NUMERICAL SIMULATION OF DEBRIS CLOUD PROPAGATION INSIDE GAS-FILLED PRESSURE VESSELS UNDER HYPERVELOCITY IMPACT

F.F. Gai, B.J. Pang, G.S. Guan

Hypervelocity Impact Research Center, Harbin Institute of Technology, P. O. Box 3020, No.2 Yikuang Street, Nangang District, Harbin 150080, P.R. China, Email: fang1981119@yahoo.com.cn

ABSTRACT

In the paper SPH methods in AUTODYN-2D is used to investigate the characteristics of debris clouds propagation inside the gas-filled pressure vessels for hypervelocity impact on the pressure vessels. The effect of equation of state on debris cloud has been investigated. The numerical simulation performed to analyze the effect of the gas pressure and the impact condition on the propagation of the debris clouds. The result shows that the increase of gas pressure can reduce the damage of the debris clouds' impact on the back wall of vessels when the pressure value is in a certain range. The smaller projectile lead the axial velocity of the debris cloud to stronger deceleration and the debris cloud deceleration is increasing with increased impact velocity. The time of venting begins to occur is related to the "vacuum column" at the direction of impact-axial. The paper studied the effect of impact velocities on gas shock wave.

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. In recent experimental studies [1-8], the structural behaviour of unshielded and shielded pressurized components to hypervelocity impact was investigated. A great variety of parameters were investigated [9-10], among them projectile parameters, vessel materials and geometries, and various vessel pressures. The damage ranged from simple front wall perforation to complete rupture of the pressure vessels. However the number of tests that can be performed in experimental programs is limited, thus numerical techniques that are capable to deal with the complex processes that are involved in hypervelocity impacts on pressure containers are needed.

In the paper, the numerical simulation of debris cloud propagation produced by projectile hypervelocity impact on pressure vessels have been carried out using the SPH (Smooth Particle Hydrodynamics) technique of AUTODYN-2D hydrocodes. The simulation results are compared with experimental results. And numerical results are consistent very well with experimental results. A great variety of parameters were investigated, among them vessel pressure, projectile parameters, and impact velocity. The effect of impact velocities on gas shock wave was studied.

2. NUMERICAL MODEL

2.1. SPH Method

SPH [11-13] is an evolving numerical technique for modeling many large deformation transient dynamic problems, including high and hypervelocity impact problems. SPH techniques, whilst currently suffering from some technical problems, could offer significant advantages over conventional grid based Lagrange and Euler techniques. Grid based Lagrangian techniques suffer principally from problems of grid tangling; this is not a problem for the gridless SPH method. The principal practical advantages of SPH over Euler techniques are the reduced computational costs and the relative ease of adding sophisticated constitutive models. And SPH hydrocode methods turned out to be an adequate tool for the simulation of the complex interaction mechanisms. Particularly the high density gradients and the fragment-gas interaction require a flexible and robust simulation method. The disadvantage of that solution is that the SPH method is computationally much more expensive than standard Lagrange or Euler methods.

2.2. Selecting Material Model

The hypervelocity experiment in [14] was selected as references cases for the numerical simulations. For the simulation of a 5.2 km/s impact on a vessel filled with nitrogen gas pressurized to 1.05MPa, Johnson-Cook strength model were used, and in order to model the gas-debris clouds interactions, Shock EOS (equation of state) and Tillotson EOS were used, respectively. Whereas air was described via an ideal gas EOS. Considered for this paper, the cylindrical pressure vessels were made of A1 2024 alloy, and the projectiles

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

were made of aluminium. The wall of vessels was 1.5mm thick, the diameter of vessels was 50 mm and the length was 100 mm.

Fig. 1 shows the initial geometry model which was built by the AUTODYN-2D is in axial symmetry. The vessel casing off the penetration zone was described using shell elements. For the penetrated front wall SPH particles were applied. In the case of simulation 10 SPH particles were set across the vessel thickness. In all simulation cases the projectile, the front wall of the vessels and the gas were modeled with SPH particles of the same dimension.

