

The Effect of Diluent Type in Atmosphere on Flame Spread over Thermally Thin Combustibles in Microgravity

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Abstract: The effects of diluent type on flame spread over thermally thin combustibles for different diluents in atmospheres have been investigated computationally. The re-absorption effect is incorporated in the problem by solving the Radiative Transfer Equation (RTE). The calculated results show that the diluent type in atmosphere has significant effect on the flame spread. For N_2 diluent, the radiation re-absorption in combustion zone and the surrounding atmosphere has little effect on the flame spread rate and the flame structure, thus the flame can be treated as optically thin flame, and the re-absorption can be neglected in the analysis. In this case, at low flow velocity, the radiation cooling effect becomes significant and manifests in lowered flame spread rate and flame temperature. In contrast, for CO_2 diluent, the re-absorption of radiation has strong effect on the flame structure and flame spread rate. Due to re-absorption, the surrounding atmosphere near the flame will absorb the thermal radiation emitted from the combustion zone. Under such conditions the conductive and radiative heat transfer from flame to fuel surface is enhanced, the radiative heat transfer plays almost equally important role in flame spread mechanism, and the flame spread rate reaches its maximum value in quiescent microgravity. With the increase of the opposed flow velocity, the heated layer around the flame is removed, and the effect of the radiation re-absorption declines, and the flame spread rate decreases monotonically.

Key words: flame spread; radiation re-absorption; microgravity

1 Introduction

The study of flame spreading over thermally thin combustibles in microgravity is essential for the improvement of fire safety in spacecraft. The mechanism responsible for flame propagation is the transfer of heat ahead of the flame to the unburned fuel. In general, at normal gravity, the effect of thermal radiation on flame spread is often neglected, because of the fact that the heat release rate of chemical reaction is much larger than the radiative heat loss rate. But in quiescent microgravity, the gravity-induced flow disappears, in such an environment, the combustion products have larger residence time, thus the radiant heat loss has greater cooling effect on the flame than in normal gravity, leading to a lowered flame temperature and a reduced flame spread rate. Due to this reason, for low O_2 concentration a radiation-quenching limit of opposed flow velocity is possible [1, 3]. This result has important practical applications to spacecraft fire safety. For example, if a fire occurs in a spacecraft, the ventilation system in the spacecraft should be turnoff to control or suppress the fire. But recent experimental results by Ronney [2] seriously challenged this fire-suppressing method. He found that in O_2 -diluent atmosphere, the diluent type has significant effect on flame spread. If the diluent gas is Ar, He, or N_2 , the flame spread rate is smaller in microgravity than in normal gravity, consistent with the experimental works by others; but if the diluent gas is CO_2 or SF_6 , the flame spread rate is larger and the limiting oxygen is lower in microgravity than in normal gravity, which means that the flame spread rate monotonically decreases as the opposing flow velocity increases, and the range of oxygen concentration required to support the flame spread is broader at quiescent microgravity than at normal gravity, thus the above fire-suppressing method is not applicable to this case. Ronney proposed two possible mechanisms for this abnormality. One possible mechanism is the effect of Lewis number, which Ronney and other researchers have investigated theoretically. Another possible mechanism is the effect of radiation re-absorption on the flame spread. For Ar, He, or N_2 diluent, the atmosphere has no ability to absorb the radiation from the flame, and most of the flame radiation is dissipated into the surroundings, but for CO_2 or SF_6 diluent, the radiation from the flame is absorbed by the surrounding atmosphere, which augments the conventional heat transfer from gas to solid fuel surface. Under such circumstance, not only conduction is the main mode of heat transfer from flame to solid surface, but also will radiant heat transfer play an important role in the mechanism of flame spread. The objective of this study is to explore the nature of re-absorption effects on flame spread rate and flame structure, as well as the factors affecting the effect of re-absorption.

2 Problem Formulation

As shown in Fig.1, the flame spread model consists of the elliptic, partial differential equations describing conservation of energy, species, mass, and momentum in the gas phase, and the ordinary differential equations for conservation of mass and energy in the solid. These equations are written in steady-state form for a single-step, Arrhenius reaction and solved for flame-fixed coordinates such that the flame sees an opposing, forced flow of speed equal to the spread rate V_f plus the velocity of an imposed forced flow V_g .

