Numerical Study on the Influence of Ventilation on the Heat Flow of Cable Fire in Narrow-long Space

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Abstract: In order to study the characteristics of heat flow field after fire in a narrow-long space, a mathematical and physical model for fire calculation in a narrow-long space is established. The control equations are simplified and deformed. The numerical program is used to solve the model. The characteristics of smoke spread, temperature field distribution and the change of fire parameters in different positions with time are obtained. The influence of ventilation on the heat flow field of fire is discussed. By analyzing the characteristics of fire flow field, it can provide reference for fire detection design in narrow-long space.

1. Introduction
The equipment in the narrow-long space, such as the nacelle, is compact. During the normal operation of the equipment, the cable will release a lot of heat to the surrounding air, which is easy to cause a fire in the high temperature environment. The statistics show that the fire has become one of the main threats to the safety [1-2]. Therefore, scholars at home and abroad have carried out a lot of simulation and Experimental Research on indoor fire. Gouutk experiment has studied the phenomenon of full-scale cabin back fire and discussed the main control parameters of back fire [3]; Rocket has studied and evaluated the fire growth model and smoke spread model of U.S. Navy ships [4]. Gaowan Zou et al. Carried out numerical simulation research on the heat flow field characteristics of ship engine room fire, measured and obtained the critical heat release rate of flashover under different ventilation factors by using the principle of oxygen consumption [5]; Hua Dong et al. Carried out numerical research on the fire development process of airtight cabin [6], and Longhua Hu studied the thermal physical characteristics of tunnel fire smoke spread [7].

There are some unique characteristics of fire in the narrow-long cabin. If we can grasp the fire characteristics of the narrow-long space better, it will be conducive to the accurate automatic detection and alarm in the early stage of fire. In this paper, the fire scene of the ship's narrow-long cabin is reproduced by using the fluid simulation software through the computer modeling in the form of simulation. The characteristics of smoke spread, the distribution of temperature field in the cabin and the difference of the change of fire characteristic parameters in different positions with the change of time are obtained. The influence of ventilation on the fire heat flow field is discussed. By analyzing the characteristics of fire flow field, it can provide a reference for the design of fire detection in narrow-long space, and it is also of great significance for the study of fire laws in other places.
2. Mathematical model

2.1. Control equations
The fire heat flow field in a narrow-long space is mainly a low Mach number flow process driven by thermal buoyancy. For this kind of general control equations of multi-component ideal gas under the action of gravity, according to the characteristics of fire flow field and the needs of calculation and solution speed, the equations are treated. The specific process has been derived and discussed in detail in reference [8-9]. Through the deformation and simplification of the velocity divergence term $\nabla \cdot \mathbf{V}$ and momentum equation in the control equation group, the following equation group can be finally obtained:

Conservation of mass equation:
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho u_j \right) = 0$$

Conservation equation of momentum:
$$\frac{\partial}{\partial t} \left( \rho u_j \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j + \tau_{ij} \right) = \rho f_j - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \tau_{ji} \right)$$

Equation of state:
$$P = P(\rho, T)$$

It is very difficult to directly solve the partial differential equations of (1) - (4). In general, the finite volume method is used to discretize the control equations and the numerical solution is used to approximate the analytical solution. The deformation of the governing equation is as follows:
$$\frac{\partial \rho \phi}{\partial t} + \nabla \cdot (\rho \phi \mathbf{V}) = \nabla \cdot \left( \Gamma_s \nabla \phi \right) + S_{\phi}$$

2.2. Combustion model
It is considered that the combustion rate of fuel and oxygen is infinitely fast, and the combustion process is only related to the mixture fraction of the two, which can simplify the calculation amount and be applicable to the simulation of fire in a large space.
$$C_4H_8O_N + v_{CH}O_2 \rightarrow v_{CO_2}CO_2 + v_{H_2}H_2O + v_{CO}CO + v_{So}So + v_{N_2}N_2$$