Frank Schäfer [14] pointed out that the characteristics of debris clouds propagation in pressurized gas are as follows: formation of jet like spikes in front of debris clouds, formation and propagation of a pure gas shock

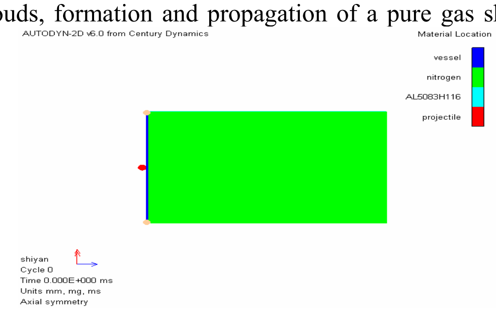


Figure 1.Initial geometry model

wave. The gas shock waves simulated by the two EOS both could be observed. The shape of the cloud is worse represented which are simulated by the Shock EOS as to be seen in Fig. 2. The result of numerical model built by Tillotson EOS showed good accordance with the

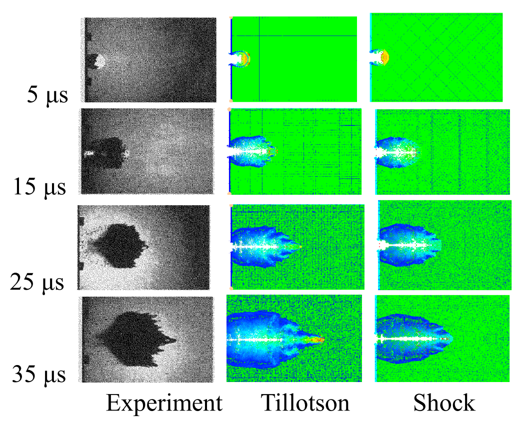


Figure 2.Comparison of numerical and experiment results [14]

experiments concerning the shape. Debris cloud pictures from numerical simulation (Fig. 2) show that the "vacuum column" is formed in impact-axial direction. And with an increase in computation time, "vacuum column" becomes thin gradually. Thus, as computation time increases, the "vacuum column" becomes thinner and thinner and eventually disappears, namely Vessel venting of gas through the impact hole occurs. Thus, the time of venting begins to occur is related to the "vacuum column" in impact-axial direction. Pictures from numerical simulation shows that the "vacuum column" did not disappear, namely Vessel venting did not occur. Thus, the simulation shows quite good accordance with the experiments concerning the venting of gas. Extension and velocities of clouds are also shown in Figs. 3-4. It shows that the result of numerical model built by Tillotson EOS shows good accordance with the experiments concerning the extension and velocity. Therefore Tillotson EOS used together with the AUTODYN SPH discretization delivers very reliable results in terms of pressure vessel impact.

2.3. Gas-Debris Clouds Interactions

The Extension and velocity of the debris cloud tip are shown in Figs. 3-4. The debris cloud tip has a higher velocity than other small fragments, and debris cloud tip is related to the large central fragment, thus it has higher kinetic energy than the small fragments around it, namely the debris cloud tip can cause more serious damage to the wall of the vessel. Fig. 2 shows that during the interaction of the hypervelocity debris cloud with the gas, a strong gas shock wave is generated. When the shock wave reaches the wall of the vessel, it produces a pressure impulse there. The intensity of this wave will, under certain conditions, cause the appearance and propagation of cracks, i.e. causing failure from the wall of the vessel. Thus the "spike" of the debris clouds and shock wave are shown to be an important factor governing the damage of the pressure vessel.

