

Effect of ambient pressure and radiation reabsorption of atmosphere on the flame spreading over thermally thin combustibles in microgravity

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Abstract For the flame spread over thermally thin combustibles in an atmosphere, if the atmosphere cannot emit and absorb the thermal radiation (e.g. for atmosphere of O₂-N₂), the conductive heat transfer from the flame to the fuel surface dominates the flame spread at lower ambient atmosphere. As the ambient pressure increases, the flame spread rate increases, and the radiant heat transfer from the flame to the fuel surface gradually becomes the dominant driving force for the flame spread. In contrast, if the atmosphere is able to emit and absorb the thermal radiation (e.g. for atmosphere of O₂-CO₂), at lower pressure, the heat transfer from flame to the fuel surface is enhanced by the radiation reabsorption of the atmosphere at the leading edge of the flame, and both conduction and thermal radiation play important roles in the mechanism of flame spread. With the increase in ambient pressure, the oxygen diffuses more quickly from ambient atmosphere into the flame, the chemical reaction in the flame is enhanced, and the flame spread rate increases. When the ambient pressure is greater than a critical value, the thermal radiation from the flame to the solid surface is hampered by the radiation reabsorption of ambient atmosphere with the further increase in ambient pressure. As a result, with the increase in ambient pressure, the flame spread rate decreases and the heat conduction gradually dominates the flame spread over the fuel surface.

Keywords: flame spread, radiation reabsorption, microgravity.

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The study of flame spreading over thermally thin combustibles in microgravity is essential for the improvement of the fire safety in spacecraft. Experiments show that the heat transfer ahead of the flame from the flame to the unburned fuel is responsible for the flame propagation and can be affected by ambient pressure; as a result, the flame spread rate changes as the ambient pressure changes. Fernandez-Pello et al.^[1] correlated the flame spread rate and Damkohler number, and found that in normal gravity the flame spread rate increases with an increase in Damkohler number. In normal gravity, when the flame spreads over thermally thin fuel surface downward, Damkohler number is proportional to $P_{\infty}^{2/3}$, which means that as the ambient pressure increases, the flame spread rate increases. In microgravity, Bhattacharjee et al.^[2-4] studied the effect of ambient pressure on flame spread by numerical simulation, and conducted microgravity experiments in the space shuttle of US, and found that although the flame spread rate becomes more sensitive to the

change in ambient pressure, the tendency that the flame spread rate increases with the ambient pressure and keeps unchanged. Thus for a long time it is generally believed that when a flame spreads over a thermally thin combustible the flame spread rate increases with ambient pressure. But Ronney's experiments challenged the above conclusion; he found that when the atmosphere can emit and absorb thermal radiation, under certain conditions, the flame spread increases to a peak value, and then decreases with the increasing ambient pressure. This paper studies the mechanism for this unusual phenomenon.

1 Theoretical analysis

As shown in fig. 1, in the flame-fixed coordinate, the flame sees an opposing forced flow with speed equal to the spread rate V_f plus the velocity of an imposed forced flow V_g , and the solid fuel approaches to the flame at the speed equal to the flame spread rate V_f .

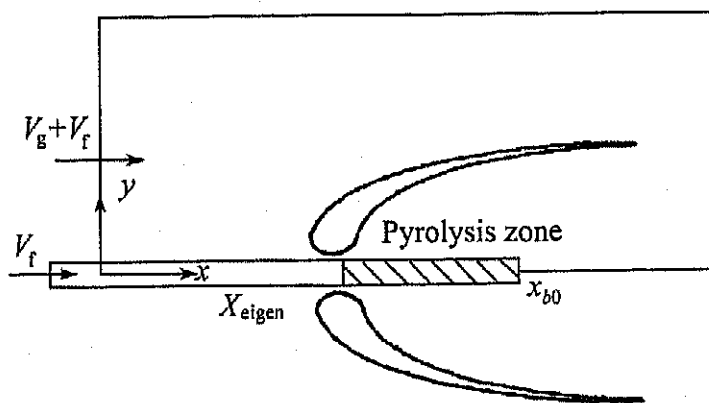


Fig. 1. Schematic of the flame spread configuration and computational domain.