2.1 Gas Phase

The conservation equations in the gas can be written in the following common form

$$\frac{\partial(\rho u \phi)}{\partial x} + \frac{\partial(\rho v \phi)}{\partial y} = \frac{\partial}{\partial x} \left(\Gamma_{\phi} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\Gamma_{\phi} \frac{\partial \phi}{\partial y} \right) + S_{\phi} \quad (1)$$

Where the variables are given in Table 1

Table 1 Meaning of variables for use with Eq. (1)

Equation	ϕ	Γ_{ϕ}	S_{ϕ}
Continuity	1	0	0
x-Momentum	u	μ	$-\partial P / \partial x$
y-Momentum	v	μ	$-\partial P / \partial y$
Fuel	m_f	μ / p_r	$A_g \rho^2 m_f m_{ox} \exp(-E_g / RT)$
Oxygen	m_{ox}	μ / p_r	$s A_g \rho^2 m_f m_{ox} \exp(-E_g / RT)$
Energy	T	μ / p_r	$\Delta H A_g \rho^2 m_f m_{ox} \exp(-E_g / RT) - q_r$

To solve the seven unknowns in the gas phase, i.e. u , v , P , T , ρ , m_f and m_{ox} , the six conservation equations and the equation of state $P = \rho RT$, along with square root dependence of viscosity on temperature are used. The computation domain and the corresponding coordinate system are illustrated in Fig.1. The origin of the x - y coordinate system is at the fuel surface usually upstream of the location at which the fuel burns out; positive- x is downstream, and positive- y is into the gas. Boundary conditions for the gas-phase equations are given below:

Upstream at $x=0$, $\phi = \phi_{\infty}$ ($u = V_f + V_g$, $v_{\infty} = 0$)

Downstream at $x = x_{\max}$, $\partial \phi / \partial x = 0$, $P = P_{\infty}$

at $y = y_{\max}$, $u = V_f + V_g$, $v = 0$, $\partial \phi / \partial y = 0$,

at $y = 0$,

if $0 < x < x_{bo}$, then $u = V_f$, $v = v_w$, $T = T_s$,

m_f and m_{ox} at fuel surface ($0 < x < x_{bo}$) are obtained from the interfacial species balance:

$$(\rho_g v \phi - \Gamma_{\phi} \partial \phi / \partial y)_{y=0} = I_{\phi}$$

for fuel $I_{\phi} = m''$, and for other gas species $I_{\phi} = 0$.

if $x_{bo} < x < x_{\max}$, then $\partial \phi / \partial y = 0$ (symmetry plane)

The quantity V_w , T_s and m'' are obtained from solution to the solid-phase problem.

2.2 Solid Phase

The solid-phase continuity and energy equations are written in the following form:

$$m'' = d(\rho_s \tau V_f) / dx \quad (2)$$

$$m'' = A_s \rho_s \tau e^{-E_s / RT_s} \quad (3)$$

$$q_{gsc} + q_{gsr} = -\rho_s \tau V_f C_s dT_s / dx + m'' [L_v^o + (C_g - C_s)(T_s - T_{\infty})] \quad (4)$$

Where q_{gsc} , q_{gsr} are conductive heat flux and radiant heat flux from gas to solid surface, and L_v^o the latent heat of solid paraffin, respectively.

The boundary conditions for above solid phase equations are:

at $x = 0$, $T_s = T_{s,\infty}$, $\rho_s = \rho_{s,\infty}$. The quantity q_{gsc} and q_{gsr} are obtained from the solution of the gas-phase equations.

To close the problem, a characteristic point x_{eigen} is chosen at the solid fuel surface, the corresponding temperature at this point is T_{eigen} , which is arbitrary chosen as needed. If x_{eigen} and T_{eigen} are chosen suitably, the calculated flame can be located in the center of the calculation domain. A burnout point x_{bo} is assigned at the solid surface downstream the characteristic point, after which the solid char is assumed to be blow-off from the

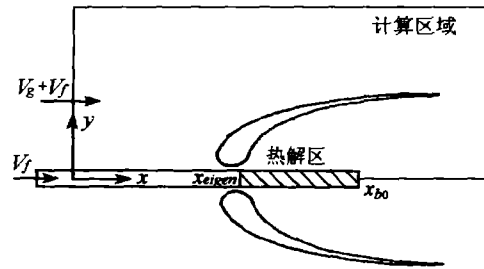


Fig.1 Schematic of the flame spread configuration and computational domain

solid fuel.

