p) ranged from 3.45 mm to 4.39 mm, and the impact velocities (v_p)of abous 7.0 km/s. The gas pressure(p_0) is between 1.56 MPa to 2.3 MPa(Nitrogen). The experimental parameters and calculated results of the r_0 and p_1 are listed in Table 1.

Table 1. Calculated Results of the r_0 and p_1

Exp.No.	D_v/mm	t_v/mm	d_p/mm	v_p/km/s	p_0/MPa	r_0/mm	p_1/MPa
01	150	0.99	3.45	6.9	2.30	28.1	9.28
02	150	0.96	4.39	7.1	1.56	27.2	21.62
03	150	0.91	4.39	7.3	1.60	26.7	23.54

Duration of the reflected pressure pulseτ_{r1} and pressure amplitude of reflected shockp_{r1}areobtained by Eq.9 and Eq.10.Table 2 containsτ_{r1} and p_{r1} that are measured in tests and calculated respectively. Table 2 shows that the deviations of τ_{r1} between experimental and calculated results do not exceed 8%, and the deviations of p_{r1} between experimental and calculated results do not exceed 3.6%. Thus, the calculated results good accordance with the experimental results. Thus the proposed models can be used for the analysis of propagation of shock wave.

Table 2. Comparison of Calculated and Experiment Results [5] of the Reflection Shock Wave Pressure and the Reflection Durations

Exp.No.	p_{r1}/MPa	$p_{r1.mea}$/MPa	$p_{r1.error}$	τ_{r1}/μs	$\tau_{r1.mea}$/μs	$\tau_{r1.error}$
01	29.95	28.80	4.0%	11.2	—	—
02	129.60	120.00	8.0%	8.6	8.2	3.5%
03	142.63	133.00	7.2%	8.3	8.0	3.6%

4.2. Analysis of Calculation Result

In the following the effect of the projectile diameter and the gas pressure on the propagation of shock wave is analyzed. The vessel wall thickness of 1 mm and a diameter of 150 mm, made of Al 5754. The gas pressure ranged from0.5 MPa to 2.0 MPa. The projectile diameters ranged from 2.0 mm to 5.0 mm, and the impact velocities of 7.0 km/s. All calculated cases are summarized in Table 3.

Figure 8 illustrates relationship between pressure amplitude just before reflection(p_1) , after reflection from the rear wall (p_{r1})and initial gas pressure. Figure 8 shows that pressure amplitude after reflection from the rear wall is higher than before reflection. The pressure amplitude before reflection from the rear wall and the pressure amplitude before reflection from the rear wall are increased with initial gas pressure and projectile diameter (kinetic energy of projectile)at impact velocity of 7 km/s.

Table 3. Calculated Case

Cal. No.	D_v /mm	t_v /mm	d_p /mm	v_p /km/s	p_0 /MPa	Cal. No.	D_v /mm	t_v /mm	d_p /mm	v_p /km/s	p_0 /MPa
01	150	1	2	7	0.5	09	150	1	2	7	1.5
02	150	1	3	7	0.5	10	150	1	3	7	1.5
03	150	1	4	7	0.5	11	150	1	4	7	1.5
04	150	1	5	7	0.5	12	150	1	5	7	1.5
05	150	1	2	7	1	13	150	1	2	7	2
06	150	1	3	7	1	14	150	1	3	7	2
07	150	1	4	7	1	15	150	1	4	7	2
08	150	1	5	7	1	16	150	1	5	7	2

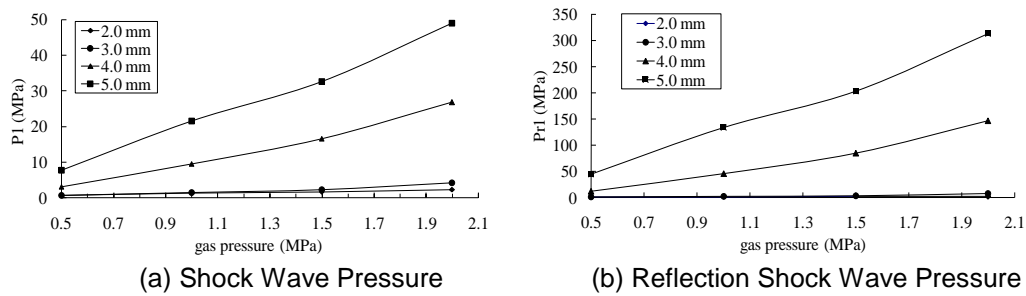(a) Shock Wave Pressure　　(b) Reflection Shock Wave Pressure

Figure 8. Pressure before Reflection and after Reflection of the Shock Wave from the Rear Wall

