

Micro-organic dust combustion considering particles thermal resistance

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Abstract: Organic dust flames deal with a field of science in which many complicated phenomena like pyrolysis or devolatilization of solid particles and combustion of volatile particles take place. One-dimensional flame propagation in cloud of fuel mixture is analyzed in which flame structure is divided into three zones. The first zone is preheat zone in which rate of the chemical reaction is small and transfer phenomena play significant role in temperature and mass distributions. In this model, it is assumed that particles pyrolyze first to yield a gaseous fuel mixture. The second zone is reaction zone where convection and vaporization rates of the particles are small. The third zone is convection zone where diffusive terms are negligible in comparison of other terms. Non-zero Biot number is used in order to study effect of particles thermal resistance on flame characteristics. Also, effect of particle size on combustion of micro organic dust is investigated. According to obtained results, it is understood that both flame temperature and burning velocity decrease with rise in the Biot number and particle size.

Key words: micro-organic dust; Biot number; particles thermal resistance; flame temperature; burning velocity

1 Introduction

Increasing in energy demands and completing of fossil fuels cause human to explore new resources for fulfilling these necessities, also the effective conversion systems have essential role in the future of energy production [1–4]. Biomass has been known as the major renewable resource [5]. Furthermore, power generation from biomass is a CO₂-neutral method and helps us to conserve our environment for future generations. Biomass is presently estimated to contribute the order 10%–14% of the world's energy supply [6].

Having low energy density, it is not economical to transport biomass fuels to power plants. However, small scale biomass conversion system is suitable for local usage. The stirling engine is one of the best available technologies for small-scale biomass power production which can be driven by many kinds of heat sources and can be incorporated into biomass energy utilization research projects as a viable prime mover [7–9]. The stirling engines are fed by micro-scale biomass up to 500 μm to enhance their efficiency.

Another important issue which threatens human properties is dust explosion phenomenon. This phenomenon occurs in wheat silos and also in industries

associating with micro-scale particles. A dust explosion is likely to occur when a finely divided combustible solid (in practice, the mean diameter of the particles should not exceed 1 mm) happens to be dispersed as a cloud in air (with a typical mass loading between 10 and 1000 g of dust per cubic meter or cloud), and when an appropriate ignition source (hot body, flame, electrical or mechanical spark, etc.) is activated inside this mixture. The heat evolved from the ignition source initiates the combustion of the particles located in the vicinity of the ignition point. These particles act themselves as an ignition source for the adjacent slabs of the mixture so that a “combustion zone” is allowed to propagate without additional input of energy throughout the cloud. This “combustion zone” has generally a finite thickness and it is called the “flame” [10].

Lycopodium has been known as a reference particle in organic dust combustion studies since it is mono-size which is a basic assumption in analytical models [11–12]. Researchers have done many studies about lycopodium dust combustion both experimentally [13–16] and analytically [17–26]. HAN et al [13] used thermal gravity analysis test (TGA) to achieve combustive properties of lycopodium particle, also they calculated burning velocity and flame temperature and flame length. PROUST [14] reported burning velocity and flame

temperature for three different particles; lycopodium, starch and sulphur. SESHADRI et al [17] studied analytically the structure of premixed flames propagating in combustible systems, containing uniformly distributed volatile fuel particles, in an oxidizing gas mixture.

In our previous research [18], we presented an analytical model for lycopodium dust combustion considering temperature difference between gas and particle. However, no thermal resistance is considered inside the particles. In this research, effect of the particles thermal resistance in the form of Biot number is included to the governing equations.

The dimensionless Biot number is an important parameter in the theory of self-heating and self-ignition of dust deposits. It is defined as

$$Bi = hr / \lambda$$

where h is the heat transfer coefficient at the boundary between the dust deposit and its environment; r is half the thickness, or the radius of the dust deposit; λ is its thermal conductivity. The Biot number expresses the ease with which heat flows through the interface between the powder deposit and its surroundings, in relation to the ease with which heat is conducted through the powder. A Biot number of zero means that the heat conductivity in the powder is infinite and the temperature distribution uniform at any time. $Bi = \infty$ implies that the resistance to heat flow across the boundary is negligible compared with the conductive resistance within the powder [27].

