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Numerical simulation of forced ventilation fire suppression for wing leading edge pool fires

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Abstract. In order to meet the requirements of the flammable liquid fire prevention regulations under AC25-863, which stipulates that in the event of ignition, the ignition and its harm of leaked flammable liquids should be minimized, this study investigates the impact on the aircraft structure and the suppression process of wing leading edge pool fires of flammable liquid leakage under forced ventilation fire suppression. Geometric modeling of the wing leading edge in the flammable liquid leakage area is performed, and the burning conditions of the flame under different conditions are simulated. The heat release rate per unit area of the pool fire surface is set to 396.67 kW/m², with ventilation speeds ranging from 0 to 3.1 m/s. Through the analysis of simulation charts and data, it is observed that as the forced ventilation rate increases, the pool fire gradually tends towards a trend of suppression.

Keywords: Wing Leading Edge, Pool Fire, Fr Number, Fire Suppression

1. Introduction

With the continuous improvement of China's scientific, technological, and economic levels, the aircraft manufacturing industry and aviation sector have experienced rapid development. The volume of air transportation is constantly increasing, and people's expectations for aircraft safety are also on the rise. Fire is one of the factors affecting flight safety. On August 20, 2007, a Boeing 737-809 (WL) flight of China Airlines, after landing at Naha Airport in Okinawa, Japan, and heading towards the parking apron, experienced a fuel leakage and subsequent fire in the right main wing fuel tank, resulting in a fierce explosion and charring fracture of the fuselage. During the operation of an aircraft, fuel may leak due to pipeline rupture or operational errors, leading to the leakage of flammable liquids. The leaked aviation kerosene can drip to form a flammable liquid surface. When an electrical arc occurs in the wing area, igniting the liquid, the leaked kerosene can cause wing fires, posing a threat to flight safety. This study analyzes the wing structure and pool fire situations caused by flammable liquid leakage based on the structure of a typical aircraft model. The obtained results can provide support for fire prevention in the wing area.

2. Fire Suppression Theory

The phenomenon of fire suppression is a complex interplay of various mechanisms, including chemistry, physics, fluid dynamics, and heat and mass transfer. At the current stage, there are still many difficulties and blind spots that have not been thoroughly researched, especially the extinguishing behavior of flames under the influence of forced ventilation flow fields.

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In the 1930s, the renowned German chemist Gerhard Damköhler introduced the concept of the Damköhler number (Da). The definition of the Damköhler number, as shown in equation (2-1), represents the ratio of the residence time scale of fuel in the combustion zone to the reaction time scale of fuel combustion during the combustion process. Essentially, it is a dimensionless parameter representing the ratio of two-time units [1]. The Damköhler number is widely applied in the analysis of combustion and fire suppression processes. Depending on the characterization of the combustion form, the definition of the time scale may vary.

$$D_a = \frac{\tau_f}{\tau_{ch}} \tag{2-1}$$

During the combustion process of pool fires, the flame surface experiences velocity gradients due to the effect of thermal buoyancy, leading to a high stretching rate of the flame surface. In this scenario, the forced ventilation airflow from the surroundings further increases the stretching rate of the flame surface. The stretching of the flame surface reduces the extinguishing limit of combustion, thereby causing the phenomenon of fire suppression.

Under the influence of forced ventilation airflow, the forced airflow mainly forms a velocity difference around the flame, causing the normal stress on the flame surface to gradually exceed the tangential stress, resulting in the stretching of the flame surface. The Froude number (Fr), defined by equation (2-1), is used to represent the ratio of inertial force to gravitational force [2]. Here, v is the forced ventilation airflow velocity, v2 represents the normal stress on the flame surface due to forced ventilation, g represents the gravitational acceleration at ambient height, D represents the characteristic radius of flame combustion, and gD represents the magnitude of tangential stress on the flame surface due to thermal buoyancy. As the Froude number increases, the normal stress gradually exceeds the tangential stress, leading to a continuous reduction in the residence time scale τ_f of fuel in the reaction zone, ultimately reaching the critical extinguishing Damköhler value for fire suppression.

