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Research on Fire Extinguishing Shell Material Selection and Parameters Optimization

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Abstract

Remote grenade is often used to fight. Fire extinguishing shell material selection and structure parameters have a great influence on fire extinguishing dispersion and even directly determine the extinguishing effect. Taking the crown fire of Mongolica 20 years old as example, the influences of fire extinguishing bombs with different shell materials on fire extinguishing dispersion are compared in this paper. Simulation of fire extinguishing bombs with different shell materials is operated by finite elements software and come to a conclusion that unidirectional short fiber reinforced composite materials is suitable for fire extinguishing bomb shell because of less power consumption and longer dispersion distance when shell bursting. In the meantime, the experiment is carried out on the sample of fire extinguishing bomb with the shell of unidirectional short fibers. The conclusion is length-diameter ratio to put plant crown fire out has better fire control effect than fire extinguishing bomb with 1.5% powder and save the use of extinguishant.

Keywords: *Fire extinguishing bomb; Shell material; Unidirectional short fiber composites; Finite element simulation.*

1. Introduction

With the global warming, forest canopy fire seriously affected the human production and life thus resulted in tremendous loss. The remote monitor, vehicle and grenade are often adapted to put out the crown fire. In the remote system, grenade is projected onto the fire by gun. After bomb bursting, ultrafine dry powders are scattered in the crown fire. Aerosol is produced after extinguishing dispersion to put out the crown fire. In the extinguishing dispersion, fire extinguishing shell material selection and structure parameters have much influence on dispersion scope and concentration, even determine the extinguishing effect.

Gui Qianbo, Wang Keyin and Zhao Rui did the researches on solid extinguishants scattering with the shell of cardboard[1-2]. The conclusion indicated dispensing radius increase with the increasing of powder ration. The cloud volume of dry ice fire extinguishants has nothing to do with quality. Cloud duration is proportional to the quality. Shen Zhaowu and Jiang Yaogang from USTC did the experiments and simulations on extinguishants shell burst with the shell of PVC[3]. Zhang Qi from BIT researched the effects of FAE combustion bomb on the speed of fuel scattering in near area [4,5]. Hui Mingjun, Song Zhidong, Li Yunhua and Xin Chunliang did the numerical simulation on cloud detonation ammunition with shell liquid fuel scattering [6,7]. Extinguishing concentration of ultrafine dry powder with diffusion even is 64.4 grams

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every cubic meter. Theoretically, 7.92kg ultrafine dry powder is needed to extinguish the fire on the Mongolica of 40 years with the average canopy volume of 123 cubic meters. According to the previous experimental data, 25-50kg dry powder is needed to extinguish the fire on this kind tree three-dimensional open space but the use ration is only 15-30 percent[8]. The main reasons of this waste are uneven dispersion, big fire extinguishing particles, gas flowing in combustion field and the projectile structures.

There is little research on the structure parameter of scattering solid ultrafine dry powders on crown fire of larger size. The finite element simulation software is applied in this paper to explore the regularity of scattering extinguishant by bombs with different shell materials and optimize the structure parameters of extinguishing bomb. This research can provide theoretical support for improving extinguishing effect and utilization of extinguishant.

2. The Structure and Parameters of Fire Extinguishing Bomb

According to the previous research on the usage of remote system in forest fire prevention and fighting, we know that the fire extinguishing bomb is consisted by shell, covers of two ends, center booster and ultrafine dry powder. Seen as figure1, the symmetric cylinder is the structure of fire extinguishing bomb.

