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Mild combustion in micro organic dust cloud considering radiation effect

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1. Introduction

Energy efficiency and clean combustion are two main challenging issues in recent fuel utilization. Flameless Oxidation (FLOX), also known as High Temperature Air Combustion - (HTAC), or Moderate and Intensive Low oxygen Dilution (MILD) combustion is a promising combustion technology among various techniques [1, 2] capable of accomplishing high efficiency and low emissions. It is based on delayed mixing of fuel and oxidizer and high flue gas recirculation in the flame zone [3].

A combustion process is named mild when the inlet temperature of the reactant mixture is higher than mixture auto-ignition temperature ($T_{reactant} > T_{ignition}$), whereas the maximum allowable temperature increase during combustion is lower than mixture auto-ignition temperature, due to dilution ($\Delta T_{combustion} < T_{ignition}$) [4].

Flameless combustion was first developed to suppress thermal NO_x formation, which plays a key role in ozone depletion and the generation of photochemical smog, in burners for heating industrial furnaces using preheated combustion air [5]. After accounting as an advanced combustion technique designed to reduce NO_x emissions, it is also known as a means which increases energy efficiency of high temperature furnaces. The use of a recuperative or regenerative system in a burner allows the optimization of the energy efficiency thanks to the heat transfer from hot exhaust gases to inlet combusting air [6].

Many studies on HTAC have been done in the recent years, and it has been proved that HTAC technology has many features that are superior to that in conventional combustion [7-11]. A comprehensive review paper summarizing both the development and current status of this technology can be found in [12]. High temperature air combustion technology was first applied in gaseous fuel combustion. When this idea is applied to combustion of pulverized coal, the same advantages as for gaseous fuels can be expected, including the enhancement of combustion stability and increase of combustion efficiency, the ability to use low-volatile coal like anthracite, and also lower pollution emissions [13-16]. Kiga et al. [13] presented the experimental results of pulverized coal combustion in high temperature and low-oxygen condition. The results indicated that increasing air preheat results in increased combustion efficiency and reduced NO_x emission, whereas decreasing the oxygen content of the combustion air leads to large reduction in combustion efficiency, accompanied with a slight decrease or increase in NO_x. Suda et al. [14] conducted experiments by injecting pulverized coal from a nozzle co-axially placed at the preheated air inlet. The results showed that for both bituminous and anthracite coals, release rate of volatile contents were remarkably enhanced and flame front distances from coal nozzle became less when air temperature increased. NO_x emission also became less with temperature increasing. The corresponding numerical studies were performed later. Numerical simulation results were of great consistency with experimental results [15]. Hannes et al. [16] carried out a set of experiment to investigate the NO_x emission of high temperature air combustion under Ar/O_2 as well as CO_2/O_2 atmospheres in order to quantify the ratio of fuel NO_x to thermal NO_x. This investigation showed a high reduction of thermal NO as well as an increase of fuel-NO which was primarily related to the decrease of the peak flame temperature.

Within a decade or two, it has been developed from laboratory tests to industrial applications which certainly are an extraordinary progress as for an energy technology. Some of industrial applications are heat treating and heating furnaces in the steel industry, gas turbines, bio gas burners, glass industry, chemical industry, combined heat and power, burners for hydrogen reformers and burners for combined heat and power (CHP) units. From viewpoints of the environment and fuel cost reduction, small scale biomass CHP plants are in demand, especially waste-fueled system, which are simple to operate and maintenance with high thermal efficiency similar to oil fired units. To meet these requirements, Stirling engine CHP systems combined with simplified biomass combustion process has been developed in which powder of less than 500 μm is mainly used, and a combustion chamber length of 3m is applied [17].

The object of this research is to study the mild combustion mode of particulate reactive flow in which biomass particles are used as a main fuel. This can be applied in the combustion chamber used in a Stirling engine system. An analytical approach is presented to evaluate the flame characteristics and their variations with respect to the percent of recirculated products. Here, Soret and Dufour effects which are described as a flow of matter caused by temperature gradient and flow of heat caused by concentration gradients, respectively, are ignored. Also, diffusion caused by pressure gradient is negligible and all external forces including gravitational effects are assumed to be negligible.

2. Formulation

2.1. Mathematical model

In the present model, a steady state and planar laminar flame propagates in a combustible mixture in one dimension. In this mixture, volatile fuel particles are uniformly distributed in the air and then they vaporize completely to create a gaseous fuel with a definite chemical structure. The combustion air is diluted with a large amount of recirculated exhaust gasses; the oxygen concentration in the main reaction region is reduced to a lower concentration with respect to the case of undiluted air, allowing for a better control of the reactants kinetic and average temperature. Since oxidization of fuel takes place in the gas phase, surface reactions can be neglected.