$$Fr = \frac{v^2}{gD}$$

3. Numerical Modeling and Verification

3.1. Geometric Modeling

Due to the diverse structural designs of fuel tanks in different aircraft models, this study focuses on the simulation modeling and research of a specific aircraft type, which represents a growing proportion in the civil aviation industry of China. By consulting the manual of a certain type of transport aircraft, the leaked flammable liquid area is mainly divided into three regions: the wing leading edge, the wing trailing edge, and the bulge region. This paper primarily focuses on the study of the relatively small-scale wing leading edge. According to the manual, the structure of the wing leading edge area is illustrated in Figures 3-1 and 3-2. If a pool fire ignites the fuel system in the wing area, it will lead to severe consequences. After simplifying the structure, a single baffle geometric model is established, as shown in Figure 3-3.

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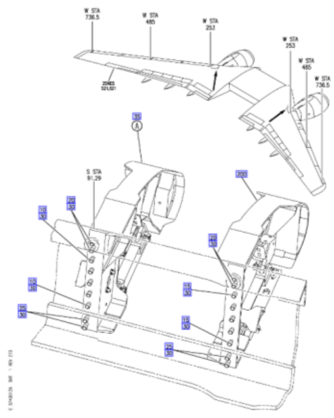

Figure 3-1. Structure of the Wing Leading Edge Area

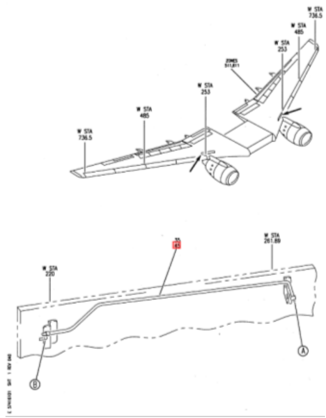

Figure 3-2. Wing Leading Edge Fuel System

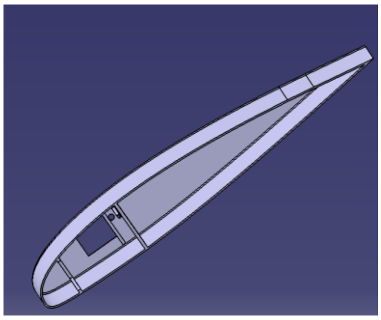

Figure 3-3. Geometric Modeling

3.2. Simulation Settings

The fire dynamics simulation software (FDS) is employed to simulate and model pool fires in the leaked flammable liquid area of an aircraft. Numerical solutions for the combustion heat-driven low-speed N-S equations are obtained by constructing and solving the governing equations in fluid dynamics, including the continuity equation, momentum conservation equation, energy conservation equation, and component equation [3]. The governing equations are as follows:

Continuity Equation:

$$\frac{\delta \rho}{\delta t} + \nabla \rho \vec{u} = 0$$

$$\mathrm{KW} \bullet m^{-2}$$

Momentum Conservation Equation:

$$\rho \ \left(\frac{\delta \vec{u}}{\delta t} + \frac{1}{2} \nabla |\vec{u}| 2 - \vec{u} \times \omega\right) + \nabla p - \rho g = \vec{f} + \nabla \cdot \tau$$

Energy Conservation Equation:

$$\frac{\delta}{\delta t}(\rho h) + \nabla \cdot (\rho h \vec{u}) = \frac{\delta p}{\delta t} + \vec{u} \cdot \nabla p - \nabla q_r + \nabla \cdot (k \nabla T) + \sum_i \nabla (h_i \rho D_i \nabla Y_i)$$

Component Equation:

$$\frac{\delta}{\delta t}(\rho Y_i) + \nabla \cdot (\rho Y_i \vec{u}) = \nabla (\rho D_i \nabla Y_i) + m'''_i$$

Where ρ is density, t is time, $\vec{u}$ is the velocity vector; $\vec{f}$ is the external force vector acting on the fluid, p is pressure, τ is the viscous stress tensor, ω is vorticity, g is gravitational acceleration; h is specific enthalpy, qr is heat radiation flux, T is temperature, K is thermal conductivity; i represents the i-th component, Yi is the concentration of the i-th component, Di is the diffusion coefficient of the i-th component, m'''_i is the mass production rate of the i-th component.