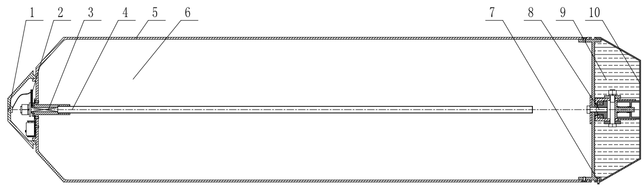

Figure 1. Structure of Grenade
1-Sensor, 2-Control Circuit Board, 3-Electric Detonator, 4-Tube Explosion, 5-Shell, 6 -Ultrafine Dry Powders, 7-Pin, 8-Connector, 9-Parachute, 10-Mask Body

When the forest crown fire happens, fire guns and grenade are sent to the area near the fire field. The projectiles are launched to the burst point. The front-end sensor of the bomb is exposed to the flam. As temperature rise, electric detonator is detonated and the ultrafine dry powder will be dispersed into fire field with the formation of aerosol to put out the crown fire. To avoid the speed of fire bomb exceeds scheduled burst point, deceleration parachute is installed on rear-end of fire grenade by parachute bomb connector to slow down the speed of fire bomb in the fire field. Primary research shows the forest fire extinguishing bomb is suitable to putting out the crown fire in small area, whose radius is 800 meters. Intelligent forest fire extinguishing navigation system goes for extinguishing major forest fires in large area.

The outer diameter of fire extinguishing bomb is 255mm based on the bomb size. The thickness of the shell is 2 mm based on the analysis of the intensity of shell. RDX explosive is in center booster and the ultrafine dry powder is in the fire extinguishing bomb. The optimal solution can be achieved based on the parameters analysis.

3. Selection of Fire Extinguishing Shell Material

The following conditions should be satisfied for choosing the fire extinguishing bomb shell materials. They are sufficient intensity, stable size, ageing resistance, handling ease and low cost. Carbon steel material and composite material are chosen for fire extinguishing bomb.

Carbon steel and composite materials are designated to be fire extinguishing shell material. Composite materials are composed by ABS plastics as matrix and glass fiber as reinforce. So the mixture has the performance of polymer and glass fiber. To optimize the shell materials, the numerical simulation and the experimental analysis are investigated in detail by finite element software to analyze the effects of two shell materials on extinguishing dispersion under the condition of the same parameters.

3.1. Computer Simulation

In order to improve the efficiency, computer simulation and experiment are adopted in this research to choose the material of fire extinguishing bomb shell.

Physical model of fire extinguishing bomb is depicted as figure 2. On account of the cylinder shape of fire extinguishing bomb, the simulation process is simplified as two-dimensional axisymmetric. In the model, air, ultrafine dry powder and explosive are supposed to be homogeneous continuous media, while the gravity is ignored. Calculation area is set up to reduce data processing and save the computing resources. Nonreflecting boundary condition is set up in the simulation area to simulate the explosion in infinite air.

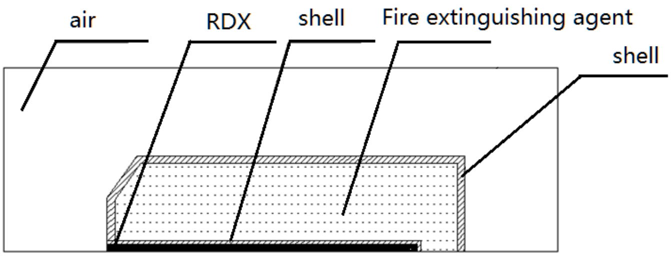

Figure 2. Physical Model of Fire Extinguishing Bomb

3.1.1. Explosive Model: High-Explosive-Burn is constitutive model of explosive. JWL equation of state is applied to describe the expansion of dynamite explosion product.

$$p = A\left(1-\frac{\omega\eta}{R_1}\right)e^{-R_1/\eta} + B\left(1-\frac{\omega\eta}{R_2}\right)e^{-R_2/\eta} + \omega\eta\rho_0 e$$
(1)

In formula (1), $\eta = \rho/\rho_0$, e is specific internal energy, e_0 is initial specific internal energy, ρ is overall material density, ρ_0 is reference density, D is detonation velocity. The rest parameters are constant. JWL state equation of RDX explosive and CJ parameter are in reference [9].