The reaction model between fuel and oxidizer is described through an overall one-step reaction as:

$$\upsilon_F\left[F\right]+\upsilon_{O_2}\left[O_2\right]+\beta\upsilon_{Prod}\left[P\right]\rightarrow\left(1+\beta\right)\upsilon_{Prod}\left[P\right].$$

Also, reaction rate is obtained from Arrhenius formula:

$$K = B\,exp\left(-\frac{E_a}{RT_f}\right).$$

where the symbols F, O_2, P denote the fuel, oxygen and product, respectively; also, the quantities $\upsilon_F, \upsilon_{O_2}, \upsilon_{Prod}$ denote their respective stoichiometric coefficients, B denotes the frequency factor, E_a is the activation energy of the reaction, is the gas constant and β is a percentage of exhaust gas which is recirculated.

Fig. 1 shows the schematic illustration of the flame structure.

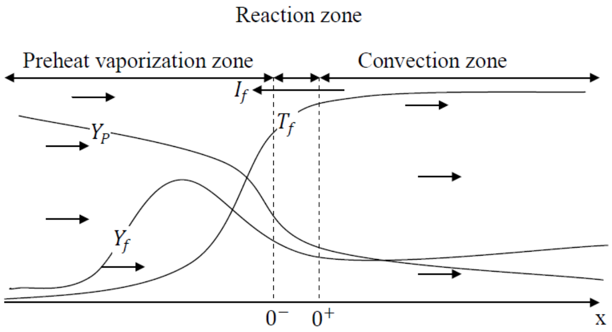

Fig. 1 Schematic illustration of the flame propagation structure

As it can be seen in this figure, there are three zones:

1- broad preheat vaporization zone,
2- thin reaction zone,
3- broad convection zone,

where in the preheat zone the temperature of particles is lower than the ignition temperature; therefore, particles start to heat up until mixture temperature reaches to the ignition temperature. Afterwards, the chemical reaction zone is started where the particles burn, and temperature remains approximately constant. It is assumed that some exhaust gases recirculate to the preheat vaporization zone, and the rest of them go to the convection zone. In the convection zone, the temperature of the combustion products falls to the ambient temperature at infinity. This division helps us to solve governing equations in each zone separately. To do so, firstly, Zeldovich number is defined as:

$$Z_e = \frac{E\left(T_f - T_u\right)}{RT_f^{\,2}},$$

where f, u denote the conditions related to flame and ambient reactant stream, respectively. From this equation, it can be inferred that when Zeldovich number is sufficiently large, the activation energy is large too, and the combustion is instantaneous, which leads to have a thin reaction zone as opposed to the preheat zone.

2.2. Governing equations

To linearize the governing equations, the following procedure is used:

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

Therefore, the governing equations for mild combustion of organic dust particles can be written as follow.

Mass conservation:

$$\rho V = Const. \tag{1}$$

Energy conservation:

$$\rho VC\frac{dT}{dx}+\beta\rho VC\frac{dT}{dx}=\lambda_u\frac{d^2T}{dx^2}+w_F\frac{\rho_u}{\rho}Q- -w_\upsilon\frac{\rho_u}{\rho}Q_\upsilon+\frac{\rho_u}{\rho}Q_r. \tag{2}$$

Gaseous fuel conservation:

$$\rho V\frac{dY_F}{dx}+\beta\rho V\frac{dY_F}{dx}=\rho_u D_u\frac{d^2Y_F}{dx^2}-w_F\frac{\rho_u}{\rho}+w_\upsilon\frac{\rho_u}{\rho}. \tag{3}$$

Mass fraction of particles:

$$\rho V\frac{dY_S}{dx}+\beta\rho V\frac{dY_S}{dx}=-w_v\frac{\rho_u}{\rho}. \tag{4}$$

Equation of state:

$$\rho T = cte, \tag{5}$$

where β is the effect of recirculated mass; ρ, Y_F and v stand for mixture density, mass fraction of gaseous fuel and superficial flow velocity, respectively. Also, λ denotes thermal conductivity coefficient which is proportional to T, while D (diffusion coefficient) is proportional to T^2. Moreover, w_F is the reaction rate defined as a gaseous fuel mass consumed per unit volume per second; Q is the heat released per unit mass of a fuel burned; Q_v is related to the heat of vaporization per unit mass of fuel; C is the heat capacity defined as a combined heat capacity of the gas, C_p, and of the particles, C_s, which can be calculated from the formula:

$$C = C_p + \frac{4\pi\left(r^3 C_s \rho_s n_s\right)}{3\rho}, \tag{6}$$

where ρ_s is the density of fuel particles presumed to be constant. Vaporization kinetics is also presumed to be calculated by the following expression:

$$w_\upsilon = A n_S 4\pi r^2 T^n, \tag{7}$$

where r is radius of fuel particle and n_s is local number density of particles (number of particles per unit volume)

The general equation of radiation transfer is:

$$\frac{dI}{dx} = \underset{I}{K_a I} + \underset{(II)}{K_s I} - \underset{(III)}{K_a I_b} - \underset{(IV)}{\frac{K_s}{4\pi}\int_{4\pi} I(\Omega) P(\theta,\Phi)\, d\Omega}, \tag{8}$$

where the terms (I), (II), (III) and (IV) are radiation intensity caused by absorption, scattering, emission, and incoming scattering brought by other particles, respectively. K_s, K_a and I are scattering coefficient, absorption coefficient, and radiation intensity, respectively. $P(\theta,\Phi)$ is phasic function of scattering.

