

Studies on the smoke dispersion when tear gas grenades exploded in different spaces

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Abstract. Tear gas is a widespread non-lethal weapon, but there is very little research on its non-lethal effectiveness at different scales of space, environment, and wind speed, which leads to no scientific guidance on the number of tear gas canisters to be used in practical applications. The effect of tear gas smoke released in different space sizes, environmental conditions, and obstacles was studied in this paper using fluent software. The results show that different spaces, media, and obstacles have different effects on smoke diffusion. Tear gas canisters in different spaces show that both are spread outward in the form of point sources. The smoke spreads outward on sunny days and spreads at a higher height on cloudy days. It has a particular guiding significance for tear gas canisters in practical applications.

Keywords: Tear gas, smoke, dispersion, space.

1. Introduction

Tear gas is non-lethal anti-riot ammunition commonly used by the armed police forces in dealing with emergencies. It burns or explodes, releasing the tear gas filled in the body to form aerosol smoke. The tear gas contained in the smoke in the effective concentration range will have a stimulating effect on the living target so that the target temporarily produces a severe reaction or lose the ability to resist. In practical, tactical applications, the magnitude of the nonlethal effectiveness of tear gas [1] depends on the size of the area covered by the smoke at the lowest effective concentration of the tear gas contained in the aerosol smoke after diffusion; Therefore, it is essential to investigate and simulate the concentration distribution of tear gas fumes under various conditions and the magnitude of the effect range.

Tear gas smoke is similar to smoke from explosions, flames, etc., with irregular geometry. Domestic and foreign scholars have proposed a variety of methods to achieve this. There are process texture function models, cellular automata models, models based on particle systems [2,3], based on Gaussian models [4], such as NS (Navier-Stokes) equations for solution [5-7], based on physical models, and based on computational fluid dynamics models [8,9], etc. Computational fluid dynamics methods (CFD) [10, 11] are less costly and can simulate a wide range of complex as well as ideal problems, and for all physical classes of problems, there are numerical solutions suitable for themselves [12], so the computational fluid dynamics model is chosen in this paper.

In the current CFD simulations, few research papers analyze the diffusion process of aerosol smoke from tear gas grenades. Most of them do not consider the influence of multiple factors on smoke movement, such as wind field, humidity, and obstacles in different spaces. There are very few studies on different environments, the scale of bomb action space, media, and wind speed, which leads to no scientific guidance basis for the number of tear gas grenades used in actual tactical applications, and the establishment of a successful computational analysis case is significant for the effect of new smoke bombs in the future. For this, in this paper, simulations were conducted under indoor ventilation conditions and outdoor weather conditions, respectively, to analyze the concentration of tear gas smoke in horizontal or vertical directions at different observation points.

2. Computational Models

ANSYS FLUENT software is a popular software for CFD simulation^[13], which is a common solver for CFD based on unstructured mesh and finite volume method. The geometry is built by SpaceClaim software, and the mesh could be imported from ANSYS software such as FLUENT MESHING. The base size of the grid is 60mm, The area in and around the tear gas inlet was grid encrypted with a local encryption size of 2mm, the total number of indoor grids is 480,000, and the total number of outdoor grids is 1.3 million.

2.1. Mathematical Models

2.1.1. Gas-phase control equation[14]

Suppose the tear gas smoke particles are uniform spheres, which can be regarded as two-dimensional constant incompressible flow without considering the phase change between the two phases, the size distribution of the particles, and the interaction between the particles, and the corresponding control equation is

(1) Mass equation:

$$\frac{\partial}{\partial t}(\rho_g) + \nabla \cdot (\rho_g \mathbf{u}_g) = 0 \quad (1)$$

In equation (1): \mathbf{u}_g and ρ_g are the velocity and density of the gas, respectively.

(2) Momentum equation:

$$\frac{\partial}{\partial t}(\rho_g \mathbf{u}_g) + \nabla \cdot (\rho_g \mathbf{u}_g \mathbf{u}_g) = -\nabla P - \nabla \cdot (\boldsymbol{\tau}_g) + \rho_g \mathbf{g} - \mathbf{S}_{p-g} \quad (2)$$

$$\boldsymbol{\tau}_g = \boldsymbol{\mu}_s [\nabla \mathbf{u}_g^T + \nabla \mathbf{u}_g] - \frac{2}{3} \boldsymbol{\mu}_g \nabla \cdot \mathbf{u}_g \mathbf{I} \quad (3)$$

