DOI: http://dx.doi.org/10.22104/jpst.2016.351 Journal of Particle Science and Technology 2 (2016) 151-161

J | P | S | T Journal of Particle Science and Technology
jpst.irost.ir
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Effect of the temperature difference between gas and organic dust on propagating spherical flames

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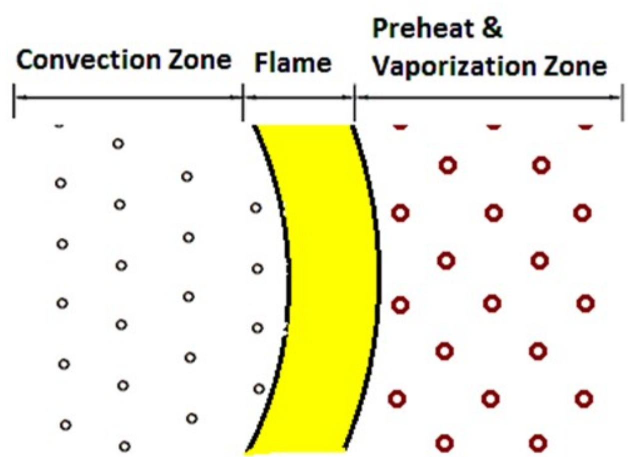
HIGHLIGHTS

- The effect of the temperature difference between gas and particle on the spherical flames was investigated.
- This research is about the investigation of real state of flame (spherical flame).
- Temperature difference results the lower gaseous fuel.
- Burning velocity, flame speed and flame temperature decreased with assumption of temperature difference.
- The particle temperatures are lower than flame temperature.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 July 2016
Received in revised form
02 September 2016
Accepted 09 September 2016

Keywords:
Combustion
Spherical Flame
Organic Dust
Burning Velocity
Particle Temperature

ABSTRACT

A new analytical study performed to investigate the effect of the temperature difference between gas and particle in propagation of the spherical flames. The combustible system is containing uniformly distributed volatile fuel particles in an oxidizing gas (air) mixture. The model includes evaporation of volatile matter of dust particles to known gaseous fuel (methane) and the single-stage reaction of gas-phase combustion. The structure of the flame is composed of a preheat zone, reaction zone, and convection zone. The study is within the framework of large activation energy and quasi-steady assumptions. The validity of theoretical prediction is confirmed by data presented in other literature including burning velocity. The obtained results illustrate the effects of the above parameter on the variations of the flame speed, temperature, particle mass fraction, flame temperature, concentration, and burning velocity for gas and particle.

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1. Introduction

Combustion of heterogeneous mixtures consisting of particles and an oxidizer is important in many areas of engineering. The risk of ignition and explosion of organic cloud particles, is always have raised as a critical challenge in industries such as agricultural, chemical, food, grain storage, coal mining and, etc. Scientists have sought for develop methods for modeling the combustion of organic particles and the prevention of their explosions in industries. Bio powder and organic particles are the suitable options for production of alternative fuel. Understanding of the physical and chemical processes of combustion of organic particles is very applicable for energy production such as boilers, large-scale furnaces and advanced spark ignition engines and gas-turbine systems for electricity generation. Recently, combustion of the synthesis gas, produced from the gasification of coal, in gas turbines is especially interested.