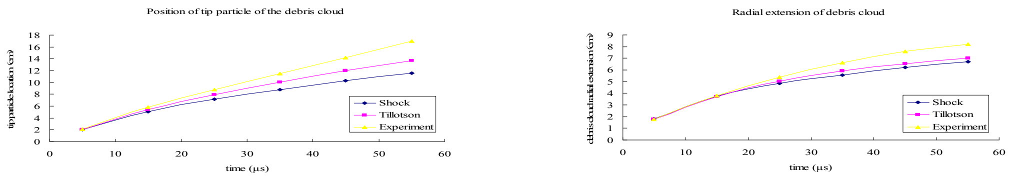
3. NUMERICAL RESULTS

In the paper the numerical simulation is performed to analyze the effect of the gas pressure and the impact condition on the propagation of the debris clouds. The gas pressure is between 1.0 MPa to 4.0 MPa. The projectile diameters ranged from 2.0 mm to 6.0 mm, and the impact velocities ranged from 4.0 km/s to 12.0 km/s. All simulated cases are summarized in Table 1. In all the simulation cases the projectiles and gas (nitrogen) were modeled with SPH particles of the same dimension. The Tillotson EOS and the Johnson-Cook strength model were used to simulate the materials behaviour.

3.1. Gas Pressure

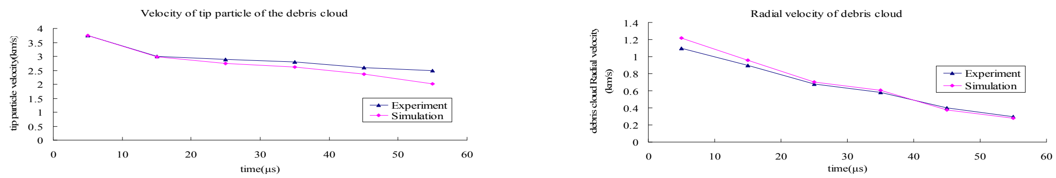
To consider the effect of gas pressure on the debris cloud, simulation cases Sim.01, Sim.02 and Sim.03 were selected. The simulation results are given in Figs. 5-6.

Figure 6 shows that aerodynamic reduces strongly the



(a) Tip particle location (b) Radial extension of debris cloud

Figure 3.Comparison of different numerical and experiment results of extension



(a) Velocity of Tip particle (b) Radial velocity of debris cloud

Figure 4.Comparison of numerical (Tillotson EOS) and experiment results of velocity

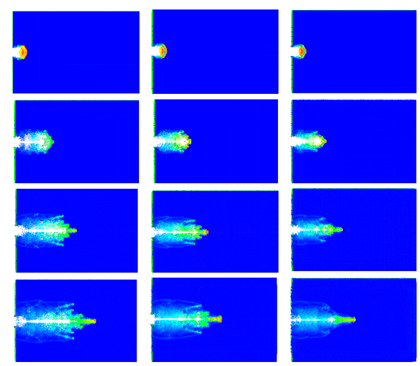
Table 1.simulation cases

Case. No	Diameter d (mm)	Velocity v (kms^{-1})	Pressure P (MPa)
Sim.01	6.0	4.0	1.0
Sim.02	6.0	4.0	2.0
Sim.03	6.0	4.0	4.0
Sim.04	4.0	4.0	1.0
Sim.05	4.0	4.0	2.0
Sim.06	4.0	4.0	4.0
Sim.07	2.0	4.0	1.0
Sim.08	2.0	4.0	2.0
Sim.09	2.0	4.0	4.0
Sim.10	6.0	8.0	1.0
Sim.11	6.0	8.0	2.0
Sim.12	6.0	8.0	4.0
Sim.13	6.0	12.0	1.0
Sim.14	6.0	12.0	2.0
Sim.15	6.0	12.0	4.0

radial and axial velocity of the debris cloud, and the velocities of debris clouds decrease with an increase in gas pressure. Thus the velocity of the debris cloud that reaches the rear wall of the vessel decreases, resulting in fewer rear wall impacts and less damage to the vessel.