$$\boldsymbol{\mu}_g = \boldsymbol{\mu}_{lam,g} + \boldsymbol{\mu}_t \quad (4)$$

In equation (2)~(4): $\boldsymbol{\tau}_g$ is the gas-phase stress tensor; $\boldsymbol{\mu}_g$ is the gas-phase viscosity, $\boldsymbol{\mu}_{lam,g}$ is the dynamic viscosity of the laminar flow of the gas phase; $\boldsymbol{\mu}_t$ is the turbulent dynamic viscosity of the gas phase; \mathbf{I} is the unit vector; \mathbf{S}_{p-g} is the force between the two phases, and its expression is

$$\mathbf{S}_{p-g} = \frac{\sum_{i=1}^N Num \cdot S_i f_{d,i}}{\sum_{i=1}^N Num \cdot S_i} = \frac{\sum_{i=1}^N S_i f_{d,i}}{\sum_{i=1}^N S_i} \quad (5)$$

In equation (5): N is the number of tear gas agents in the grid; Num is the number of real tear gas particles represented by a single simulated particle; S_i is the spherical surface area of the computational grid where the tear gas smoke particles are located.

1.1.2. Kinematic equations

Calculated by considering only the role of gravity, Saffman (Saffman) lift, and gas traction, according to Newton's second law, the equation of motion of the tear gas can be expressed as

$$m_i \frac{du_i}{dt} = m_i g + F_s + F_D \quad (6)$$

In Eq. (6): m_i, u_i denote the mass and velocity of the tear gas canister, respectively; g is the acceleration of gravity; F_s is the Saffman lift force; F_D is the gas traction force.

$$m_i = \rho_i V_i \quad (7)$$

$$F_s = 1.6 \times (\mu \cdot \rho_g)^{\frac{1}{2}} d_i^2 |v_g - v_i| \left| \frac{\partial v_g}{\partial y} \right|^{\frac{1}{2}} \quad (8)$$

$$F_D = 3\pi \cdot \mu \cdot \mathbf{u}_i \cdot d_i \quad (9)$$

In Eqs. (7)~(9):: ρ_i, v_i, d_i are the density, volume, and particle size of tear gas, respectively; μ, ρ_g are the viscosity coefficient and density of air, respectively.

2.2. Interior model building

The geometric model of the flow field is based on the fact that the armed police, in dealing with emergencies and in anti-terrorist operations, often need to drop tear gas canisters into the room according to specific wartime needs in order to achieve a stimulating effect on terrorists, and the actual working conditions are simplified. The diffusion characteristics of tear gas smoke are simulated with practical reasons.

The geometric calculation area for this simulation is shown in Figure a. The specific geometry is a rectangular area of 5m in length, 3m in height, and 3m in width, with a 1×2m door, a 0.7m square window, and a 50mm radius circle for the tear gas release entrance, and some associated interior obstructions.