3.2.1. Selection of Reactants. Aviation kerosene is composed of various alkanes, alkenes, and catalytic components. The combustion process is complex, and for simplification, a single component is selected. Through parameter measurements of aviation kerosene, its molecular formula is determined to be C10.62H21.61[4], Normal decane (C10H22) with a similar molecular formula is chosen as the reactant.

3.2.2. Ignition Source Settings. Oil pool fires are primarily chosen for analysis. Due to the slow formation of the oil pool after fuel leakage from ruptured pipes, parameters provided by the industry are used, with the selected characteristic radius of the oil pool set at 0.2m.

Once aviation kerosene forms an oil pool due to pipe rupture and is ignited by exposed cables, a stable burning phase is selected for analysis. The unit area heat release rate at this phase is set to 396.67 kW/m² [5].

3.2.3. Temperature Detection Settings. Temperature measurement surfaces are arranged in a cross shape directly above the center of the ignition source. Temperature measurement points are set at Z=0.1, 0.2 and 0.3m.

3.2.4. Boundary Conditions. The simulation region is hexahedral, with the height set in the range of 0m to 11000m. During aircraft operation, as the wing leading edge is a non-enclosed area, the critical wind speeds are set at 0m/s and 3.1m/s.

3.3. Grid Independence Analysis and Model Verification

During numerical simulation and modeling, the choice of grid size can significantly impact the accuracy of results. The FDS technical manual provides a formula (Equation 5) for calculating the grid size [5].

$$R^* = \left(\frac{Q}{\rho_a C_p T_a \sqrt{g}}\right)^{\frac{2}{5}}$$

Where R^* is the characteristic diameter of the fire, measured in meters; Q is the heat release rate of the fire, measured in KW; ρ_a is the air density, measured in kg/m³; C_p is the specific heat capacity of air, measured in KJ/(kg·K); T_a is the air temperature, measured in K; g is the gravitational acceleration, measured in m/s². As this study involves simulation at different heights, the parameters are calculated using the average values at different heights. The calculated R^* is approximately 0.198m. Various grid quantities are chosen to simulate the temperature value at a height of 0.3m for grid independence analysis, as shown in Figure 3-4.

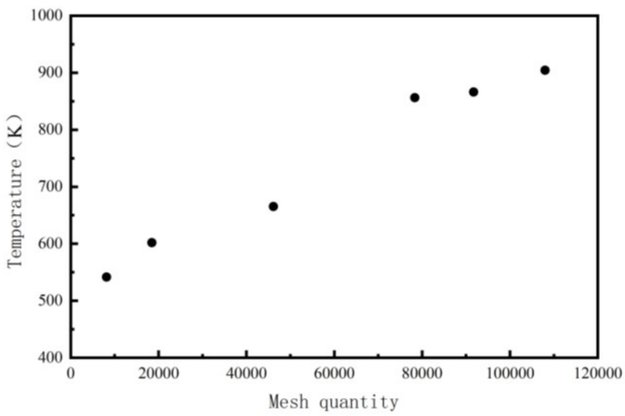

Figure 3-4. Grid independence analysis

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Comparison with actual experimental data under similar conditions [6] is presented in the table below:

Grid Quantity	Experimental Value (K)	Simulated Value (K)
8160	892.45	541.45
18480		601.75
46170		665.35
78336		856.25
91732		866.25
108000		904.25

It can be observed that with an increasing number of grids, the simulated temperature values stabilize. The simulated data closely matches the experimental data when the grid quantity reaches 108000. Therefore, a grid quantity of 108000 is chosen for the simulation.

4. Results Analysis

4.1. Sensitivity Analysis of Fr Number Influencing Factors

Since the Froude number (Fr) is composed of multiple related parameters, when analyzing its impact on fire suppression, it is necessary to separately analyze the factors and sensitivity of each parameter. The method of controlling variables is employed to systematically analyze the individual parameters' influence on fire suppression by keeping other relevant parameters constant. The trends of the maximum temperature in the study area with the variation of individual parameters are shown in Figures 4-1 to 4-3.