In a given set of impact conditions, the pressure can be increased (within the pressure limits of the vessel) to the point where the entire debris cloud is ablated and no rear wall damage occurs. However, higher internal pressure increases the stress in the pressure vessel wall, which increases the potential for catastrophic rupture of the vessel depending on the extent of the HVI (hypervelocity impact) damage [6]. Thus pressurized gas could reduce the damage of the debris clouds' impact on the rear wall of vessels when the pressure

5 μs
15 μs
25 μs
35 μs



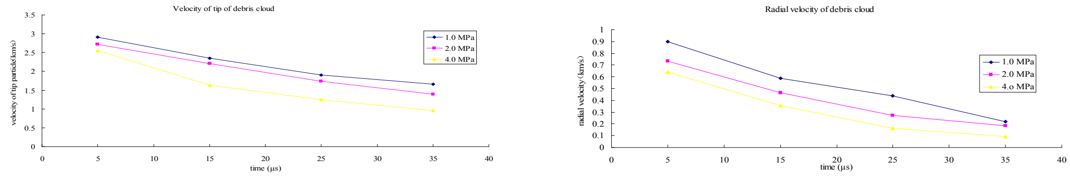
1.0 MPa 2.0 MPa 4.0 MPa

Figure 5.Comparison of results on different pressure

value is in a certain range.

3.2. Projectile Diameters

To consider the effect of projectile diameters on the debris cloud, simulation cases Sim.08, Sim.05 and Sim.02 were selected. The simulation results are given in Figs. 7-8. Length to radial of debris cloud ratio is decreases with an increase in the projectile diameter, and the fragment size increases with an increase in projectile diameter, and the extension of the debris cloud also increases with an increase in projectile diameter. The axial and radial velocities of these morphologic features were shown to be the same, regardless of sphere diameter, when debris clouds produced by impacts with similar bumper thickness to projectile diameter ratios and impact velocities were compared [15]. Fig. 7 shows that the extension of the debris cloud also increases with an increase in projectile diameter in the condition of pressurized gas, and the number of the "spike" at the tip of debris clouds increases with an increase in projectile diameter. Fig. 8 shows that at the same impact velocity and under the



(a) Velocity of Tip particle (b) Radial velocity of debris cloud

Figure 6.Comparison of velocity on different pressure

same vessel pressure, the smaller projectile lead the axial velocity of the debris cloud to stronger deceleration.

To consider the effect of gas pressure on the radial extension of the debris cloud, simulation cases Sim.01-Sim.09 were selected. The simulation results are given in Fig. 9. It shows at the condition of the same impact velocity, the different gas pressure and the different projectile diameter, the radial velocity of the debris clouds is the same. Therefore at the same impact velocity and under the different projectile diameter and vessel pressure, the projectile diameter has less effect on the radial velocity of the debris cloud.

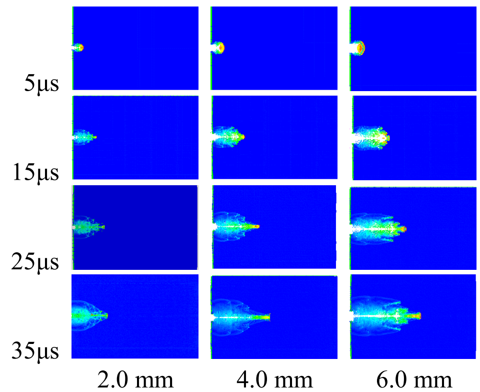
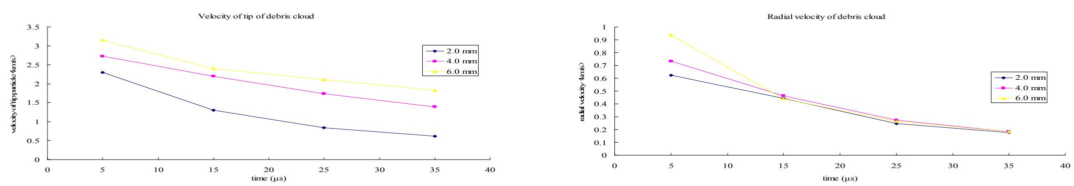