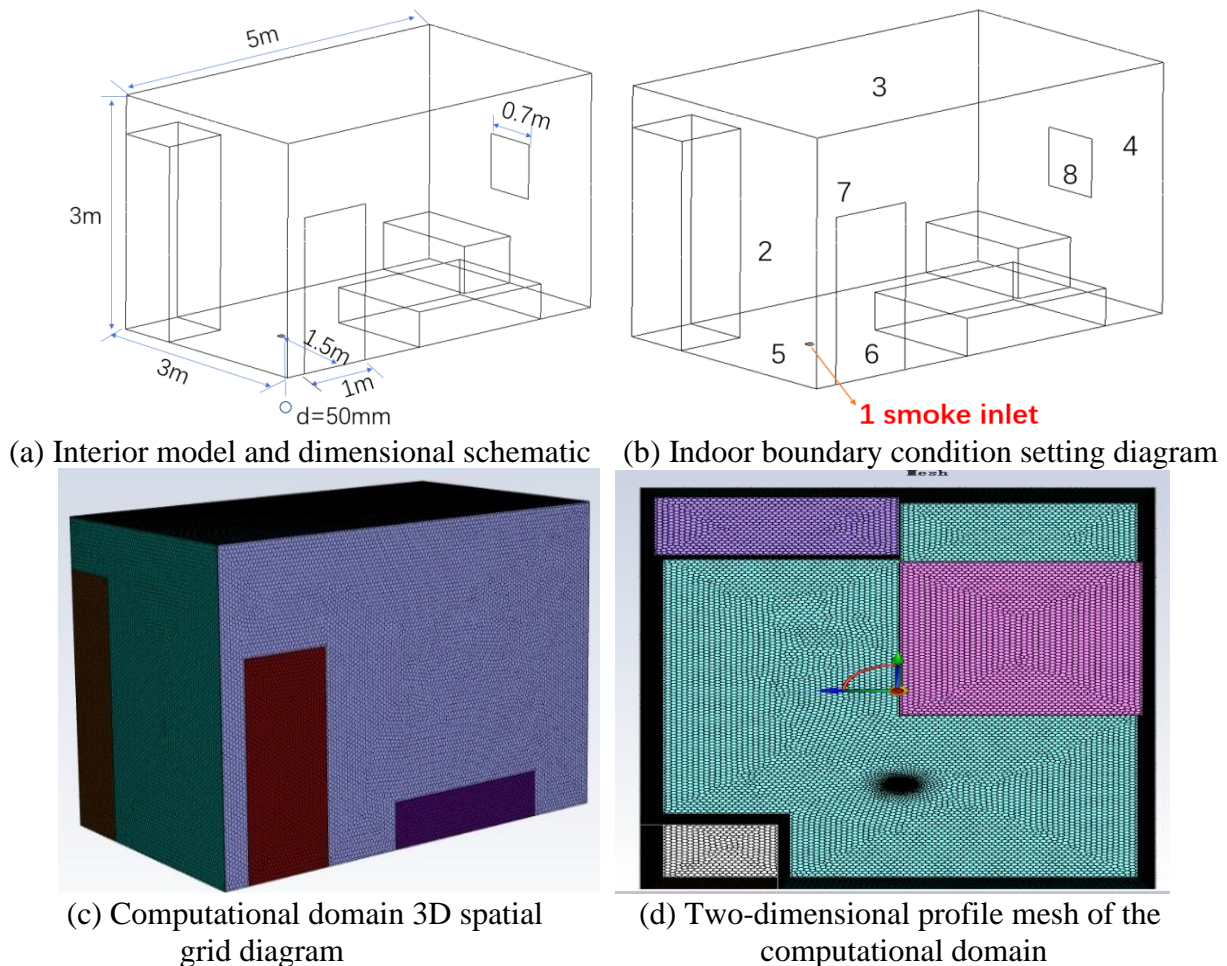


Figure 1. Geometric model of the interior, mesh, and boundary conditions diagram

Meanwhile, for the geometric model shown in Fig. a for meshing, Fluent meshing was selected for unstructured meshing, and by determining the mesh size of the whole space, a combination of polyhedral and hexahedral core meshing was used for body meshing, the specific division is shown in Fig. b and Fig. c. In order to accurately capture the motion trajectory of the smoke diffusion, the

area around the tear gas inlet was meshed and encrypted, and the total number of meshes shown was 480,000.

In order to make the results of the simulation more accurate, the boundary conditions were also calibrated (as shown in Figure d), and the specific settings were combined with the actual situation as follows. In the Figure, 1 is the mass flow inlet for tear gas delivery, 6 is the velocity inlet for the door, 8 is the pressure outlet for the window, and 2, 3, 4, 5, 7 are all set with the boundary conditions wall.

2.3. Outdoor model building

The geometric model of the flow field takes the jungle combat common to the armed police force in dealing with large-scale mass events and the territory of urban clusters as the research background, combines some practical factors, and simplifies the actual working conditions.

The computational geometry model for this simulation is shown in Figure e, with specific geometric dimensions of 6 m in length, 5 m in width, and 6 m in height. The tear gas release entrance is a circle with a radius of 50 mm and some associated indoor obstacles.

