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Numerical Simulation of Temperature Effects on Warhead Explosion Products*

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Abstract: Relation between mass density of explosive detonation products and time is studied under three kinds of confinement conditions, i. e., no confinement, weak confinement, and rigid confinement by coupling of BKW code, JWL code and LS-DYNA program, respectively. Associated with HOM equation of state, explosion products temperature decaying with time is inferred, and theoretical method is proposed to calculate explosion products temperature of warhead. Results imply that temperature and its decaying rate in explosion products region are non-uniform. Confinement condition plays an important role in controlling of explosion products mass density and its temperature. Rigid confinement could postpone the decaying of the explosion products density and temperature, but the decaying time does not scale up in spite of the doubling of the shell thickness.

Key words: equation of state; temperature; explosion products; numerical simulation; confinement condition

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1 Introduction

More and more objectives can be attacked in future war. Different objectives correspond to their corresponding damaged sensitivities. Conventional warhead is designed object-oriented from conventional chemical explosive charge to fuel-air-explosive weapon, and to thermobaric bomb in Afghanistan of war in 2001. Relatively inert metal powder, but a latent high energy material, such as aluminum, is applied widely in explosive. In order to choose suitable aluminum powder, especially in shape and size, temperature effect of explosion products has to be considered due to its activation to initial metal oxidation[1]. To the best of our knowledge, the literature about this effect seems absent. Under present technological conditions, many problems need to be solved if temperature of explosion products is tested accurately. These problems lie mainly in two aspects. Firstly, material which can suffer from high temperature of 2 500～4 000 K, and simultaneously be sensitive to temperature and minute in micron size, is sought difficultly. Secondly, temperature response of sensor lags behind temperature variation. Therefore, it is an important measure to evaluate temperature of explosion products by means of numerical simulation[2-3].

2 Equation of State of Explosion Products

For a selected explosive, BKW code is carried out[3-4]. The results are, mass density of explosive

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1.64 g/cm^3, detonation velocity 6 930 m/s, detonation pressure 21 GPa, detonation temperature of CJ state is 2 937 K, and isentropic adiabatic index of detonation products is 2.85. HOM equation of state of detonation products are

$$\ln p = -3.657\,69 - 2.475\,871\ln v + 0.218\,735\,1(\ln v)^2 + 0.062\,259\,68(\ln v)^3 + 0.018\,294\,05(\ln v)^4 \quad (1)$$

$$\ln T = 7.572\,2 - 0.443\,278\,3\ln v + 0.093\,283\,38(\ln v)^2 + 0.002\,578\,583(\ln v)^3 - 0.003\,187\,935(\ln v)^4 \quad (2)$$

$$\ln e = -1.515\,413 + 0.536\,258\,3\ln p + 0.097\,387\,66(\ln p)^2 + 0.009\,284\,769(\ln p)^3 + 0.000\,349\,579\,1(\ln p)^4 \quad (3)$$

Where p is pressure, v is specific volume, and e is specific inner energy.

Applying above results, JWL equation of state of detonation products can be inferred from HOM equation of state of detonation products by JWL Code that was compiled by Sam Shaw. Provided for next LS-DYNA, JWL equation of state of detonation products in this case is given by[5]

$$p = A_1\left(1 - \frac{\omega}{R_1 v}\right)e^{-R_1 v} + B_1\left(1 - \frac{\omega}{R_2 v}\right)e^{-R_2 v} + \frac{\omega e}{v} \quad (4)$$

Where p is pressure, v is specific volume, and e is specific inner energy. A_1, B_1, R_1, R_2 and ω are parameters in JWL equation of state, here $A_1 = 374$ GPa, $B_1 = 3.23$ GPa, $R_1 = 4.15$, $R_2 = 0.95$, $\omega = 0.30$, $e = 7.0$ GJ/m^3.