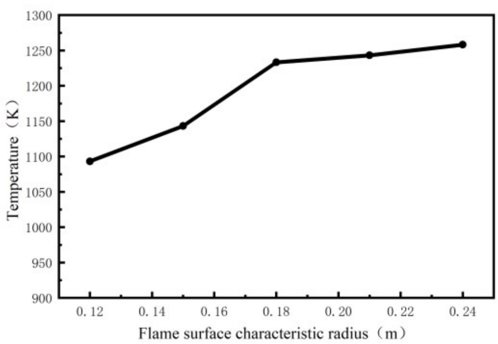

Figure 4-1. Variation with Flame Surface Characteristic Radius

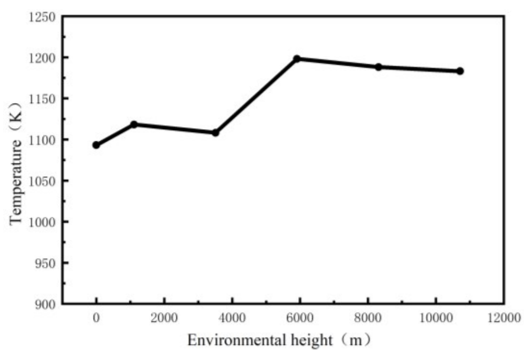

Figure 4-2. Variation with Environmental Height

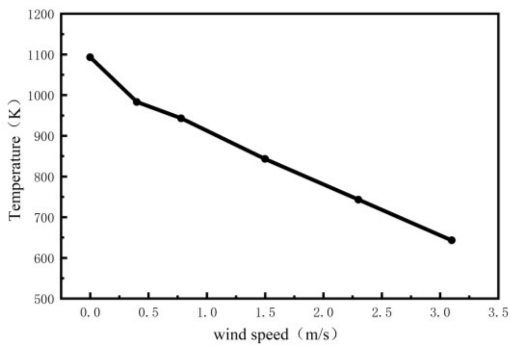

Figure 4-3. Variation with Wind Speed

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Through the analysis of the results, it is observed that during the fire suppression process with varying Fr numbers, as the flame surface characteristic radius and gravitational acceleration increase, the combustion of the flame intensifies first and then tends to stabilize under the influence of thermal buoyancy. The phenomenon of fire suppression is mainly caused by the normal stress brought about by the ventilation speed (v), leading to the lowering of the flame surface temperature and the emergence of a trend towards fire suppression.

Therefore, in the process of reducing the hazards of fire in the leaked flammable liquid area, the main approach is to increase the ventilation speed, reduce the flame surface characteristic radius, and lower the environmental height. This will result in the appearance of a trend towards fire suppression. Among these methods, increasing the ventilation speed has the most significant and favorable effect. Hence, this paper proposes the use of forced ventilation for fire suppression to meet regulatory requirements and thereby achieve the goal of reducing hazards.

4.2. Forced Ventilation Fire Suppression Process Analysis

Using numerical simulation, the variation of the combustible liquid pool fire with the Froude number (Fr) under the real operating conditions of an aircraft is simulated. The primary focus is on the maximum temperature of the flame and the geometric stretching dimensions of the flame. The occurrence of the fire suppression process is judged by observing whether the maximum temperature decreases and if the flame surface stretches and ruptures.

4.2.1. Trend of Flame Geometric Characteristics with Fr Number Variation. During combustion of the pool fire, changes in the geometric dimensions of the flame represent the thermal radiation hazard of the flame to the external environment. The burning effect of the flame on various components of the wing poses a hazard to flight safety. To observe the changes in the hazard range of flame geometric characteristics with Fr number variation, the trends of flame stretching length and flame height under different boundary conditions at different heights with Fr number variation are shown in Figures 4-4 and 4-5.