In the direction of the flame spread, the balance of the heat conduction and heat convection leads to the following flame characteristic length

$$L_g = \alpha_g / V_r = \lambda_g / (\rho_g C_g V_r).$$

When the Lewis number is unity, L_g can be used to measure the concentration gradients of various reactants. The smaller the L_g , the bigger the diffusion rates of the reactants, which is favorable to the combustion.

In the analysis of the flame spread, another important parameter is the optical mean absorption length L_a of the atmosphere, representing the traveling distance of thermal radiation in the atmosphere. A short optical mean absorption distance L_a means that the surrounding gas can easily absorb the thermal radiation.

The ambient pressure can affect the above two parameters, changing the flame-spread features. But for different atmospheres, the flame spread demonstrates different characteristics related with ambient pressure. For the atmosphere with less the ability to emit or absorb thermal radiation, the optical mean absorption length L_a is larger; the flame can be treated as optically "thin". In this case, the effect of radiation reabsorption on the flame spread can be neglected. At lower ambient pressure, the flame has a greater characteristic length L_g , leading to slower oxygen diffusion and chemical reaction in the flame. Meanwhile, the radiance of the flame is lower; thus the thermal radiation from the flame to the solid surface is weaker, and the heat conduction is the main mode of heat transfer from the flame to the solid surface. With the increase in ambient pressure, the flame characteristic length L_g decreases, and the oxygen diffusion as well as the chemical reaction in the flame is enhanced, and the flame peak temperature is raised; thus at the leading edge of the flame, the conductive heat flux is augmented. At the same time, the concentration of combustion

products increases, leading to stronger radiant heat transfer from the flame to the solid surface. Because of the above reasons, the flame spread rate increases with the ambient pressure.

For the atmosphere with the ability to emit or absorb thermal radiation, the radiation reabsorption of the atmosphere affects the heat transfer from the flame to the fuel surface in two aspects. Firstly, the flame not only directly heats the fuel surface by conduction and radiation, but also heats the surrounding gas by radiation reabsorption. Then the radiation-heated gas at the leading edge of the flame heats fuel surface by conduction and radiation, so there is a tendency that the heat transfer from the flame to the fuel surface can be enhanced by radiation reabsorption of surrounding atmosphere. Secondly, the radiation reabsorption of surrounding atmosphere hampers the direct heating of fuel by the flame. Obviously, due to the above contradictory effects of radiation reabsorption on the heat transfer from the flame to the fuel surface, it is impossible to determine how the flame spread rate will change with the increase in the ambient pressure only by theoretical analysis. In order to investigate this problem comprehensively, a numerical method will be used in our study.

2 Problem formulation

The flame spread model is described by the elliptic partial differential equations for conservations of energy, species, mass, and momentum in the gas phase, and the ordinary differential equations for conservations of mass and energy in the solid, as well as the radiation model.

2.1 Gas phase

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

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

The variables are given in table 1

Table 1 Meaning of variables in 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	$\Delta H A_g \rho^2 m_f m_{ox} \exp(-E_g / RT) - q_r$

$u, v, m_f, m_{ox}, T, P, \mu$ and P_r refer to gas flow velocity in x and y directions, gaseous fuel mass fraction, oxygen mass fraction, gas temperature, ambient pressure, gas viscosity coefficient, and Prandtl number, respectively. $A_g, E_g, s, \Delta H$ and q_r refer to pre-exponential factor and activation energy of gas chemical reaction, stoichiometric ratio of chemical reaction, heat of combustion and radiant heat loss rate, respectively.

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. Boundary conditions for the gas-phase equations are given as follows.