2.3. Thermal radiation model
Considering the complexity of thermal radiation, it is very difficult to simulate completely, and the model is generally simplified reasonably. The radiation control equation is:
$$\mathbf{s} \cdot \nabla I(\mathbf{x}, \mathbf{s}) = \kappa (\mathbf{x}) \int_0^1 \left[ l_s(\mathbf{x}) - I(\mathbf{x}, \mathbf{s}) \right]$$

3. Simulation model

3.1. Geometric model
There are many devices and structures in the narrow-long space. The narrow-long space is simplified in the simulation calculation. The simplified longitudinal section is a semi trapezoid structure, the right side wall is heating equipment, the left side is a V-shaped space, the overall size of the upper deck (length*width) is 50m*2.0m, the overall size of the lower floor (length*width) is 50m*0.8m, and the height is 2.0m. Other equipment in the cabin are also simplified to accurately capture the fire information, the grid size of the fire source and its surrounding area is 0.02M, and the side length is adopted in other areas. The total grid number of the whole calculation space is about 4 million. The surface solid is assumed to be adiabatic boundary, and there is no heat loss.
In the calculation process, large eddy simulation (LES) technology based on Deardorff model is used to solve the turbulence model. The finite volume method (FVM) is used to calculate the radiation. The time differential discretization of the iterative variables is based on the dominant second-order prediction/correction mechanism, and the CFL condition is used to ensure the stability of the iteration.

3.2. Location and size of fire source
According to the actual situation of the equipment in the narrow-long space, combined with the causes of cable fire recorded in the relevant literature [8], and considering the influence of different fire source positions on the detection and alarm device, respectively simulate the heat flow field when the fire occurs in two typical positions, i.e. the fire source is located at the upper part of the edge and the lower part of the edge of the narrow-long space. The fire source is set at a distance of 4m from the end face.

The actual situation of fire source is very complex. Based on the reaction of combustion process as real as possible, the fire source is abstracted and simplified. Combined with the international standard ISO16733, the most commonly used disaster model. Four kinds of standard fires are defined by different fire growth factors. In the T2 fire characteristic development curve, the time when the fire source power of slow fire, medium fire, fast fire and super fast fire reaches 1MW is given, which are 75s, 150s, 300s and 600s respectively. Refer to Lee data in SFPE fire protection manual "electric cable traces", the HRR value of cable is 1071kw/m2. Plastic foam fire is a fast fire with a growth factor of 0.0469kW/s2 and a fire area of 0.18m2. The maximum 55s is 192.8kW, so the fire source long time TAU_Q=-64, HRR=1071kW/m2. The growth rate of heat release is shown in Figure 1.

3.3. Layout of measuring points
In order to analyze the rule of temperature change under various working conditions, the characteristic parameters are recorded during the calculation process, and temperature measuring points are arranged
on the plane of the central section of the fire source. The specific location of the measuring points is shown in Figure 2, the sampling period is 0.2s, and the frequency is 5Hz.

3.4 Calculation method
In this paper, the CFD numerical simulation method is used. According to the characteristics of fire flow field in narrow-long space, the calculation process is described as follows: 1) initial, setting the initial environment conditions including time step and sum of variables; 2) calculating the parameter prediction value at the next moment; 3) judging the convergence or not according to the speed prediction value and the speed value obtained in the second step; 4) judging the stability by combining CFL; 5) solving the parameter calibration Positive value; 6) compare with the speed divergence value obtained in step 5 to determine whether it converges or not; 7) return to step 2 for further calculation; 8) repeat the iteration to complete the calculation.