Figure 9 illustrates relationship between pressure amplitude just beforereflection (p_2), after reflection(p_{r2}) from the frontwall and initial gas pressure.Figure 9 shows that the pressure amplitude before reflection and after reflection from the front wall are increased with increased theinitial gas pressure and projectile diameter.Figure 9 also illustrates that shock waves generated in gas under hypervelocity impact of projectile with a diameters less than 3.0 mm damp out completely inside thepressure vesselat impact velocity of 7 km/s. Fracture of front wall is governed then by the effect of the inflationpressure and corresponds to a burst under quasi-static inflation.
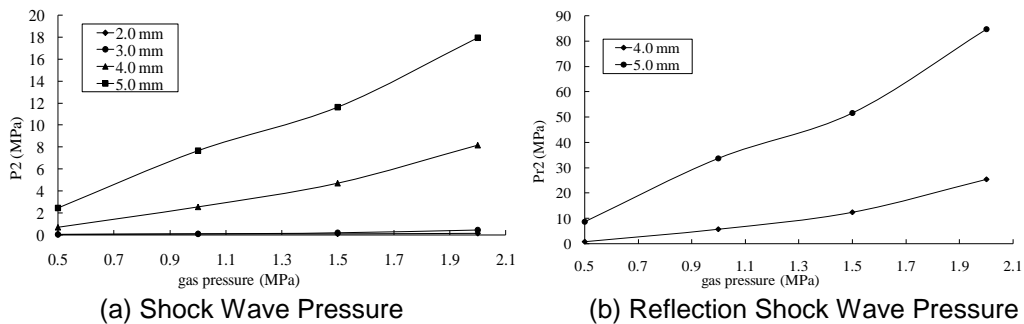

(a) Shock Wave Pressure　　(b) Reflection Shock Wave Pressure

Figure 9. Pressure before Reflection and after Reflection of the Shock Wave from the Front Wall

5. Conclusions

Applying one-dimensional shock wave theory and numerical simulation method the process of shock wave propagation in the gas is analyzed, and model of shock wave propagation is built.

(1) Pressure amplitude of shock wave is obtained. The pressure amplitude of a shock wave increases are increased with the initial gas pressure and projectile diameter at impact velocity of 7 km/s.

(2) Pressure pulse duration is obtained.

(3) Fracture of pressure vessel's front wall which are impacted at 7 km/s by projectile with a diameter less than 3.0 mm is governed by the initial gas pressure.

Acknowledgements

References

[1] N. N. Smirnov, A. B. Kiselev, K. A. Kondratyev and S. N. Zolkin, "Impact of Debris Particles on Space Structures Modeling", Acta Astronautica, vol.67, (2010), pp.333-343.

[2] J. Huang, X. M. Zhao, L. S. Ren, L. Yi, Z. X. Zhou and S. Liu, "A New Engineering Model of Debris Cloud Produced by Hypervelocity Impact", International Journal of Impact Engineering, vol.56, (2013), pp.32-39.

[3] Y. T. Igor, "Analysis of Burst Conditions of Shielded Pressure Vessels Subjected to Space Debris Impact", Journal of Pressure Vessel Technology, vol.127, (2005), pp.179-183.

[4] R. Q. Chi, "Research and Modeling of Debris Cloud Produced by Hypervelocity Impact of Projectile with Thin Plate", Dissertation for the Doctoral Degree in Engineering, Harbin Institute of Technology, (2010).

[5] Y. T. Igor, F. K. Schäfer, E. E. Schneider and M. Lambert, "Analysis of the Fracture of Gas-Filled Pressure Vessels under Hypervelocity Impact", International Journal of Impact Engineering, vol.23, (1999), pp.905-919.

[6] G. S. Guan, "Hypervelocity Impact Characteristic Investigation of Spacecraft Space Debris Shield Configuration", Dissertation for the Doctoral Degree in Engineering, Harbin Institute of Technology, (2006).

[7] D. O. Greory and M. N. Angela, "Hypervelocity Impact Testing of Pressure Vessels to Simulate Spacecraft Failure", International Journal of Impact Engineering, vol.26, (2001), pp.555-566.

[8] S. Hiermaier and F. K. Schäfer, "Hypervelocity Impact Fragment Clouds in High Pressure Gas Numerical and Experimental Investigtions", International Journal of Impact Engineering, vol.23, (1999), pp.391-400.

[9] E. L. Christiansen and J. H. Kerr, "Debris Cloud Ablation in Gas-Filled Pressure Vessels", International Journal of Impact Engineering, vol.20, (1997), pp.173-184.

[10] F. F. Gai, B. J. Pang and G. S. Guan, "Numerical Investigation on the Characteristics of Debris Clouds Produced by Hypervelocity Impact on Pressure Vessels", Chinese Journal of High Pressure Physics, vol.23, (2009), pp.223-228.

[11] F. F. Gai, B. J. Pang and G. S. Guan, "Model for the Deceleration of Secondary Debris Produced by Hypervelocity Impact on Pressure Vessels", Chinese Journal of High Pressure Physics, vol.26, (2012), pp.177-184.

[12] V. B. Adamskii, "Integration of the System of Self-Similar Equations in the Problem of an Impulsive Load on a Cold Gas", Akust. Zh., vol.2, (1956), pp.3-9.

[13] A. I. Zhukov and Y. M. Kazhdan, "On the Motion of a Gas under the Action of a Short Duration Impulse", Akust. Zh., vol.2, (1956), pp.352-357.

[14] W. X. Li, "One-Dimensional Non steady Flow and Shock Waves", National Defence Industry Press, Beijing, (2003).