3 Computed Models and Parameters

Cylindrical explosive of radius in 5.6 cm and height in 50 cm, is initiated at lower end on its center line of the cylinder under three confinement conditions in air, respectively, as showed in Fig. 1 and Fig. 2. No confinement, weak confinement (5 mm steel shell in thickness in entire seal), and rigid confinement (10 mm steel shell in thickness in entire seal) represent the three different confinement conditions. Origin of coordinate is set at center of cylindrical explosive. In order to model process of central line initiation, auxiliary explosive detonation velocity is assumed to be 8 400 m/s. So detonation time along central line is given by $t = l/u = 0.50/8\,400 = 59.5$ μs, approximately 60 μs. Coordinates (centimeter unit), such as (0, 25), (0, 20), (0, 15), (0, 10), (0, 5), (0, 0), (0, −5), (0, −10), (0, −15), (0, −20), (0, −25) along axis of the explosive, correspond in turn to their initiation times 60, 54, 48, 42, 36, 30, 24, 18, 12, 6, 0 μs. Air medium in radial domain in modeling is 30 times the radius of cylindrical charge [0, 168], and range of air medium in axis domain is given by [−100, 100].

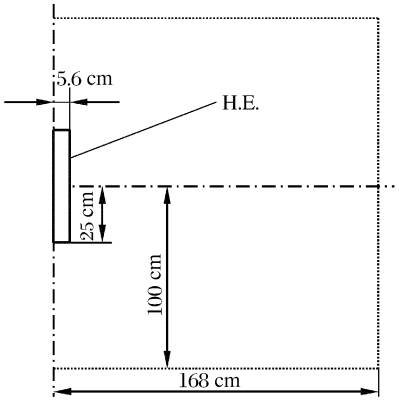


Fig. 1 Model of naked charge in air

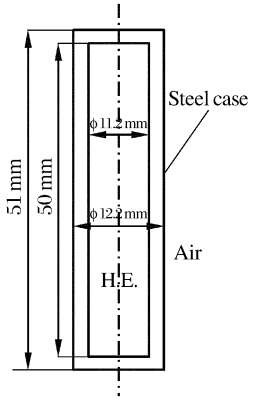


Fig. 2 Charge in shell

Equation of state of air is given by[5]

$$p = c_0 + c_1\mu + c_2\mu^2 + c_3\mu^3 + (c_4 + c_5\mu + c_6\mu^2)e \quad (5)$$

Where c_0, c_1, c_2, c_3, c_4, c_5 and c_6 are constants. $\mu = \frac{1}{v} - 1$, v is relative specific volume. In expanding element, $c_2 = c_6 = 0$, e is specific inner energy. Mass density of air is 1.293 g/m^3, $c_4 = 0.4$, $c_5 = 0.4$, $c_0 = c_1$

$=c_2=c_3=c_6=0$, initial specific inner energy is 2.5 μJ/m^3, initial relative volume is 1. Mass density of steel for shell is $\rho=7.83$ Mg/m^3, shear modulus $G=77$ GPa, Poisson's radio 0.3, yield stress $\sigma=$ 900 MPa.

Explosion of device in infinite air can be assumed to be a two-dimension process because of axisymmetric characteristics of the model. Both air and explosive, or steel, are meshed, and axisymmetric ALE method is adopted.

4 Computed Results and Analysis

Detonation products in elevated temperature and pressure expand and do work outwards, which results in decreasing of pressure, temperature, and mass density rapidly due to sparse wave's effects. Fig. 3 shows contours of mass density field at time of 204.86 μs with no confinement condition of explosive. It is evident that the shape of charge plays an important role in mass density distribution of detonation products.