The physical mechanisms of two-phase flow were studied lower than gas flows. Whereas considerable researches have been done on the spray reactions, but the study of the reaction of two-phase flow were considered very low. The solid phase has a greater thermal inertia than the gas phase. Therefore the temperature difference between the gas phase and the solid occurs. Temperature difference between the particle and the gas changes reactive characteristics such as reaction temperature, gas velocity and reaction components. Many studies have been conducted on the flame propagation in the cloud of particles. Elkotb et al. developed a theoretical model to determine the ignition characteristics of organic dust [1]. Liu et al. [2] investigated the flame propagation through the hybrid mixture of coal dust and methane in a combustion chamber. Proust [3] declared a few fundamental aspects about ignition and flame propagation in dust clouds. In another study, Proust [4] measured laminar burning velocities and maximum flame temperatures for combustible dust air mixtures such as mixtures of starch-dust air, lycopodium air mixtures and sulphur and flour air mixtures. Eckhoff clarified the differences and similarities between dust and gases [5]. Combustion of flammable dust clouds is seriously studied in the last fifty years, and a lot of experimental data is obtained [6,7]. Bidabadi [8] studied flame propagation among cloud particles according to the temperature difference between the particle and gas in the planar flame. In another study, Bidabadi et al [9] investigated the effect of Lewis number and heat loss on the combustion n of organic particles. Effect of radiation on combustion of organic particle cloud was analyzed by Bidabadi [10]. In all these studies, the flames had planar shape and had no stretch.The mean of these studies was investigation of basic properties of particles combustion such as flame speed, flame temperature, burning velocity and released energy in different concentration.

Heterogeneous nature of coal and air mixture gets it into the complicated combustion process. Because the coal particles have different properties and different dimensions. Also uniform distribution of particles is very hard. In studies of combustion of coal particles a few simplifications were done. Essenhigh and Saba [11] and Bhaduri and et al. [12] not regarded the temperature difference between the particle and the gas. The model of Essenhigh did not consider to the volatility and chemical reactivity of particles. Radiation and temperature difference between gas and particle were considered in modeling of Ozerova [13] but not included coal volatility. Smoot et al. [14] presented complicated modeling for homogeneous and heterogeneous combustion of char and volatile matter. Krazinski [15] presented radiation model with basic descriptions of homogeneous and non-homogeneous combustion process. However, their model was for a stoichiometric condition. Another model presented by Scott and et al. [16] for homogeneous and non-homogeneous combustion. This model described the propagation of planar flame. The volatile matter is C3H8 and combustion products are CO2 and H2O. Bidabadi et al. [8] investigated combustion of lycopodium particles by considering the temperature difference between gas and particles. Also Bidabadi et al. [9] presented the effects of the temperature difference between gas and particle, different Lewis numbers, and heat loss from the walls in the structure of premixed flames propagation in a combustible system containing uniformly distributed volatile fuel particles in an oxidizing gas mixture.

Here, the spherical shape of flame was considered, because a steady flame in the unbounded space can exist only as a spherical combustion [17]. Mills and Matalon [17] suggested a thermal diffusion model of a spherical flame with a single-stage reaction. By using the matching of asymptotic expansions [17-19] an approximate solution of the problem of steady state spherical diffusion flame were obtained. The above mentioned studies of spherical flame investigated the gaseous fuels. Purpose of this study was to obtain an analytical description of the effect of the temperature difference between the gas and the particles on propagating spherical flame in premixed organic dust-air. It is a noteworthy work because the flame propagation phenomenon in dust cloud is not yet clarified well. It is presumed that the fuel particles vaporize first to yield a gaseous fuel, which is oxidized in the gas phase. The characteristic Zeldovich number is large, which implies that the reaction term in the preheating zone is negligible. Required relations between the gas and the particles are derived from equations for premixed flames of organic dust. Subsequently, the governing equations are solved by an analytical method. Finally, the variation of the temperatures of the gas and the particles, the mass fraction of the particles, the flame temperature, and the burning velocities of the gas are obtained as a function of φ_u.

2.Mathematical model

The premixed, one-dimensional, adiabatic spherical flame propagation of coal dust is analyzed. Figure 1 shows the schematic depiction of the structure of the flame. It includes a wide region of preheat and evaporation, a thin reaction zone and convection zone. To determine the structure of these regions, the numbers of approximations and simplifications have been introduced in the governing conservative equations as follow. It Assumed that :

- The initial number density of particles (number of particles per unit volume), n_s, and the initial particle radius (r_p), is known.
- All external forces such as the gravitational effects are negligible.
- Diffusion resulting from the pressure gradient and the Dufour and Soret effects are assumed to be negligible.
- The diffusive thermal model neglecting thermal expansion (constant values for density ρ, specific heat C_p, diffusion coefficients of fuel D, thermal conductivity k, and heat of reaction Q) is employed.

