Effects of Plume Heat Feedback in Heptane Pool Fires: Insight from Theory and Simulation

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Abstract. The heat feedback of flame plumes is a main form of energy transfer and a significant contributor to fire growth and spread. The paper introduces the case of heptane pool fires in open spaces. A corresponding formula is proposed along with the simplified model of plume heat feedback based on the analysis of heat balance equations of pool fires. A hybrid CFD model of heptane pool fire simulation methodology is used to study the fire characteristic parameters and plume heat feedback effects in the combustion process of pool fires. The results suggest that plume heat radiation and convection effects cause about 53% and 37% of the total mass loss rate in the combustion process of 1m^2 heptane pool fire and thus that they play an important role on the occurrence and development of liquid fires.

Introduction

Fire plume heat radiation and transfer characteristics are closely related to fire occurrence and spread. It is not only the foundation of fire spread but the direct reason for casualty in fire[1,2]. Thus, the research on fire plume heat radiation and transfer characteristics contributes to ship fire fighting and its structural design for fire control[3,4,5]. As the typical combustion form, pool fires can reflect fire occurrence and spread rules and has widely drawn attention of domestic and foreign scholars. Based on the theoretical and simulation analysis on the interaction of heat convection，heat radiation and heat conduction between the pool fire plume and fuels, the paper investigates the impact factors of pool fire heat effects and the effects of heat feedback and transfer on fire occurrence, its spread and personnel evacuation.

Taking heptane pool fire as an research object, the paper carries out the theoretical analysis and simulation verification on the mechanism of thermal radiation and heat transfer. To illustrate it as follows: (1) It analyzes the thermal effect of heptane combustion and establishes a set of pool fire heat balance equations. (2) It studies the plume heat radiation and convection effects based on the cylinder model of pool fire plume. It also illustrates the interrelationship between pool fire burning and plume thermal feedback. (3)It makes a simulation on heat feedback effects in the heptane combustion process by constructing the CFD model of pool fires in the open space.

Theory analysis on pool fire heat effects

Pool Fire Heat Balance Equations. As shown in Figure 1, based on the energy conservation equation[6,7], the heat balance equations of heptane pool fire are as follows:

$$\dot{Q}_f = \dot{Q}_{f,abs} \tag{1}$$

$$\dot{Q}_f = \dot{Q}_{f-cond} + \dot{Q}_{f-rad} + \dot{Q}_{f-conv} + \dot{Q}_{s-cond} + \dot{Q}_{s-rad} + \dot{Q}_{s-conv} \tag{2}$$

$$\dot{Q}_{f,abs} = \dot{Q}_{heat} + \dot{Q}_{evap} + \dot{Q}_{re-rad} \tag{3}$$

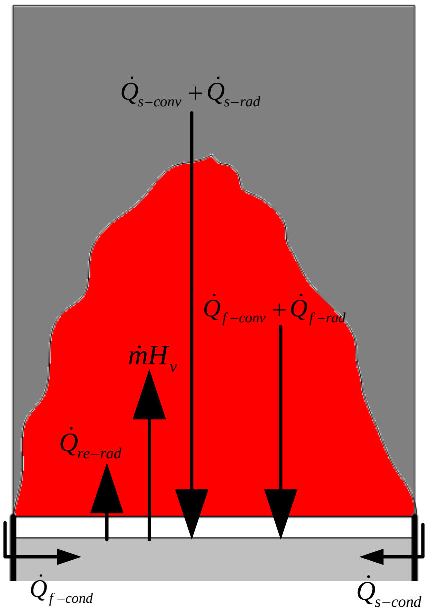

Fig. 1. Energy transfer in the heptane combustion process

Where $\dot{Q}_f$ is the heat quantity from the fire plume to the fuel surface, $\dot{Q}_{f,abs}$ is the heat absorption on the fuel surface, $\dot{Q}_{f-cond}$, $\dot{Q}_{f-rad}$, $\dot{Q}_{f-conv}$ are respectively the conductive heat, radiant heat, convective heat from the fire flame to the fuel surface from fire plume (in the luminous zone), $\dot{Q}_{s-cond}$, $\dot{Q}_{s-rad}$, $\dot{Q}_{s-conv}$ are respectively three of these from smoke plume (in thenon-luminous zone), $\dot{Q}_{re-rad}$ is the radiant heat loss by the reflection of the fuel surface, $\dot{Q}_{heat}$ is the heat absorption of heptane in the heating process, $\dot{Q}_{evap}$ is the heat absorption of heptane in the evaporating process.