To analyze combustion of organic dust, flame structure is divided into three zones. The first zone is preheat zone where the rate of chemical reaction is small. The second zone is an asymptotically thin reaction zone where convection and rate of vaporization of the particles are negligible in comparison with reaction rate, and finally there is a post-flame zone. In next section, the conservation equations and required state equations which are needed to formulate the phenomenon are completely described. At the end, we compare our results with experimental results, and it is shown that our results are in reasonable agreement with experimental results [13–15, 28–30].

2 Governing equations

A one-dimensional steady model is used to simulate the combustion of organic dust which flame is propagated in a uniformly distributed mixture of fuel particles. Initial density of the particles is n_u , and the initial radius of the particles is r_u . Biomass pyrolysis involves numerous extremely complex reactions with many intermediate and final products. According to this, many models of biomass degradation were presented by different scientists [31]. In this work a new model is presented to

analyze lycopodium organic dust flame. Also one step global pyrolysis model is used in which it is presumed that organic fuel decomposes into volatiles.

The kinetics of pyrolysis is expressed by

$$w_{pyr} = 4\pi An_s r^2 (T - T_u)^n \tag{1}$$

Above formula is used for particles with no thermal resistance, which means the maximum rate of pyrolysis. According to Fig. 1, we use below equation to correlate variation of pyrolysis rate as a function of Biot number:

$$w_{pyr} = \exp(-Bi) \times 4\pi An_s r^2 (T - T_u)^n \tag{2}$$

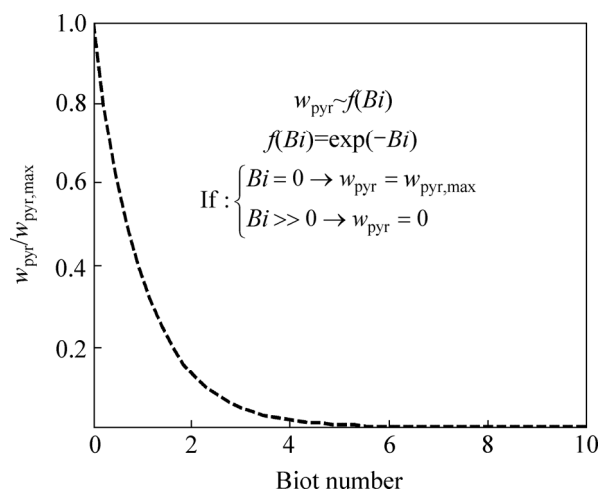


Fig. 1 Organic dust pyrolysis rate as a function of Biot number

Since large percent of produced gas is methane, the gas properties are considered same as methane. It is also presumed that by burning fuel mixture in an air oxidizer bed, CO_2 and H_2O are the products of combustion. Figure 2 shows a schematic figure of flame structure divided into three zones: preheat zone, reaction zone and post flame zone.

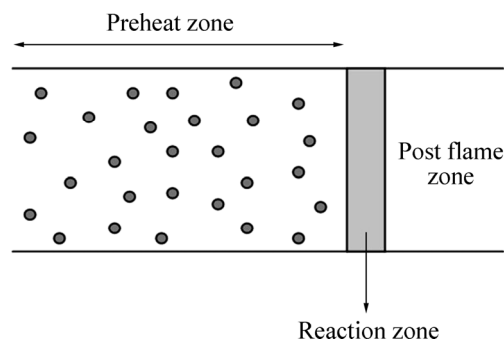


Fig. 2 Flame structure of dust particles

Reaction occurs in a thin zone $O(\epsilon)$ whereas preheat and post flame zones have considerable length. This assumption is based on asymptotic flame analysis or high Zeldovich number, and ϵ is defined as a reciprocal of Zeldovich number.

The Zeldovich number, which is presumed to be

large, is defined as

$$Ze = \frac{E(T_f - T_u)}{RT_f^2} \quad (3)$$

where the subscript f denotes conditions in the flame and the subscript u denotes conditions in the ambient reactant stream.