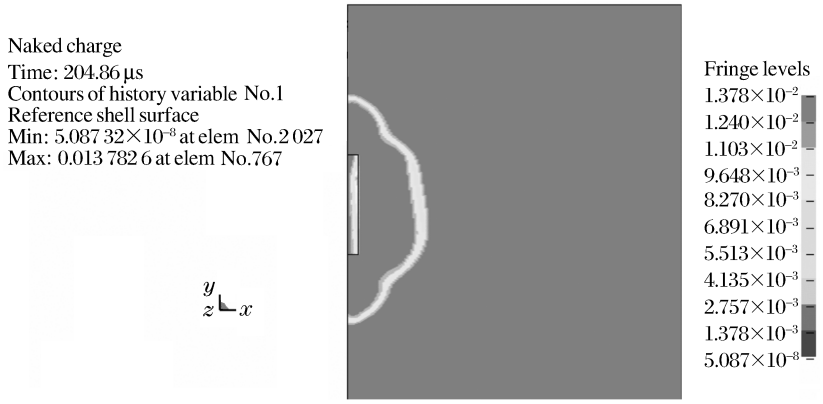


Fig. 3　Contours of detonation products density at 204.86 μs

Typical elements 489, 492, 496 on horizontal symmetry plane of cylindrical charge locate at center of cylindrical charge, middle point of radius, end point outward of radius respectively. Mass density of detonation products at these elements varies with time, which is shown in Fig. 4 to Fig. 6. It can be found from the figures that mass density of detonation products increases transiently at first (in CJ state), then decreases (in expansion phase). This case is consistent with classical detonation

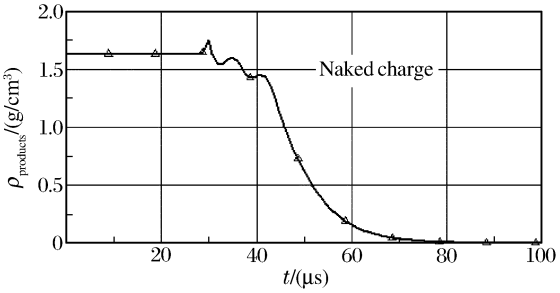


Fig. 4　Temporal curve of detonation products density at element No. 489

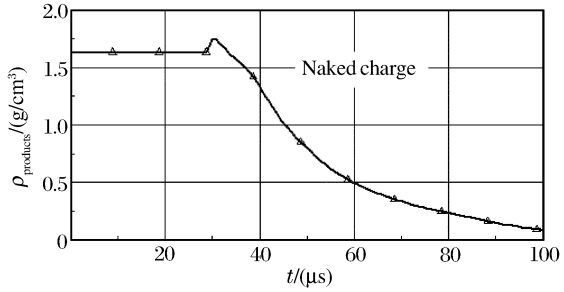


Fig. 5　Temporal curve of detonation products density at element No. 492

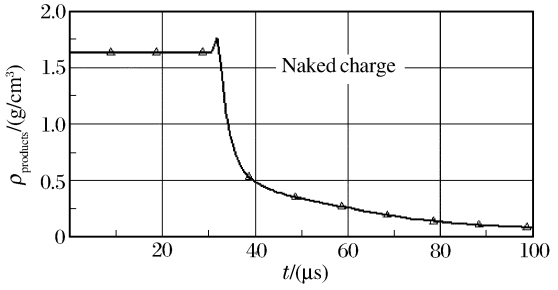


Fig. 6　Temporal curve of detonation products density at element No. 496

theory[3] . Mass density and its change rate are different at varied site in explosion products region although their change trends are accordant. In the phase computed, decay rate of mass density at center of charge changes from low firstly to high finally, and that on edge of charge decays faster, as shown in Fig. 7. Fig. 4 showed that, decaying time of mass density at center charge from maximum value to minimum value is about 50 μs.

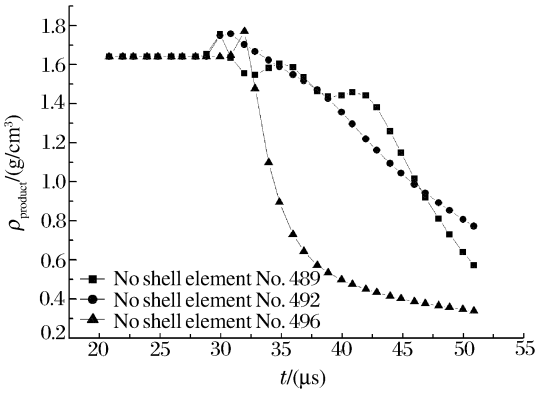


Fig. 7 Contrast temporal curves of detonation products density at different elements with no shell

Mass density of explosion products varying with time is shown in Fig. 8 and Fig. 9 under weak and rigid confinement, respectively. Changing trends of mass density under the three kinds of confinement are similar to a certain degree. "Oscillation" phenomena of initial density at center of charge are shown in Fig. 10, and the more intensive the confinement, the longer the oscillation plateau, and the wider the area of the oscillation phenomena. It is clear that density of explosion products decays slow when confinement of charge becomes intensive.

