Analysis of factors influencing infrared extinction area of explosive smokescreen

Haihao He a, Youlin Gu a,b,c,*, Jiajie Fang a,b,c, Yihua Hu a,b,c, Hao Cao a, Wanying Ding a, Xinyu Wang a, Xi Chen a

a National University of Defense Technology, Hefei, 230007, China
b State Key Laboratory of Pulsed Power Laser Technology, National University of Defense Technology, Hefei, 230007, China
c Advanced Laser Technology Laboratory of Anhui Province, Hefei, 230007, China

ARTICLE INFO

Keywords: Smokescreen Smoothed particle hydrodynamics Charge ratio Blast radius Infrared extinction area

ABSTRACT

Objectives: Comparative studies of different smokescreen designs are essential to determine differences in extinction performance. This study aims to investigate the extinction performance of explosive smokescreen under different conditions, and to provide an evaluation method for the optimal design of its charge structure.

Methods: The process of formation of the smokescreen with a cylindrical charge structure is described based on the smoothed particle hydrodynamics method. The blast radius and particle density distribution of the smokescreen were calculated for different charge structures and charge ratios through simulations. Lambert–Beer's law was combined to obtain the infrared extinction area. An analysis was then conducted to determine the influence of the number of baffles in the charge structure and charge ratio on the extinction performance of the smokescreen. Field tests were conducted to verify the simulation results.

Results: Increasing the number of baffles in the projectile structure made the particle distribution of the smokescreen more uniform and resulted in a larger infrared extinction area. However, too much of the explosives caused the smokescreen to be sparse, reducing the infrared extinction area.

1. Introduction

With the continuous development of modern laser and infrared detection technologies, corresponding countermeasures are valued worldwide [1]. Smokescreen is an effective means of interfering with enemy's detection and has the advantages of low cost, fast speed, and high efficiency. The extinction performance of smokescreen is influenced by factors such as charge structure and charge ratio [2]. Therefore, establishing a method to study the influence of explosive smokescreen design parameters on its extinction performance is an important challenge.

Lately, various scholars have studied the formation process and extinction performance of smokescreens. Several models and algorithms have been proposed to effectively calculate the infrared extinction characteristics of smokescreens [3, 4]; for example, an infrared smoke-screen model was proposed to analyse its extinction performance based on extinction area, particle dispersion, and temperature attenuation [5]. The optical characteristic parameters and mechanical equations were combined to analyse the smokescreen formation process. This method can predict the infrared extinction performance of smokescreens in different environments. Research on the formation process of smoke-screen mainly relies on the solution of the Navier–Stokes equation [6]. Xu et al. analysed the thermal effect of the exothermic combustion of smokescreen on the initial cloud and established a simulation model for the extinction performance of an explosive smokescreen by combining computational fluid dynamics (CFD) and Navier–Stokes equations [7]. A study on the variation in smokescreen length and height showed that this model is closer to the experimental value than the Rachman model. In addition to the method of studying the smoke-screen formation process based on kinetic equation, it is also feasible to directly depict the image in the infrared band by combining optical properties with the physical scene [8, 9]. Zhang et al. proposed a method for the dynamic modelling of infrared smokescreens based on the Discrete Phase Model (DPM) [10]. The method considers the physical scene and physical state of the smoke bomb, such as the trajectory and temperature. The influence of projectile rotation on the infrared extinction performance of a smokescreen was studied, and the similarity ratio between the simulation and experiment.
was 94%. The method of combining optical properties with physical scenes can solve the problem caused by over-simplification of the model [11]. Additionally, Gaussian, Lagrangian, and Eulerian diffusion models are commonly used to analyse the distribution of aerosol particles during a smoke explosion [12, 13, 14]. Ferrero et al. established a Lagrangian particle model to simulate smoke distribution in a complex environment [15]. The research demonstrated that this model could calculate the smoke particle distribution under fire, turbulence, and other conditions, and had better accuracy than the Euler model when the atmospheric environment was complex. It is important to understand the formation mechanism and influencing factors of smokescreen, which is key to studying its extinction performance [16, 17]. However, thus far, most studies have only investigated the infrared extinction characteristics after the formation of smokescreens, and there are few studies on the factors affecting the extinction performance of explosive smokescreens.