2.3 Radiation Model

To consider the radiation re-absorption, the Radiative Transfer Equation (RTE) must be solved. The RTE for a non-scattering gas is

$$\mathbf{s} \cdot \nabla I(\mathbf{x}, \mathbf{s}) = k(\mathbf{x})[I_b(\mathbf{x}) - I(\mathbf{x}, \mathbf{s})] \quad (5)$$

where $I(\mathbf{x})$ is the radiation intensity, $I_b(\mathbf{x})$ is the source term given by the Planck function, \mathbf{s} is the unit normal direction vector and $k(\mathbf{x})$ is the absorption coefficient.

In the solution, the usual mean Planck absorption coefficient a_p is used. In this study, only the radiation from CO_2 and H_2O is considered, a_p is calculated by a formula recommended by Rogg as follows:

$$a_p = P[X_{\text{CO}_2} a_{p,\text{CO}_2}(T) + X_{\text{H}_2\text{O}} a_{p,\text{H}_2\text{O}}(T)] \quad (6)$$

where $a_{p,i}$, X_i are the mean Planck absorption coefficient, and mole fraction of species i , respectively, and P is the ambient pressure.

The boundary condition for the radiation intensity leaving the gray diffuse wall is given as

$$I_w(\mathbf{s}) = \varepsilon I_{bw} + \frac{1-\varepsilon}{\pi} \int_{\mathbf{s}' \cdot \mathbf{n}_w < 0} I_w(\mathbf{s}') |\mathbf{s}' \cdot \mathbf{n}_w| d\Omega \quad (7)$$

where $I_w(\mathbf{s})$ is the intensity at the wall, ε is the emissivity, and I_{bw} is the black body intensity at the wall.

The RTE is solved using techniques similar to those for convective transport in finite volume methods for fluid flow, thus the name given to it the Finite Volume Method (FVM). To obtain the discretized form of the RTE, the unit sphere is divided into a finite number of solid angles. In each grid cell, a discretized equation is derived by integrating equation (5) over the cell ijk and the control angle $\Delta\Omega_i$, to obtain

$$\int_{\Delta\Omega_i} \int_{ijk} \mathbf{s} \cdot \nabla I(\mathbf{x}, \mathbf{s}) dV d\Omega = \int_{\Delta\Omega_i} \int_{ijk} k(\mathbf{x})[I_b(\mathbf{x}) - I(\mathbf{x}, \mathbf{s})] dV d\Omega \quad (8)$$

The volume integral on the left hand side is replaced by a surface integral over the cell faces using the divergence theorem. Assuming that the radiation intensity I is constant on each of the cell faces, the surface integral can be approximated by a sum over the cell faces.

The radiant heat flux vector \mathbf{q}_r is defined

$$\mathbf{q}_r(\mathbf{x}) = \int \mathbf{s} I(\mathbf{x}, \mathbf{s}) d\Omega \quad (9)$$

The radiant loss term in the energy equation is

$$-\nabla \cdot \mathbf{q}_r(\mathbf{x}) = k(\mathbf{x})[U(\mathbf{x}) - 4\pi I_b(\mathbf{x})] \quad (10)$$

In words, the net radiant energy gained by a grid cell is the difference between the absorbed radiant energy and the emitted radiant energy.

3 Results and Discussion

The gas phase equations were solved using SIMPLEC in a computational domain of 0.6m by 0.3m with a 400 by 200 uniform grid system. Every 20 iterations in the gas, the boundary conditions are updated by solving the solid phase equations, and the radiation parameters are updated by solving the RTE that take the gas property field as input. This sequence is repeated about 100 times to obtain convergence in spread rate and radiation parameters.

