Temperature Field Simulation of Launcher and Missile under Fire Condition

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Abstract: In order to figure out the temperature field distribution of the launcher and the missile under fire conditions, the geometric model of the launcher and the missile was established. The temperature field of a typical pool fire flame was simulated, and the temperature field distribution of the launcher and internal missile under the typical pool fire flame was calculated. The results show that the maximum temperature of the outer surface of the launcher after firing 3600s is 1238K, the highest temperature of the missile surface can reach 690K, the maximum temperature of the missile center is 333K. The heat transfer by radiation plays a major role in the whole heat transfer process, which accounts for 88.35%.

1. Introduction
Accidental fires such as fires of flammable materials and fires of electronic equipment may occur during the working situation of the launcher. The safety of the launcher and missile might be affected in the high temperature environment. In order to figure out the temperature field distribution of the launcher and missile under high temperature conditions, we used method of finite element simulation to replace the traditional fire test, so that we could save the experiment cost and reduce the experimental risk. At present, most of the heat conduction calculations for air-containing interlayers are based on parameter correction, which can equal the heat transfer of the air portion [1]. This approach is often directed to specific regular air fluids, but for complex air interlayers, this equivalent accuracy might be reduced. In this paper, ANSYS Fluent software was used, the calculation method of conjugate heat transfer was adopted. Convection, conduction and radiation were all considered, so more accurate results were obtained [2]. And the heat flux ratio of three kind of heat transfer methods were calculated respectively.

2. Heat transfer theory
In the high temperature flame environment, there are three heat exchange forms between the flame, the launcher and the missile, namely heat conduction, heat convection and heat radiation. In this paper, the heat transfer at the connection between the inner and outer can of the launcher, between the thermal insulation layer and the outer wall of the inner can, between the outer wall of the inner can and the adapter, and between the adapter and the outer wall surface of the missile are heat conduction. The three-dimensional unsteady heat conduction differential equation is:
\[
\frac{\partial t}{\partial \tau} = -\frac{\lambda}{\rho c} \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) + \frac{\Phi}{\rho c} \tag{1}
\]

Where \( \rho \) is the density, \( c \) is the specific heat, \( \tau \) is the time, \( \lambda \) is the conductivity coefficient, \( t \) is the temperature, and \( \Phi \) is the heat generated by the internal heat source per unit volume per unit time [3].

There is convective heat transfer between the flame flow field and the outer wall of the launcher, and between the missile and the surrounding air. In this paper, thermal convection mainly exists in the heat exchange between air and wall. The basic formula is Newton's cooling formula:

\[
q = h(t_w - t_f) \tag{2}
\]

Where \( t_w \) is the wall temperature, \( t_f \) is the fluid temperature, and \( h \) is the convective heat transfer coefficient.

Radiation heat exchange exists between the flame flow field and the outer wall surface of the launcher and between the various parts inside the launcher. When an object with a temperature of \( T_1 \) is contained by another object with a temperature of \( T_2 \), the formula for radiative heat transfer between the two objects is as follow:

\[
\Phi = \varepsilon A \sigma (T_1^4 - T_2^4) \tag{3}
\]

Where \( \Phi \) is the heat flux, \( \varepsilon \) is the radiation rate, \( A \) is the radiation surface area, \( \sigma \) is the Boltzmann constant, and \( T \) is the radiator temperature.

### 3. Flame numerical model establishment

There are many forms of fire scenes, the most typical of which are pool fire flames and jet flames. A pool fire flame is generally a type of flame that is formed by a flammable liquid leaking around an object and igniting. The spray flame is usually a flame caused by a leaking medium having a certain pressure [4].

The pool fire flame has the highest probability of occurrence during the use of the launching device. Many scholars at home and abroad have studied the numerical model of the pool fire flame. The heating of the launcher by the pool fire flame is mainly caused by the thermal radiation and convection of the high-temperature flame fluid, so the flame temperature plays an important role in the simulation. For carbon-oxygen fuels, Sandia National Laboratories uses a constant value of 1073K or 1273K to describe the temperature rise model of the flame [5]. In this paper, the flame temperature is chosen to be a constant temperature of 1273K.