The heat feedback of pool fires is positively correlated to the heptane burning rate and it is related to the shape, radiation emission rate and spatial distribution of temperature of pool fire plume. The hypotheses are put forward so as to simplify the analysis of the heat transfer law in the heptane combustion process:

(1) Compared with fire flame, the smoke plume has no direct contact with the fuel surface. Thus, its heat feedback effect on heptane can be neglected.

(2) In the stable combustion stage of pool fire, the temperature of heptane fuel keeps unchanged and the endothermic effect of pool edges and the heat radiation loss from the heptane surface can be neglected.

(3) When the distance from the target object to the pool fire flame meets the requirement $R > 3D$, the pool fire plume can be replaced by a fire wall through the centerline of heptane pool and the heat radiation to the target object is equal to the one from the fire wall.

(4) In the process of analyzing on the heat transfer law of fire plame by the single-zone model, the radiation emission rate of the whole flame surface is uniform.

Based on the above hypotheses on the pool fire combustion, to solve the simultaneous equations (1)-(3) to get

$$\dot{Q}_{f-cond}+\dot{Q}_{f-rad}=\dot{Q}_{heat}+\dot{Q}_{evap}=\dot{m}H_v \quad (4)$$

Where H_v is the latent heat of vaporization from heptane and c_p is the heat capacity at constant pressure.

Heat Feedback Effects Of Fire Plume. The heat feedback effect of fire plume refers to the heat transfer between the fire plume and heptane fuel including conductive heat, radiant heat and convective heat. It runs through the whole process of fire generation and spread. Based on Hypothesis 2, the paper theoretically analyzes the heat radiation and convection of fire plume.

(1) Heat radiation effect of fire plume

The heat radiation effect of fire plume is an electromagnetic radiation from the pool fire flame and it is related to the flame shape, size and the surface position. The cylinder model of pool fire flame is established to calculate its thermal radiation and the heat radiation under windless condition is[8]

$$\dot{Q}''_{f-rad} = \tau E F_{top} + \tau E F_{side} \tag{5}$$

$$F_{top} = 0.5 \times (2 + H_f^2 / r^2 - \sqrt{(2 + H_f^2 / r^2)^2 - 4}) \tag{6}$$

$$F_{side} = (\sqrt{4r^2 + H_f^2} - H_f) / 4\pi \tag{7}$$

$$E = \xi \delta T_f^4 \tag{8}$$

Where τ is the atmospheric transmittance and it can be calculated by $\tau = 1 - 0.058 \ln(R)$, R is the ideal gas constant, r is the pool fire radius, F_{top}, F_{side} is respectively the top and side view facters of fire plume, E is the radiation emission power, H_f is the height of fire plume which can be calculated by the empirical formual $H_f = 0.23\dot{Q}^{2/5} - 1.02D$, T_f is the average temperature of fire plume.

To get the average temperature and the radiation emission power, the paper carries out the study on the heat radiation flux of the target under windless condition, which is located at the place away from the pool centerline $4r$ and with a equal height of liquid surface. Its heat radiation flux equations are as below[9,10]:

$$\dot{Q}''_{f-rad} = \tau E F \tag{9}$$

$$F = \frac{1}{\pi s} \tan^{-1}\left(\frac{h}{\sqrt{s^2 - 1}}\right) - \frac{h}{\pi s} \tan^{-1}\left(\frac{\sqrt{s-1}}{\sqrt{s+1}}\right) + \frac{Ah}{\pi s \sqrt{A^2 - 1}} \tan^{-1}\left(\frac{\sqrt{(A+1)(s-1)}}{\sqrt{(A-1)(s+1)}}\right) \tag{10}$$

Where $s = 2r/D$, $A = (s^2 + 1)/2s$, $h = 2h_f/D$. By solving the simultaneous equations (5)-(10), the heat radiation feedback of heptane surface can be got by the heat radiation flux $\dot{Q}''_{f-rad}$ of the target object.