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 $y = y_{\max}$: $\partial\phi/\partial y = 0$, $P = P_\infty$;

at $y = 0$: $u = V_f$, $v = v_w$, $T = T_s$, if $0 < x < x_{bo}$;

m_f and m_{ox} at fuel surface ($0 < x < x_{bo}$) are obtained from the interfacial species balance $(\rho_g v \phi - \Gamma_\phi \partial\phi/\partial y)_{y=0} = I_\phi$; $I_\phi = m''$, for fuel and $I_\phi = 0$ for other gas species.

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

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

2.2 Solid phase

The continuity and energy equations in solid-phase 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, L_v^o is the latent heat of solid pyrolysis. And A_s , E_s , τ and ρ_s refer to the pre-exponential factor and activation energy of chemical reaction, half thickness and density of the solid fuel, respectively.

The boundary conditions for the 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, with corresponding temperature as T_{eigen} , which is arbitrarily chosen. 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, and the solid char is assumed to be blown off from the solid fuel.

2.3 Radiation model

Before calculating the radiation reabsorption, the radiant transfer equation (RTE) must be solved. The RTE for a nonscattering gas is

$$s \cdot \nabla I(x, s) = a_p(x) [I_b(x) - I(x, s)], \quad (5)$$

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

In the solution, the usual mean Planck absorption coefficient a_p is used. In this study, only the

radiations from CO_2 and H_2O are considered. a_p is calculated by a formula recommended by Rogg^[5] 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 $a_{p,i}$ and X_i are the mean Planck absorption coefficient, and mole fraction of species i , respectively, and P is the ambient pressure.

The radiant heat loss term in the energy equation is

$$-\nabla \cdot q_r(x) = a_p(x)[U(x) - 4\pi I_b(x)], \quad U(x) = \int_{4\pi} I(x,s) d\Omega. \quad (7)$$

This means that 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 0.3 m by 0.1 m with a 200 by 100 uniform grid system. After 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 with 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 computed results of flame spread rate are illustrated in fig. 2, which shows the flame spread rate versus the ambient pressure for different atmospheres. For the atmosphere of 30% O_2 + 70% N_2 , the flame spread rate decreases monotonically with the ambient pressure. In contrast, for the atmosphere 30% O_2 + 70% CO_2 , at a pressure of 2.5 kg/cm^2 , the flame spread rate reaches its maximum value. When the ambient pressure is less than 2.5 kg/cm^2 , the flame spread rate in-

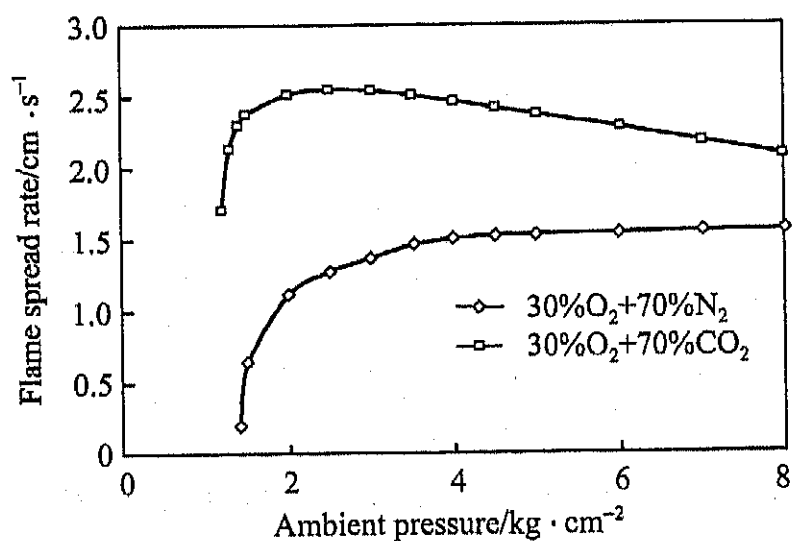


Fig. 2. The effect of ambient pressure on flame spread rate.

creases with the ambient pressure; when the ambient pressure is about 0.12 kg/cm^2 , the flame is quenched. When the ambient pressure is greater than 2.5 kg/cm^2 , the flame spread rate decreases with the ambient pressure. The above results are consistent in tendency with Ronney's experiments. In this case, when the ambient pressures are 0.25, 0.5, 1.0, 1.5 and 2.0 kg/cm^2 , respectively, the flame spread rates are 0.3, 0.7, 1.0, 0.9 and 0.7 cm/s .