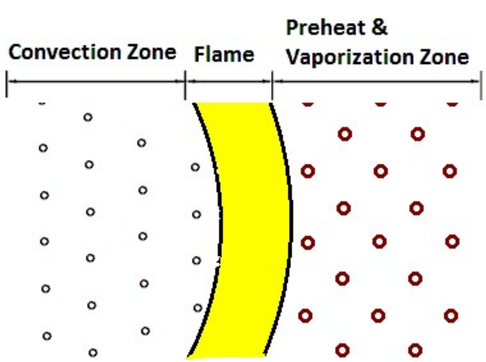

Fig. 1. Schematic shape of the structure of the flame

-The fuel particles evaporated to the known gaseous compound (methane) that can be oxidized.
- The numbers of particles are so much that the distance between the particles is less than flame radius around each particle.
- The velocity of the particle and gas is equal.
- Heterogeneous reaction was ignored.
- Combustion process considered as a single reaction step.
- In Pre-heating and evaporation zone, the chemical reaction between fuel and oxidizer is small,
- Pre-heating and evaporation zone, determined by equilibrium between convection, diffusion, and evaporation terms in the conservation equations. The kinetics of evaporation is defined by the Eq.1.

$$\tilde{W}_v = 4\pi\tilde{a}\,\tilde{n}_s\,\tilde{r}_p^2\,(\tilde{T}-\tilde{T}_\infty)^n \tag{1}$$

Where $\tilde{W}_v$ is unit mass per unit volume of evaporated gaseous fuel per second. The $\tilde{a}$ and $\tilde{n}_s$ are fixed values. $\tilde{T}$ is the gas temperature. The overall reaction rate, regardless of the surface reaction of particle, is proposed in Arrhenius form as follow:

$$\tilde{\omega} = \tilde{\rho}\,\tilde{A}\,\tilde{Y} exp\left(-\frac{\tilde{E}}{\tilde{R}_{gas}\,\tilde{T}_f}\right) \tag{2}$$

Where $\tilde{A}$, $\tilde{E}$ and $\tilde{R}_{gas}$ represent the frequency factor, the activation energy of the reaction and the universe gas constant respectively. Zeldovich number was defined as Eq. 3 and assumed that the zeldovich number is very high.

$$Ze = \frac{\tilde{E}(\tilde{T}_f - \tilde{T}_\infty)}{\tilde{R}_{gas}\,\tilde{T}_f^{\,2}} \tag{3}$$

The subscript "f" represents the flame conditions and subscript "u" represents the far field region from reaction zone. The reaction rate was written in Arrhenius form. It is assumed that activation energy of reaction is high. As result characteristic Zeldovich number, Ze, is a large number.

The mathematical model has been employed in numerous articles and research works for the calculation of the spherical coordinate system [20-28]. This method was employed for derivation of the conservation equations. The equations of one dimensional propagation (propagation in the radial coordinate), the steady state with assumption of low Mach number and equal velocity of gas and particles in spherical coordinates is as follows:

The Energy conservation equation:

$$-\tilde{\rho}\tilde{u}\widetilde{C_p}\frac{\partial}{\partial\tilde{r}}\tilde{T} = \frac{\frac{\partial}{\partial\tilde{r}}\left(\tilde{r}^2\tilde{\lambda}\frac{\partial}{\partial\tilde{r}}\tilde{T}\right)}{\tilde{r}^2} + \tilde{Q}\,\tilde{\omega} - \widetilde{W}_v\,\tilde{Q}_v \quad (4)$$

Where $\tilde{u} = \frac{d\tilde{r}(t)}{dt}$ is the flame propagation speed. The gaseous fuel mass fraction conservation equation:

$$-\tilde{\rho}\tilde{u}\frac{\partial}{\partial\tilde{r}}\tilde{Y} = \frac{\frac{\partial}{\partial\tilde{r}}\left(\tilde{r}^2\tilde{\rho}\tilde{D}\frac{\partial}{\partial\tilde{r}}\tilde{Y}\right)}{\tilde{r}^2} - \tilde{\omega} + \widetilde{W}_v \quad (5)$$