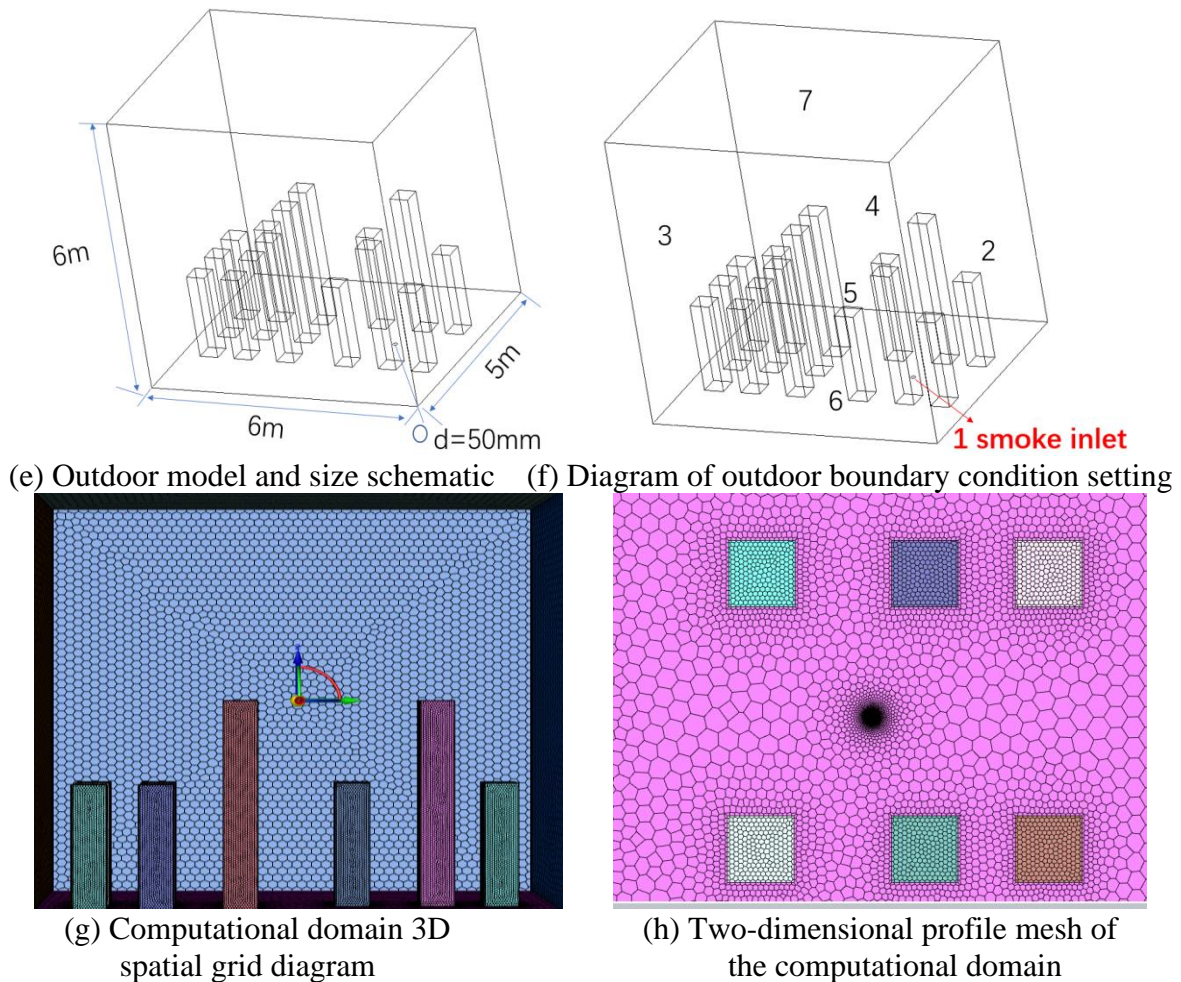


Figure 2. Geometric model, mesh, and boundary conditions of the outdoor area

At the same time, the geometric model shown in Figure 2 was meshed using the same meshing method as in Figure 1, and the specific partitioning is shown in Figure g and Figure h. In order to accurately capture the trajectory of the smoke diffusion, the area around the tear gas inlet was meshed and encrypted, and the total number of meshes shown is 1.3 million.

In order to make the simulation results more accurate, the boundary conditions were calibrated simultaneously (as shown in Figure 2), and the specific settings were combined with the actual situation as follows. In Fig. f, 1 is the mass flow inlet for tear gas injection, 2 is the velocity inlet, the

velocity of wind inlet is 1m/s, the velocity of the smoke inlet is 0.15kg/s, 3 is the pressure outlet, 4, 5, 6, 7 are set as the boundary conditions for the wall, and the rest are the obstacle.

3. Results and discussion

In practice, the diffusion of tear gas smoke is affected by many factors, such as wind speed, the size of different spaces, the size of the smoke particle diameter, different humidity weather of the space, etc. Whereas for specific tear gas, the particle diameter is fixed in the case of maintaining a certain wind speed. The size of the space and different humidity weather becomes essential.