(2) The heat convection effect of fire plume

The heat convection is heat transfer between fire plume and the liquid surface and it is related to the temperature of fire plume and the liquid surface. Thus, the heat convection of heptane surface is as below[11,12,13]:

$$\dot{Q}_{f-conv} = hA(T_f - T_s) \tag{11}$$

Where h is the convective heat transfer coefficient and its value is $h = 10W/(m^2 \cdot K)$, T_s is the temperature of the liquid surface, that is the ambient temperature.

(3) The combined effects of fire plume

The heat feedback effects on heptane from fire plume play an important role in the generation and spread of pool fires. Besides, the mass loss rate is an important representation of pool fires. Thus, the paper establishes the below equation to analyzes the heat feedback effects on heptane fuel.

$$\dot{m}_i = \dot{Q}_{f-i} / L_v \quad i = rad, conv \tag{12}$$

Where L_v is heptane's latent heat of evaporation.

Thus, the total mass loss rate $\dot{m}$ in the combustion process is

$$\dot{m} \approx \dot{m}_{f-rad} + \dot{m}_{f-conv} \tag{13}$$

The CFD simulation analysis on heptane pool fire

Taking the heptane pool fire in the open space as the research object, the paper carries out a simulation analysis on the heat release rate, mass loss rate and the heat radiation flux of the target object which is away from its centerline 2.26m and has a height consistent with the liquid surface during the combustion process of hapetane pool fire by the simulation software Pyrosim, where the area of the pool is $1\times1m^2$ and the liquid height is 8mm. The simulation results of the parameters are shown as below.