Between the above two atmospheres, the only difference is in the type of diluents in the atmospheres. In the mathematical model, the difference is expressed as the concentrations of CO_2 and N_2 , and the corresponding absorptivity and radiativity to the concentrations of CO_2 and N_2 , whereas other chemical or physical properties remain constant. Thus it is reasonable to postulate that the radiation emission and its reabsorption of the atmosphere should be responsible for the

different effects of ambient pressure on the flame spread rates in atmospheres with different diluent types.

3.2 Flame structure

The analysis of flame structure will promote the understanding of the effect of the ambient pressure on the flame spread. Fig. 3 shows the distributions of temperature contours of flame under circumstance of different atmospheres and different ambient pressures. For the atmosphere of 30% O₂ + 70% N₂, the flame size increases with the ambient pressure, whereas for the atmosphere of 30% O₂ + 70% CO₂, as the ambient pressure increases, the heated-layer around the flame decreases.

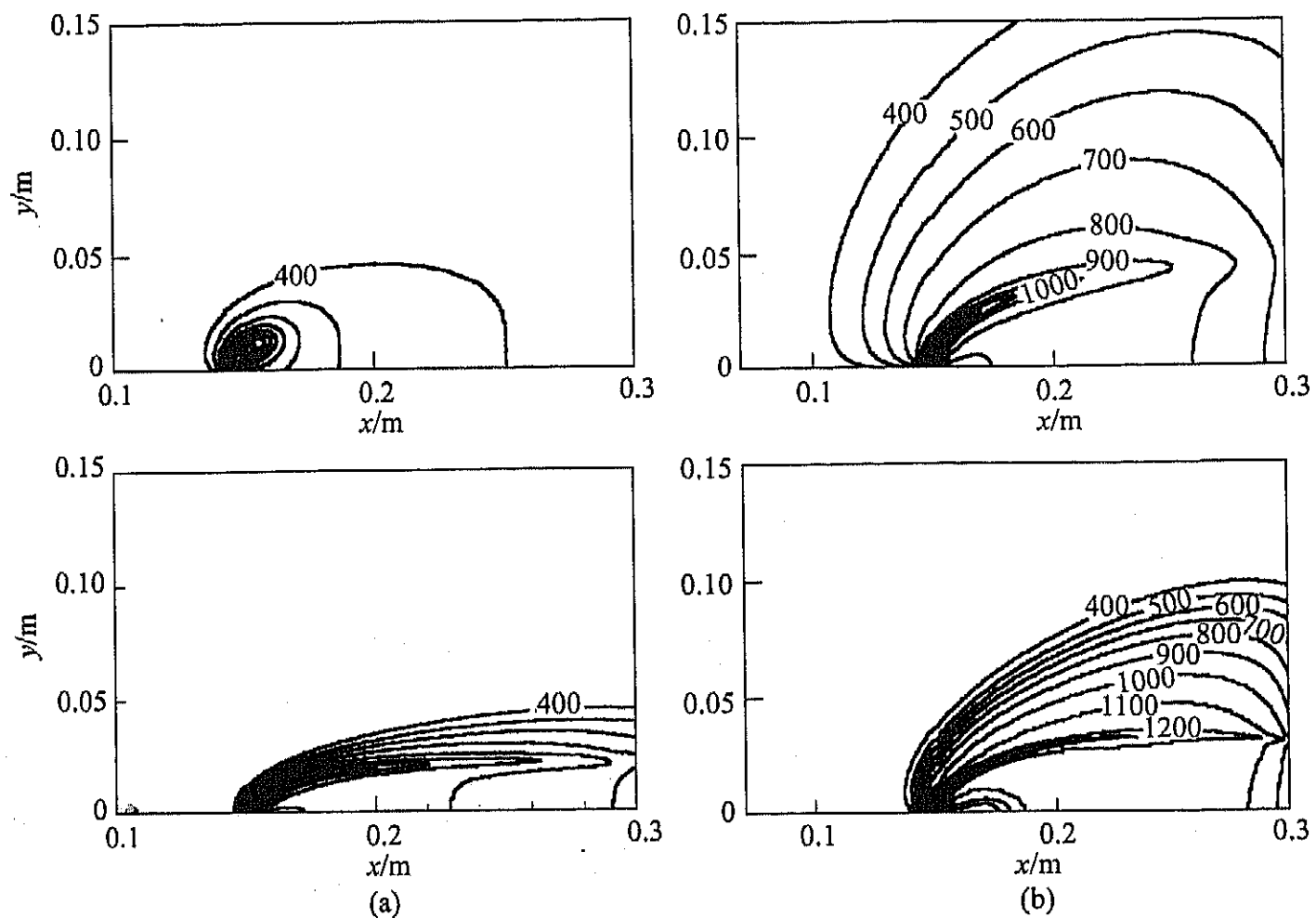


Fig. 3. The effect of ambient pressure on the flame structure. (a) In the atmosphere of 30% O₂ + 70% N₂; (b) in the atmosphere of 30% O₂ + 70% CO₂.

For the sake of convenience, the distance between the contour of 400 K and the leading edge (where the heat flux from gas to the fuel surface is the maximum) in the direction of flame spread is defined as the heated layer thickness of the surrounding gas.

For the atmosphere of 30% O₂ + 70% N₂, the flame size is controlled by the heat release rate of chemical reaction and the heat loss rate in the flame. In a quiescent microgravity environment, oxygen enters the flame mainly by diffusion. As the ambient pressure increases, the