Mass conservation, organic particles mass conservation (solid particles), fuel mixture conservation equations along with energy conservation equation are used to formulate the physical phenomena of solid particle combustion. Furthermore, equation of state of fuel mixture is used to restrict the equations in atmospheric combustion condition to have a unique solution for our problem.

The governing equations in this problem are nonlinear which can be transformed into a linear form by introducing an independent variable x that is related to the spatial coordinate x' as

$$x = \int_0^{x'} \left(\frac{\rho}{\rho_u} \right) dx' \quad (4)$$

The conservation equations and their related boundary conditions are written as below.

Mass conservation:

$$\rho V = cte \quad (5)$$

Energy conservation:

$$\rho V C \frac{dT}{dx} = \lambda_u \frac{d^2 T}{dx^2} - \exp(-Bi) w_{pyr} Q_{pyr} \frac{\rho_u}{\rho} + w_{chem} \frac{\rho_u}{\rho} Q \quad (6)$$

where λ is the heat conductivity; w_{chem} is the gaseous fuel consumption rate; w_{pyr} is the organic particles devolatilization rate; Q is the heat released from combustion; Q_{pyr} is the heat absorbed by particles for devolatilization; C is the heat capacity of mixture.

Fuel mixture conservation:

$$\rho V \frac{dY_F}{dx} = \rho_u D_u \frac{d^2 Y_F}{dx^2} + \exp(-Bi) \times w_{pyr} \frac{\rho_u}{\rho} - w_{chem} \frac{\rho_u}{\rho} \quad (7)$$

where Y is the mass fraction and D is the mass diffusion coefficient in the above equation.

Equation of state:

$$\rho T = cte \quad (8)$$

Solid particles mass conservation:

$$\rho V \frac{dY_s}{dx} = -\exp(-Bi) \times w_{pyr} \frac{\rho_u}{\rho} \quad (9)$$

Heat capacity of the fuel mixture is expressed as

$$C = C_p + \frac{4\pi(r^3 C_s \rho_s n_s)}{3\rho} \quad (10)$$

Boundary conditions are:

$$\begin{cases} x = -\infty : T = T_u, Y_s = Y_{Fu} \text{ and } Y_F = 0 \\ x = +\infty : T = T_b, Y_s = \text{finite and } Y_F = 0 \end{cases} \quad (11)$$

3 Nondimensionalization of governing equations

These parameters are used to nondimensionalize governing equations:

$$\begin{aligned} \theta &= \frac{(T - T_u)}{(T_f - T_u)}, y_F = \frac{Y_F}{Y_{Fc}}, y_s = \frac{Y_s}{Y_{Fc}}, m = \frac{\rho V}{\rho_u V_u}; \\ Z &= \frac{\rho_u V_u C}{\lambda_u} x \end{aligned} \quad (12)$$

In above equation T_f is flame temperature and Y_{Fc} is defined as

$$Y_{Fc} Q = C(T_f - T_u) \quad (13)$$

Finally, these dimensionless quantities are defined as

$$\begin{aligned} \omega_{chem} &= \frac{\lambda_u w_{chem}}{(\rho_u V_u)^2 C Y_{Fc}}, \gamma = \frac{4.836 A n_u^{1/3} \lambda_u (T_f - T_u)^n}{V_u^2 \rho_u^{4/3} C Y_{Fc}^{1/3} \rho_s^{2/3}}, \\ y_s &= \frac{4\pi n_s \rho_s r^3}{3\rho Y_{Fc}}, q = \frac{Q_{pyr}}{Q} \end{aligned} \quad (14)$$

where V_u is burning velocity.

It is supposed that q has negligible quantity (close to zero) which means that released heat from reaction is greater than absorbed heat by particles for devolatilization. In this case we replace θ with θ_0 , thus dimensionless equations yield:

$$\begin{cases} \frac{d\theta_0}{dZ} = \frac{d^2 \theta_0}{dZ^2} + \omega_{chem} \frac{\rho_u}{\rho} \\ \frac{dy_F}{dZ} = \frac{d^2 y_F}{dZ^2} + \exp(-Bi) \times \gamma y_s^2 \theta_0^n - \omega_{chem} \frac{\rho_u}{\rho} \\ \frac{dy_s}{dZ} = -\exp(-Bi) \times \gamma y_s^2 \theta_0^n \end{cases} \quad (15)$$

The above equations are solved in each zone according to their boundary conditions and appropriate assumptions in order to obtain a reliable model for organic dust combustion to predict flame characteristics.