The particles mass fraction conservation equation:

$$-\tilde{\rho}\tilde{u}\frac{\partial}{\partial\tilde{r}}\widetilde{Y}_s = -\widetilde{W}_v \quad (6)$$

The effect of the temperature difference between the gas and the particles can be taken into account by the energy conservation equation for particles:

$$\tilde{u}_s\frac{d\tilde{T}_s}{d\tilde{r}} = \frac{3\tilde{\lambda}}{\tilde{\rho}_s\tilde{C}_s r_p^{\,2}}\left(\tilde{T} - \tilde{T}_s\right) \quad (7)$$

Dimensionless conservation equations

By using laminar and planar flame velocity, flame radius, flame thickness and mass fraction of gaseous fuel, the dimensionless parameters are defined as follow:

$$r = \frac{\tilde{r}}{\tilde{\delta}}, \quad Y = \frac{\tilde{Y}}{\tilde{Y}_{FC}}, \quad T = \frac{\tilde{T}-\tilde{T}_\infty}{\tilde{T}_f-\tilde{T}_\infty}, \quad T = \frac{\tilde{T}_s-\tilde{T}_\infty}{\tilde{T}_f-\tilde{T}_\infty}, \quad U = \frac{\tilde{u}}{\tilde{S}_u}, \quad U_s = \frac{\tilde{u}_s}{\tilde{S}_u} \quad (8)$$

Where $\tilde{\delta}, \tilde{Y}_{FC}, \tilde{S}_u$ respectively are planar flame thickness, mass fraction of evaporated flammable volatile fuel from solid fuel particle in reaction zone and planar flame speed. The quantity $\tilde{Y}_{FC}$, is chosen such that

$$\tilde{Y}_{FC}\tilde{Q} = \tilde{C}_p(\tilde{T}_f - \tilde{T}_\infty) \quad (9)$$

Where $\tilde{T}_f$ is the maximum temperature attained in reaction zone, calculated neglecting the heat of vaporization of the particles. The flame thickness defined as below:

$$\tilde{\delta} = \frac{\tilde{\lambda}}{\tilde{\rho}\,\tilde{C}_p\,\tilde{S}_u} \quad (10)$$

The quantities $\tilde{a}$ and n are constants which are presumed to be known, the quantity $\tilde{n}_s$ is local number density of particles (number of particles per unit volume), and can be used to calculate the $\tilde{C}_p$ as follow.

$$\tilde{C}_p = \tilde{C}_{p,air} + \frac{4\pi\tilde{r}_p\tilde{C}_s\rho_s n_s}{3\rho} \quad (11)$$

The $\tilde{C}_p$ is the combined heat capacity, and the $\tilde{C}_{p,air}$ and $\tilde{C}_s$ are heat capacity of air and the particles respectively. The ρ_s is the density of a fuel particle and is presumed to be constant. By placing the above equations in dimensionless relations and assuming negligible vaporization heat compared to reaction heat, new conservation equations are obtained:

$$-U\frac{\partial}{\partial r}T = 2\frac{\partial}{r\,\partial r}T + \frac{\partial^2}{\partial r^2}T + \omega \quad (12)$$

$$-U\frac{\partial}{\partial r}Y = \frac{1}{Le}\left(2\frac{\partial}{r\,\partial r}Y + \frac{\partial^2}{\partial r^2}Y\right) - \omega \quad (13)$$

$$-U\frac{\partial}{\partial r}Y_s = -M\,Y_s^{\,2/3}T^n \quad (14)$$

$$-U_s\frac{d}{dr}T_s = \tau.(T - T_s) \quad (15)$$

Where:

$$M = \frac{4.836\,\tilde{\lambda}\,\tilde{a}\,\tilde{n}_s^{\,1/3}\left(\tilde{T}_f - \tilde{T}_\infty\right)^n}{\tilde{S}_u^{\,2}\tilde{C}p\,Y_{FC}^{\,1/3}\,\tilde{\rho}_s^{\,2/3}\,\tilde{\rho}^{\,4/3}} \quad (16)$$