3.1 Flame Spread Rate

The results of spread rate from computations are illustrated in Fig.2, which shows the computed flame spread rate versus the opposed flow velocity as a function of CO_2 concentration in the atmosphere. The oxygen level in the atmosphere is 30% by mass, diluent gases are N_2 and CO_2 mixture. If all diluent in the atmosphere is N_2 and the opposed flow velocity is close to zero, the flame spread rate increases with the increase of opposed flow velocity, due to the radiation cooling effect (this region is defined as radiation cooling -controlled region^[4]), consistent with microgravity tests and numerical simulations by other researchers^[1, 3, 4]. When the O_2 concentration remains constant, and N_2 in the atmosphere is gradually replaced by CO_2 , the flame spread rate increases with the increase of CO_2 concentration, and the radiation cooling controlled region gradually gets narrow, and when CO_2 concentration is above 60%, the radiation cooling controlled region finally disappears. When N_2 in atmosphere is completely replaced by CO_2 , the flame spread rate decreases monotonically with the increase of air flow velocity. The experiments by Ronney show that when the diluents in atmosphere is CO_2 , the flame spread rate in quiescent microgravity is larger than that in quiescent normal gravity, which means the flame spread rate decreases due to the presence of natural convection in normal gravity. Obviously the calculated results are consistent with Ronney's results in tendency^[2]. In computation, the concentrations of CO_2 and N_2 are variables, correspondingly the absorptivity and radiance change with CO_2 and N_2 concentration, whereas other chemical or physical properties remain constant. Thus we can conclude that the radiation emission and its re-absorption should be responsible for the disappearance of the radiation cooling controlled region.

3.2 Flame Structure

The analysis of flame structure will promote the understanding of the effect of thermal radiation and its re-absorption on flame spread. Fig.3 shows the distribution of temperature contours of flame under circumstance of different atmospheres and different opposed air-flow velocities. The flame structures in the atmosphere of 30%O₂+70%CO₂ have three distinct characteristics, compared with the flame in the atmosphere of 30%O₂+70%N₂:

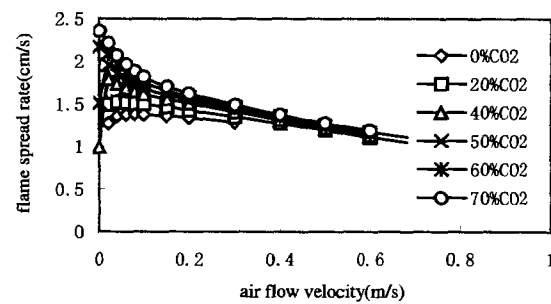


Fig.2 Spread rate as a function of opposed flow velocity

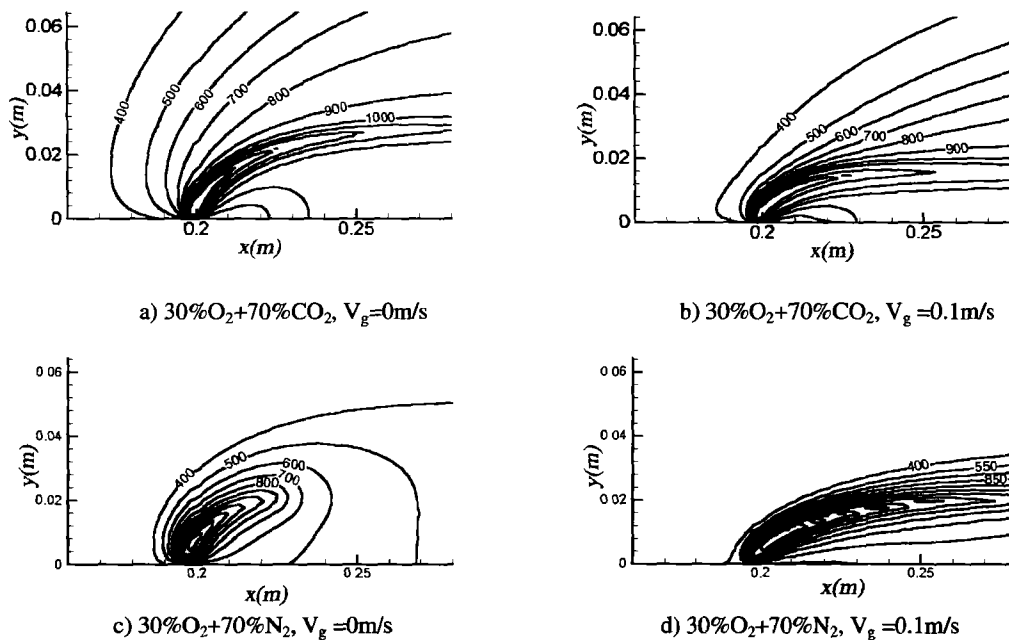


Fig.3 Temperature contours for different atmospheres and different opposed flow velocity