4 Solution of governing equation in each zone

4.1 Preheat zones ($-\infty < z < 0$)

In the asymptotic solution ($\epsilon \rightarrow 0$), it is possible to neglect reaction term, because in preheat zone particles pyrolyze to yield a gaseous fuel and there is no reaction.

Energy equation and boundary conditions are

$$\begin{cases} \frac{d\theta_0}{dZ} = \frac{d^2\theta_0}{dZ^2} \\ Z = 0 \rightarrow \theta_0 = 1 \\ Z = -\infty \rightarrow \theta_0 = 0 \end{cases} \quad (16)$$

By solving above equation the nondimensional temperature distribution is

$$\theta_0 = \exp(z), z \leq 0 \quad (17)$$

Mass conservation equation of organic particles converts to:

$$\frac{dy_s}{dZ} = -\exp(-Bi) \times \gamma y_s^{\frac{2}{3}} [\exp(z)]^n Z = -\infty \rightarrow y_s = \frac{Y_{Fu}}{Y_{Fc}} = \alpha \quad (18)$$

Y_{Fu} in the above equation is amount of fuel mixture that is available in initial particles.

Thus,

$$y_s = \left[\alpha^{\frac{1}{3}} - a \cdot \exp(nZ - Bi) \right]^3 \quad (19)$$

a in above equation is defined in below terms:

$$\alpha = \frac{\gamma}{3n} \quad (20)$$

Thus conservation equation of fuel mixture is changed to:

$$\frac{dy_F}{dZ} = \frac{d^2y_F}{dZ^2} + \gamma \left[\alpha^{\frac{1}{3}} - a \cdot \exp(nZ - Bi) \right]^2 \times \exp(nZ - Bi) \quad (21)$$

Boundary conditions are:

$$\begin{cases} Z = -\infty \rightarrow y_F = 0 \\ Z = 0^- \rightarrow y_F = 0 \end{cases} \quad (22)$$

Finally by solving fuel mixture equation, below equation is obtained:

$$\begin{cases} y_F = C_1 e^Z - \frac{\gamma \alpha^{\frac{2}{3}}}{n^2 - n} e^{(nZ - Bi)} + \frac{2\gamma \alpha^{\frac{1}{3}}}{4n^2 - 2n} e^{(2nZ - 2Bi)} - \frac{\gamma \alpha^2}{9n^2 - 3n} e^{(3nZ - 3Bi)} \\ C_1 = \frac{\gamma \alpha^{\frac{2}{3}}}{n^2 - n} e^{-Bi} + \frac{2\gamma \alpha^{\frac{1}{3}}}{4n^2 - 2n} e^{-2Bi} - \frac{\gamma \alpha^2}{9n^2 - 3n} e^{-3Bi} \end{cases} \quad (23)$$

and

$$-\left[\frac{dy_F}{dZ} \right]_{0^-} = \left[3a\alpha^{\frac{2}{3}} e^{-Bi} + a^3 e^{-3Bi} - 3a^2 \alpha^{\frac{1}{3}} e^{-2Bi} \right] \quad (24)$$

4.2 Post flame zone ($0 < z < +\infty$)

Before analyzing the reaction zone, the post-flame zone is primarily investigated.

$$\theta = 1, y_s = \text{constant}, y_F = 0 \quad (25)$$

In the post-flame zone, the available mass fraction of solid particles is approximately equal to the quantity of y_s at the end of the vaporization zone (i.e., $Z=0^-$).