Figure 7.Comparison of results on different projectile diameters



(a) Velocity of Tip particle (b) Radial velocity of debris cloud

Figure 8.Comparison of velocity on different diameters

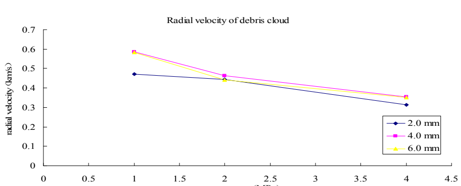


Figure 9.Comparison of radial velocity on different velocities and pressure

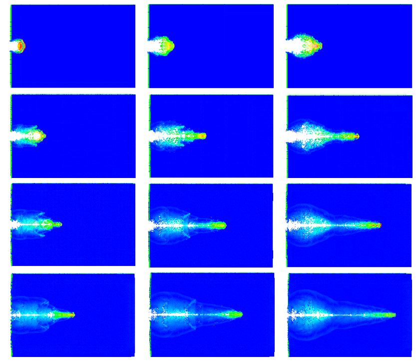
3.3. Impact Velocities

To consider the effect of projectile velocities on the debris cloud, simulation cases Sim.03, Sim.12 and Sim.15 were selected. The simulation results are given in Figs. 10-11.

The size of the large fragment was shown to be dependent on the impact velocity, when similar bumper thickness to projectile diameter ratios were compared, and the size of the large fragment has a power-law dependence on the impact velocity [16]. The simulation result shows that the deceleration of the tip particle increases with an increase in the impact velocity (Fig. 11). Although the deceleration of the debris cloud increases, the extension of the debris cloud still increases with an increase in the impact velocity. Fig. 10 shows that the "spike" at the tip of the debris clouds is longer with an increase the projectile diameter, namely the velocity of the tip particle is higher than small fragments around it.

4. SHOCK WAVE

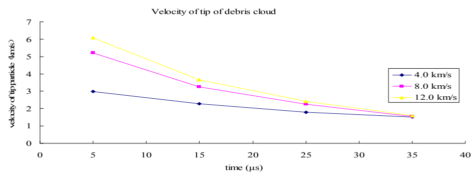
The paper studied the effect of impact velocities on gas shock wave in the condition of the same projectile diameter (2.0 mm) and the same vessel pressure (1.0 MPa), while impact velocities ranged from 0.5 km/s to 7.0 km/s. The simulation results are given in Fig. 12. The result shows that during the interaction of the hypervelocity debris clouds with the gas, a strong gas shock wave is generated. Shock waves in the gas are generated by the shock waves transmitted from the front of vessel and by the moving fragments. Shock waves by the shock waves transmitted from the front of vessel are moving away from the impacted wall, Fig. 13 shows that the particle velocity in the wave decreases rapidly with time. While the pressure vessel was not perforated by the projectile (0.5 km/s and 1.0 km/s), shock waves by the shock waves transmitted from the front of vessel was quite distinct in the simulation. While impact velocities were 1.5 km/s and 2.0 km/s, Shock waves in the gas by the shock waves transmitted from the front of vessel and by the moving fragments were also quite distinct in the simulation. With the increase in the impact velocity, the shock wave was not distinct. While impact velocities were 2.5 km/s - 7.0 km/s, none but shock waves in the gas by the moving fragments were