Since absorption coefficients of gases and particles are strongly related to the particles size and particles density, the following expressions for these parameters can be written. The absorption coefficient for particles is:

$$K_a = \frac{3}{2} Q_a \frac{\sigma}{\rho d}. \tag{9}$$

By considering the light scattering which is only caused by particles, it yields:

$$K_s = \frac{3}{2} Q_s \frac{\sigma}{\rho d}; \tag{10}$$

$$K_a + K_s = K_t. \tag{11}$$

By solving Eq. (8) with respect to required boundary conditions, the following general expression for the radiation transfer is obtained:

$$Q_r = K_a I_f e^{K_t x}, \tag{12}$$

where

$$I_f = \frac{K_a}{K_t} \frac{\sigma T^4}{\pi}.$$

The boundary conditions for the model are considered as:

$$\left.\begin{array}{llll} \text{At } x = -\infty, & Y_F = 0, & T = T_u, & Y_s = Y_{Fu}; \\ \text{At } x = \infty, & T = T_b, & Y_F = \text{Finite}, & \end{array}\right\} \tag{13}$$

where T_b denotes the final adiabatic flame temperature and Y_{Fu} is the mass fraction of the fuel available in the particles.

2.3. Nondimensionalization

In order to simplify the governing equations, following dimensionless parameters are defined:

$$\left.\begin{array}{lll} \theta = \dfrac{\left(T - T_u\right)}{\left(T_f - T_u\right)}; & y_F = \dfrac{Y_F}{Y_{FC}}; & m = \dfrac{\rho V}{\rho_u V_u}; \\ z = \dfrac{\rho_u V_u C}{\lambda_u} x; & y_s = \dfrac{Y_s}{Y_{FC}}, & \end{array}\right\} \tag{14}$$

where T_f, V_u represent maximum temperature and the burning velocity of the propagated flame in a combustible mixture of organic fuel particles, respectively. Using following parameters which are defined as:

$$\left.\begin{array}{l} q = \dfrac{Q_v}{Q};\ Y_{FC} Q = C\left(T_f - T_u\right);\ \ w = \dfrac{\lambda_u w_F}{\left(\rho_u V_u\right)^2 C Y_{FC}}; \\ B' = \dfrac{K_a I_f \lambda u}{\rho \rho_u C^2 \left(T_f - T_u\right)};\ \ C' = \dfrac{K_t \lambda_u}{\rho_u C}; \\ y_s = \dfrac{4\pi r_s n_s \rho^3}{3\rho Y_{FC}};\ \ \gamma = \dfrac{4.836 A n_u^{\left(\frac{1}{3}\right)} \left(T_f - T_u\right)}{V_u^2 \rho_u^{\left(\frac{4}{3}\right)} C Y_{FC}^{\left(\frac{1}{3}\right)} \rho_S^{\left(\frac{2}{3}\right)}}. \end{array}\right\} \tag{15}$$

Non-dimensionalized governing equations are obtained as follow:

$$\left.\begin{array}{l} m(1+\beta)\dfrac{d\theta}{dz} = \dfrac{d^2\theta}{dz^2} + w\dfrac{\rho_u}{\rho} - q\gamma\theta^n y_S^{\left(\frac{2}{3}\right)} + \\ \qquad + \dfrac{B'}{V_u^2} exp\left(\dfrac{C'}{V_u} z\right); \\ m(1+\beta)\dfrac{dy_F}{dz} = \dfrac{d^2 y_F}{dz^2} - w\dfrac{\rho_u}{\rho} + \gamma\theta^n y_S^{\left(\frac{2}{3}\right)}; \\ m(1+\beta)\dfrac{dy_S}{dz} = -\gamma\theta^n y_S^{\left(\frac{2}{3}\right)}. \end{array}\right\} \tag{16}$$

For simplicity, Lewis number which is defined as a ratio of diffusion of heat to diffusion of mass is assumed to be unity:

$$Le = \frac{\lambda}{\rho C D} = 1. \tag{17}$$

Dimensionless forms of the boundary conditions are:

$$\left.\begin{array}{l} At\ \ z = -\infty \rightarrow y_s = \dfrac{Y_{Fu}}{Y_{FC}} = \alpha, \quad y_F = 0,\ \ \theta = 0; \\ At\ \ z = \infty \rightarrow y_F = \text{Finite}, \qquad \theta = \theta_b = \dfrac{T_b - T_u}{T_f - T_u}. \end{array}\right\} \tag{18}$$