3.1.2. Shell Model: Cowper-Symonds model is used to calculate the yield stress of fire extinguishing bomb with the carbon steel shell.

$$\sigma_y = \left[1+(\varepsilon/C)^{1/p}\right](\sigma_0 + \beta E_p \varepsilon_p^e)$$
(2)

$$E_p = E_{\tan} \cdot E \cdot (E - E_{\tan})$$
(3)

In formula (2) and (3), σ_y is yield stress, ε is strain rate, σ_0 is initial stress, ε_p^e is effective plastic strain, E_p is plastic hardening modulus, $E_{\tan}$ is tangent modulus, E is Young modulus. Specific reference values can be found in reference [10].

ABS plastics are the primary structure of composite material and the glass fibers are the reinforcing material. Properties of composites and glass fiber are both embodied in mixture. Taiwan's Qimei resin PA-707 is selected as ABS plastic and the glass fiber is 30%. Orthotropic elastic model is used to denote the composite material shell. The main parameters of the model can be found in reference [8].

Table 1. Unidirectional Short Fiber Model

Tensile Strength MPa	Shear Modulus GPa	Elasticity Modulus GPa	Poisson Ration	Density g/cm^3
342.5	22.01	3.70	0.291	1.492

Taylor originally proposed the fracture stress criterion of fire extinguishing bomb shell[11,12]. In his theory, it is supposed that radial crack doesn't spreads in compressive stress area, but in the shell's circumferential tensile stress area. So the circumferential tensile stress on the front of crack is zero ($\sigma_s = 0$).The radial crack propagation depth of bomb in the process of outer radial expansion is :

$$y = TP/\sigma_s$$
(4)

In the above formula, T is shell wall thickness. σ_s is the material yield limit. P is pressure of detonation products.

When the pressure of detonation products reduces to the material yield limit ($P = \sigma_s$),the shell collapse. The rupture radius of fire extinguishing bomb is:

$$\frac{a_r}{a_0} = \left(\frac{P_0}{\sigma_s}\right)^{1/2\gamma}$$
(5)

In the above formula, a_0 is the initial inner radius of cylindrical shell. P_0 is average initial pressure of detonation products. γ is the polytrophic exponent of explosive.

3.1.3.Air Model: Linear Ploynomia state equation is applied to describe air model, which is Null hydrodynamic model from reference [6].

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E$$
(6)

In formula (4), E is initial internal energy of air. $\mu = \rho - \rho_0/\rho_0$. ρ/ρ_0 is the ration of current density and initial density. To ideal air, $C_0 = C_1 = C_2 = C_3 = C_6 = 0$, $C_0 = C_1 = C_2 = C_3 = C_6 = 0$, γ =1.4.

3.1.4. Fire Extinguishment Model: Dry powder extinguishment is often used in forest fire extinguishing bomb because of its high efficiency, environmental protection property and easy accessibility. The particle size of dry powder extinguishments is directly related to fire extinguishing effectiveness. The particle size of ultrafine dry powder ranges from

3 μm to 5 μm . Ultrafine dry powder can inhibit the flam and put up the fire. In addition, the ODP of ultrafine dry powder is zero, which indicates it has environmental protection property. MAT-SOLL-AND-FOAM model is used to describe the fire extinguishment.

3.2. Result and Analysis

RDX explosive is detonated on the section point. Lagrange element is used to calculate shell. Euler element is used to calculate air. ALE element is applied to calculate explosive. Explosive, shell, extinguishment and air grid are defined coupling by command. It is supposed fire extinguishments dispersion area is small to reduce the calculation. It is supposed that the fluid cell boundary is transmitting to ensure the fire extinguishment dispersion unaffected by boundary. The initial velocity of fire extinguishment dispersion is described in figure 3.