Currently, the application of the smoothed particle hydrodynamics (SPH) method in the field of explosions has achieved various results [18]. In particular, several scholars have systematically studied the entire process of cylindrical rigid body explosions, including particle distribution, influencing factors, and motion processes, based on physical models and numerical simulations [19, 20, 21, 22]. Since the SPH method was proposed, it has been widely used in astrophysics, engineering applications, and other fields [18, 23, 24, 25]. The application of the SPH method in explosion simulation has received increasing attention from scholars because it can easily describe the deformation process of a material and capture the free surface boundary. Chen et al. studied the explosions of cylindrical shells in water [26]. The Open–MP interface was added to the improved SPH algorithm, which solved the general 3D explosion problem. The research showed that the explosion model established by the SPH method could accurately predict the explosion process of a cylindrical shell. The projectile structure of the smokescreen was designed as a cylinder; therefore, the SPH method can be applied well [27, 28]. Cheng et al. studied the effects of different wall thicknesses and spacings on cylindrical shell composite structures under explosion loads [29]. It was found that a stronger explosion load and larger deformation would lead to a more obvious impact on the cylindrical shell [30]. This shows that the SPH method can analyse the influence of factors, such as the charge ratio in the explosion problem, on the results. The shape of the charge also has a significant influence on the explosion outcome [31]. Spherical explosions have a larger shock wave than cones and hemispheres, and the cones have a greater velocity. However, existing research has not analysed the particle concentration and distribution characteristics, and influencing factors of smokescreen after an explosion in air. The particle concentration and distribution of smokescreen is the key to its extinction performance.

Herein, a calculation method for the infrared extinction performance of smokescreen was established by combining the SPH method with Lambert–Beer’s law. The effects of different charge structures and charge ratios on the smokescreen extinction performance were considered. Changes in the pressure, velocity, distribution, and displacement of the smoke particles were analysed and compared. This study provides a computational method for evaluating the infrared extinction performance of smokescreen, which can provide guidance for optimising the projectile structure of smokescreens.

2. Materials and test conditions

2.1. Test materials

The charge structure of the smoke device is cylindrical with a sealing cap at the top. The central burst tube is made of cyclotrimethylene nitramine.

Table 1. Atmospheric conditions of test.

| Test  | Temperature (°C) | Humidity (rh) | Wind speed (m/s) |
|-------|------------------|---------------|------------------|
| Test1 | 22.0             | 71.5          | 0.4              |
| Test2 | 24.7             | 66.6          | 0.8              |
| Test3 | 27.0             | 91.5          | 1.3              |

Figure 1. Diagram of smoke device. (a) Shell (b) Smokescreen material (c) Central burst tube (d) Baffles.

Figure 2. Field test diagram.
(RDX), and the outer surface of the burst tube is made of a new smokescreen material, which has the advantages of low cost and no pollution. The baffles are placed in the device in a cross shape. The outer side of the device is the shell. The material of the shell and the baffles is fibre-reinforced plastics (FRP), as shown in Figure 1.

2.2. Test equipment

This is a static test, and the smokescreen bomb is triggered by a detonator and detonating cord. The area of the smoke screen extinction performance test was $400 \times 120$ m. The terrain was flat and open without bushes, and the height of vegetation on the light path of the test instrument was less than 0.5 m.