3.1. Comparison under different spaces

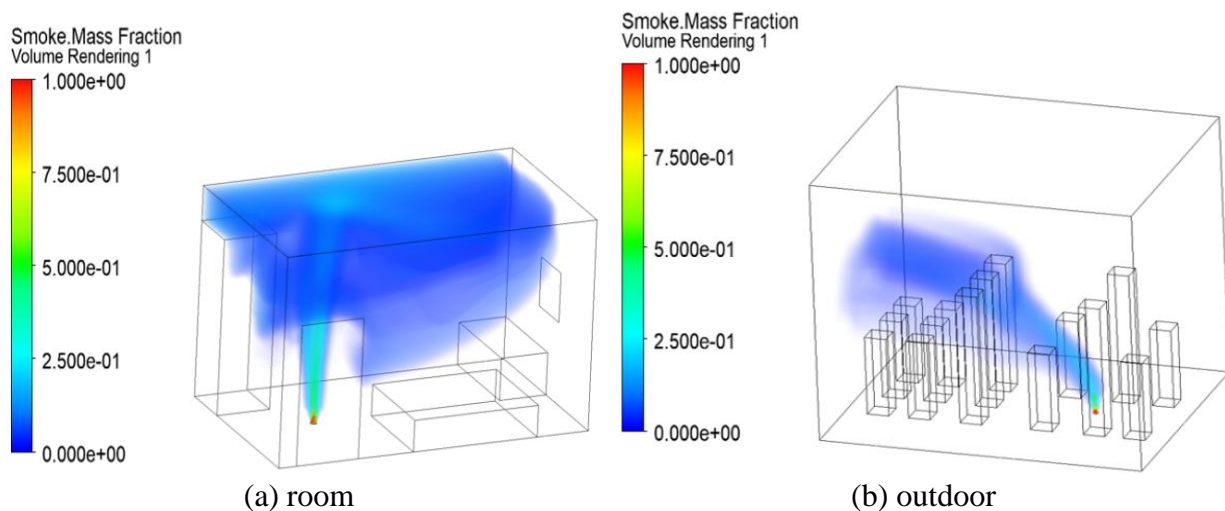


Figure 3. Comparison of smoke simulation in different spaces

Fig. 3 (a) and (b) are the simulated effects of tear gas smoke under the same diffusion time, and their smoke spaces are indoor and outdoor, respectively. By comparison, this smoke space is not only a single small indoor space but also a large outdoor space, which is more diverse and extends the application field of tear gas smoke simulation.

Figure 4 shows the flow field and concentration distribution in different spaces in the middle cross-section. As can be seen from Figure c1 and Figure d1, because the flow velocity of the flow field is low, it forms a flow field distribution with the release source of the projectile as the center and spreads around, mainly because it is not easy to spread out because it is driven by its release velocity and various forces such as gravity, traction and random force they are subjected. The comparison result between c1 and d1 is shown that the wind speed in the outdoor environment has a larger area of action. Therefore, the smoke is not yet diffused to a height of 3m before being blown away by the wind. From a1 and b1 correspond to the concentration distribution chart. The color represents high and low concentration distribution, blue represents low concentration, and red represents high concentration. It can be seen that the basic form of the point source of smoke, the highest concentration of the nozzle, as the smoke rises and close to the outlet, the concentration gradually decreases, and can see the influence of the building on the diffusion of smoke.