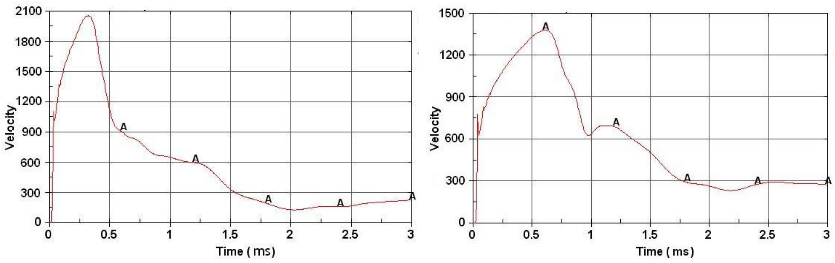

Figure 3. Dispersion Velocity of Fire Extinguishing Bomb Bursting (a) Composite Material (b) Steel Material

Figure 3 shows that the max dispersion velocity of fire extinguishment with composite material shell is bigger than that of steel material shell. Dispersion radius can be calculated by max velocity. When fire extinguishment burst, the dispersion velocity increases at first but decrease later. According to reference [1,2], in the accelerated phase, if the pressure of detonation gas is bigger than atmosphere ($p \geq p_c$), it is called isentropic adiabatic expansion process and exists $pV^K = const = \overline{p}V_0^k = p_c V_c^k$. In a similar way, if $p \leq p_c$, it is called Non isentropic adiabatic expansion process and exists $pV^K = const = p_c V_c^\gamma$. In this process, dispersion radius is related to charging radius, charge density and detonation velocity. Because the charge density and detonation velocity are determined by explosive, it is known that $r_1 = 30.78 r_0$, r_1 is dispersion radius in the accelerated phase, r_0 is the charging radius. When the detonation gas separates from fire extinguishment, the dispersion velocity begins decrease. In this phase, the dispersion distance is determined by the motion state of fire extinguishment. When dispersing, the fire extinguishment particles are affected by inertial force (F_1), air resistance (F_2), generalized buoyancy (F_3), gravity and additional forces. Force balance equation is established by force equilibrium principle.

$$F_1 + F_2 + F_3 + G - F_4 = 0 \tag{7}$$

The following formula is inferred from the deceleration of fire extinguishment particles and equations.

$$r_2 = \tau_v (u_{po} - u_p) = u_{p0} \tau_v \left[1 - \exp\left[- \frac{t}{\tau_v} \right] \right]$$

(8)

The final expansion radius is described by the formula:

$$r_{2\max} = u_{p0} \tau_v = u_{p0} \frac{\rho_p d_p^2}{18\mu}$$

(9)

Turbulent phase comes after the deceleration. In turbulent phase, cloud radius of fire extinguishment stops growing wider. With the influence of uneven internal pressure, fire extinguishments roll over in the range of dispersion and tend to be steady. The results of numerical simulation demonstrate the maximum velocities of fire extinguis hments with composite material shell and carbon steel material are respectively 2050m/s a nd 1380m/s. According to the above formula, dispersion distances are respectively 5.8m a nd 6.5m.

Therefore, dispersion radius of fire extinguishment particles increases with the increasing of initial velocity. Energy consumption resulted from composite material shell cracks only occupies 1%-3% of total explosive. Most of the energy is converted into kinetic energy to ensure the effectiveness of extinguishment. In addition to its low-density, some composite material shell is burnt in explosion, so the debris threats less to the firemen and other creatures in the forest. Results of numerical simulation show composite material is more suitable for fire extinguishment shell than steel. The following experiment is applied to analyze the influence of shell on fire extinguishment dispersion.

4. Experimental Analysis

In the experiment, fire is lit in a barrel on the center ground to imitate the crown fire. High-speed cameras are set up to record the fire extinguishment dispersion. To ensure the accuracy, three experiments are carried out on every sample bomb. Figure 4 describes the experimental system layout [13,14]. The average dispersions are in Table 2. Figure 5 describes the process of fire extinguishment dispersing powder.

