Calculation Analysis on the Fuel Preheating Mechanisms in Surface Fire Spread over a Horizontal Fuel Bed

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ABSTRACT

This work aims to investigate the effects of heat radiation and convection in the near field and far field of a spreading flame front over a horizontal fuel bed. Model calculations are made to examine different fuel preheating mechanisms that affect the fire spread. The results indicate that the convective cooling effect is important and could not be ignored. For the fuel elements in the near field, the radiation from the flame front and the combustion zone is not sufficient for fuel preheating, and the mechanism of convective heating should be considered. The convective cooling of the fuel bed has a considerable long influence range ahead of the flame front, while the influence range of convective heating is in a shorter length scale. The flame radiation on fuel preheating takes effect in the whole field. There is a sharp increase of the temperature when fuel elements get closer to the flame front in the near field due to the combined effects of three heating mechanisms. The contributions of the flame radiation, the combustion zone radiation and the convective heating to fuel preheating are of the same magnitude in the near field. The combustion cooling takes effect in the far field, while the convective cooling coefficient affects both far field and near field.

KEYWORDS: Fire spread, flame radiation, convective cooling, convective heating.

NOMENCLATURE

ρ	fuel density (kg m^{-3})
c	specific heat capacity (J·kg^{-1}·K^{-1})
T_s	fuel surface temperature (K)
X	distance away from flame front (m)
α	absorptivity of the medium (m^{-1})
ε_f	flame emissivity
ε_c	emissivity of fuel bed
σ	Stefan-Boltzmann constant
T_f	flame temperature (K)
T_a	ambient temperature (K)
T_{fm}	film temperature (K)
h	convective heat transfer coefficient (W·m^{-2}·K^{-1})
R	rate of fire spread (m·s^{-1})
T_c	radiative temperature of fuel bed (K)
ρ_b	dry fuel bed density (kg·m^{-3})
c_f	specific heat of dry fuel (J·kg^{-1}·K^{-1})
ρ_w	density of moisture within the fuel (kg·m^{-3})
c_w	specific heat of water (J·kg^{-1}·K^{-1})
l	heat of vaporization of water at 373 K (J·kg^{-1}·K^{-1})
T_i	ignition temperature (K)
T_g	hot gas temperature (K)

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INTRODUCTION

Prediction of rate of spread (ROS) is a fundamental problem in wildland fire research. The heat transfer mechanisms for preheating of unburnt fuels is the major focus for physical modelling of fire spread. In early works, a physical model was proposed to predict the rate of spread (ROS) over a horizontal fuel bed in still air by de Mestre et al. [1]. It was indicated that when only radiative heat transfer was considered, the predicted ROS was thirteen times the measured value, while when natural convective cooling was introduced in the model, a good agreement was achieved. Baines [2] calculated the temperature of the fuel bed surface based on the model of de Mestre et al. [1]. It was found that the surface temperature immediately ahead of the flame front was much lower than ignition temperature. One possible explanation is that besides radiative heat transfer, there is an additional short-range convective heating effect for fuel elements close to the flame front. Natural convection was found to take effect in the far field, while the flame-induced convection exists only in the near field of the flame (close to the flame) [3]. Considerable efforts [4-8] have been devoted to explaining fuel preheating mechanisms for linear fire line in a horizontal fuel bed in still air, however, the quantitative comparison between heat radiation and heat convection are not fully understood.

This paper aims to investigate the effects of heat transfer mechanisms on fuel preheating in both near field and far field of the flame front. Specifically, the considered fuel preheating mechanisms include flame radiation, combustion zone radiation, convective heating and cooling.

FIRE SPREAD MODEL

In the model calculation, the considered fuel preheating mechanisms include flame radiation, the radiation from combustion zone, radiation loss and the convective cooling to the ambient. The heat conduction through the fuel bed is ignored. The governing equation (refer to [2]) for fuel surface temperature along the fuel bed centerline is expressed as

$$-R\rho c\frac{dT_s}{dX} = \alpha\varepsilon_f\sigma\left(T_f^4 - T_a^4\right)W(X) + \alpha\varepsilon_c\sigma\left(T_c^4 - T_a^4\right)U(X) - \alpha\sigma\left(T_s^4 - T_a^4\right) - 4h\alpha\left(T_s - T_a\right), \qquad (1)$$

where X denotes the distance away from the flame front, ρc is given by

$$\rho c = \begin{cases} \rho_b c_f + \rho_w c_w + \dfrac{\rho_w l}{373 - T_a}, & T_s < 373\,\mathrm{K} \\ \rho_b c_f, \quad T_s > 373\,\mathrm{K} \end{cases}, \qquad (2)$$

$W(X)$ and $U(X)$ are the view factors respectively from the flame front and combustion zone to the fuel elements. Here R 0.0049 m/s, T_f = 1093 K, T_a = 296 K, T_c = 1139 K. For other parameters, refer to Refs. [1-2].