$$\tau = \frac{3\tilde{\lambda}_f\tilde{\lambda}}{\tilde{\rho}\tilde{\rho}_s\tilde{S}_u^2\tilde{C}_s\tilde{C}_p r_p^2} \quad (17)$$

$$Y_s = \frac{4\pi\,r_p^3\,\tilde{\rho}_s\,\tilde{n}_s}{3\tilde{\rho}\tilde{Y}_{FC}} \quad (18)$$

Boundary conditions

In the combustion products it is assumed that all combustible materials from evaporating of volatile matter of particles completely reacted and mass fraction of combustible materials are zero.

$$Y = 0 \;, \quad 0 \le r < r_f^{\,-} \quad (19)$$

The solid remaining material after evaporation of volatile matter of particles in the flame zone and convection zone is very small and its value is assumed to be zero.

$$Y_s = 0 \quad , \tilde{Y}_s = 0 \, , \qquad 0 \le r \le r_f \tag{20}$$

The temperature of combustion products in the convection zone is constant and equal to flame temperature.

$$T = 1 \quad , \tilde{T} = \tilde{T}_f \, , \qquad 0 \le r < r_f^{-} \tag{21}$$

In region far from flame (unburned area) temperatures of gas and particle are equal to ambient temperature, and we have.

$$T = 0 \quad , \tilde{T} = \tilde{T}_\infty \, , \qquad r = \infty$$
$$T_s = 0 \quad , \tilde{T}_s = \tilde{T}_\infty \, , \qquad r = \infty \tag{22}$$

On the boundary between the reaction zone and preheat zone temperature is equal to:

$$T = T_f \quad , \tilde{T} = \tilde{T}_f^{+} \, , \qquad r = r_f^{+} \tag{23}$$

By solving energy equation using the given boundary conditions, temperature distribution in preheat zone is obtained as follow.

$$T(r) = T_f - \frac{(\int_{r_f}^{r} e^{\int_{r_f}^{x}\left(-\frac{U.x+2}{x}\right)dx} dx)T_f}{\int_{r_f}^{\infty} e^{\int_{r_f}^{x}\left(-\frac{U.x+2}{x}\right)dx} dx} \tag{24}$$

For region away from flames in unburned zone there is relation $Y_s = \alpha$ and $\tilde{Y}_s = Y_{Fu}$, so by solving Eq. 13 we have.

$$Y_s = \frac{1}{27}M^3\left(\int_{\infty}^{r}\frac{T^n}{U}dx\right)^3 + \frac{1}{3}M^2\left(\int_{\infty}^{r}\frac{T^n}{U}dx\right)^2 \alpha^{1/3} + M\left(\int_{\infty}^{r}\frac{T^n}{U}dx\right) \alpha^{2/3} + \alpha$$

$$r_f^{+} \le r < \infty \tag{25}$$

Introducing Eq. 25 into conservation equation of gaseous fuel mass fraction and using given boundary condition yield the result:

$$Y(r) = (\int_{\infty}^{r}(-Le\, M(\int_{\infty}^{x} Y_s(x)(T(x))^n e^{\int_{\infty}^{x}\frac{U.x.Le+2}{x}dx}dx)e^{-\int_{\infty}^{x}\frac{U.x.Le+2}{x}dx})dx) \tag{26}$$

For the particles temperature:

$$T_s = \frac{U_s}{\tau}\frac{d}{dr}T + T \tag{27}$$

Matching conditin

The reaction zone is much thinner than the preheat zone and equilibrium zone. In order to adequately resolve the reaction zone, the spatial coordinate is stretched by introducing coordinate transform $\eta = \frac{r-r_f}{\varepsilon}$. To analyze the structure of reaction zone following definition are introduced.