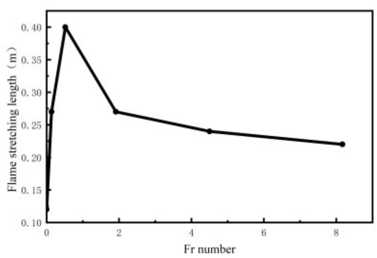

Figure 4-4(a). Flame Stretching Length at 0 km

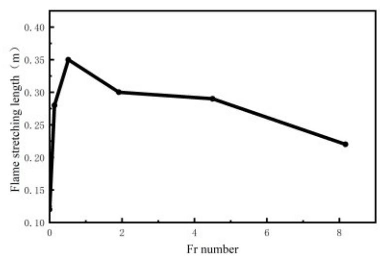

Figure 4-4(b). Flame Stretching Length at 1.11 km

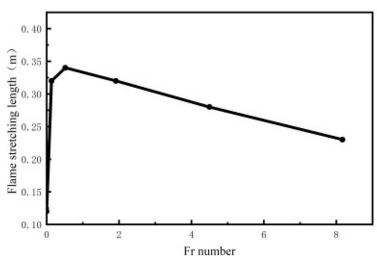

Figure 4-4(c). Flame Stretching Length at 3.51 km

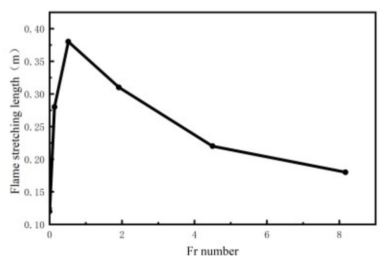

Figure 4-4(d). Flame Stretching Length at 5.91 km

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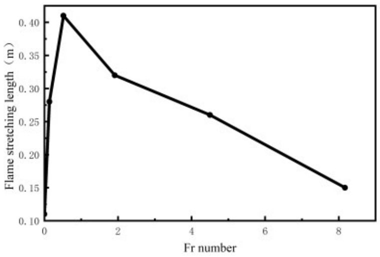

Figure 4-4(e). Flame Stretching Length at 8.31 km

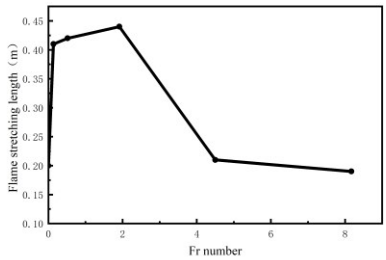

Figure 4-4(d). Flame Stretching Length at 10.71 km

From Figure 4-4, it can be observed that the trend of flame stretching length remains consistent at different heights. With the increase of Fr number, the flame stretching length initially increases and then decreases, tending towards extinction. At low Fr numbers, the flame stretching length increases because the higher inflow velocity brings a large amount of oxygen, enhancing the combustion effect of the flame, making the burning more intense. As Fr numbers increase, the inflow becomes too large, resulting in a short residence time for fuel in the reaction zone, inhibiting the combustion effect and leading to a trend towards fire suppression.