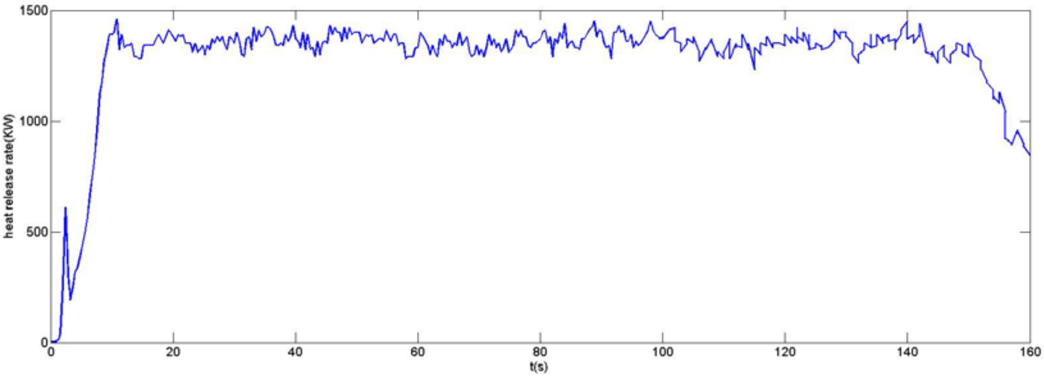

Fig.2 The change curve of the heat release rate

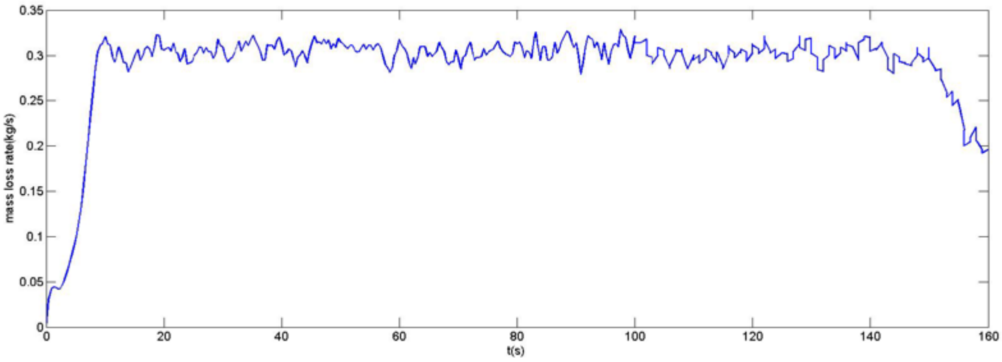

Fig.3 The change curve of mass loss rate

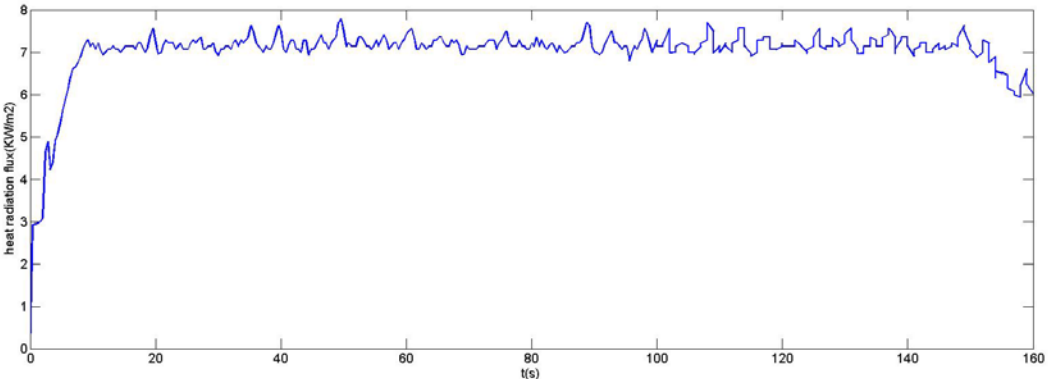

Fig.4 The change curve of heat radiation flux of the target object

The changing curves of fire smoke parameters show that:

(1) In the initial stage of the pool fire combustion, it changes from the initial stage to the stable stage rapidly and the whole duration time is about 15s. What's more, the average heat release rate at the stable stage is about 1350KW.

(2) The change laws of the mass loss rate and heat radiation flux are consistent with heat release rate. The average mass loss rate and heat radiation flux are about 0.3kg/s and $7KW/m^2$, respectively.

Based on the simulation analysis on the pool fire heat release rate, mass loss rate and heat radiation flux on key parts, the paper carries out the theory analysis on the heat radiation flux, heat convection flux and the mass loss rate effected by the both.

As shown in figure 5, the mass loss rates effected by the heat radiation flux and heat convection flux from the fire plume are consistent with the total mass loss rate of the pool fire in the pool fire combustion process: The average mass loss rate induced by the heat radiation flux effect and the heat convection effect is about 0.16kg/s and 0.11kg/s, account for 53% and 37%, respectively.

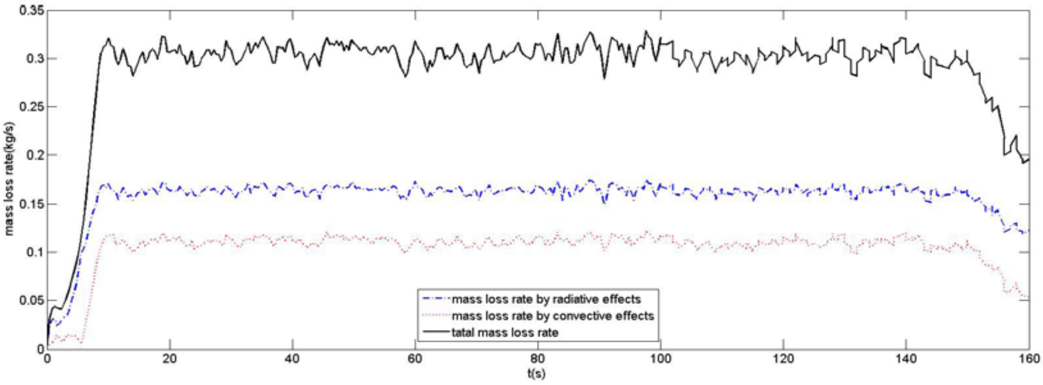

Fig.5 the change curve of mass loss rate effected by the heat feedback effects

Conclusions

Based on the heat balance equations of heptane pool fires, the paper establishes the theoretical models of heat feedback effects to analyze the heat radiation and heat convection effect on heptane fuel, as well as the combined effects of the both. What's more, the CFD simulation model of $1m^2$ heptane pool fire is established to the further study on the heat feedback effects. By the simulation analysis on the heat release rate, mass loss rate and the heat radiation flux of the pool fire, the paper also studies influencing factors of the mass loss rate in heptane pool fire. the results show that: the heat radiation and heat convection effect are the main factors on the combustion of heptane fuel. Thus, to reduce effects of heat radiation and heat convection of fire plume on the fire source is an effective method to limit the spread of fire.

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