First, in quiescent microgravity, the thickness of the heated layer of atmosphere around the flame is thicker than its counterpart in 30%O₂+70%N₂. For convenience, the thickness of heated layer is defined as the distance between the leading edge (where the conductive heat flux has its maximum value) of the flame and the temperature contour of 400K in the direction of flame propagation. In the atmosphere of 30%O₂+70%N₂, the surrounding gas does not absorb the thermal radiation from flame, and the gas can be heated only by conduction from flame, thus the heated layer is very thin. For CO₂ diluents, the atmosphere will be heated by thermal radiation from flame, due to the radiation re-absorption of CO₂, leading to a thicker heated layer of atmosphere near the leading edge of flame. Fig. 3 shows that the heated layer near the flame in quiescent 30%O₂+70%N₂ is only 1.3cm, while in quiescent 30%O₂+70%CO₂, the heated layer of ambient atmosphere increases to 2.8cm.

Second, ahead of the flame leading edge and near the fuel surface, the gas temperature is greater than that of the fuel surface. In 30%O₂+70%N₂ atmosphere, ahead of the flame leading edge and near the fuel surface, the temperature contours is always sunken, which means that the temperature of fuel surface is higher than that of the gas, and the heat transfers from fuel surface to gas by conduction. But if the atmosphere is 30%O₂+70%CO₂, ahead of the flame leading edge, the temperature contours become bulgy, which means that the gas temperature is greater than that of the fuel surface, thus the heat transfers from gas to fuel surface by conduction. Obviously the former is caused by the fact that the thermal radiation from the flame can be absorbed by fuel surface, but can not be absorbed by the atmosphere, while the latter is caused by the radiation re-absorption of CO₂ in the atmosphere, which produces a higher gas temperature near the fuel surface than that of the fuel surface.

Third, the heating effect of thermal radiation on the atmosphere near the flame is strongly affected by two factors: one factor is the ability of thermal radiation re-absorption of the atmosphere, which has been discussed above; another is the opposed flow. In quiescent environment, the characteristic residence time of combustion products has its maximum value, leading to a thickest heated layer in the surrounding atmosphere near the flame. When the air flows, the radiation-heated layer around the flame is removed away down stream of the flame. Thus, the greater the opposed flow velocity, the thinner the radiation-heated layer. For the atmosphere of

30%O₂+70%CO₂, as the opposed flow velocity increases from 0.0m/s to 0.1m/s, the radiation-heated layer decreases from 2.8cm to 1.5cm, as shown in Fig. 3.

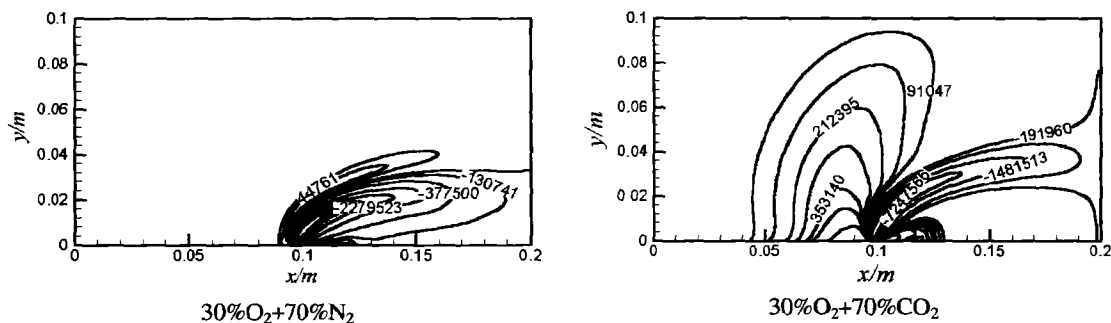


Fig.4 The distribution of net radiation gain rate in gas field

The change in flame structure also can be found from the net radiation-gain rate at each grid in the computational domain. As shown in Fig.4, for diluent N₂, the net radiation-gain rate in flame is negative, indicating that the radiation is an energy sink and has cooling effect on the flame. In the closest region near the flame, the net radiation-gain rate is positive, but the absolute value of it is quite small compared with that of the net radiation-gain rate in the flame. This region is formed by the diffusion of CO₂ from flame to the outside of the flame. In the region far away from the flame, the net radiation-gain rate is almost zero, meaning that the atmosphere has not the ability to absorb thermal radiation. For diluent CO₂, the net radiation-gain rate in the flame is negative, and the absolute value is much larger than the corresponding value in 30%O₂+70%N₂ atmosphere, indicating that the thermal radiation cooling effect on the flame is enhanced by the additional radiating species CO₂ coming from the ambient atmosphere. It is noted that ahead of the flame there is a region in which the net radiation-gain rate is positive and the value is larger than in 30%O₂+70%N₂ atmosphere.