The radiation rate of the outer wall of the container is determined by its own material, since the outer wall of the container is burnt by the fuel in the fire environment, the emissivity is 0.98. Due to the complexity of the flame flow field motion, there is no accurate conductivity coefficient of it. In this paper, the value of 56W·m⁻²·K⁻¹ measured by the Sandia National Laboratory Fire Experiment is used as the convective heat transfer coefficient between the launcher and the flame flow field [6].

### 4. Model establishment and pre-processing

#### 4.1 Geometry model establishment

The launcher is the main part of the missile launching device, which can realize important functions such as missile storage and auxiliary launching, and protect the missile [7]. The launcher has a complex structure and a large number of components, so the launcher is simplified during modeling. When simplifying, the part which was of less influence on temperature was omitted, and the part that had a dominant influence on temperature was retained.
The launcher model was divided into four parts, namely the outer can, the inner can, the thermal insulation layer, and the adapter between the cans. The outer can was composed of a cylindrical can shell and a reinforcing ring, and the inner can was suspended on the outer can. There was a certain air gap between the outer can and the inner can, and a thermal insulation layer was attached to the outer can. Between the inside of the inner can and the outer side of the missile, there were four adapters for missile fixation, horizontal damping and temperature isolation. The launcher and missile geometry model is shown in Figure 1, and a partial enlarged view is shown in Figure 2.

4.2 Establishment of finite element model

This paper uses ANSYS Fluent for temperature field simulation calculations. Since the entire heat transfer process involves three different heat transfer modes, and involves fluid-solid coupling between the air fluid and the launcher and the missile solid, the conjugate heat transfer calculation is required. Fluent needs to set the common plane of the conjugate plane before performing the conjugate calculation. Boolean operations were used in SolidWorks to deduct the launcher and the missile to get the air layer. The air layer was assembled with the launcher and the missile.

The overall geometry model was imported into ANSYS Geometry for common node setup, and the air was set as the same part as the adjacent object. The mesh module was added to ANSYS Workbench, and the geometric data connection was transmitted to the mesh for meshing. The mesh size was set to 10-150mm according to the size of each part of the model. In the end, a total of 1.65 million grids were obtained, and the average grid quality was 0.8. The grid quality met the calculation requirements. The finite element model is shown in the figure.
4.3 Add material properties

The inner can of the launcher was made of steel, so the material was set as structural steel. The insulation layer was a special material with low thermal conductivity and low density. The inter-can adapter material was polyurethane. The missile was set to the same material. Material properties are shown in the table 1. The emissivity of the outer wall surface of the missile was set to 0.75, the emissivity of the inner wall of the outer can and the inner wall of the inner can of the launcher were set to 0.8, the emissivity of the outer surface of the thermal insulation layer was set to 0.95, and the emissivity of the outer wall of the outer can of the launcher was set to 0.98.

| Geometry      | Density/ (kg·m⁻³) | Conductivity coefficient/ (W·m⁻²·K⁻¹) | Specific heat / KJ·kg⁻¹·K⁻¹ |
|---------------|-------------------|----------------------------------------|----------------------------|
| Launcher      | 8030              | 16.27                                  | 502.48                     |
| Insulation layer | 220               | 0.035                                  | 754                        |
| Adapter       | 1100              | 0.024                                  | 1200                       |
| Missile       | 1900              | 0.3                                    | 1464.4                     |