Figure 2 shows the layout of the field test site. The test site was set on a flat outdoor ground, and a smokescreen device was placed on the bomb rack perpendicular to the direction of the infrared heat source. Infrared and high-speed cameras were used to record the test process. The infrared camera consisted of SC7700BB mid-infrared and far-infrared detectors developed by the China Electronics Technology Group Corporation. The spectral range of the mid-infrared camera was 1.5–5.1 $\mu$m, and the resolution was 640 $\times$ 512. The spectral range of the far-infrared camera was 8–12 $\mu$m. The frame rate of the high-speed camera was 4000 frames per second. The weather station integrated temperature, humidity, and other sensors to measure the test condition data. The distance from the bomb rack to the heat-source array was 70m, and the distance from the infrared camera to the bomb rack was 310m.

The infrared heat source was composed of 66 rectangular lamp arrays, 11 in each row, for a total of six rows. The power of the single radiation source was 275 W. The heat-source array was arranged in a space with a width of 50 m and height of 16 m. The horizontal distance between two adjacent heat sources was 5 m, the vertical distance was 3 m, and the height of the lowest heat source from the ground was 1 m.

2.3. Weather condition

According to the national military standard of China, the test wind speed should be less than 3 m/s and the atmospheric vertical stability should be isothermal. Herein, the actual meteorological conditions during field test of smokescreen performance, are shown in Table 1.

3. Numerical simulations

3.1. Basic theory of SPH method

The SPH method is based on integral interpolation, and the target is discretised into several particles, all of which carry information, such as...
The law of motion in the conservation of mass and momentum is obtained by governing equations and time integration.

3.1.1. Integral representation

In the SPH method, integral representation and particle approximation methods are mainly used to complete the approximate calculation in the numerical simulation [18]. The integral representation is formulated as follows:

\[
 f(x) = \int_{\Omega} f(x') \delta(x - x') dx'
\]

where \( \Omega \) contains the entire computational domain of the \( x \) volume, \( f \) is the field function of the point in space, \( \delta(x - x') \) is a function of Dirac. The smooth kernel function \( W(x - x', h) \) is used to approximate the Dirac function, which can be written as:

\[
 f(x) = \int_{\Omega} f(x') W(x - x', h) dx'
\]

Table 2. Parameters of Mat-Johnson-Cook.

| Parameters      | Value  | Unit | Parameters      | Value  | Unit |
|-----------------|--------|------|-----------------|--------|------|
| Materials (MID) | 1      | —    | Input constants (N) | 0.26   | —    |
| Density (RO)    | 1.3    | g/cm\(^3\) | Input constants (C) | 0.014  | —    |
| Shear elasticity (G) | 0.714 | E5   | Input constants (M) | 1.03   | —    |
| Young's modulus (E) | 2.1 E5 | MPa  | Damage constant (D\(_1\)) | 2.5    | —    |
| Input constants (A) | 0.122 | —    | Damage constant (D\(_2\)) | 0      | —    |
| Input constants (B) | 0.051 | —    | Minimum plastic strain at fracture (EFMIN) | 1 E-6  | —    |

Table 3. Parameters of Mat-high-explosive-Burn.

| Parameters      | Value  | Unit | Parameters      | Value  | Unit |
|-----------------|--------|------|-----------------|--------|------|
| Materials (MID) | 5      | —    | Marking variable (BETA) | 0      | —    |
| Density (RO)    | 1.09   | g/cm\(^3\) | The bulk modulus of elasticity (K) | 0      | —    |
| Detonation velocity (D) | 0.3 | cm/\(\mu\)s | Shear modulus (G) | 0      | —    |
| Detonation pressure (PCJ) | 0.0436 | E5   | Yield stress (SIGY) | 0      | —    |

Table 4. Parameters of Eos-Jones-Wilkens-Lee (JWL).

| Parameters      | Value  | Unit | Parameters      | Value  | Unit |
|-----------------|--------|------|-----------------|--------|------|
| Material type number (EOSID) | 5     | —    | Material constant (R\(_2\)) | 0.9    | —    |
| Material constant (A) | 2.14 E5 | MPa  | Material constant (OMEG) | 0.15   | —    |
| Material constant (B) | 0.00182 | E5   | Initial internal energy (E\(_0\)) | 0.042  | MPa |
| Material constant (R\(_1\)) | 4.2    | —    | Initial relative volume (V\(_0\)) | 1.0    | —    |

Figure 5. Model diagram of SPH method. (a) geometrical configuration (b) representation of the cylinder with particles.
where \( h \) is used to define the smooth length of the smooth kernel function. The integral representation of SPH method is shown in Eq. (1) and Eq. (2).