3.3 The Mechanism of Heat Transfer from Flame to the Fuel Surface

From equation (10), it can be seen that the effect of radiation can be divided into two parts, one part is the emitted radiation, which has the cooling effect on the combustion products and the surrounding atmosphere, another part is the absorbed one, which has two effects on the combustion products and surrounding atmosphere. For the combustion products in combustion zone, it balances a part of the emitted thermal radiation, preventing the decrease in temperature caused by the cooling of thermal radiation. In the surrounding atmosphere, temperature is lower, and the radiation emission rate is relatively lower than in the combustion zone, in this case, the emission re-absorption rate is larger than radiation emission rate, thus the gas in this region is heated due to the difference between the re-absorption and the emitted radiation. If the atmosphere contains no radiating species, the heat is transferred from gas to solid surface mainly by conduction at the flame tip, but if the atmosphere contains radiating species, the emitted thermal radiation from the high temperature zone will heat the surrounding region ahead of the flame tip. So the heated layer thickness ahead of the flame will be larger than that in the case of no radiating species in the atmosphere. The heat transfer from gas to solid surface will be enhanced by two reasons. The first reason is that the thicker heated layer will lead to a higher conductive heat flux from gas to surface. The second reason is the enhanced direct radiant heat transfer from the combustion region to the solid surface because of the higher concentration of CO₂, as well as the radiation from the heated surrounding atmosphere. With the increase of the opposed flow, the heated atmosphere around the flame will be removed from the circumference of the flame, which means the heated layer ahead of the flame tip will become thinner due to the presence of opposed flow. Consequently, the heat transfer from the gas to the solid surface will be reduced, leading to a decrease in the spread rate.

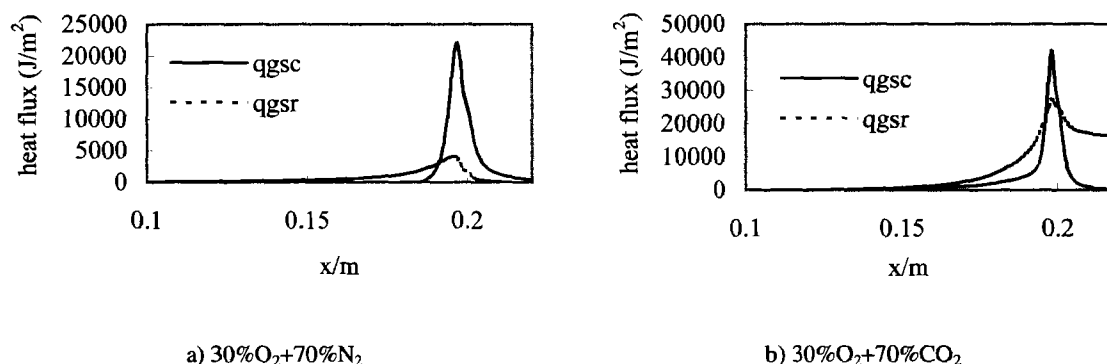


Fig.5 Distribution of heat fluxes q_{gsc} and q_{gsr} along fuel surface

The conductive heat flux q_{gsc}'' and radiant heat flux q_{gsr}'' are illustrated in Fig.5 for two atmospheres: 30%O₂+70%N₂ and 30%O₂+70%CO₂. For the first atmosphere, the radiant heat flux ahead of the flame tip is larger than the conductive heat flux, but near the flame tip the radiant heat flux is much smaller than the conductive heat flux, the total radiative heat flux ahead of the flame leading edge is much smaller than the total conductive heat flux, thus the radiant heat transfer from gas to fuel surface has small effect on the spread rate, and flame-spread is dominated by conductive heat transfer. For the second atmosphere, though the peak value of radiant heat flux is still smaller than that of conductive heat flux, the total radiant heat flux to the fuel surface is larger than the total conductive heat flux, thus the flame spread is radiation-controlled.