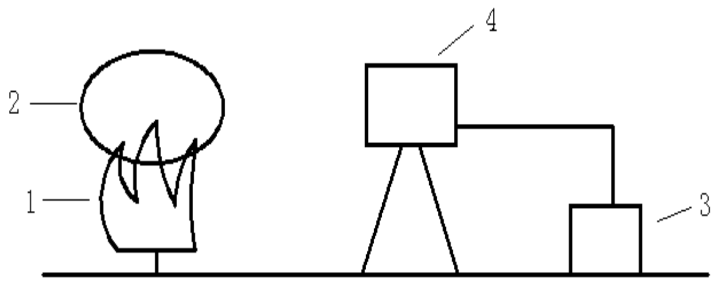

Figure 4. Experimental System Layout
1-Analog crown fire, 2-Extinguishing agent diffusion region, 3- Infrared Thermal Imager, 4- High-Speed Camera

Figure 5. The Process of Fire Extinguishment Dispersing Powder

Table 2. The Results of Fire Bomb Static Explosive

number	Shell material	R(m)	H(m)	V(m^3)	Diffusion concentration g/m^3
A	Compound material	3.3	6.4	205	68
B	Compound material	3.3	6.3	202	69
C	Compound material	3.4	6.2	212	66
D	carbon steel	2.9	6.5	171	81
E	carbon steel	2.8	6.7	176	79
F	carbon steel	3.1	6.4	193	72

Two sample bombs with different material are analyzed based on Table 2. Average dispersion radius of sample bomb with composite material is 3.23m and that of carbon steel is only 2.97m. Average dispersion altitude of sample bomb with composite material is 6.3m and that of carbon steel is 6.53m. Sample bomb with composite material has bigger dispersion volume and its high dispersion density reaches to 64.4 g/m^3. The above analysis shows the explosives with the same weight have different energy consumption because of different shell material. carbon steel shell with high yield limit consumed most energy when bursting and dispersing. In addition, carbon steel shell can suffer more hoop stress and increase the solid extinguishment axial dispersion altitude. On the analysis of maximum dispersion velocity and solid particles stress in flow field, we reach the conclusion that fire extinguishing bomb with composite material shell has larger dispersion radius and better safe reliability.

5. Structure Parameter Optimization of Fire Extinguishing Bomb

Once choosing the shell material, based on the experience of FAE, length-diameter and powder ration of fire extinguishing bomb are the parameters determining the extinguishing dispersion. In this paper, numerical simulation and experiment of length-diameter and powder ration will be carried out on the extinguishing bombs with unidirectional fiber composite materials to analyze the effects of length-diameter and powder ration on dispersion mechanism. The experimental results in Table 3.

Table 3. The Results of Fire Bomb Static Explosive

Number	The ratio of length to diameter	powder ration	R(m)	H(m)	V(m3)	Concentration g/m^3	Dispersion shape
A	3.3	1.5%	3.2	7	150	86	Ellipsoid
B	3.3	2%	3.4	6.7	162	80	Sphere
C	3.3	2.5%	3.9	6.3	200	65	Flattened sphere
D	3.8	1.5%	3.4	7.2	174	74	Ellipsoid
E	4.3	1.5%	3.3	7.5	170	76	Ellipsoid

6. Conclusions

By analyzing the mechanical property and broken condition of carbon steel and composite materials, effect of bomb shell on extinguishing dispersion is indentified by finite element method and experiment measurement. The simulation results and experimental results are consistent. When bursting, the bomb with composite materials has bigger extinguishing dispersion area because of its smaller yield strength and little energy consumption. It indicates that this kind of composite material is more suitable for extinguishing bomb shell than carbon steel. Numerical simulation and experiment of length-diameter and powder ration are carried out on the extinguishing bombs with unidirectional fiber composite materials. It comes to the conclusion that the bigger length-diameter ration is, the smaller the dispersion radius and the higher the extinguishing disperses. Also the experiment indicates the bigger the powder ration is, the bigger the dispersion radius and the higher the extinguishing disperses. Analysis shows that unidirectional short fiber shell extinguishing bomb with the length of 840mm and the powder weight of 200g has the best effect in putting out the crown fires.

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