The impact of combustion zone radiation is limited by the large absorptivity of the fuel bed, and usually the effective influence range is confined to a distance of about 2 cm or less [2]. Therefore, the combustion zone radiation is mainly near field radiation, and $U(X)$ is negligible if X > 0.02 m.

The boundary conditions for the temperature field are

$$T_s\big|_{X=0} = T_i = 593\ \mathrm{K},\ T_s\big|_{X\to\infty} = T_a = 296\ \mathrm{K}. \qquad (3)$$

For free convection, the convective heat transfer coefficient h is expressed as [9]

$$Nu = \frac{hD}{\lambda} = CRa^{n} , \tag{4}$$

where Nu is the Nusselt number, Ra is the Rayleigh number, D is the characteristic length, λ is the thermal conductivity of air, C and n are the constants. The convective heat transfer coefficient h in Eq. (1) is thus calculated to be $h = 1.02\lambda Ra^{0.148} / D$ = 44.4 W·m^{-2}·K^{-1}. The coefficient h = 44 W·m^{-2}·K^{-1} was used in Baines' work [2], and the fitting to the experimental data was better than that of h = 23.2 W·m^{-2}·K^{-1} [1]. Thus, h = 44 W·m^{-2}·K^{-1} is employed in this study.

This model is used to calculate the effects of convective cooling, convection heating, flame radiation, combustion zone radiation and radiation loss on fuel surface temperature.

RESULTS AND DISCUSSION

Convective cooling

We first calculate the fuel surface temperature with no consideration of the convective cooling, i.e. the convection term $4h\alpha(T_s - T_a)$ in Eq. (1) is ignored. The results are presented in Fig. 1. As shown, the fuel temperature T_s decreases almost linearly with distance away from the flame front. The results significantly deviate from the experimental data, and in particular, the fuel temperature immediate ahead of the flame front $T_s|_{X\to 0}$ = 867 K is much higher than the ignition temperature T_i of 593 K. Therefore, the mechanism of convective cooling could not be ignored. This implies that convective cooling plays an important part in the heat balance during fire spread.

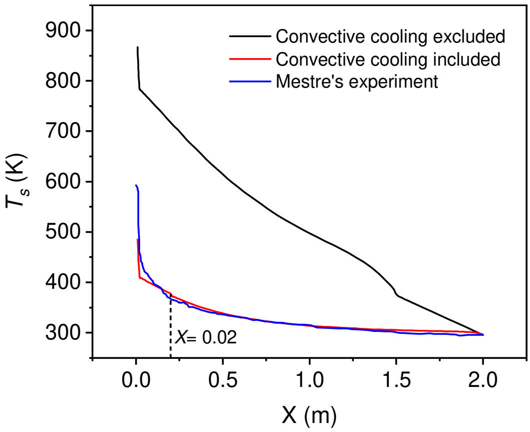

Fig. 1. Fuel surface temperature with or without convective cooling.

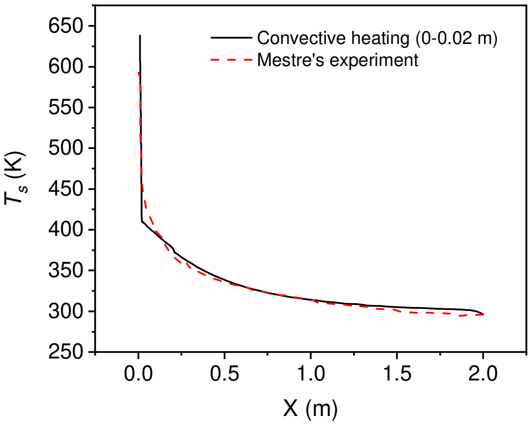

Fig. 2. Considering convective heating in the near field.