4. Calculation results and analysis
Assuming that the fire is caused by the high temperature of the cable in the narrow-long space, on the premise that the cable keeps heating, considering the 69℃ high temperature of the deck and the 80 ℃ temperature of the heating equipment to generate heat independently and couple, taking the cable (solid) spread fire as the fire source, simulate the heat flow field when the fire occurs at the typical position on the upper edge of the narrow-long space. The calculation time is 1000s, in which 800s is the time when the space environment reaches steady state, and 200s is the heat flow field formed in the early stage of fire. According to the simulation results, the temperature of each measuring point changes with the development of fire. Two working conditions with and without ventilation are simulated.

| Time | (a) No ventilation | (b) Ventilation |
|------|-------------------|----------------|
| t=30s| ![Image](image1.png) | ![Image](image2.png) |
| t=90s| ![Image](image3.png) | ![Image](image4.png) |

Figure 3. Smoke spread at different times

Figure 3 (a) the distribution of smoke spread at different times when the fire source is located at the upper edge shows that the smoke generated by the fire source at the edge moves upward at the fire source when t=30s, and starts to spread laterally around after hitting the upper wall, but because one end of the space is closed, the left end wall has a certain impact on the spread of fire smoke, which is reflected in the smoke in the fire. At the left end of the wall, the smoke spreads to the lower part. At 180s of the fire, the space at the lower edge of the left side is basically covered by the smoke of the fire, while the other end is not disturbed by the smoke (the length of the smoke is about 25m, and about 11m is not spread by the smoke). This is because the narrow-long space structure causes the resistance of the smoke in the horizontal direction to be greater than the downward buoyancy resistance, and the smoke is not enough to continue to move forward. Instead, move down. However, the fire smoke in the common space will spread to the lower part of the space only after it is completely dispersed at the top of the whole space.

Figure 3 (b) shows that when the fire occurs for t=30s, the smoke generated by the fire source at the edge moves upward at the fire source and starts to spread laterally around after hitting the wall, but
due to the ventilation effect, the smoke moves more to the lower layer than that without ventilation. At the same time, the dispersion of flue gas to the downstream of the ventilation field is intensified and the accumulation of flue gas near the vent is restrained. At \( t=90 \) s, it can be seen that the distance of smoke spreading to the downstream of ventilation field is longer under the action of ventilation. When \( t=180 \) s, the space is basically covered by fire smoke, rather than like smoke gathering at one end under the condition of no ventilation.

| Time    | (a) No ventilation | (b) Ventilation |
|---------|---------------------|-----------------|
| \( z=0.5 \) m | ![Temperature distribution](image1.png) | ![Temperature distribution](image2.png) |
| \( t=30 \) s       | 35 37 39 41 43 45 47 49 51 53 55 | 35 37 39 41 43 45 47 49 51 53 55 |
| \( t=60 \) s       | 35 37 39 41 43 45 47 49 51 53 55 | 35 37 39 41 43 45 47 49 51 53 55 |
| \( t=180 \) s      | 35 37 39 41 43 45 47 49 51 53 55 | 35 37 39 41 43 45 47 49 51 53 55 |

| Time    | (a) No ventilation | (b) Ventilation |
|---------|---------------------|-----------------|
| \( z=1.6 \) m | ![Temperature distribution](image1.png) | ![Temperature distribution](image2.png) |
| \( t=30 \) s       | 35 45 55 65 75 85 95 105 115 125 135 | 35 45 55 65 75 85 95 105 115 125 135 |
| \( t=60 \) s       | 35 45 55 65 75 85 95 105 115 125 135 | 35 45 55 65 75 85 95 105 115 125 135 |
| \( t=180 \) s      | 35 45 55 65 75 85 95 105 115 125 135 | 35 45 55 65 75 85 95 105 115 125 135 |

Figure 4. Temperature distribution at different times

From Figure 4 (a), When \( z=0.5 \) m, the average section temperature changes in the range of 35-55°C. When \( t=30 \) s, the temperature difference is not obvious. The overall temperature is about 47°C. When \( t=60 \) s, the temperature under the fire source increases obviously and gradually extends to both sides. Because the smoke gathers at the edge, the high temperature area expands in 180s when the fire occurs, and the high temperature smoke distribution is uneven, resulting in a large temperature distribution Differences. The average temperature of the section at \( z=1.6 \) m changes in the range of 35-135°C.