### 3.1.2. Particle approximation

In Eq. (3) and Eq. (4), the continuous integral expression is discretised into the corresponding summed form of the particles in the support domain [26]:

\[
f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W_{ij}(3)
\]

\[
W_{ij} = W(R_{ij}, h) = W(R_{ij}, h)\quad(4)
\]

Where, \( N \) is the total number of fluid-particle points in the support domain at position \( x \); \( m \) and \( \rho \) are the mass and density of the particle; \( R_{ij} = r_{ij}/h \), refers to the relative distance between particle \( i \) and particle \( j \); and \( r_{ij} = |x_i - x_j| \), represents the distance between particles.

In the SPH method, the target-particle field function is added to the weighted average of the surrounding particle field functions. The smooth function is used as the weight function, and the discretisation process is performed as follows:

\[
\frac{\partial f(x_i)}{\partial x_i} = - \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) \frac{\partial W(x_i - x_j, h)}{\partial x_i}\quad(5)
\]

The derivative of the field function at particle \( i \) is written as follows:

\[
\nabla f(x_i) = - \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) \nabla W_{ij}\quad(6)
\]

The derivative after discretisation is expressed as:

\[
\nabla \cdot f(x_i) = \rho_i \sum_{j=1}^{N} m_j \left[ \frac{f(x_i)}{\rho_j^2} + \frac{f(x_j)}{\rho_i^2} \right] \nabla W_{ij}\quad(7)
\]

\[
\nabla \cdot f(x_i) = \frac{1}{\rho_i} \sum_{j=1}^{N} m_j [f(x_i) + f(x_j)] \cdot \nabla W_{ij}\quad(8)
\]

The field function \( f(x) \) is expressed in the form of paired particles. This form of expression can give the derivative of the field functions a certain symmetry, which is in line with the principles of action and reaction forces. The pressure gradient and velocity divergence are expressed as

\[
\text{Grad}(p_i) = \rho_i \sum_{j=1}^{N} m_j \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial x_i}\quad(9)
\]

\[
\text{Div}(u_i) = - \frac{1}{\rho_i} \sum_{j=1}^{N} m_j u_j \frac{\partial W_{ij}}{\partial x_i}\quad(10)
\]

The particle approximation can be calculated by Eqs. (5), (6), (7), (8), (9), and (10).

### 3.1.3. Boundary conditions

For particles near the boundary in the SPH method, the support domain may be "truncated", resulting in missing particles. Because of the lack of particles, the symmetry and normalisation of the kernel function in the calculation process cannot be satisfied, and thus the simulation accuracy is greatly reduced. Figure 3 shows the boundary particles, which are subject to interactive forces, when the particles are in contact.

This study uses the virtual particle method to solve the precision problem. As shown in Figure 4, the lack of internal particle boundaries is compensated for by arranging the boundary particles on the wall surface. These virtual particles also have parameters such as mass and density and participate in solving the governing equations. The velocity and position of the virtual particles remain unchanged relative to the boundary. Assume that, on a stationary wall, the virtual particle has zero velocity and no change in position. This method ensured the stability of the pressure and density of the boundary particles.