We then include the convective cooling for calculating the fuel surface temperature. As shown in Fig. 1, the calculated data agree well with the experimental data in the far field of the flame front (0.02 m X < 2 m) , where the fuel surface temperature T_s increases slowly with decreasing X. In the near field of the flame front (0 < X < 0.02 m), the fuel surface temperature T_s increases rapidly with decreasing X. This indicates that the preheating mechanism in the near field plays a major role in raising T_s to the ignition temperature. However, the fuel surface temperature immediately ahead of the flame front $T_s|_{X\to 0}$ = 485 K is much lower than the ignition temperature. Therefore for fuel elements in the near field, the radiation from the flame front and that from the combustion zone are not sufficient for fuel preheating, and a kind of convective heating induced by hot gas puffing over the fuel bed should also be considered.

We now examine the contribution of radiative heating in the near field, for which, the radiation from the flame front and that from the combustion zone are discussed separately. We found that when both radiative heating mechanisms are considered, the fuel surface temperature immediately ahead of the flame front is $T_s|_{X\to 0}$ = 485 K. When only flame radiation is considered, the fuel surface temperature is $T_s|_{X\to 0}$ = 412 K. When only combustion zone radiation is considered, Eq. (1) is changed as

$$\begin{cases} -R\rho c\dfrac{dT_s}{dX} = \alpha\varepsilon_f\sigma\left(T_f^{\,4}-T_a^{\,4}\right)W(X)-\alpha\sigma\left(T_s^{\,4}-T_a^{\,4}\right)-4h\alpha\left(T_s-T_a\right), \quad 0.02 < X < 2\text{ m} \\ -R\rho c\dfrac{dT_s}{dX} = \alpha\varepsilon_c\sigma\left(T_c^{\,4}-T_a^{\,4}\right)U(X)-\alpha\sigma\left(T_s^{\,4}-T_a^{\,4}\right)-4h\alpha\left(T_s-T_g\right), \quad 0 < X < 0.02\text{ m} \end{cases}, \tag{5}$$

then the fuel surface temperature $T_s|_{X\to 0}$ = 418 K. The results indicate that the contributions of flame radiation and combustion zone radiation to fuel preheating are of almost same importance.

Near-field convective heating

As discussed above, the convective cooling of the fuel bed is very important in a considerably long influence distance ahead of the flame front. Comparatively, when the convective heating is considered, it is important on a shorter length scale, since it depends on hot gases puffing over the fuel bed and the gases rise rapidly because of buoyancy [2]. Thus convective heating is assumed in the near field ($0 < X < 0.02$ m). For fuel preheating in the near field, the model includes flame radiation, radiation from combustion zone, radiation loss and convective heating by hot gases. For fuel preheating in the far field, the model includes flame radiation, radiation from combustion zone, radiation loss and convective cooling to the environment. The governing equation is expressed as

$$\begin{cases} -R\rho c\dfrac{dT_s}{dX} = \alpha\varepsilon_f\sigma\left(T_f^{\,4}-T_a^{\,4}\right)W(X)+\alpha\varepsilon_c\sigma\left(T_c^{\,4}-T_a^{\,4}\right)U(X) \\ \qquad\qquad -\alpha\sigma\left(T_s^{\,4}-T_a^{\,4}\right)-4h\alpha\left(T_s-T_a\right), \quad 0.02 < X < 2\text{ m} \\ -R\rho c\dfrac{dT_s}{dX} = \alpha\varepsilon_f\sigma\left(T_f^{\,4}-T_a^{\,4}\right)W(X)+\alpha\varepsilon_c\sigma\left(T_c^{\,4}-T_a^{\,4}\right)U(X) \\ \qquad\qquad -\alpha\sigma\left(T_s^{\,4}-T_a^{\,4}\right)-4h\alpha\left(T_s-T_g\right), \quad 0 < X < 0.02\text{ m} \end{cases}, \tag{6}$$

The calculated fuel surface temperature for convective heating in the near field is presented in Fig. 2. The results have a better agreement with the experimental data. There is a sharp increase of the temperature when fuel elements get close to the flame front. The fuel temperature immediately ahead of the flame front $T_s|_{X\to 0}$ = 638 K is slightly higher than the ignition temperature, which may be due to the overestimate of flame temperature, emissivity, or hot gas temperature.