oxygen diffusion rate becomes greater, leading to intensified chemical reaction and higher temperature in the flame. On the other hand, with the increase in ambient pressure, the radiant heat loss rate per unit volume increases due to denser radiating products (such as H₂O and CO₂). As a comprehensive result, the flame temperature rises, hence the flame spread rate and flame size increase. Especially

when the pressure is lower, the oxygen diffusion is slower; thus in the flame, the chemical reaction is almost controlled by the diffusion rate of oxygen. Under such a condition, the flame temperature and size are very sensitive to the ambient pressure. Without the ability to absorb the thermal radiation from the flame, the flame can only heat the surrounding atmosphere by thermal conduction; as a result, the heated layer surrounding the flame is very thin.

In the atmosphere of 30% O₂ + 70% CO₂, because CO₂ is able to absorb the thermal radiation from the flame (in the analysis, CO₂ is assumed to be a gray body), the whole visible space can be heated by the thermal radiation from the flame. For this reason, the heated-layer of surrounding gas is much larger than that for the atmosphere of 30% O₂ + 70% N₂. As the ambient pressure increases, the atmosphere's ability to absorb the thermal radiation from the flame will be strengthened; thus the part of the thermal radiation absorbed by the surrounding atmosphere increases. That is to say, the surrounding gas has the shielding ability to keep the thermal radiation from escaping from the flame; and the greater the pressure, the greater the shielding ability. Thus the heated layer of the surrounding gas decreases with the increasing pressure. In fig. 3, when the pressure increases from 1.5 to 8.0 kg/cm², the heated layer decreases from 4.0 to 1.5 cm.