### 3.1.4. Artificial viscosity

Artificial viscosity is introduced in the SPH method to suppress non-physical numerical oscillations and prevent penetration when particles approach each other [14]. In Eq. (11), the artificial viscosity is expressed as follows:

\[
\nabla \cdot f(x_i) = \rho_i \sum_{j=1}^{N} m_j \left[ f(x_i) + f(x_j) \right] \cdot \nabla W_{ij}\quad(11)
\]
\[ \begin{aligned} \Pi_{ab} &= \begin{cases} -\frac{\pi c \phi_{ab}}{\rho_{ab}} + \frac{\tilde{p}^2}{\rho_{ab}} & v_{ab} \cdot r_{ab} < 0 \\ 0 & v_{ab} \cdot r_{ab} \geq 0 \end{cases} \end{aligned} \] (11)

where \( c \) is acoustic velocity, \( \phi_{ab} = (h v_{ab} \cdot r_{ab})/(r_{ab}^2 + \phi^2) \), \( \phi^2 = 0.01h^2 \), \( r_{ab} = (c_a + c_b)/2, \tilde{p}_{ab} = (\rho_a + \rho_b)/2 \).

### 3.1.5. Elastic plastic constitutive model for solids

The solid collision between two particles adopts the ideal elastic-plastic constitutive relation, and the formula is expressed as [12]:

\[
\begin{align*}
S^e_{ab} &= \Delta t \left( 2G \left( \frac{\varepsilon_{\rho}}{3} - \frac{1}{3} {\varepsilon_{\rho}}^T \varepsilon \right) + S^\rho \varepsilon^\rho + S^\| \varepsilon^\| \right) + S^\omega_{ab} \\
\end{align*}
\] (12)

where \( S^e_{ab} \) is the deviatoric stress component at the \( n \) time step and \( G \) is the shear modulus. The strain rate tensor and rotation rate tensor are expressed as:

\[
\dot{\varepsilon}^\rho = \frac{1}{2} \left( \frac{\partial \varepsilon^\rho}{\partial x^\alpha} + \frac{\partial \varepsilon^\rho}{\partial x^\beta} \right) \\
\dot{\varepsilon}^\| = \frac{1}{2} \left( \frac{\partial \varepsilon^\|}{\partial x^\alpha} - \frac{\partial \varepsilon^\|}{\partial x^\beta} \right) 
\] (13)

Obtain particle approximations for strain rate and spin rate components by using following equations:

\[\text{Figure 7. Simulation result of front view (left) and side (right) view with different number of baffles. (a) 0 baffles (b) 2 baffles (c) 4 baffles.}\]
\[ \dot{\epsilon}_{ij}^{\text{pl}} = \frac{1}{2} \sum_{j=1}^{N} \frac{m_j}{\rho_j} \left( \nu^\alpha_{ji} \frac{\partial W_{ij}}{\partial x_i^\alpha} + \nu^\beta_{ji} \frac{\partial W_{ij}}{\partial x_i^\beta} \right) \]  

(15)

The incremental plastic work is given by:

\[ \Delta W_p^{(n)} = \frac{1}{2} \left( \sigma_p^{(n+1)} + \sigma_p^{(n)} \right) \Delta \epsilon_{ij}^{(n)} \left( \frac{m}{\rho^{(n+1/2)}} \right) \]  

(17)

The incremental equivalent plastic strain is as follows:

\[ \Delta \epsilon_{ij}^{(n)} = \frac{\sigma_p^{(n)} - \sigma_y}{3G} \]  

(18)

The Elastic plastic constitutive model for solids is generally calculated by the collision formula between ideal particles, e.g. Eqs. (12), (13), (14), (15), (16), (17), and (18).
Figure 5(a) represents the geometric model. The smokescreen device modelled by the SPH method is shown in Figure 5(b).

3.2. Governing equation based on SPH method

In Eqs. (19), (20), and (21), solving fluid mechanics problems based on the SPH method includes the following governing equations [1]:

\[
\frac{d\rho}{dt} = -\rho \frac{\partial \sigma^\alpha}{\partial x^\alpha} \tag{19}
\]

\[
\frac{dv^\alpha}{dt} = \frac{1}{\rho} \frac{\partial \sigma^\alpha}{\partial x^\alpha} \tag{20}
\]

\[
\frac{de}{dt} = \frac{\sigma^\alpha}{\rho} \frac{\partial v^\alpha}{\partial x^\alpha} \tag{21}
\]