4.3 Reaction zone ($z=0$)

In this zone the rate of reaction is considerable and convection and devolatilization terms are negligible in comparison with diffusion and reaction terms. It means:

$$\frac{d\theta_0}{dZ} \approx 0, \frac{dy_F}{dZ} \approx 0, \gamma y_s^{\frac{2}{3}} \theta_0^n e^{-Bi} \approx 0 \quad (26)$$

Governing equations in this zone convert into below equations:

$$\begin{cases} \frac{dy_s}{dZ} = 0 \rightarrow y_s = cte \\ \frac{d^2\theta_0}{dZ^2} = -\omega_{\text{chem}} \frac{\rho_u}{\rho} \\ \frac{d^2y_F}{dZ^2} = \omega_{\text{chem}} \frac{\rho_u}{\rho} \end{cases} \quad (27)$$

In above equation, gaseous fuel reaction rates are defined as

$$\begin{cases} \omega_{\text{chem}} = \frac{\lambda_u w_{\text{chem}}}{(\rho_u V_u)^2 C Y_{Fc}} \\ W_{\text{chem}} = v_g W_g k_g C_g \\ k_g = B_g \exp\left(-\frac{E_g}{RT}\right) \end{cases} \quad (28)$$

where C , W and k are the molar concentration, relative molecular mass and the constant rate of the overall reaction, respectively; v is stoichiometric coefficient of the fuel components which represent the amount of produced gas in devolatilization process. The above kinetics, Arrhenius law, has been widely used as a kinetics of pyrolysis process in foodstuffs and biomass [11–12, 16, 32–36] and kinetics of surface diffusivity phenomenon in adsorption refrigeration systems, too [37].

In order to analyze reaction zone expansion parameter $\varepsilon=1/Ze$ is defined to expand reaction zone. By using ε all of our previous parameters are expanded and rewritten as

$$\eta = \frac{Z}{\varepsilon}, y^* = \frac{y_F - y_{F_F}}{\varepsilon}, t = \frac{1 - \theta_0}{\varepsilon} \quad (29)$$

where y_{F_F} is mass fraction of fuel mixture prior to reaction zone. By using above expanded parameters, conservation

Eq. (27) is rewritten as

$$\begin{cases} \frac{d^2 t}{d\eta^2} = \varepsilon \omega_{\text{chem}} \frac{\rho_u}{\rho} \\ \frac{d^2 y^*}{d\eta^2} = \varepsilon \omega_{\text{chem}} \frac{\rho_u}{\rho} \end{cases} \quad (30)$$

Solving the above equations, burning velocity is achieved which is the primary purpose of this article.

$$V_u^2 = 2\varepsilon^2 D_{uF} v_g B_g (1+b) \cdot \exp\left(-\frac{E_g}{RT_f}\right) \quad (31)$$

According to Eq. (31), burning velocity is a function of T_f which is an indeterminate parameter. We need another expression to dependently calculate both of these parameters. In the resumption, procedure of finding this expression is explained.

In Eq. (27) by combining each side of the energy and gaseous fuel conservations equations together, it yields:

$$\frac{d^2 \theta_0}{dZ^2} + \frac{d^2 y_F}{dZ^2} = 0 \quad (32)$$

By integrating Eq. (32) from $Z=0^-$ up to $Z=0^+$, it is possible to achieve below matching condition:

$$\left[\frac{d\theta_0}{dz} \right]_{0^-} + \left[\frac{dy_F}{dz} \right]_{0^+} = 0 \quad (33)$$

Finally, by substituting Eqs. (17) and (24) into Eq. (33) below expression, which connects burning velocity and flame temperature together, it achieves:

$$3a\alpha^{\frac{2}{3}} e^{-Bi} + \alpha^3 e^{-3Bi} - 3a^2 \alpha^{\frac{1}{3}} e^{-2Bi} - 1 = 0 \quad (34)$$

5 Results and discussion

In order to predict flame characteristics, like burning velocity and flame temperature, explicit expression for the burning velocity in Eq. (31) should be solved simultaneously with Eq. (34). For $\phi_u > 1$, the equivalence ratio based on the fuel available in the initial fuel particles and the final adiabatic temperature can be calculated.

$$\begin{cases} \phi_u = \frac{17.18 \times Y_{Fu}}{(1 - Y_{Fu})} \\ C(T_b - T_u) = \frac{v_F W_F Q}{v_{O_2} W_{O_2}} Y_{O_{2u}} \end{cases} \quad (35)$$

where $Y_{O_{2u}}$ is the mass fraction of oxygen in the ambient reactant stream and W_{O_2} represents the relative molecular mass of oxygen.