3.3 The mechanism of heat transfer from flame to the fuel surface

Fig. 4 shows the distribution of conductive and radiant heat fluxes from the flame to the fuel surface near the flame tip for different atmospheres. For the atmospheres 30% O₂ + 70% N₂ and

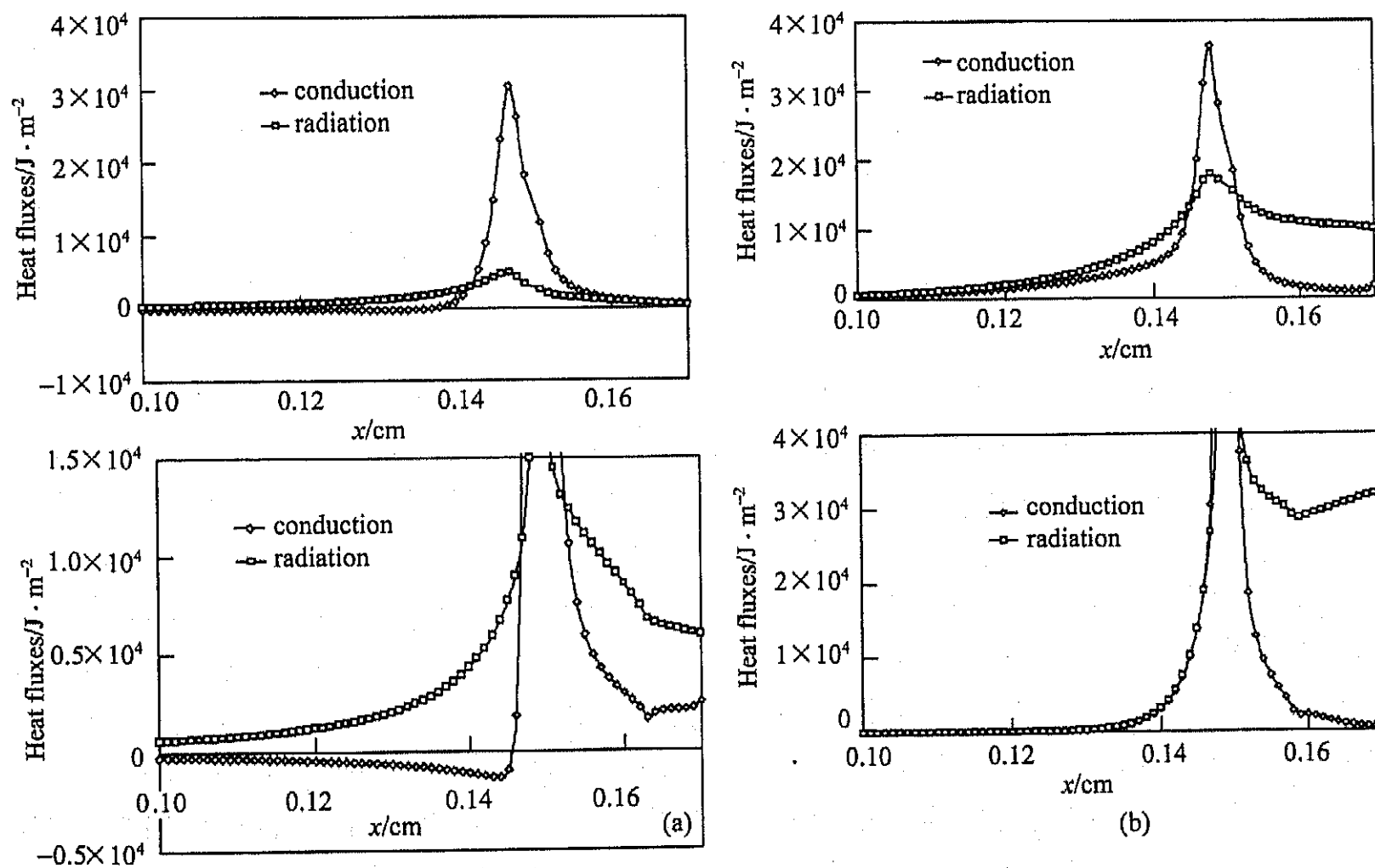


Fig. 4. The effect of ambient pressure on the conductive and radiant heat flux over the fuel surface. (a) In the atmosphere of 30% O₂ + 70% N₂; (b) in the atmosphere of 30% O₂ + 70% CO₂.

30% O₂ + 70% CO₂, the effects of ambient pressure on the distributions of conductive and radiant heat fluxes demonstrate different features.