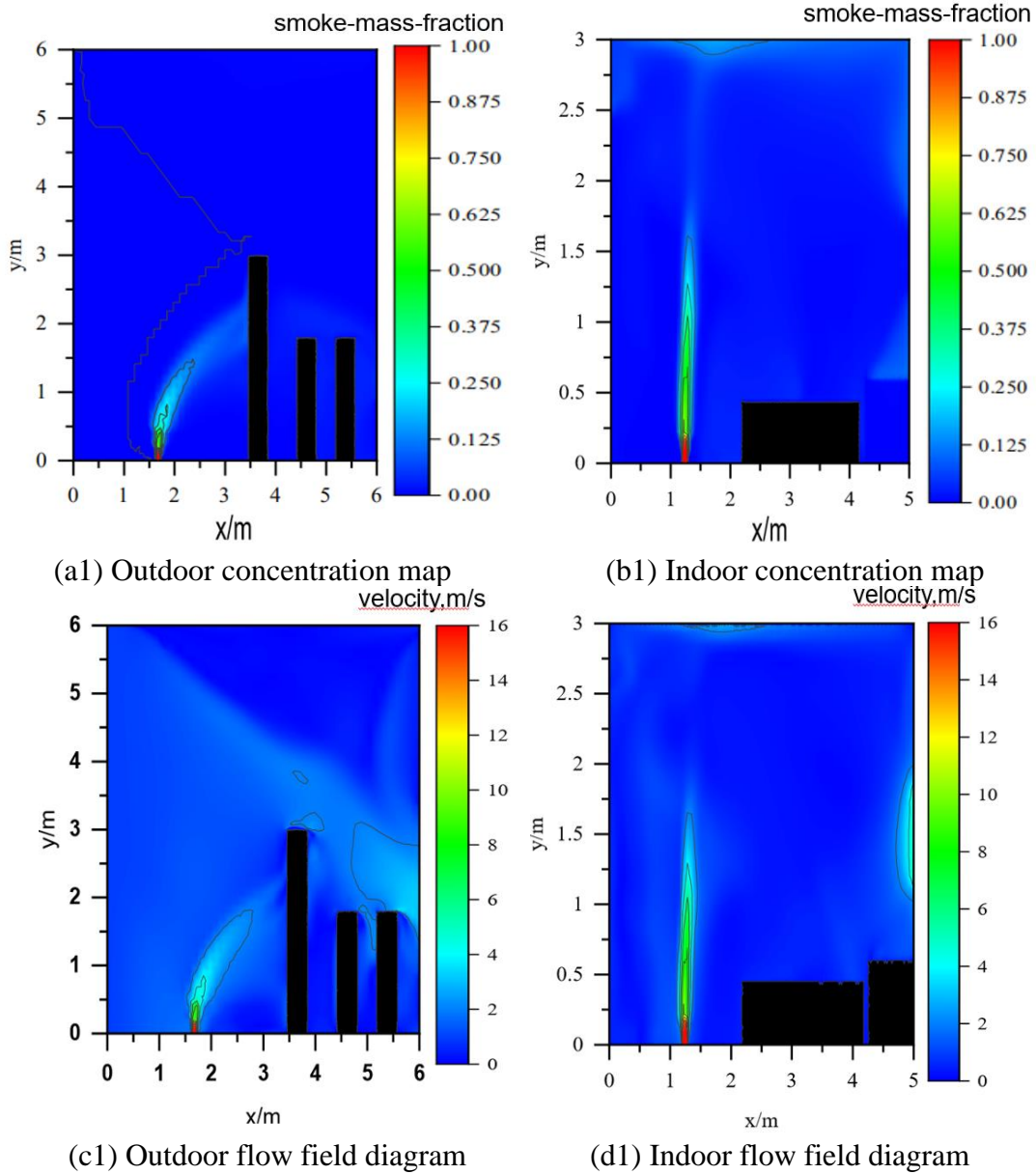


Figure 4. Flowfield diagram and concentration distribution on the medium cross-section of tear gas

3.2. Comparison of smoke concentration under different weather conditions

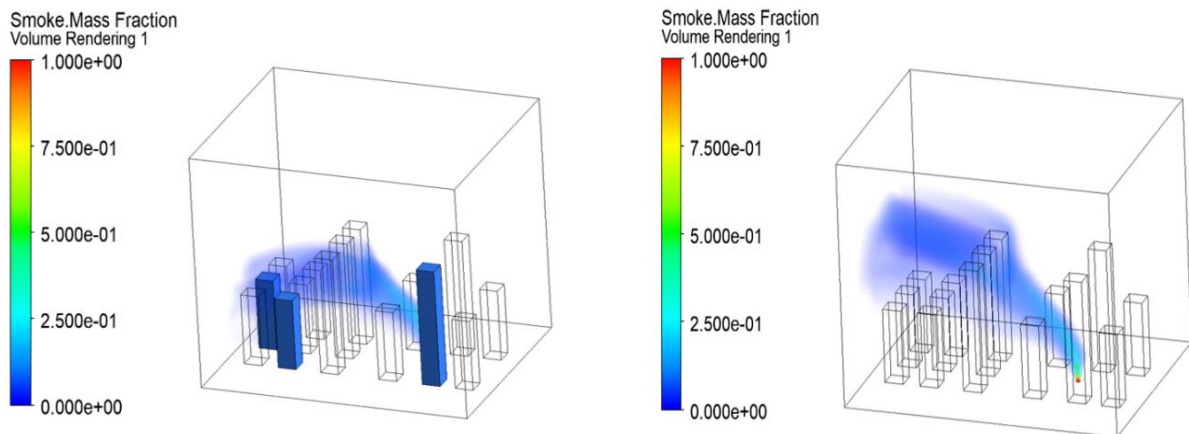


Figure 5. Comparison of smoke concentration under different weather conditions

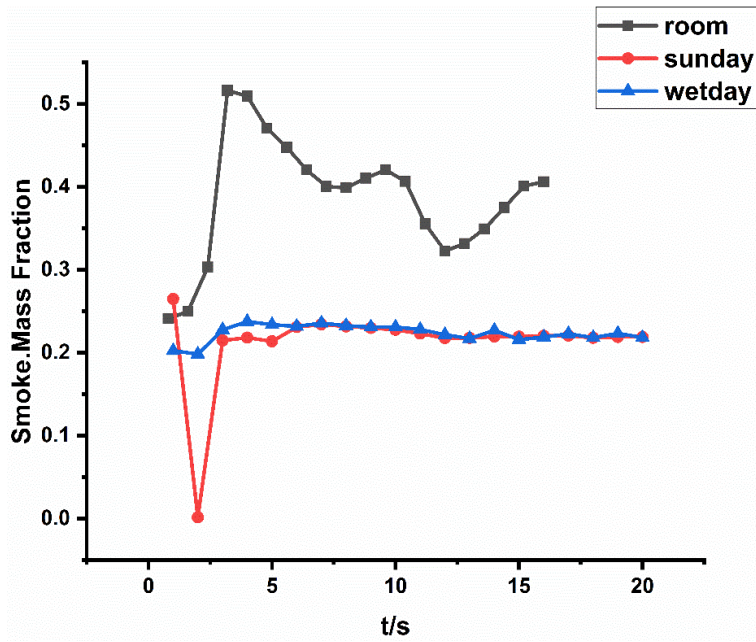


Figure 6. Comparison of smoke concentration at the same point with time

Similarly, we simulated the smoke concentration distribution in different weather conditions, with the radiation model on a sunny day and humidity set to 50%, and on a cloudy day, humidity set to 80%. It can be seen that the tendency of the smoke to spread outward is greater in cloudy conditions, involving a wider area and a higher height.