where \(\sigma = [\sigma^{\alpha\beta}]\) is the Cauchy stress tensor, \(v\) is the velocity, \(\rho\) is the fluid density, and \(e\) is the internal energy per unit of mass. The Cauchy stress tensor can be expressed as Eq. (22) and Eq. (23):

\[
\sigma^{\alpha\beta} = -p \delta^{\alpha\beta} + \mu \varepsilon^{\alpha\beta} \tag{22}
\]

\[
\varepsilon^{\alpha\beta} = \frac{\partial v^\beta}{\partial x^\alpha} + \frac{\partial v^\alpha}{\partial x^\beta} - \frac{2}{3} (\nabla \cdot v) \delta^{\alpha\beta} \tag{23}
\]

where \(p\) is the isotropic pressure, \(\mu\) is the viscosity coefficient, and \(\varepsilon = [\varepsilon^{\alpha\beta}]\) is the shear strain-rate tensor.

3.3. Material model

3.3.1. Shell and baffles model

The Johnson–Cook model was used in this study to describe the damage on the FRP shell and diaphragm, made during the extrusion...
the mass extinction coefficient 

\[ \text{mass extinction coefficient} = \frac{C}{\text{mass concentration of the smokescreen material}} \]

In this study, the NULL model was selected to describe smokescreen materials. This model must be used together with the state equation, which is expressed as Eq. (26) and Eq. (27):

\[ \sigma_I = A + B (\epsilon_p)^n \left[ 1 + C \ln \left( \frac{\dot{\epsilon}_p}{\dot{\epsilon}_0} \right) \right] \left[ 1 - (T^*)^\kappa \right] \]

(24)

where \( \epsilon_p \) is the equivalent plastic strain; \( \dot{\epsilon}_p \) is the equivalent plastic strain rate; \( T^* \) is the dimensionless temperature; and \( n, k, A, B, C \) are constants.

### 3.3.3. Smokescreen material model

In this study, the NULL model was selected to describe smokescreen materials. This model must be used together with the state equation, which is expressed as Eq. (26) and Eq. (27):

\[ \sigma_I = 2 \mu \dot{\gamma} \]

(26)

\[ \frac{N}{m^2} \sim \left[ \frac{N}{m^2} \right] \left[ \frac{1}{s} \right] \]

(27)

where \( \mu \) is the dynamic viscosity and \( \dot{\gamma} \) is the deviatoric strain rate.

### 3.4. Lambert–Beer’s law

Lambert–Beer’s law was combined to obtain the concentration of smokescreen required for effective extinction and the infrared extinction area of the smoke was calculated [32]. Lambert–Beer’s law can be expressed as Eq. (28):

\[ A = KcL \]

(28)

where \( c \) is the mass concentration of the smokescreen material, \( L \) is the thickness of light passing through the light-absorbing medium, and \( K \) is the mass extinction coefficient of the smokescreen material.

### 4. Results and discussion

The effects of the charge structure and charge ratio were analysed by changing the number of baffles and diameter of the explosive column (ECD). The number of baffles was set to 0, 2, and 4. The ECD was set to 9, 10, and 11 mm.

In the numerical simulation, the displacement distance of the smoke particles along the z-axis was selected as the explosion radius. After the simulation, the space was divided to count the number of particles in each area to obtain the particle density distribution of the smokescreen. Lambert–Beer’s law was used to calculate the infrared extinction area.

#### 4.1. Convergence test

The SPH method exhibits good convergence properties [33]. To avoid the fluctuation in stability of model during the calculation, explicit dynamic analysis was used in this study. Explicit kinetic analysis of the SPH model can avoid non-convergence of the calculation [34, 35].

The global kinetic energy, internal energy, and total energy changes were monitored during the calculation to aid in testing the convergence of the model. Figure 6 shows that in the calculation process, the global total energy is always equal to the sum of the kinetic and internal energies. Therefore, the model displays good stability.