Since q (i.e. as a ratio of the required heat for vaporizing the fuel particles to the overall released heat in the flame) has a small amount, it can be neglected ($q = 0$). By considering above explanation and $m = 1$, θ^0 denotes the nondimensionalized temperature. Thus, governing equations can be rewritten as:

$$\left.\begin{aligned}
&(1+\beta)\frac{d\theta^\circ}{dz} = \frac{d^2\theta^\circ}{dz^2} + w\frac{\rho_u}{\rho} + \frac{B'}{V_u^{\,2}}exp\left(\frac{C'}{V_u}z\right);\\
&(1+\beta)\frac{dy_F}{dz} = \frac{d^2 y_F}{dz^2} - w\frac{\rho_u}{\rho} + \gamma\left(\theta^\circ\right)^n y_S^{\left(\frac{2}{3}\right)};\\
&(1+\beta)\frac{dy_S}{dz} = -\gamma\left(\theta^\circ\right)^n y_S^{\left(\frac{2}{3}\right)}.
\end{aligned}\right\} \tag{19}$$

In order to obtain solutions for these differential equations, in the limit of $Ze \to \infty$ with assumption $\gamma = O(1)$, the asymptotic approach is utilized. Now, the conservation equations governing in each zone are solved separately.

3. Solutions

3.1. Preheat zone ($-\infty < x < 0^-$)

It is assumed that the reaction zone is located at $z = 0$; thus, $z < 0$ represents the preheat zone, and $z > 0$ represents the convection zone. In the preheat zone, the chemical reaction between fuel and oxidizer is small; as a result of which the conservation equations for this zone are obtained by balancing between the convective, diffusive, and vaporization terms. Hence, it yields:

$$(1+\beta)\frac{d\theta^\circ}{dz} = \frac{d^2\theta^\circ}{dz^2} + \frac{B'}{V_u^{\,2}}exp\left(\frac{C'}{V_u}z\right). \tag{20}$$

Since T_f is the flame temperature in the reaction zone, the boundary conditions for above equation is:

$$z = 0 \to \theta^\circ = 1;\ z = -\infty \to \theta^\circ = 0. \tag{21}$$

The dimensionless temperature in preheat zone is obtained as:

$$\begin{aligned}
\theta^\circ = &\left[1 + \frac{B'/V_u^{\,2}}{\left(\frac{C'^2}{V_u^{\,2}} - \frac{(1+\beta)C'}{V_u}\right)}\right]exp\left((1+\beta)z\right) -\\
&-\left[\frac{B'/V_u^{\,2}}{\left(\frac{C'^2}{V_u^{\,2}} - \frac{(1+\beta)C'}{V_u}\right)}\right]exp\left(\frac{C'}{V_u}z\right),\quad z \le 0.
\end{aligned} \tag{22}$$

Regarding the following boundary conditions:

$$\left.\begin{aligned}
&z = 0^- &&\to y_F = y_{Ff};\\
&z = -\infty &&\to y_F = \frac{dy_F}{dz};\qquad y_S = \alpha.
\end{aligned}\right\} \tag{23}$$

It yields:

$$\left.\begin{aligned}
&y_S = \left\{\alpha^{1/3} - \frac{a}{(1+\beta)^2}exp\left[(1+\beta)nz\right]\right\}^3,\qquad z \le 0;\\
&a = \frac{\gamma}{3n}\left[1 + \frac{B'/V_u^{\,2}}{\left(\frac{C'^2}{V_u^{\,2}} - \frac{(1+\beta)C'}{V_u}\right)}\right]^n;
\end{aligned}\right\} \tag{24}$$

$$-\left[\frac{dy_F}{dz}\right]_{0^-} = \frac{3a\alpha^{\frac{2}{3}}}{(1+\beta)} - \frac{3a^2\alpha^{\frac{1}{3}}}{(1+\beta)^3} + \frac{a^3}{(1+\beta)^5} - Y_{Ff}, \tag{25}$$

where the superscript – (0^-) denotes the conditions on the interface between the preheat zone and the reaction zone.

3.2. Reaction zone ($0^- < x < 0^+$)

Since the reaction zone is very narrow, as a result of large value of Zeldovich number, the convective and vaporization terms are small in comparison with diffusive and reactive terms. In this zone, particles are oxidized and burnt, and the burning velocity is obtained by analyzing this zone. Thus, the governing equations are followed as:

$$\left.\begin{aligned}
&\frac{d^2\theta^\circ}{dz^2} = -w\frac{\rho_u}{\rho};\\
&\frac{d^2 y_F}{dz^2} = w\frac{\rho_u}{\rho};\\
&(1+\beta)\frac{dy_S}{dz} = 0.
\end{aligned}\right\} \tag{26}$$

In order to solve the equations in the reaction zone, the following expansion variable $\left(\frac{1}{\varepsilon}\right)$ is defined:

$$\left.\begin{aligned}
&\varepsilon = \frac{1}{Ze};\ \eta = \frac{Z}{\varepsilon};\ t = \frac{1-\theta^\circ}{\varepsilon};\\
&y = \frac{y_F - y_{Ff}}{\varepsilon};\ b = \frac{y_{Ff}}{\varepsilon}.
\end{aligned}\right\} \tag{27}$$