For the atmosphere containing radiating species, the effects of radiation reabsorption on the mechanism of flame spread rate can be reflected in two aspects. On one hand, not only the larger heated layer thickness surrounding the flame promotes the conductive heat transfer from the flame to the fuel surface, but also the radiant heat transfer to the fuel surface is enhanced due to the denser radiating species, both of which are helpful for the flame spread. On the other hand, the peak temperature of the flame decreases because of the radiant heat loss, which is favorable to the flame spread.

As shown in fig. 4, for the atmosphere of 30% O₂ + 70% N₂, at a pressure of 1.5 kg/cm², near the leading edge of the flame, the conductive heat flux is larger than the radiant heat flux from the flame to the fuel surface. This means that the conduction is the main driving force for the flame spread. As the ambient pressure increases, the flame characteristic length decreases; the diffusions of various substances and the chemical reaction as well as the flame spread are enhanced. In fig. 4, at the pressure of 8.0 kg/cm², in the upstream of the leading edge of the flame, the radiant heat flux is larger than the conductive heat flux from the flame to the fuel surface. It means that the increase in thermal radiation becomes one of the main driving forces for the flame spread.

For the atmosphere of 30% O₂ + 70% CO₂, at a pressure of 1.5 kg/cm², except near the leading edge of the flame, the radiant heat flux over the fuel surface is larger than the conductive heat flux, and the heated area of the fuel surface extends a long distance to the upstream of the flame, which means that the thermal radiation is the main driving force for the flame spread. Due to the radiation reabsorption, the surrounding gas over the flame is heated to a temperature higher than that of the fuel surface, so that the conductive heat flux from the gas to the fuel surface is positive. Near the leading edge of the flame, though the conductive heat flux is still larger than the radiant heat flux, its peak value is close to the value of nearby distribution. At the pressure of 8.0 kg/cm², significant changes can be found in the distributions of the conductive and radiant heat fluxes over the fuel surface. At the leading edge, though the radiant heat flux remains smaller than the conductive heat flux, in the downstream of the flame, the radiant heat flux is greater than the conductive heat flux over the fuel surface, and in the upstream of the flame, the heated length of the fuel surface is shortened as a result of the smaller optical mean absorption length L_a .

Fig. 5 shows the total radiant and conductive heat fluxes Q_{rad} and Q_{con} from gas to solid surface ahead of the flame leading edge as a function of ambient pressure for different atmospheres. In the atmosphere of 30% O₂ + 70% N₂, for smaller pressure, the total conductive heat flux Q_{con} is larger than the total radiant heat flux Q_{rad} , meaning that the conduction from gas to solid surface is the main driving force for flame spread. As the ambient pressure increases, the total radiant heat flux Q_{rad} increases monotonically, whereas the total conductive heat flux first increases, and then decreases slightly. At last, when the ambient pressure is larger than a critical value, the total radiant heat flux Q_{rad} becomes greater than the total conductive heat flux Q_{con} , and the thermal radi-

tion becomes the main driving force for the flame spread. It is noted that at the pressure of 8.0 kg/cm^2 , at the leading edge, the total conductive heat flux Q_{con} is still larger than the radiant heat flux Q_{rad} . The reason for the phenomenon that the total conductive heat flux decreases with the ambient pressure is that at closest region near the flame tip, due to radiation, the temperature at fuel surface is greater than the adjacent gas, so that the heat is transferred from the fuel surface to the gas.