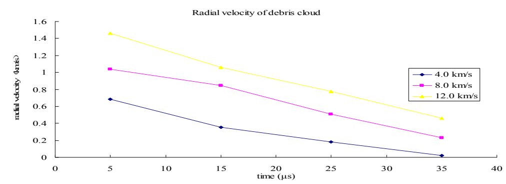
5μs 15μs 25μs 35μs

4.0 km/s 8.0 km/s 12.0 km/s

Figure 10.Comparison of results on different projectile velocities

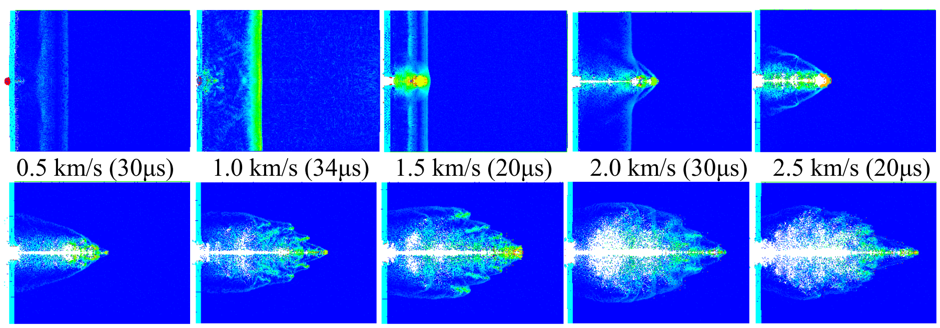


(a) Velocity of Tip particle



(b) Radial velocity of debris cloud

Figure 11.Comparison of velocity on different velocities



3.0 km/s (20μs) 4.0 km/s (20μs) 5.0 km/s (20μs) 6.0 km/s (20μs) 7.0 km/s (20μs)

Figure 12.shock wave propagation at different velocities

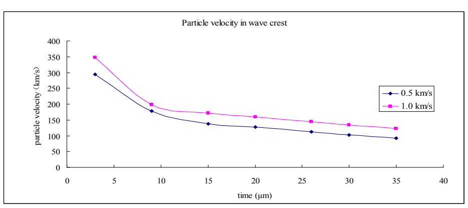


Figure 13. Particle velocity in wave crest

distinct in the simulation. In the axial direction the gas shock wave remains attached to the debris cloud and the radial extension of the shock wave were stronger than the radial extension of the debris cloud.

5. TIME OF VENTING OCCUR

In the condition of the different impact velocity, the different projectile diameter and the different vessel pressure, the average diameter (35 μs after impact) of the "vacuum column" is given in Fig. 14. It shows that the average diameter of the "vacuum column" increases with an increase in the impact velocity and the diameter of projectile, and decreases with an increase in the gas pressure. Thus the time of venting begins to occur was related to the "vacuum column" at the direction of impact-axial, and the time of venting begins to occur earlier when kinetic energy of projectile was lower and gas pressure was higher.

6. CONCLUSIONS

The numerical simulation of the debris cloud propagation produced by projectile hypervelocity impact on the pressure vessels has been carried out by using the SPH technique of AUTODYN-2D hydrocodes. Better numerical results can be obtained through

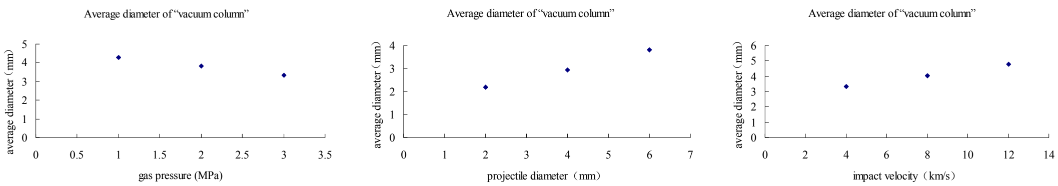


Figure 14. Effect of different parameters on "vacuum column"

Tillotson EOS, which are consistent very well with experimental results. The results show:

1) The increase in gas pressure can reduce the damage of the debris clouds' impact on the back wall of the vessels when the pressure value is in a certain range.
2) At the same impact velocity and under the same vessel pressure, the smaller projectile leads the axial velocity of the debris cloud to stronger deceleration. The projectile diameter has less effect on the radial velocity of the debris cloud.
3) At the same projectile parameters and under the same vessel pressure, the deceleration of the debris cloud increases with an increase in the impact velocity.
4) The time of venting begins to occur is related to the "vacuum column" at the direction of impact-axial. The time of venting begins to occur earlier when kinetic energy of projectile was lower and gas pressure was higher.
5) Shock waves by the shock waves transmitted from the front of vessel was quite distinct in the simulation at lower impact velocity, and the particle velocity in the wave decreases rapidly with time. The shock waves faded away in the simulation with an increase in the impact velocity.