Here, it is needed to define boundary conditions. Boundary conditions can be obtained by matching this zone with the solutions obtained in the preheat zone $(\eta \to -\infty)$ and with the convection zone $(\eta \to \infty)$:

$$\left.\begin{aligned}
&\eta \to +\infty &&\frac{dt}{d\eta} = \frac{dy}{d\eta} = 0;\\
&\eta \to -\infty &&\frac{dt}{d\eta} = -(1+\beta).
\end{aligned}\right\} \tag{28}$$

It yields:

$$t = y. \tag{29}$$

Since, the analysis is restricted to the cases where fuel is the limiting reactant in the reaction zone and oxygen is in excess, the reaction rate w_F can be written as: $w_F = \upsilon_F W_F K C_F$; $K = B\,exp\left(-\frac{E}{RT}\right)$,

where C, W and υ are the molar concentration, molecular weight and stoichiometric coefficient of the fuel components. k is the rate constant of the overall reaction, respectively:

$$w = \frac{\lambda_u w_F}{(\rho_u V_u)^2 C Y_{FC}};$$

$$w = \frac{\lambda_u \upsilon_F W_F C_F B}{(\rho_u V_u)^2 C Y_{FC}} exp\left(-\frac{E}{RT}\right). \tag{30}$$

From above equations, it is concluded that:

$$\frac{d^2 t}{d\eta^2} = \Lambda(b+y)exp(-t), \tag{31}$$

where $\Lambda = \frac{\upsilon_F \lambda_u B\varepsilon^2}{\rho_u V_u^2 C} exp\left(-\frac{E}{RT_f}\right)$.

It yields:

$$2(1+b)\Lambda = (1+\beta)^2. \tag{32}$$

Now, the burning velocity can be evaluated as:

$$V_u^2 = \frac{2(1+b)\upsilon_F \lambda_u B\varepsilon^2}{\rho_u C(1+\beta)^2} exp\left(-\frac{E}{RT_f}\right). \tag{33}$$

If the values of parameters b and T_f are known, V_u which is defined as a burning velocity calculated by neglecting vaporization heat of fuel particles can be evaluated. Since the thickness of reaction zone is too small, it is justifiable to set $y_{Ff} = 0$; it means $b = 0$. For calculating the burning velocity (V_v), the following equation is used:

$$V_v = V_u\, exp\left(-\frac{qZe}{2}\right). \tag{34}$$

In order to obtain T_f in the reaction zone, the following condition is used:

$$\left[\frac{dy_F}{dz}\right]_{z\to 0^+} + \left[\frac{d\theta^0}{dz}\right]_{z\to 0^+} = \left[\frac{dy_F}{dz}\right]_{z\to 0^-} + \left[\frac{d\theta^0}{dz}\right]_{z\to 0^-}, \tag{35}$$

where the superscript + (0^+) denotes the conditions on the interface between the convection zone and the reaction zone. By considering $O(\varepsilon)$ for gradients at 0^+, and substituting Eqs. (25) and (28) into Eq. (35) with respect to $y_{Ff} = 0$, it yields:

$$\frac{3a\alpha^{\frac{2}{3}}}{(1+\beta)} - \frac{3a^2\alpha^{\frac{1}{3}}}{(1+\beta)^3} + \frac{a^3}{(1+\beta)^5} - (1+\beta) = 0. \tag{36}$$

4. Results

It is assumed that the gas released from vaporization of fuel is methane. Therefore, products are CO_2, H_2O, N_2. Here, the values of parameters used in calculations are summarized as below:

$\lambda_u = 14.644\times10^{-2}$ j/(msk); $\rho_u = 1.135$ kg/m^3; $Q_a = 0.8$; $\rho_s = 1000$ kg/m^3.

Parameters of the appropriate overall chemical kinetics rate are $E = 96.23$ kj/mole and $B = 3.5\times10^6$ mol^{-1} s^{-1}. Calculations of flame characteristics based on present model have been done, and the following results are derived.

The variations of burning velocity (V_V) versus equivalence ratio (φ_u) for different values of r_u are shown in Fig. 2. It can be seen, for given value of φ_u the burning velocity increases with decreasing the value of r_u. In Fig. 3 flame temperature as a function of equivalence ratio for different values of particle radius is plotted.

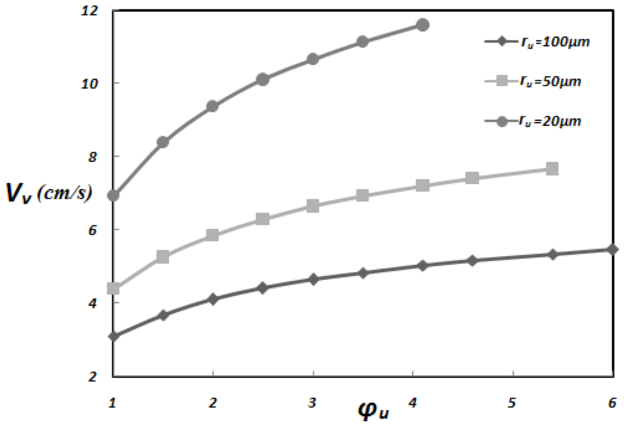

Fig. 2 Variation of the burning velocity as a function of φ_u for different values of r_u