For the convective heat transfer mechanism in the near field, when the convective cooling effect is changed to convective heating, the calculations show that the fuel surface temperature $T_s|_{X\to 0}$ increases from 485 K to 638 K, with a temperature difference of 153 K. This indicates the convective heating is very important for fuel preheating in the near field. It is also suggested that the convective heating is more reasonable than convective cooling as a convection term in the near field.

To examine the contribution of various heating mechanisms to fuel surface temperature in the near field, only one heating mechanism was considered each time. The calculated results are presented in Fig. 3. When the flame radiation, the combustion zone radiation and the convective heating are considered separately, the fuel surface temperature $T_s|_{X\to 0}$ is obtained as 503, 501, and 505 K respectively, and the curves of $T_s \sim X$ are very close to each other. The results indicate that the contributions of the flame radiation, the combustion zone radiation and the convective heating to fuel preheating are of the same magnitude. It also reveals that radiative heating is the dominant mechanism for fuel pre-heating, while the combined effects of three heating mechanisms control the fuel surface temperature increasing to ignition temperature in the near field.

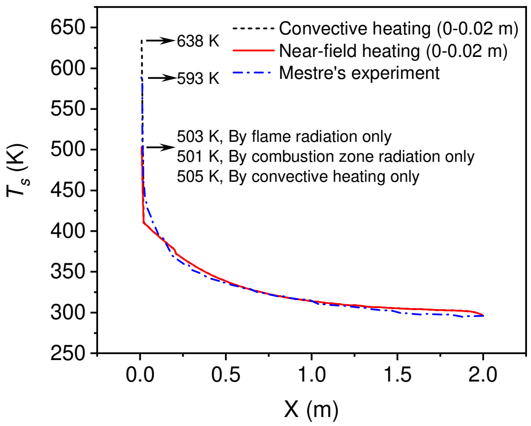

Fig. 3. Fuel surface temperature under various heating mechanisms in the near field.

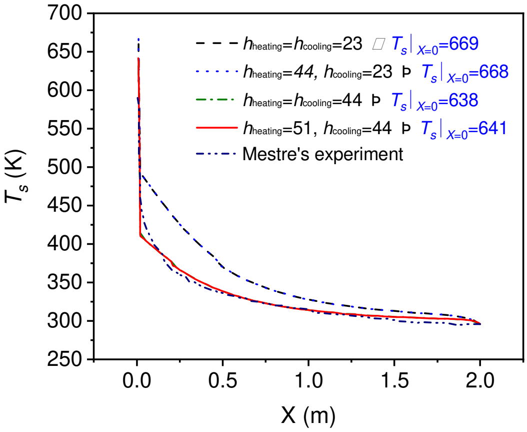

Fig. 4. Fuel surface temperature *v.* convective heat transfer coefficient.

The flame radiation on fuel preheating takes effect in the whole field. Comparatively, the combustion zone radiation and convective heating take effects in the near field, with fewer effects in the far field. These are the main cause that the fuel surface temperature T_s increases slowly with decreasing X in the far field then increases rapidly in the near field.

Convective heat transfer coefficient

The convective heat transfer coefficient is the key parameter in calculating both convective heating and cooling. The coefficient is related to film temperature, external flow, turbulence status, etc. The value h = 23.2 W·m^{-2}·K^{-1} [1] and h = 44 W·m^{-2}·K^{-1} [2] are used for calculating the convective cooling. In the above discussion, $h_{cooling}$ = 44 W·m^{-2}·K^{-1} and $h_{heating}$ = 44 W·m^{-2}·K^{-1} are employed to calculate the convective cooling and heating, respectively. The film temperature is higher in the near field than that in the far field. When the film temperature T_{fm} = 600 K, the coefficient could be obtained by Eq. (4), then we have $h_{heating}$ = 51 W·m^{-2}·K^{-1}.

To examine the effects of coefficient h on the fuel surface temperature, different values of $h_{cooling}$ and $h_{heating}$ are used, and the results are shown in Fig. 4. When $h_{cooling}$ = 23 W·m^{-2}·K^{-1}, the calculated results are higher than the experimental data in both far field and near field. When $h_{cooling}$ = 44 W·m^{-2}·K^{-1}, the calculated results fit better to the experimental data. The results indicate that convective cooling coefficient affects both far field and near field, while the effect of convective heating coefficient is only in near field. It is obvious that the fuel surface temperature increases with decreasing $h_{cooling}$ both in the near field and far field, while it increases with increasing $h_{cooling}$ in the near field.