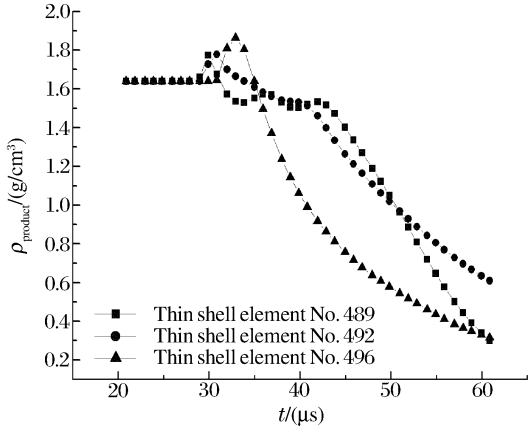


Fig. 8 Contrast temporal curves of detonation products density at different elements with thin shell

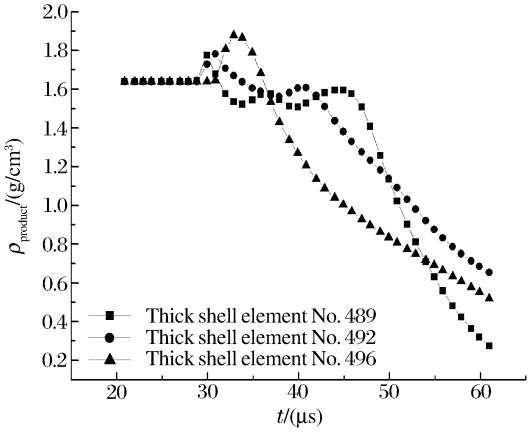


Fig. 9 Contrast temporal curves of detonation products density at different elements with thick shell

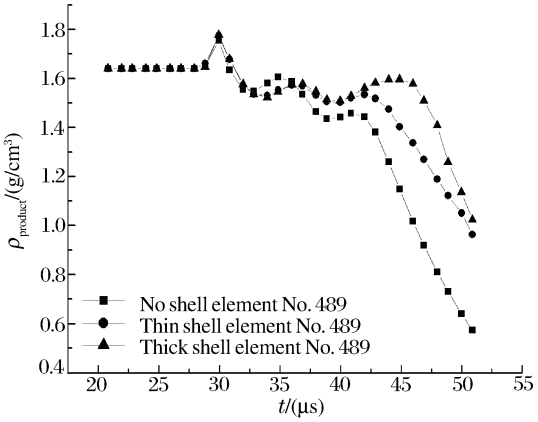


Fig. 10 Contrast temporal curves of detonation products density at No. 489 element with different shell

Mass density at the same element under different confinement conditions is obtained in order to contrast decaying rate of density, which is shown in Fig. 10. Density of explosion products decays faster under no confinement, while slower under rigid confinement. In the latter case, slow decrease of density and temperature is helpful to ignite metal powder that acts as high energetic additive[1]. Therefore it is reasonable to infer that metal powder, of a certain weight percentage, shape and size, etc, added in explosive must best match the type of explosive, confinement condition, and so on.

Mass density of explosion products of the

charge in thin shell (weak confinement) followed an exponential decay function in the selected time space. As shown in Fig. 11, density at element 496, decaying with time, is achieved. Exponential decay function of density is given by

$$\rho = \rho_0 + A_1 e^{-t/t_1} = 0.336\,16 + 59.704\,27 e^{-t/9.058\,32} \qquad 32.851\,52 \leqslant t \leqslant 50.881\,61 \qquad (6)$$

Where ρ is mass density of explosion products, g/cm^3, t is time, μs.