$$y^* = \frac{Y_g - Y_{gF}}{\varepsilon}, \; t = \frac{1-T}{\varepsilon}, \; \varepsilon = \frac{1}{Ze},$$
$$\eta = \frac{r-r_f}{\varepsilon}, \; t_s = \frac{1-T_s}{\varepsilon} \tag{28}$$

Where Y_g and Y_{gF} respectively are gasified fuel and total gaseouse fuel that burned in reaction zone. The matching conditions for the inner and outer solutions at the upstream and downstream boundary of the reaction zone (ie.$\eta \to \pm\infty$) are

$$\lim_{\eta\to-\infty} T_s(\eta) = \lim_{r\to r_f^-} T_s(r)$$
$$\lim_{\eta\to+\infty} T_s(\eta) = \lim_{r\to r_f^+} T_s(r) \tag{29}$$

$$\lim_{\eta\to-\infty} T(\eta) = \lim_{r\to r_f^-} T(r)$$
$$\lim_{\eta\to+\infty} T(\eta) = \lim_{r\to r_f^+} T(r) \tag{30}$$

$$\lim_{\eta\to-\infty} Y(\eta) = \lim_{r\to r_f^-} Y(r)$$
$$\lim_{\eta\to+\infty} Y(\eta) = \lim_{r\to r_f^+} Y(r) \tag{31}$$

$$\lim_{\eta\to-\infty} \frac{dT(\eta)}{d\eta} = \lim_{r\to r_f^-} \frac{dT(r)}{dr}$$
$$\lim_{\eta\to+\infty} \frac{dT(\eta)}{d\eta} = \lim_{r\to r_f^+} \frac{dT(r)}{dr} \tag{32}$$

$$\lim_{\eta\to-\infty} \frac{dT_s(\eta)}{d\eta} = \lim_{r\to r_f^-} \frac{dT_s(r)}{dr}$$
$$\lim_{\eta\to+\infty} \frac{dT_s(\eta)}{d\eta} = \lim_{r\to r_f^+} \frac{dT_s(r)}{dr} \tag{33}$$

$$\lim_{\eta\to-\infty} \frac{dY(\eta)}{d\eta} = \lim_{r\to r_f^-} \frac{dY(r)}{dr}$$
$$\lim_{\eta\to+\infty} \frac{dY(\eta)}{d\eta} = \lim_{r\to r_f^+} \frac{dY(r)}{dr} \tag{34}$$

The definition of t and η yeilds.

$$\frac{dT}{dr} = -\frac{dt}{d\eta}, \qquad \frac{dT_s}{dr} = -\frac{dt_s}{d\eta} \tag{35}$$

Thus derivative matching conditions are.

$$\lim_{\eta\to-\infty}\frac{d\,t_s(\eta)}{d\eta} = -\lim_{r\to r_f^-}\frac{dT_s(r)}{dr}$$
$$\lim_{\eta\to+\infty}\frac{d\,t_s(\eta)}{d\eta} = -\lim_{r\to r_f^+}\frac{dT_s(r)}{dr} \tag{36}$$

$$\lim_{\eta\to-\infty}\frac{d\,t(\eta)}{d\eta} = -\lim_{r\to r_f^-}\frac{dT(r)}{dr}$$
$$\lim_{\eta\to+\infty}\frac{d\,t(\eta)}{d\eta} = -\lim_{r\to r_f^+}\frac{dT(r)}{dr} \tag{37}$$

$$\lim_{\eta\to-\infty}\frac{dy^*(\eta)}{d\eta} = \lim_{r\to r_f^-}\frac{dY(r)}{dr}$$
$$\lim_{\eta\to+\infty}\frac{dy^*(\eta)}{d\eta} = \lim_{r\to r_f^+}\frac{dY(r)}{dr} \tag{38}$$

In the reaction zone the convective terms and the vaporization terms in the conservation equations are presumed to be small in comparison to the diffusion term and the reaction term. Therefore, the reaction zone is governed by the following reaction-diffusion equations:

$$\frac{1}{\eta^2.\varepsilon^4 + 2.\varepsilon^3\eta + {r_f}^2\varepsilon^2}\frac{d}{d\eta}\left((\eta.\varepsilon + r_f)^2 \frac{d(1-\varepsilon t)}{d\eta}\right) = \omega \tag{39}$$