From Figure 4 (b), it can be seen that the average section temperature at \( z=1.6 \) m changes in the range of 35-135°C. At \( t=30 \) s, except for the high temperature above the fire source, the temperature difference at other positions is not obvious. At \( t=60 \) s, the temperature near the fire source is significantly higher. At \( t=120 \) s, the high temperature area of the section is further expanded. At \( t=180 \) s, the section temperature is generally higher, but due to the role of ventilation The high-temperature flue gas mainly moves to the downstream of the ventilation field, and there is less high-temperature flue gas near the air supply outlet and the temperature is lower.

From the temperature distribution of different sections, it can be seen that the temperature of the section near the top is higher as a whole, and the temperature of the section near the bottom is lower, which is due to the high temperature of the upper layer caused by the high temperature flue gas moving towards the top.
Figure 5. Temperature changes over time

Figure 5 (a) after the fire, the temperature of 10 temperature detectors t1-t10 changes with time. The results show that the temperature of T10 measurement point near the fire source starts to rise first, and the change trend of other measurement points is the same. In t7-t10, the temperature decreases with the increase of height, while in T1-T6, the temperature increases with the increase of height. The temperature of T4-T6 far away from the fire source and at the lower measuring point has a small change range, and the temperature of t7-t10 above the fire source is higher than that of T1-T6 far away from the fire source. After 40 s, the temperature curves of T1 and T7 at the upper measuring point are basically the same, and the temperature of T1 at the upper measuring point is lower than that of T7 after 160 s with the spread of flue gas.

Figure 5 (b) the temperature of each measuring point shows that the change trend of t1-t10 temperature with time is the same as that when there is no wind. Under the influence of ventilation, the temperature curve fluctuates greatly. The temperature of T4-T6, the lower measuring point far away from the fire source, changes less. The temperature of T7-T10 near the fire source is higher than that of T1-T6, indicating that the temperature of the measuring point closer to the fire source is higher.

In the actual project, there is a certain randomness in the occurrence of fire. What the detector is not directly above the fire source is a high probability event. The detection should be carried out as soon as possible and accurately. The temperature of T1-T6 measuring point directly above the non fire source changes with time at the initial stage of fire. The maximum temperature of T1-T6 measuring point under ventilation and no ventilation conditions is shown in the figure below. Because the maximum value of the measurement point is accidental, in order to better measure the temperature of each measurement point in the real fire process, RMS is used to express the temperature.

Figure 6. Maximum and RMS temperature

Figure 6(a) maximum temperature shows that the maximum temperature of T4 in ventilation is higher than that in no ventilation, which is due to the complex effect of flame turbulence in
combustion, it may occur that the maximum temperature in ventilation is higher than that in no ventilation. As shown in Figure 6(b), the RMS temperature of each measuring point is lower than that of no wind, which is caused by the heat being taken away during ventilation. The temperature of T6 and RMS of the measuring point with high upper temperature is close to 100 °C lower than the maximum.

5. Conclusion
Through the above calculation and analysis, we can get:

(1) For the narrow space, the smoke moves upward at the fire source, and starts to laterally around after floating to the upper wall surface. Different from the common space, the smoke is completely dispersed at the top, completely covered by the smoke at one end of 180s, and the other end is not disturbed by the smoke. This is because the structure of the narrow space leads to the continuous increase of the resistance of the smoke in the horizontal direction, until it is greater than the resistance down. Under the action of ventilation, the smoke can spread to the whole space in about 150s.

(2) Under the action of ventilation, the flame turbulence is more obvious and the temperature fluctuation range is larger. At the same time, because of the heat taken away by ventilation, the temperature of ventilation is slightly lower than that of no ventilation. Especially for the high temperature measuring points, the temperature drop is larger.

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