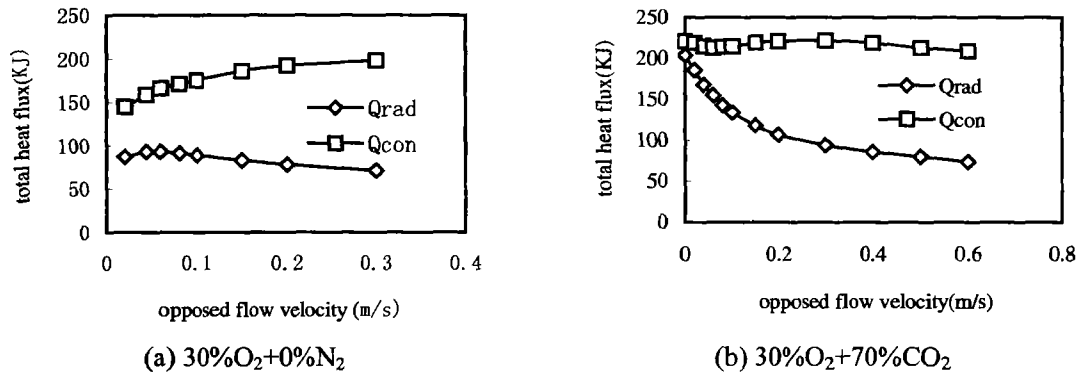


Fig.6 The effect of air flow on the total radiative heat flux and conductive heat flux from gas to fuel surface

Fig.6 shows the total radiative and conductive heat fluxes from gas to solid surface ahead of the flame leading edge as a function of air flow velocity for different atmosphere. In the atmosphere of 30%O₂+70%N₂, the total conductive heat flux is much larger than the total radiative heat flux, meaning the conduction from gas to solid surface is the main driving force for flame spread. As the opposed flow velocity increases, the total conductive heat flux increases monotonically, and the total radiative heat flux first increases, then decreases slightly. In quiescent atmosphere of 30%O₂+70%CO₂, the total radiative heat flux is almost equal to the total conductive heat flux, meaning that radiation and conduction almost make same contribution to the flame spread. With the increase of opposed flow velocity, the total conductive heat flux remains almost constant (slightly increases first, then slightly decreases), but the total radiative heat flux sharply decreases. Thus, the total heat flux from gas to solid surface decreases with the increases of the air-flow velocity.

According to Ronney's experimental results, for CO₂ diluent the flame spread rates were slightly higher at normal gravity than in quiescent microgravity, which means that as the opposed flow velocity increases, the flame spread rate will decreases slowly. But in the present study, it is found that, in the atmosphere of 30%O₂+70%CO₂, the flame spread rate is quite larger in quiescent environment than in opposed flow field with large flow velocity, which means that with the increase in opposed flow velocity the flame spread rate decreases sharper than in practice. The difference between experiments and simulations is likely caused by the calculation of the absorption coefficient. Naturally, only in a relatively small number bands, can radiation be emitted or absorbed by CO₂ and H₂O, but in this study the atmosphere is regarded as gray gas, which can emit and absorb radiation in overall spectrum, thus the effect of thermal radiation re-absorption on flame spread is over-predicted, leading to an exaggerated flame spread rate in quiescent environment. Fortunately, in spite of the above shortcoming in the treatment of radiation re-absorption, the computed results are qualitatively agreement with the experimental one. In order to remedy the defect, a wide band model will be used to calculate the absorption coefficient of CO₂ and H₂O in the future study.

4 Conclusions

The effects of radiation and its emission re-absorption on flame spread over thermally thin combustibles for different diluents in atmospheres have been investigated computationally. The re-absorption effect is incorporated in the problem by solving the RTE. When the ambient atmosphere contains no radiating medium, the radiation re-absorption in combustion zone and the surrounding atmosphere has little effect on the flame spread rate and the flame structure, thus the flame can be treated as optically thin flame, and the re-absorption can be neglected in the analysis. In this case, at low flow velocity, the radiation cooling effect become significant and manifests in lowered flame spread rate and flame temperature. When the ambient atmosphere contains radiating medium, such as CO₂, the re-absorption of radiation has strong effect on the flame structure and flame spread rate. Due to re-absorption, the surrounding atmosphere near the flame will absorb the thermal radiation emitted from the combustion zone. Under such conditions the conductive and radiative heat transfer from flame to fuel surface is

enhanced, the radiative heat transfer plays almost equally important role in flame spread mechanism, and the flame spread rate reaches its maximum value in quiescent microgravity. With the increase of the opposed flow velocity, the heated layer around the flame is removed, and the effect of the radiation re-absorption declines, and the flame spread rate decreases monotonically.

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