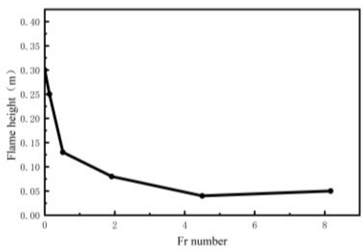

Figure 4-5 (a). Flame Height at 0 km

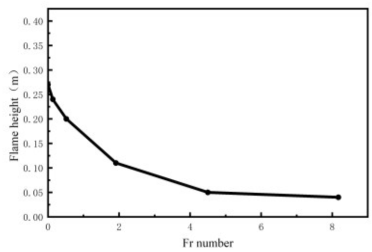

Figure 4-5(b). Flame Height at 1.11 km

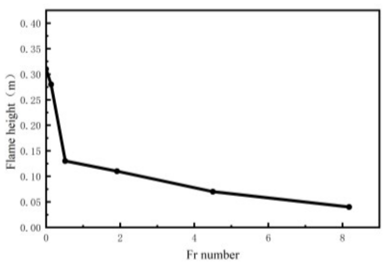

Figure 4-5(c). Flame Height at 3.51 km

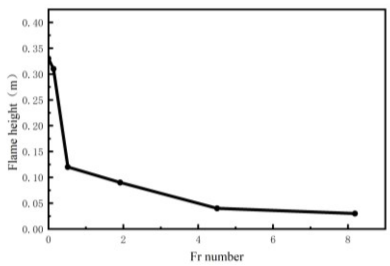

Figure 4-5(d). Flame Height at 5.91km

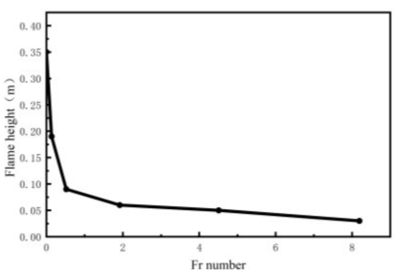

Figure 4-5(d). Flame Height at 8.31 km

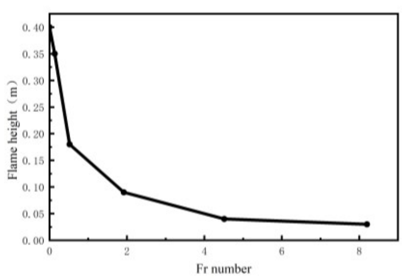

Figure 4-5(e). Flame Height at 10.71 km

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From Figure 4-5, it can be observed that the flame height decreases with the increase of Fr number and tends to stabilize. As Fr numbers increase, the flame height becomes very low, resulting in a small flame hazard range. Apart from the potential damage caused by the flame burning in the oil pool area, other components and lines within the vertical height are not within the hazard range, effectively reducing the hazard of combustible liquid burning.

4.2.2. Flame Extinguishment Trend with Fr Number Variation. Through theoretical analysis, it is found that as the ratio of inertial force to gravity force continuously increases, the residence time of fuel in the reaction zone decreases, leading to a decrease in the Damköhler number (Da) and the occurrence of blowout. The flame extinguishment process is characterized by observing the flame tilt angle and the region's maximum temperature at different heights with Fr number variation, as shown in Figures 4-6 and 4-7.

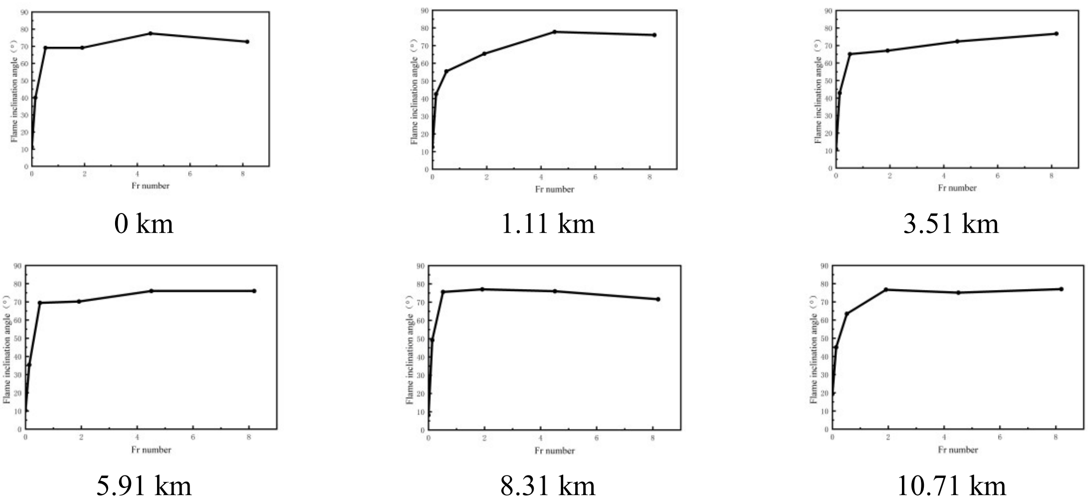


Figure 4-6. Flame Tilt Angle at Different Heights with Fr Number Variation

From Figure 4-6, it can be concluded that the flame tilt angle at different altitudes follows a similar trend with the increase of Fr number, showing a sharp increase followed by stabilization. At high Fr numbers, due to the excessively high flow velocity in the flow field, the flame stretching effect becomes significant. It is prone to flame surface stretching and rupture. Under high flow velocity, small holes may appear on the flame surface, leading to flame surface rupture and the entry of cold air, causing the flame temperature to drop and resulting in flame extinguishment [7]. The cloud chart reveals that flame surface rupture occurs at a high tilt angle. Further analysis is conducted by observing the changes in the maximum temperature in the flame region to observe the flame extinguishment phenomenon.