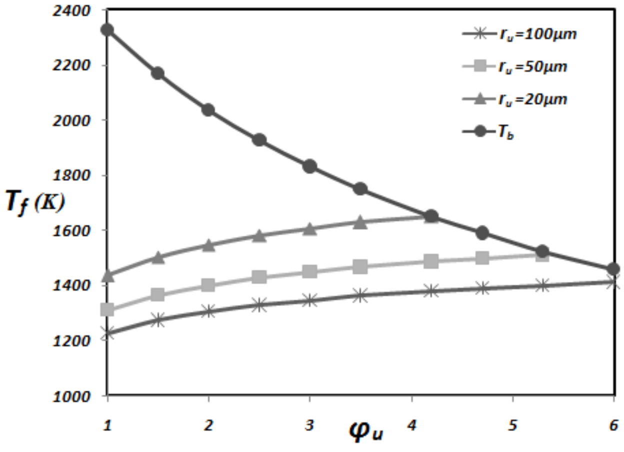

Fig. 3 Variation of the flame temperature as a function of φ_u for different values of r_u

As shown in Figs. 2 and 3, the smaller particles are, the higher flame temperature and burning velocity will be. By decreasing the radius of particles, the ratio of the surface to the volume of heat transfer increases, which is led to enhancement of heat transfer rate to particles;

therefore, the particles vaporize and reach to the ignition temperature sooner; finally, burning velocity and flame temperature increase with decreasing the particles radius.

Later studies have shown that in combustion problem due to high level of temperature, radiation plays an important role in flame structure and its characteristics such as flame temperature and burning velocity. This effect becomes more obvious in combustion of solid particles. Since the absorption coefficient of particles is higher than absorption coefficient of gasses, the radiation should be taken into account in combustion of particles. In the present study, the radiation emitted from the reaction zone to the preheat zone has been considered. We can infer from the Fig. 4 that the radiation results in temperature rise of the particles and gas mixture. In Fig. 5 the variations of the burning velocity versus equivalence ratio by considering radiation effect are plotted.

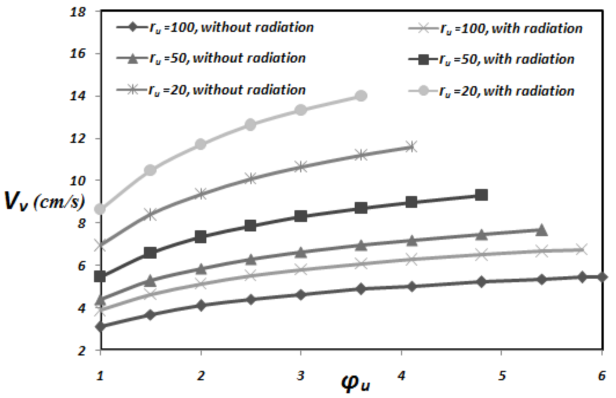

Fig. 4 Effect of radiation on burning velocity for different values of r_u

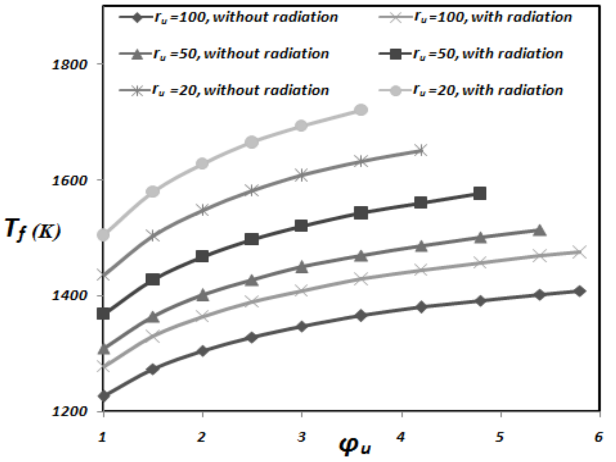

Fig. 5 Effect of radiation on flame temperature for different values of r_u

Since the modeling of radiation term in the combustion of fine particles is complicated, some simplifications were made in order to find the influence of radiation on flame velocity and flame temperature. Not only a source term is needed to be considered in the preheat zone, leading to increase in flame velocity, but also an additional sink term neglected in this study is required to be taken into account in the flame zone. Thus, the flame velocity and temperature presented here is somewhat overestimated, but it is more reliable than the case in which radiation effect is ignored; higher flame velocity is gained when the radiation term is considered.

In Figs. 6 and 7 the variations of the burning velocity and flame temperature versus equivalence ratio for different amounts of recirculated products are reported. By increasing the recirculation amount of hot exhaust gases, the combustion air is diluted more, as a result of which flame temperature and burning velocity are reduced. As combustion proceeds in lower temperature through increase in recirculated mass, lower level of NO_x emission is gained, which is very important in control of pollutants.