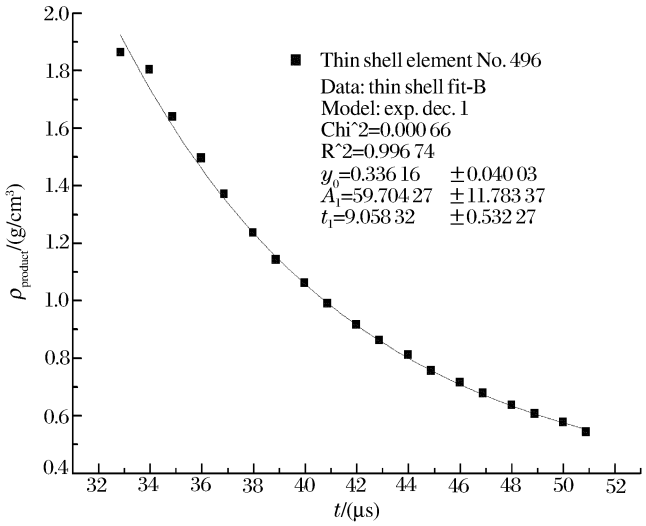


Fig. 11　Fitted curve of detonation products density

Mass density of products undergoes decay process from maximum value of 1.864 5 g/cm^3 to minimum value of 0.544 44 g/cm^3 in about 18 μs.

At last, temperature of explosion products decaying with time is achieved when Eq. (2) and Eq. (6) are solved together

$$T = \exp[7.572\,2 - 0.443\,278\,3\ln v + 0.093\,283\,38(\ln v)^2 + 0.002\,578\,583(\ln v)^3 - 0.003\,187\,935(\ln v)^4] \qquad (7)$$

Where $\ln v = -\ln(0.336\,16 + 59.704\,27 \cdot e^{-\tau/9.058\,32})$, $32.851\,52 \leqslant \tau \leqslant 50.881\,61$.

As shown in Fig. 12, for the ignition temperature of 2 300 K of aluminum particles[6], heating time of detonation products is about 4.98 μs under the weak confinement condition. Obviously, heating time in expansion region of detonation products is much longer than that in detonation region.

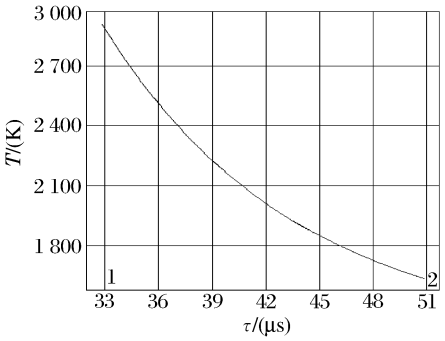


Fig. 12　Temperature of explosion products decaying with time

Similarly, simulation results show that the decaying rate of the explosion products temperature under three kinds of confinement conditions, respectively, no confinement, weak confinement and rigid confinement, is different, and its time of the temperature decaying to 2 300 K is 1.12, 4.98 and 5.80 μs. The decaying time does not scale up in spite of the doubling of the thickness of the shell.

5　Conclusions

A numerical method is adopted to quantify temperature effects of warhead explosion products under different confinement conditions. Temperature of explosion products decaying with time is achieved by using the HOM state equation and density decaying equation together. BKW code, JWL code and LS-DYNA program are general numerical tools that are applied widely in explosive formulation design and its dynamic behavior. Simulation results are consistent with the similar experimental results of B. Leal[7] and M. F. Gogulya[8]. Therefore, this method is reasonable and can provide theoretical guide.

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战斗部爆轰产物温度效应数值模拟

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摘要: 利用 BKW 代码、JWL 方程和 LS-DYNA 程序, 研究了无约束、弱约束和强约束等三种战斗部约束条件下炸药爆轰产物密度随时间的变化关系, 再结合爆轰产物 HOM 状态方程获得爆轰产物温度随时间的衰变函数。给出了战斗部爆轰产物温度的理论计算方法。研究表明, 爆轰区内爆轰产物温度及其衰减速率并不均匀, 战斗部炸药的约束条件对爆轰产物密度和温度有重要影响, 强约束可以延缓爆轰产物密度和温度的衰减, 相同情况下仅战斗部壳体厚度加倍并不会导致爆轰产物密度和温度的衰减情况同比例变化。

关键词: 物态方程; 温度; 爆轰产物; 数值模拟; 约束条件

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