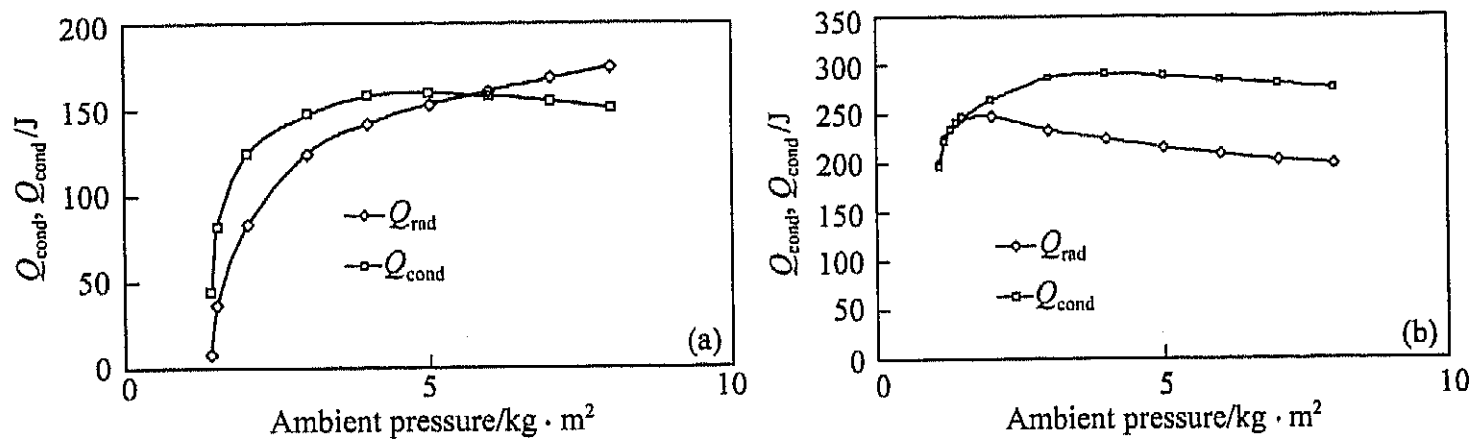


Fig. 5. Total conductive heat flux Q_{cond} and total radiant heat flux Q_{rad} versus the ambient pressure.

For the atmosphere of 30% $\text{O}_2 + 70\% \text{CO}_2$, at lower ambient pressure, the conductive heat flux is almost equal to the radiant heat flux, thus the thermal radiation and conduction constitute the mechanism of the flame spread. With the increase in the ambient pressure, the shielding effect of atmosphere on the thermal radiation is enhanced, leading to a decrease in total radiant heat flux from the gas to the fuel surface. At the same time, the heated layer of surrounding gas is also reduced due to the shielding effect, resulting in less conductive heat flux from the gas to the fuel surface. By now, the question raised in the theoretical analysis is answered: for the atmosphere with strong ability to emit or absorb the thermal radiation, how does the flame spread rate change with the ambient pressure?

4 Conclusions

The above calculation and analysis show that, for the flame spreading over thermally thin combustibles in different atmospheres with different radiation characteristics, the effects of the ambient pressure on the flame spread demonstrate different features. For the atmosphere of 30% $\text{O}_2 + 70\% \text{N}_2$, at lower pressure, the flame heats the fuel surface mainly by conduction. With the increase in ambient pressure, oxygen gas diffuses into the flame more quickly, and the flame burns more intensively, leading to a higher peak temperature. At the same time, the radiating products become denser, leading to a bigger radiativity. Therefore, the conductive and radiant heat fluxes increase, and conductive and radiant heat transfers are the main driving forces for the flame spread, and the flame spread rate increases with the ambient pressure. For the atmosphere of 30% $\text{O}_2 + 70\% \text{CO}_2$, at lower pressure, the thermal radiation from the flame to the fuel surface plays almost the same important role as the conduction in the mechanism of flame spread. Due to the limitation

of the supply of oxygen on combustion, as the ambient pressure increases, the combustion is enhanced, and the flame spread rate increases. But if the pressure is greater than a critical value, the shielding effect of the ambient atmosphere on the thermal radiation becomes stronger, so that the thermal radiation intensity at the fuel surface ahead of the flame tip decreases, and the conductive heat transfer from the flame to the fuel surface increasingly becomes the dominant driving force for the flame spread. Meanwhile, the heated layer thickness surrounding the flame decreases as the ambient pressure increases, and the conductive heat transfer from the gas to the fuel surface decreases. Thus, with the increase in ambient pressure, the flame spread rate decreases.

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