Where

$$\omega = \frac{\tilde{\lambda}\,\tilde{A}\,\tilde{Y}(r)}{\tilde{\rho}\,Y_{FC}c_pSu^2}exp\left(-\frac{\tilde{E}}{\tilde{R}\,\tilde{T}}\right) \tag{40}$$

The reaction term can be rewritten as follow

$$\omega = \phi(y^* + b)exp(-t) \tag{41}$$

That

$$\phi = \frac{\tilde{\lambda}\,\tilde{A}\varepsilon\, exp(-{}^{E}/_{RT_f})}{\tilde{\rho}\,Y_{FC}c_pSu^2} \tag{42}$$

The quantity ε is very small number, and for k>1 the ε^k approximately taken to be zero. The derivative of energy equation of particle gives.

$$-U_s\frac{d^2}{dr^2}T_s = \tau.\left(\frac{d}{dr}T - \frac{d}{dr}T_s\right) \tag{43}$$

By inserting equivalent parameters from Eq.27 in the reaction zone we have:

$$-\frac{d^2t}{d\eta^2} = (\omega.\varepsilon) \tag{44}$$

$$\frac{d^2y^*}{Le.d\eta^2} = -\omega.\varepsilon \tag{45}$$

$$U_s\frac{d^2t_s}{\varepsilon.d\eta^2} = \tau.\left(-\frac{dt}{d\eta} + \frac{dt_s}{d\eta}\right) \tag{46}$$

By Mathematical manipulations result relation between t and y^*

$$t = \frac{y^*}{Le} \tag{47}$$

Substituting $t.Le=y^*$in Eq.40 yield

$$\omega = \phi(t.Le + b)exp(-t) \tag{48}$$

By defining P=dt/dη and $(dt_s)/d\eta=P_s$ we have.

$$\frac{d}{d\eta} = \frac{d}{dt}\frac{dt}{d\eta} = \frac{d}{dt}P,$$
$$\frac{d}{d\eta} = \frac{d}{dt_s}\frac{dt_s}{d\eta} = \frac{d}{dt_s}P_s \tag{49}$$

Consequently Eq.39 yields

$$-P.dP = (\omega.\varepsilon)dt \tag{50}$$

$$U_s\frac{dP_s}{\varepsilon.d\eta} = \tau.(-P + P_s) \tag{51}$$

Matching with the convection and vaporization zone, yields

$$P = \frac{dt}{d\eta} = -\frac{dT}{dr} \tag{52}$$

$$\left.\frac{d}{dr}T\right|_{r=r_f^-} = \left.\frac{dt}{d\eta}\right|_{\eta=-\infty} = 0,\ P(-\infty) = 0 \tag{53}$$

$$-\left.\frac{d}{dr}T\right|_{r=r_f^+} = \left.\frac{dt}{d\eta}\right|_{\eta=+\infty} = F,\ P(+\infty) = F \tag{54}$$

$$\left.\frac{d}{dr}T_s\right|_{r=r_f^-} = \left.\frac{dt_s}{d\eta}\right|_{\eta=-\infty} = 0\ ,\ P_s(-\infty) = 0 \tag{55}$$

$$-\frac{d}{dr}T_s\Big|_{r=r_f^+} = \frac{dt_s}{d\eta}\Big|_{\eta=+\infty} = F_s,\ P_s(\infty) = F_s \quad (56)$$

As defined.

$$t = \frac{1-T}{\varepsilon} = \frac{T_f - T}{\varepsilon.(T_f - T_u)}$$

$$t_s = \frac{1-T_s}{\varepsilon} = \frac{T_s - T}{\varepsilon.(T_f - T_u)} \quad (57)$$

$$t^+ = \frac{T_f - T_f^+}{\varepsilon.(T_f - T_u)}\ ,\ r_f = r_f^+ \text{ and } \eta \to +\infty \quad (58)$$

$$t(-\infty) = 0\ ,\ r_f = r_f^- \text{ and } \eta \to -\infty \quad (59)$$

$$t_s(-\infty) = 0, r_f = r_f^- \text{ and } \eta \to -\infty \quad (60)$$

Integrating Eq.49and50 using the boundary condition shown in Eq.52 to Eq.59 yields.