Flame temperature

When $h_{heating}$ = 51 W·m^{-2}·K^{-1} and $h_{cooling}$ = 44 W·m^{-2}·K^{-1}, the fuel surface temperature $T_s|_{X\to 0}$ = 641 K is higher than ignition temperature, maybe due to overestimate of flame temperature, emissivity, convective heating. Since the flame radiation takes effect on fuel preheating is in both near field and far field, the variation of flame temperature also affects the whole field. The calculated fuel surface temperature for different flame temperatures is shown in Fig. 6. It is obvious that the fuel surface temperature increases with increasing flame temperature. When T_f = 1093 K, the calculated values agree better with the experimental data. Since the flame temperature T_f = 1093 K is used in the model, the overestimate of $T_s|_{X\to 0}$ is not caused by using higher flame temperature.

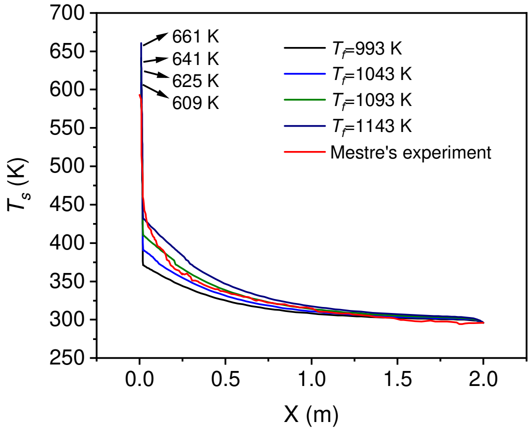

Fig. 5. Fuel surface temperature *v.* flame temperature.

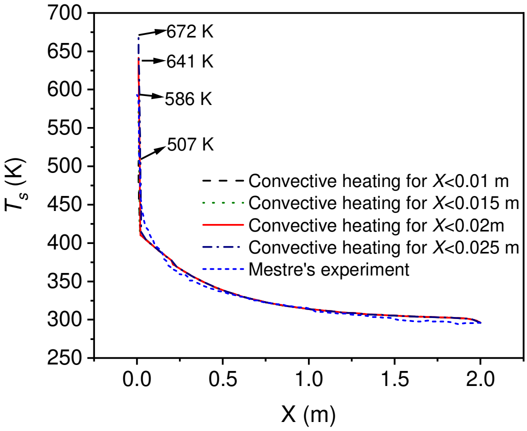

Fig. 6. Fuel surface temperature *v.* convective heating influence range.

Convective heating influence range

The convective heating influence range is assumed in the near field for X < 0.02 m. For various influence range, the calculated fuel surface temperature is presented in Fig. 6. The results indicate that fuel surface temperature $T_s|_{X\to 0}$ increases with increasing influence range. For influence range X < 0.015 m, the fuel surface temperature $T_s|_{X\to 0}$ is lower than the ignition temperature. For the influence range X < 0.025 m, the fuel surface temperature $T_s|_{X\to 0}$ is much higher than the ignition temperature. Therefore, the influence range X < 0.02 m is more reasonable. It is demonstrated that the convective heating mainly affects the near field.

In summary, the parameters used in the model are reasonable, including convective cooling coefficient $h_{cooling}$ = 44 W·m^{-2}·K^{-1}, flame temperature T_f = 1093 K, the convective heating influence range X < 0.02 m.

CONCLUSION

This paper presents a calculation analysis on surface fire spread. Heat radiation and convection are quantitatively analyzed. The major results are summarized as follows.

(1) For fuel preheating mechanism, the convective heating and the combustion zone radiation take effect in the near field, the convective cooling affects in the far field, while the flame radiation and the radiation loss affect in both near field and far field.

(2) For fuel elements closer to the flame front, the fuel surface temperature increases slowly in the far field then increases rapidly in the near field. The contributions of flame radiation, combustion zone radiation and convective heating to fuel preheating are of the same magnitude in the near field. Radiative heating is the dominant mechanism for fuel pre-heating. Fuel surface temperature increases to ignition temperature in the near field due to the combined effects of three heating mechanisms.

(3) Convective heating coefficient only affects near field, while convective cooling coefficient affects both far field and near field.

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