#### 4.2. Influence of charge structure

Figure 7 (a) (b) (c) and Figure 8 (a) (b) (c) show that the concentration distribution of smokescreen particles becomes more uniform with increase in the number of baffles in the smokescreen charge structure because of the increasing thrust of the baffles. Two peaks appear in the particle density distribution graph for the two baffles, indicating that the particles are distributed towards the sides owing to the effect of the baffles. While using four baffles, the particle density distribution was symmetrical and more evenly distributed.

Figure 9(a) shows the velocity profile of the particles at the boundary of the smokescreen for different number of baffles. The drop in the velocity curve was due to collisions between particles. By increasing the number of baffles, which means more thrust, the velocity of the particles increases. The effect of different number of baffles on particle pressure is shown in Figure 10(a). The pressure of the particles rapidly increases at the moment of explosion and decreases sharply. The fluctuations in the pressure values were caused by collisions between the particles. According to Figure 11 (a), the blast radius of the smokescreen expands as the number of baffles increases. Figure 12(a) shows that the infrared extinction area of the smokescreen is significantly affected by the charge.
structure. Greater the number of baffles, larger is the infrared extinction area of the smokescreen.

To summarise, the baffle was embedded in the warhead structure of the smokescreen bomb, which adjusted the propagation direction of the detonation wave. As shown in Table 5, the peak pressure of the particles without the baffle was 1680 kPa and the velocity was 0.0415 cm⋅μm⁻¹. When there were two baffles, the peak pressure of the particles was 2400 kPa and the velocity was 0.0472 cm⋅μm⁻¹. When four separators were added, the peak pressure of the particles was 5960 kPa, and the velocity was 0.0522 cm⋅μm⁻¹. Therefore, the included angle between the detonation wave front and shell wall becomes smaller after adding the baffle. When the angle decrease, the pressure acting on the particles

Figure 14. Comparison of test and simulated.
increases, which is beneficial for increasing the speed of the particles and expanding the explosion radius of the smokescreen. The analysis of the results shows that the peak pressure of the two baffles was 42.9% higher than that of the no baffle, and the particle velocity increased by 13.7%. The peak pressure of the four baffles was 148.3% higher than that of the two baffles, and the speed increased by 10.6%. Owing to the increased pressure and velocity of the particles, the overall explosion radius of the smoke screen increased by 20.6% and 13.9%, respectively. As shown in Figures 7 and 8, the particle distribution of the smokescreen changed after the explosion because the baffle adjusted the propagation direction.

Figure 15. Comparison of simulated and test data. (a) ECD = 11 mm (b) 2 baffles (c) 4 baffles.

Figure 16. Infrared extinction area.
of the detonation wave. The number of particles in the simulation is approximately 110,000. Because of the effect of the baffle, the particle area with a relatively concentrated centre is scattered. As shown in Figure 12(a), although the number of particles in the central area of the smokescreen has decreased, it still has infrared extinction ability, and the infrared extinction area has improved. In view of this, the projectile structure with two baffles are more suitable for covering rectangular areas, and the projectile structure with four baffles are more suitable for covering circular areas.

4.3. Influence of charge ratio

Figure 9(b) shows the velocity curves of the particles at the boundary of the smokescreen with different ECD. This indicates that the velocity of the particles is affected by the charge ratio. The pressures on the particles at different ECD are shown in Figure 10(b). The more dynamite used, the greater is the pressure on the smokescreen particles.

Figure 11(b) shows the influence of the charge ratio on the blast radius of the smokescreen. The blast radius of the smokescreen increased significantly with increasing charge ratio. According to Figure 12(b), the infrared extinction area of smokescreen first increases and then decreases after increasing the charge ratio. The concentration of smokescreen particles is reduced when the charge ratio is too large; thus, the infrared extinction area is reduced. Therefore, it is important to reasonably set the ECD and control the charge ratio to obtain an optimum extinction effect for smokescreen.