To evaluate accuracy of the presented model, the obtained burning velocity and flame temperature are compared with experimental results [1–15, 28–30]. As

shown in Fig. 3, it is understood that our result is in a reasonable agreement with experimental data.

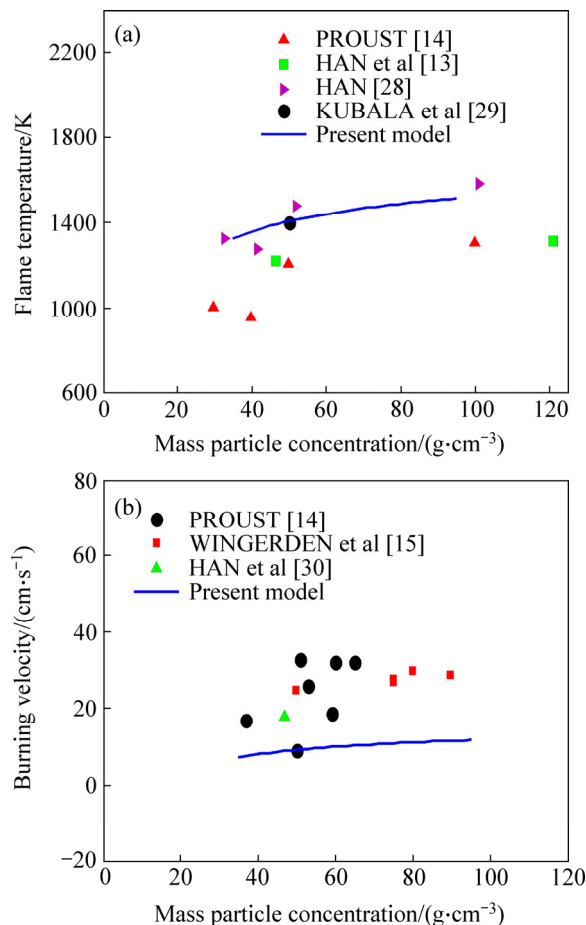


Fig. 3 Variation of flame temperature (a) and burning velocity (b) as a function of mass particle concentration for both present model ($Bi=0.2$, $T_u=300$ K, $r_u=15.5$ μm) and experimental data [13–15, 28–30]

In gas flame analysis, two types of resistances exist against the flame propagation: heat transfer resistance and chemical reaction resistance. In dry dust flame, pyrolysis (devolatilization) resistance is also added to those resistances. In fact, the interactions between these resistances in each flame control the flame characteristics, like flame temperature and burning velocity. It is clear that mass transfer resistance exists in all types of the above flames.

As shown in Fig. 4, by increasing Biot number, flame temperature and burning velocity decrease. This happens because thermal resistance of particles increases. This results in different temperature layers inside particle, and consequently different pyrolysis rates observed inside particle. By increasing Biot number, amount of produced gaseous fuel decreases and a lower flame temperature and burning velocity are achieved.

According to Fig. 4, by increasing equivalence ratio, both flame temperature and burning velocity increase. In fact, pyrolysis resistance decreases by increasing in the

mass particle density.

Effect of particle size on flame properties is illustrated in Fig. 5. By decreasing particle size, effective surface, which is exposed to heat, increases and eventually improves the pyrolysis process which increases the amount of generated fuel mixture. As shown in Fig. 5, flame temperature and burning velocity increase by reducing the particle size. Furthermore, as shown in Fig. 5(a), it is understood that by increasing equivalence ratio, adiabatic temperature decreases due to excess

amount of fuel which is remained unburned because of insufficient oxidizer. It should be noted that in measuring adiabatic temperature, rate of reaction is neglected, and the only factor that affects adiabatic temperature is the combustion heat which is related to the enthalpy of formation.