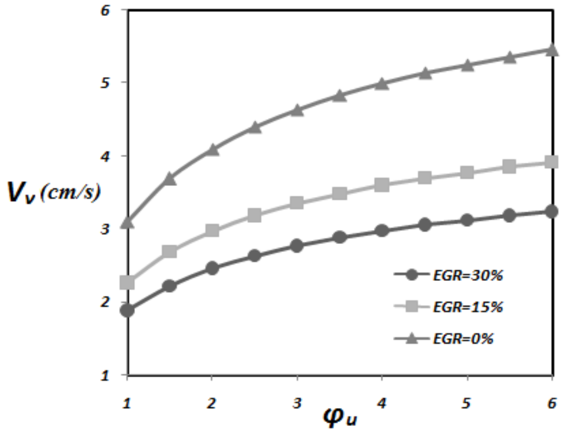

Fig. 6 Variation of the burning velocity versus φ_u for different amounts of recirculated products

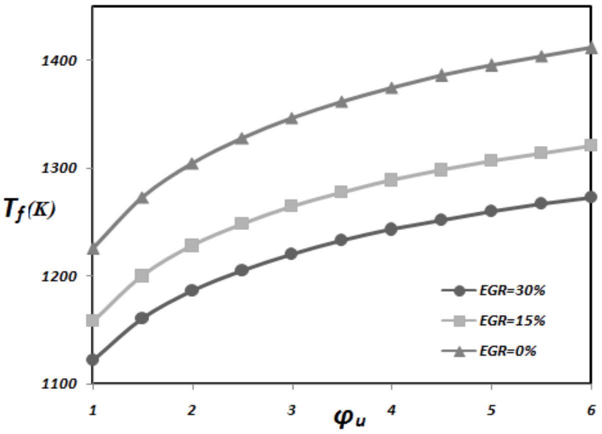

Fig. 7 Variation of the flame temperature versus φ_u for different amounts of recirculated products

5. Conclusions

The mild combustion mode of particulate reactive flow in which biomass particles are used as a main fuel has been investigated. An analytical approach has been used to evaluate the flame characteristics and their variations with respect to the percent of recirculated products. The radiation and particle size effects have been also studied. It has shown that the radiation effect causes flame temperature to increase and smaller particle to culminate to higher flame temperature. Utilizing exhausted gases recirculated leads to a lower flame temperature, thereby hazardous emissions are reduced. Furthermore, there is a limitation in recirculated gases amount.

References

1. **Cho, E.S.; Chung, S.H.** 2004. Characteristics of NO_x emission with flue gas dilution in air and fuel sides, KSME Intl. J. 18: 2303-2309. http://dx.doi.org/10.1007/BF02990235.
2. **Cho, E.S.; Chung, S.H.** 2009. Improvement of flame stability and NO_x reduction in hydrogen-added ultra lean premixed combustion, J. Mech. Sci. Technol. 23: 650-658. http://dx.doi.org/10.1007/s12206-008-1223-x.
3. **Cho, E.S.; Danon, B.; Arteaga Mendez, L.D.; de Jong, W., Roekaerts, D.J.E.M.** 2009. Characteristics of multi-burner positioning and operating mode in a FLOXTM furnace, 1st International Conference on Sustainable Fossil Fuels for Future Energy, Rome, Italy, 1-6.
4. **Cavaliere, A; de Joannon, M.** 2004. Mild combustion, Prog. Energy Combust. Sci. 30: 329-366. http://dx.doi.org/10.1016/j.pecs.2004.02.003.
5. **Baukal, C.E.; Schwartz, R. E.** 2001. The John Zink Combustion Handbook, CRC Press, TULSA, Okla, 750p.
6. **Katsuki, M.; Hasegawa, T.** 1998. Science and technology of combustion in highly preheated air, Proc. Comb. Inst. 27**:** 3135-3146. http://dx.doi.org/10.1016/S0082-0784(98)80176-8.
7. **Yang, W; Blasiak, W.** 2004. Combustion performance and numerical simulation of a high temperature air-LPG flame on a regenerative burner, Scand. J. Metallurgy 33: 113-120. http://dx.doi.org/10.1111/j.1600-0692.2004.00675.x.
8. **Schaffel, N; Mancini, M; Szlek, A; Weber R.** 2009. Mathematical modeling of MILD combustion of pulverized coal, Combust. Flame 156: 1771-1784. http://dx.doi.org/10.1016/j.combustflame.2009.04.008
9. **Hasegawa, T.; Mochida, S; Gupta, A.K.** 2002. Development of advanced industrial furnace using highly preheated air combustion, J. Propul. Power 18: 233-239. http://dx.doi.org/10.2514/2.5943.
10. **Tsuji, H.; Gupta, A.K; Hasegawa, T.; Katsuki, M.; Kishimoto, K.; Morita, M.** 2003. High temperature air combustion: from energy conservation to pollution reduction, CRC Press, New York.
11. **Lille, S.; Blasiak, M; Jewartowski, M.** 2005. Experimental study of the fuel jet combustion in high temperature and low-oxygen content exhaust gases, J. Energy 30: 373-384. http://dx.doi.org/10.1016/j.energy.2004.05.008.
12. **Weber, R.; Mancini, M.** 2008. Recent developments in flameless combustion technology, Proceeding of the 8th European Conference on Industrial Furnaces and Boilers, Vilamoura, Portugal.
13. **Kiga, T.; Yoshikawa, K; Sakai, M; Mochida, S.** 2000. Characteristics of pulverized coal combustion in high-temperature preheated air, J. Propul. Power 16: 601-605. http://dx.doi.org/10.2514/2.5614.
14. **Suda, T.; Takafuji, M; Hirata, T; Yoshino, M; Sato, J.** 2002. A study of combustion behavior of pulverized coal in high-temperature air, Proc. Comb. Inst. 29: 503-509. http://dx.doi.org/10.1016/S1540-7489(02)80065-7.
15. **He, R.; Suda, T.; Takafuji, M; Hirata, T; Sato, J.** 2004. Analysis of low no emission in high temperature air combustion for pulverized coal, Fuel. 83: 1133-1141. http://dx.doi.org/10.1016/j.fuel.2003.12.010.
16. **Hannes, S.; Dragisa, R.; Malte, F; Anja, S; Reinhold, K; Gunter, S.** 2009. NO_x-Emissions from flameless coal combustion in air, Ar/O2 and CO2/O2, Proc. Comb. Inst. 32: 3131-3138. http://dx.doi.org/10.1016/S1540-7489(02)80065-7.
17. **Sato, K.; Ohaiwa, N.; Ishikawa, A; Imogima, H; Nishiyama, A; Moriya, Y.** 2008. Development of small scale CHP plant with a wood powder stirling engine, Int. J. Power Energy Syst. 2: 1221-1231. http://dx.doi.org/10.1299/jpes.2.1221.