In the initial stage of detonation, a process in which the central high-energy explosive column undergoes a detonation reaction and drives the extinction material to be compacted around, the pressure value changes suddenly. Subsequently, the pressure increases sharply over a short period of time and decays rapidly. When ECD was 9 mm, the particle velocity was 0.0419 cm⋅µm\(^{-1}\). When the ECD was 10 mm, the particle velocity was 0.0445 cm⋅µm\(^{-1}\), and the growth rate was 6.2%. When ECD was 11 mm, the particle velocity was 0.0451 cm⋅µm\(^{-1}\), and the growth rate was 1.3%. Therefore, increasing the quantity of explosives increases the rate of smoke formation; however, after a certain amount, increasing the explosives does not significantly increase the rate of smoke formation. Simultaneously, owing to the increase in explosives, the explosion radius of smokescreen also increases. As the explosion radius increases, the particle concentration decreases. It can be seen from the results that when the ECD is larger than 10 mm, the infrared extinction area of the smokescreen decreases. Therefore, according to the parameters of the simulated smokescreen in this study, the extinction performance with an ECD of 10 mm is the best.

4.4. Comparison and verification

A comparison of the test and numerical simulation images at different times is shown in Figure 14 (a) (b) (c) (d). The image shows that this method can reflect the shapes and changes of a smokescreen in the early stage of an explosion. Figure 13 shows an image of the smokescreen captured by the infrared camera. Figure 15 (a) (b) (c) show that the blast radius of the smokescreen obtained by the numerical simulation is consistent with the results of the field test. When ECD was 11 mm, the infrared extinction area obtained by the simulation was 26.32 m\(^2\) and test result was 27.9 m\(^2\). When the number of baffles were two and four, the infrared extinction areas obtained by simulation were 37.98 m\(^2\) and 45.75 m\(^2\), respectively. The corresponding results of the test were 34.24 and 43.31 m\(^2\), as shown in Figure 16. The simulation results were consistent with the test results. Therefore, the model in this study can simulate the explosion process and analyse the extinction performance of smokescreen. The deviation may have been caused by the variation in the air resistance and wind in the field test. The simulation was performed under ideal conditions. This limitation needs to be addressed in follow-up research.

images captured at different times. (a) 10 ms (b) 20 ms (c) 30 ms (d) side view at 30 ms.

5. Conclusion

Herein, the SPH method and finite element analysis were used to establish the initial model of smokescreen and simulate the release of explosive smokescreen. The blast radius and particle density distribution of the smokescreen were calculated for different charge structures and charge ratios. Lambert–Beer’s law was combined to calculate the infrared extinction area of the smokescreen. The variation law of the infrared extinction area of the smokescreen was analyzed under different conditions.

The infrared extinction area of smokescreen was significantly affected by the charge structure. The blast radius of the smokescreen increases, and the distribution of particle density becomes more uniform as the number of baffles increases. This is beneficial for obtaining a larger infrared extinction area. Therefore, this type of smokescreen can have better extinction performance by appropriately increasing the number of baffles. The blast radius increases with an increase in the charge ratio. However, the particle density distribution of smokescreen is sparse when the dynamite quantity is too large. It is possible to obtain a smaller infrared extinction area when excessive dynamite is used. It is necessary to design a suitable charge ratio to promote the extinction performance.

The examples presented above demonstrate that this model can calculate the infrared extinction area and effectively evaluate the extinction performance of smokescreens. The results presented herein are highly significant in engineering practices, particularly, the analysis of the factors influencing extinction performance in the design of smoke-screen charge structures.

Declarations

Author contribution statement

Haihao He, Youlin Gu, Jiajie Fang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools; Wrote the paper.
Yihua Hu, Hao Cao, Wanying Ding: Performed the experiments; Wrote the paper.
Xinyu Wang, Xi Chen: Conceived and designed the experiments; Analyzed and interpreted the data.

Funding statement

Professor youlin gu was supported by National Natural Science Foundation of China [62075241], Advanced Laser Technology Laboratory Foundation of the Anhui Province of China [20191003].

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