4.4 Fluent calculation condition setting

The solver was set to a pressure-based solver, the gravity was set to -9.81 m/s² in the Y direction and the energy equation was turned on. The viscous model was set to the standard k-ε standard turbulence model and the radiation model was set to the standard DO model [8]. Due to the large temperature gradient calculated in this calculation, the change of air fluid properties with temperature cannot be ignored. By referring to the experimental data and fitting the data, the density, thermal conductivity, specific heat, and viscosity coefficient of the air fluid were obtained as a function of temperature. The curve is as shown in the figure 4. The polynomial option was selected when setting the air fluid properties, and the coefficients of the polynomial between each physical quantity and temperature were entered. The flame condition was added by setting external conditions of the outer wall surface of the launcher. When setting, the thermal boundary of the outer wall of the launcher was set to mix. The external convection coefficient was set to 56 W·m⁻²·K⁻¹, the external fluid temperature was set to 1273K, and the external emissivity was set to 0.98. During initialization, the temperature of all objects was set to 297.15K at normal temperature, the calculation time was set to 3600s, the time step was 1s, and the number of iterations was set to 20.
5. Simulation and analysis

After the setting was completed, the calculation was started. The convergence of the calculation was judged by observing the residual values of the equations in the calculation process. After the calculation reached stability, the residual value was less than $1e^{-3}$, so the calculation converged. 0s, 1200s, 2400s, and 3600s are selected, and the temperature nephogram of the outer surface of the launcher is shown in the figure 5, and the temperature nephogram of the center section is shown in the figure 6, the temperature nephogram of the outer surface of the missile is shown in the figure 7. (From left to right corresponds to 0s, 1200s, 2400s, 3600s) It can be see from the figures that as the fire time elapses, the temperature gradually diffuses from the outside to the inside, and the temperature distribution of the gas in the gap gradually becomes uniform.
Figure 7. Temperature nephogram of the outer surface of the missile

Temperature-time Curves of certain points on the outer surface of Launcher and Missile are shown in figure 8. Taking the middle of the outer surface of the launcher as an example, the temperature rise rate is the highest during the period of 0~480 s, and the average rate is 1.92 K/s. In the 480 s~960 s, the temperature rise rate decreases by an average of 0.44 K/s. Between 960s and 3600s, the temperature rise rate is slow, with an average of 0.027K/s. The maximum temperature of the launcher is 1238.3K, and the highest temperatures in the middle, top and tail of the launcher are 1204.3K, 1149.9K and 1111.9K respectively.

The top and bottom of the missile are directly exposed to the heat radiation from the launcher, and the temperature rises significantly. Taking the top as an example, the average temperature increase rate is 0.05K/s in 0~480s, and the average temperature rise rate is 0.11 K/s in 480s~3600s. The highest temperature of the top of the missile can reach 670K, and the highest temperature at the bottom can reach 690K. The side temperature of the missile is less affected by the protection temperature of the air layer and the heat insulation layer, and the maximum temperature is 414.9K. The temperature of the missile center is the lowest, and the maximum temperature is 333.2K.

Figure 8. Characteristic point temperature time curve

The air flow between the inner and outer cans of the launcher and the air flow between the inner can and the missile are as shown in figure 9. The top, middle and bottom inner air respectively refer to the air interlayer between the inner can of the launcher and the top, side and bottom of the missile, and the outer air refers to the air interlayer between the inner and outer cans of the launcher. Since the air interlayer between the inner and outer cans is relatively large, the flow rate caused by heat changes greatly. The air separation between the inner can and the missile is relatively small, so the flow rate caused by buoyancy is small. The Flux report tool is used to calculate the heat transfer amount of the outer surface of the missile. The total heat flux of the missile is 266501W, and the heat flux of radiant heat transfer is 235476W. Therefore, the radiation heat transfer can be 88.35% of the total heat transfer.
6. Conclusion
Through establishing geometric models, finite element models and simulating, we can find out that, under the burning condition of typical pool fire flame for 3600s, the maximum temperature of the outer surface of the launcher can reach 1238.3K, and the highest temperature of the outer surface of the missile is located at the bottom of the missile, and the highest temperature can reach 690K. The high-temperature area of the missile is mainly distributed at the top and the bottom of the outer surface of the missile. The internal temperature of the missile changes little, and the missile center temperature is up to 333.2K. Radiation heat transfer plays a major role in the process of heat transferring from the outside to the inside, which accounts for 88.35%.

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