At the end, temperature of the gaseous fuel is shown as a function of dimensionless distance (Z) in different Biot numbers and particle sizes. As shown in Fig. 6, by increasing Biot number or particle size, gaseous fuel

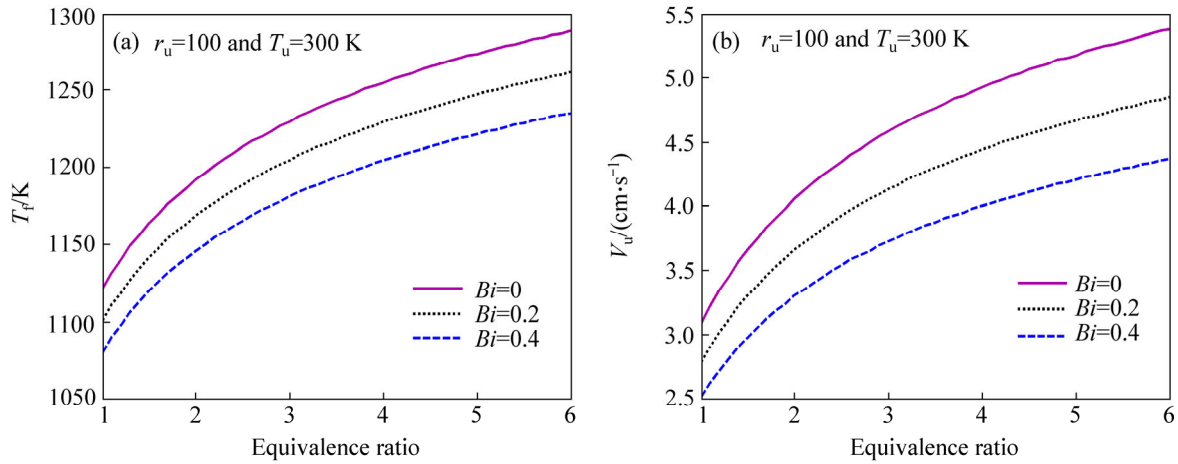


Fig. 4 Variation of flame temperature (a) and burning velocity (b) as a function of equivalence ratio in different Biot numbers

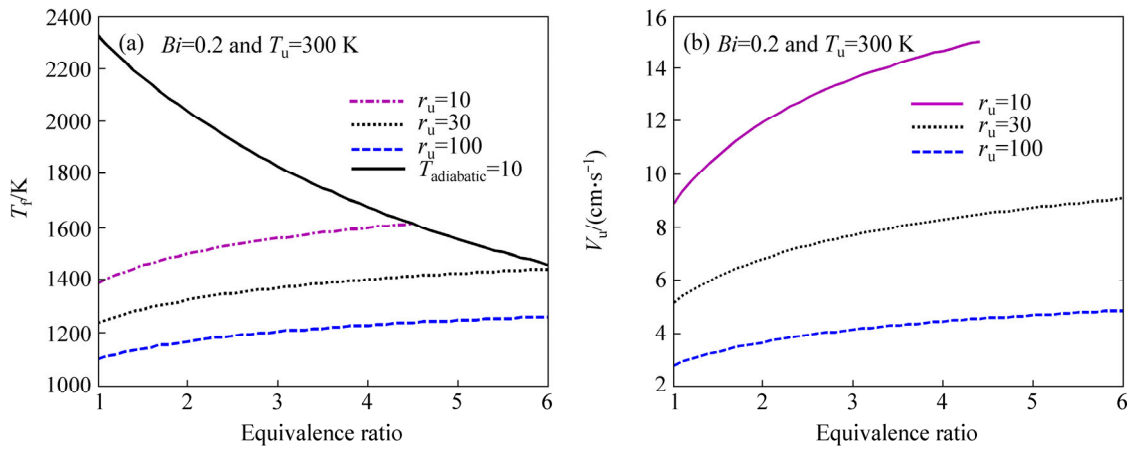


Fig. 5 Variation of flame temperature (a) and burning velocity (b) as a function of equivalence ratio in different particle sizes