REFERENCES

1. Piekutowski, A.J. (1996). Formation and Description of Debris Clouds Produced by Hypervelocity Impact. *NASA Johnson Space Center*, NASA Contractor Report 4707, Contract NAS8-38856, February.
2. Whitney, J.P. (1993). Hypervelocity Impact tests of Shielded and Unshielded Pressure Vessels. *NASA Johnson Space Center*, JSC 32294.
3. Friesen, L.J. (1995). Hypervelocity Impact Tests of Shielded and Unshielded Pressure Vessels Part II. *NASA Johnson Space Center*, JSC 27081, July.
4. Lambert, M. (1997). Hypervelocity Impact Testing Impacts Pressure Vessels. *ESTEC Second*, Extension to Contract 10556/93 YME/ML/2745, October.
5. Schäfer, F. (2001). Hypervelocity Impact Testing Impacts on Pressure Vessels Final Report. *EMI*, EMI Report I-27/01, April.
6. Christiansen, E.L. & Kerr, J.H. (1997). Debris Cloud Ablation in Gas-Filled Pressure Vessels. *International Journal of Impact Engineering*. 20, 173-184.
7. Zhang, W., Pang, B.J. & Zhou J.X. (2000). Experimental Investigation of Velocity Impact on Gas Filled Pressure Vessels. *Explosion and Shock Waves*. 20(4), 353-358. (in Chinese)
8. Zhang, W., Guan, G.S., Ha, Y. & Pang, B.J. (2004). Experimental Investigation of High Velocity Projectile Impact Damage on Pressure Vessels. *Journal of Experimental Mechanics*. 19(2), 229-235. (in Chinese)
9. Telitchev, I.Y. & Eskin, D. (2003). Engineering Model for Simulation of Debris Cloud Propagation inside Gas-Filled Pressure Vessels. *International Journal of Impact Engineering*. 29, 703-712.
10. Maveyraud, C., Vila, J.P., Sornette, D., Floc'h, L.C., Dupillier, J.M. & R. Salomé. (2001). Numerical Modeling of the Behaviour of High Pressure Vessel under Hypervelocity Impact. *Mec. ind*. 2, 57-62.
11. Randles, P.W. & Libersky, L.D. (1996). Smoothed Particle Hydrodynamics: Some Resent Improvements and Applications. *Computer Methods in Applied Mechanics and Engineering*. 139, 375-408.
12. Katayama, M., Toda, S. & Kibe, S. (1997). Numerical Simulation of Space Debris Impacts on the Whipple Shield. *Acta Astronautica*. 40(12), 859-869.
13. Gordon, R.J., Robert, A.S. & Stephen, R.B. (1996). SPH for High Velocity Impact Computations. *Computer Methods in Applied Mechanics and Engineering*. 139(1-4), 347-373.
14. Hiermaier, S. & schäfer, F. (1999). Hypervelocity Impact Fragment Clouds in High Pressure Gas Numerical and Experimental Investigations. *International Journal of Impact Engineering*. 23, 391-400.
15. Piekutowski, A.J. (1997). Effects of Scale on Debris Cloud Properties. *International Journal of Impact Engineering*. 20, 639-650.
16. Piekutowski, A.J. (1995). Fragmentation of a Sphere Initiated by Hypervelocity Impact with a Thin Sheet. *International Journal of Impact Engineering*. 17, 627-638.