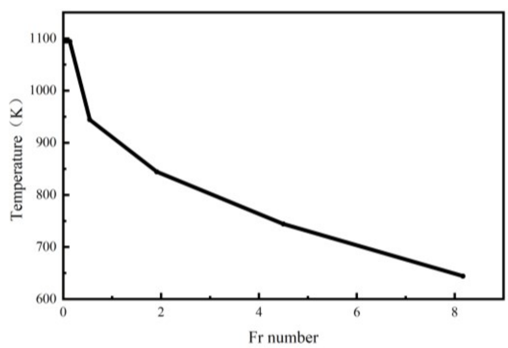
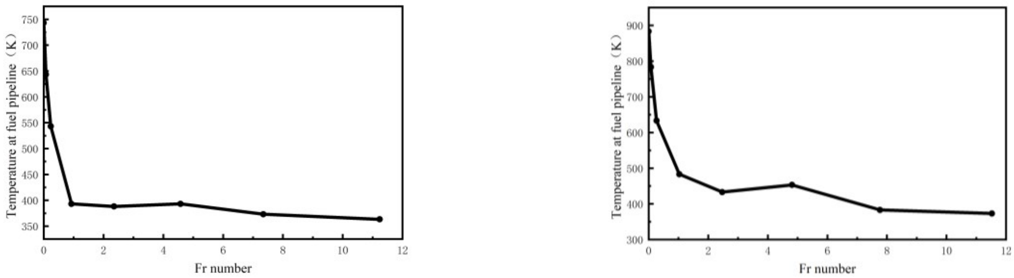


Figure 4-7. Trend of Maximum Temperature in the Region with Fr Number Variation

From Figure 4-7, it can be observed that as Fr number increases, the flame temperature continuously decreases. As described in theoretical analysis, flame surface rupture leads to a decrease in temperature, resulting in flame extinguishment. The results indicate that forced ventilation fire suppression can cause the combustion of the combustible liquid pool fire to extinguish, minimizing potential hazards and ensuring safety.

4.3. Safety Analysis of Fuel Pipeline at Wing Leading Edge

As there is a fuel pipeline at the wing leading edge, it is essential to focus on the temperature variation at the fuel pipeline location while analyzing its hazards. Failure to monitor the temperature changes at the fuel pipeline location may result in significant safety incidents, such as combustion or explosion, especially if the fuel pipeline experiences high temperatures. The temperature variation at the fuel pipeline location is observed at ground level and cruising altitude with respect to the Froude number (Fr), as shown in Figure 4-8. These two scenarios represent the operational conditions during most of the aircraft's flight time and are therefore considered representative.



(a) Ground Level (b) Cruising Altitude

Figure 4-8. Trend of Temperature Variation at Fuel Pipeline Location with Fr Number

From the figure, it can be observed that at ground level, the temperature at the fuel pipeline location sharply decreases with the increase of Fr number and then stabilizes, remaining within the safe temperature range. At cruising altitude, the temperature at the fuel pipeline location shows a slower decreasing trend with fluctuations as Fr number increases. When Fr number exceeds 8, the temperature decreases to a safe range.

5. Conclusion

In the consideration of the flame extinction process with varying Froude numbers (Fr), the primary focus has been on the influence of incoming airflow speed on flame extinction. As the airflow speed continuously increases, leading to an increase in Fr number, the maximum temperature within the region consistently decreases, indicating a trend toward flame extinction.

The continuous increase in Fr number results in the continual stretching of the flame surface, leading to a reduction in flame height and an initial increase followed by a decrease in flame stretching length. During this process, the residence time of fuel in the reaction zone decreases, ultimately resulting in flame extinction. As the flame surface is stretched, the flame tilt angle continuously increases, and flame stretching and rupture occur. At this point, the inflow of cold air into the ruptured area of the flame further reduces the flame temperature, leading to flame extinction.

Analyzing the geometric shape of the flame allows for the definition of the approximate flame hazard zone. Simulation results indicate that forced ventilation during flame extinction can reduce the flame hazard zone and lower the temperature at the critical area (fuel pipeline). This further confirms that, in the event of igniting combustible liquid leakage, forced ventilation for flame extinction can minimize the ignition and associated hazards of the leaked combustible liquid.

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