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NESMARKUS DEGIMAS ORGANINIŲ MIKRODALELIŲ DULKIŲ DEBESYJE

Reziumė

Šiame darbe nagrinėjamas kietųjų dalelių masės judėjimo poveikis nusistovėjusiam liepsnos plitimui tolygiai pasiskirsčiusių lakių organinių dalelių debesyje. Atlikta asimptotinė analizė pagrįsta dideliu Zeldovičiaus skaičiumi arba aukštu degimo reakcijos lygiu. Ši 1D laminarinė liepsna suskirstyta į tris zonas: pašildymo zoną, kurioje cheminės reakcijos greitis yra nedidelis ir garavimas turi didelę įtaką temperatūrų ir masių pasiskirstymui, reakcijos zoną, kurioje dalelių konvekcijos ir garavimo greičiai yra maži, ir konvekcijos zoną, kurioje difuzijos dedamoji tvarumo lygtyje yra nežymi. Šiame modelyje daroma prielaida, kad išgaravusios dalelės užleidžia vietą degioms dujoms; išmetamosios dujos sugrįžta į pašildymo zoną, kur susimaišo su pirminėmis dalelėmis ir degiomis dujomis arba neleidžia orui labai įkaisti ir taip palaiko palyginti žemą liepsnos temperatūrą. Tiriant liepsnos charakteristikas, esant įvairiems kietojo mišinio santykiams, atsižvelgiama į spinduliavimo ir masės judėjimo veiksnius. Spinduliavimas iš reakcijos zonos į dalelių ir dujų mišinį, vykstantis pašildymo zonoje, didina liepsnos temperatūrą ir degimo greitį. Kadangi karštos išmetamosios dujos nukreipiamos į tiekiamo oro srautą, degimo oras atskiedžiamas, todėl liepsnos temperatūra, o atitinkamai ir NOx emisija, mažėja.

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MILD COMBUSTION IN MICRO ORGANIC DUST CLOUD CONSIDERING RADIATION EFFECT

Summary

This paper presents the effect of mass recirculation on the structure of steady state flame propagation in a uniform cloud of volatile organic particles. Based on large Zeldovich number or high reaction rate of combustion, asymptotic analysis is used. This one-dimensional laminar flame structure is divided into three zones. The first zone is a preheat zone in which the rate of chemical reaction is small, and evaporation plays a significant role in temperature and mass distribution. The second zone is a reaction zone in which convection and vaporization rates of particles are small. The third zone is a convection zone in which diffusive terms in the conservation equations are negligible. In this model, it is assumed that particles vaporize to yield a gaseous fuel; also, a massive exhaust gas recirculates to the preheat zone where it mixes with primary particles and gases either to dilute the combustion air and to generate relatively low flame temperature. At last, the flame characteristics for different equivalence ratios of the solid mixture are studied by considering the effects of radiation and mass recirculation. Radiations from reaction zone to the mixture of particles and gases existed in the preheat zone increase flame temperature and burning velocity. As the hot exhaust gases are recirculated to the inlet combustion air, the combustion air is diluted; thus, flame temperature and consequently NO_x emission are decreased.

Keywords: flameless combustion, analytical model, organic particle, laminar premixed flame, radiation effect.

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