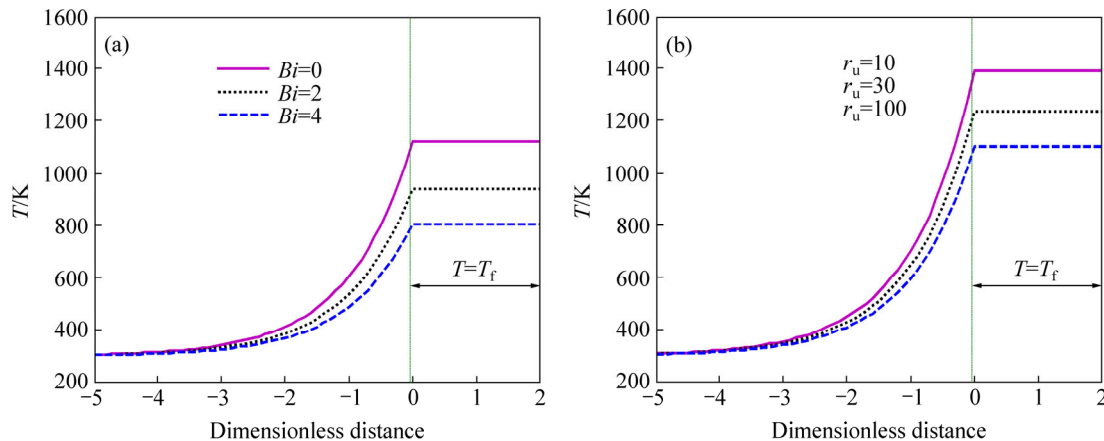


Fig. 6 Variation of gaseous fuel temperature as a function of dimensionless distance in different Biot numbers (a) and particle sizes (b)

temperature decreases since flame temperature is diminished.

6 Conclusions

1) From obtained results, it is understood that an increase in Biot number causes a decrease in both flame temperature and burning velocity. In fact, by increasing Biot number, different thermal layers are formed inside particles in which every layer has different pyrolysis rate, and consequently less amount of gaseous fuel is produced during pyrolysis procedure. Less amount of fuel is available to be burnt in reaction zone.

2) Effect of particle size is investigated. A reduction in particle size increases the amount of generated fuel mixture, which increases both flame temperature and burning velocity.

3) Finally, by increasing equivalence ratio, both flame temperature and burning velocity increase due to reduction in pyrolysis resistance.

Nomenclature symbol

B	Frequency factor characterizing rate of gaseous fuel oxidation
b	$b=Y_{gF}/\varepsilon$ scaled mass fraction of fuel at the boundary between the reaction zone
C	Heat capacity of mixture
C_p	Heat capacity of the gas
C_s	Heat capacity of a solid particle
D	Diffusion coefficient
E	Activation energy of fuel
k	Fuel reaction constant rate
m	Defined in Eq. (12)
n_s	Local number density of particles (number of particles per unit volume)
Q	Released heat per unit mass of consumed fuel particles Heat associated with volatilizing unit mass of solid fuel particles
Q_{pyr}	Heat associated with moisture evaporation from particles
q	$q=Q_{vap}/Q$, dimensionless volatile volatilization heat
q_{dry}	$q_{dry}=Q_{dry}/Q$, dimensionless latent heat of drying
R	Gas constant
r	Radius of the particle
T	Temperature
T_f	Flame temperature
t	Defined in Eq. (29)
V_u	Burning velocity

ω_{chem}	Reaction rate characterizing consumption of gaseous fuel
w_{vap}	Volatilization rate of solid fuel particles
x	Axial coordinate
Y	Mass fraction
Y_{Fc}	Defined in Eq. (13)
y_F	Defined in Eq. (12)
y_s	Defined in Eq. (12)
y	Defined in Eq. (29)
Ze	Zeldovich number, Eq. (3)
Z	Scaled independent variable, Eq. (12)

Greek symbol

α	$\alpha = (Y_s _{-\infty} / Y_{Fc})$
ε	$\varepsilon=1/Ze$, expansion parameter Eq. (29)
η	Independent variable defined in Eq. (29)
θ	Defined in Eq. (12)
λ	Thermal conductivity
ρ	Density of the reactant mixture
ρ_s	Density of a solid particle
φ_u	Equivalence ratio based on fuel available in the particles in the ambient reactant stream (ϕ_{ai_u})

Subscript

g	Gaseous fuel
F	Conditions at the reaction zone
s	Solid particles
u	Conditions in the ambient reactant stream

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