To further observe the specific changes, an observation point P was set at a distance of (0, 50, 900) from the smoke release points of the three cases to monitor the changes in smoke concentration over time, as shown in Figure 6, where the concentration of indoor observation point P increased sharply during the time period of 0~4 s. It was because that the wind did not effectively disperse the smoke curtain that remained near point P during the initial stage, and the highest concentration peak occurred here. The wind did not effectively disperse the smoke curtain near the P point in the initial stage, and the highest concentration peak occurred here. For the observation point P on a clear day, there was a precipitous drop in the time period 0~3s because the area of outdoor smoke was large, and the smoke at point P was blown away by the wind just after it spread out. As the smoke continued to diffuse around the middle of the building, the concentration gradually approached a stable level. The overall concentration of P at the observation point does not change much under cloudy conditions, showing slight fluctuations because the cloudy sky acts as a barrier to radiation, blocking the daytime radiation and the nighttime radiation from the ground upward, thus reducing the vertical temperature gradient and making the atmosphere close to a neutral state.

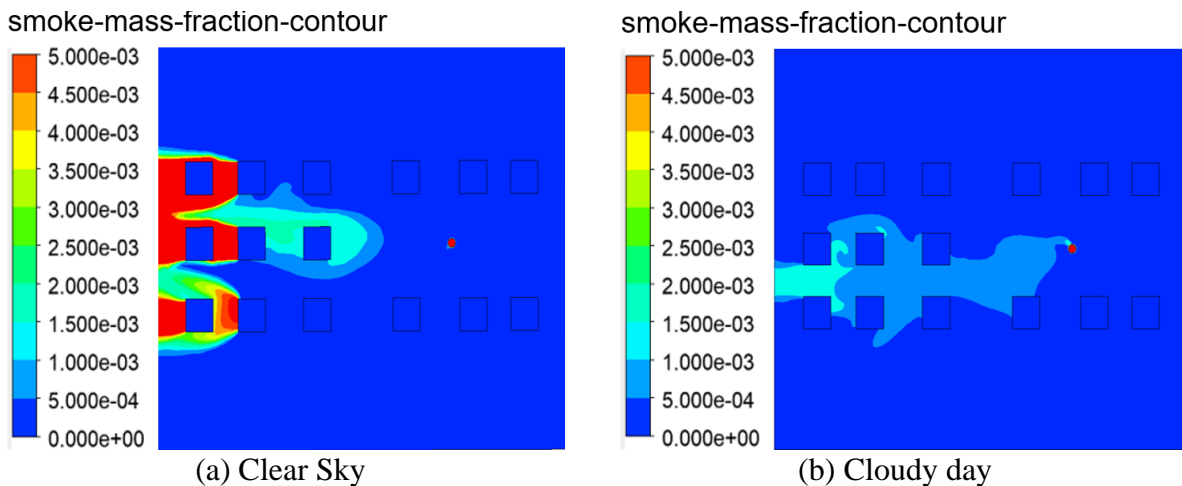


Figure 7. Concentration distribution of Z=0 cross-section for different weather

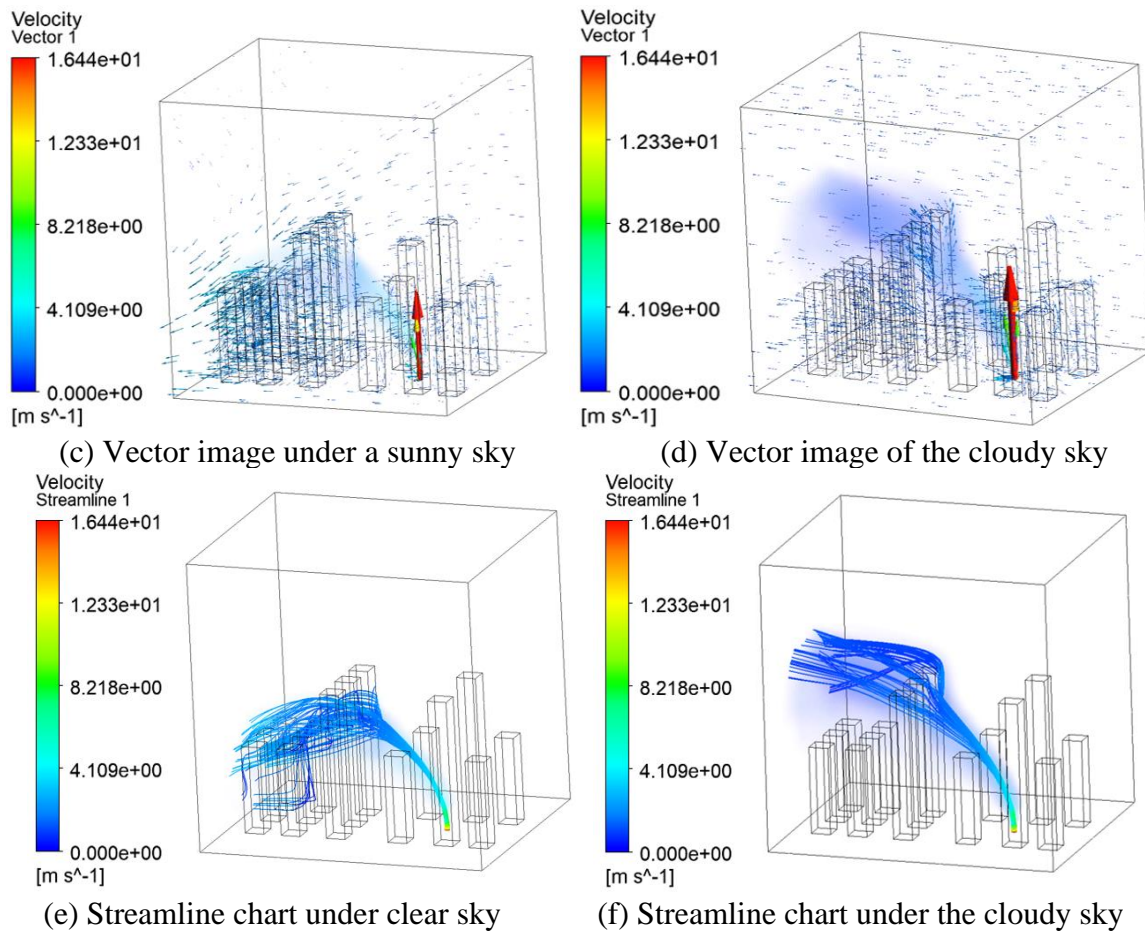


Figure 8. Comparison of streamline and vector diagrams under different weather

Figure 7 compares the smoke concentration distribution plots for two types of weather with $Z=0$. It can be seen that the smoke concentration near the exit is higher and spreads farther under the clear sky. The smoke shape oscillates and spreads fast, and the smoke spreads quickly to the ground and affects the surroundings. Moreover, in the corresponding concentration distribution diagram for cloudy days, with a certain wind speed, the atmospheric stability is neutral when the vertical diffusion is greater than the horizontal diffusion.

From the vector and streamline diagrams in different weather in Figure 8, it can be seen that the concentration of tear gas smoke inlet is the highest. The wind speed decreases, and the gradient of wind speed increases in other places due to the obstacle and other effects, while the wind speed increases and the gradient becomes smaller in places farther away from the obstacle and over the obstacle. For c and d, both weather on the windward side of the obstacle, as the height increases, the speed gradually increases, tilted upward, a climbing trend, but in overcast conditions, this trend is more prominent, while on the leeward side, there is a particular weak return flow. It can be seen that both are radiating from the entrance of the tear gas smoke to the exit under the influence of wind speed, while the total height of the smoke at a distance from the exit face is higher in cloudy days compared to the highest point of the smoke in clear days.

4. Conclusion

In this paper, the diffusion model of exploding tear gas smoke was established using fluent software, and the diffusion characteristics of tear gas smoke under different obstacles, different spaces, and different humidity were numerically simulated. After calculation and analysis, it is summarized as follows:

(1) The diffusion of tear gas smoke indoors and outdoors showed different diffusion behaviors, the difference being that the wind speed and obstacles play a more significant role in the diffusion of smoke in large spaces outdoors. The similarity is that both are point sources to the outside.

(2) By comparing the concentration distribution of tear gas smoke diffusion under different weather conditions, the same cross-section, vector diagram, and streamline diagram were observed from the same fixed smoke concentration observation point. It was found that the tendency of smoke diffusion to the outside was greater under sunny weather, while the height of smoke diffusion was higher under cloudy weather, and the closer the location to the ventilation window, the lower the concentration of smoke, both vertically and horizontally.

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