$$P^2 = -2.\varepsilon\big(b + Le(1+t)\big)\phi \quad (61)$$

$$P_s = e^{\frac{\varepsilon.\tau.\eta}{U_s}} \int_{-\infty}^{\eta} -\frac{\varepsilon.\tau.P}{U_s} e^{\frac{-\varepsilon.\tau.z}{U_s}} dz \quad (62)$$

By inserting equivalent terms for P and P_s in Eq60 and 61 we have.

$$\frac{T_f e^{\int_{rf}^{r}\frac{U.x-2}{x}dx}}{\int_{rf}^{\infty}\left(e^{\int_{rf}^{x}\frac{U.x-2}{x}dx}\right)dx} = (2.\varepsilon(b + Le)\phi)^{0.5} \quad (63)$$

$$T_s = 1 - \frac{\varepsilon^2.\tau}{U_s}\int_{-\infty}^{\eta}((\int_{-\infty}^{z} P.e^{\frac{-\varepsilon.\tau.x}{U_s}}dx).e^{\frac{\varepsilon.\tau.z}{U_s}})\,dz \quad (64)$$

Here it assumed that particle velocity and gas velocity is equal ($U=U_s$). Accordingly, the following Figures show the combustion behavior considering temperature difference between gas and dust.

Verification

For negligible pressure rise in propagating premixed flame, the produced gas of combustion process assumed to be stationary[29]. As a result, the flame front propagation speed is equal to the flame speed, i.e. the $S_b = d\tilde{r}_f/dt$.

Here ‘‘extraction’’ method has been used to obtain planar (unstretched) flame speed from spherical flame speed. Means of ‘‘extraction’’ is to obtain the unstretched laminar flame speed and Markstein length from the spherical flame front propagation history $r_f = r_f(t)$.

Based on semi-phenomenological considerations, the following correlation between the local flame speed, Su, and the flame radius, $\tilde{r}_f$, was proposed by Markstein [30].

$$S_b/S_u = 1 + L_b/\tilde{r}_f \quad (64)$$

Where S_u and L_b are, respectively, the laminar speed of adiabatic freely-propagating planar flame and Markstein length. This model contains several parameters. Some of them seem a kind of adjusting parameters. The values of adjusting parameters were presented below. These values are taken from properties of coal particles. The table 1 presents the values of adjusting parameters.

Table. 1.
The values of adjusting parameters.

$\tilde{A}$	3.4×10^{-5} kg/K.s.m^2
n	1.333
$\tilde{A}$	3.5 ×(mol.s)$^{-1}$
$\tilde{E}$	96 kJ/mol
$\tilde{Q}$	50 MJ/kg
$\tilde{Q}_v$	0.01× $\tilde{Q}$
ρ_u	1.35×10^{3} kg/m^3
$\tilde{T}_{inf}$	300 K
$\tilde{R}_{gas}$	8.314 J /K.mol
$\tilde{C}_{air}$	1205 J/kg K
$\tilde{C}_{p.s}$	1256 J/kg.K
$\tilde{\lambda}_u$	14.6538×10^{-2} J/(m.s.K)

Prior measurements of Su for coal–air at atmospheric pressure are reported in literatures. Strehlow et al measured burning velocity of coal dust flame [31]. They studied the burning velocity of 40 micron coal particles. In this reference Strehlow studied Coal dust combustion and suppression. The comparison between experimental results of Strehlow and results reported by this paper represents acceptable agreement. A Comparison between results of this research and Strehlow’s work in condition was made on Fig. 2.

The comparison between the burning velocity obtained by extraction method for premixed coal–air from presented model in 40 micron particle size and overall equivalence ratio has a good conformity with burning velocities resulted from Strehlow’s results.

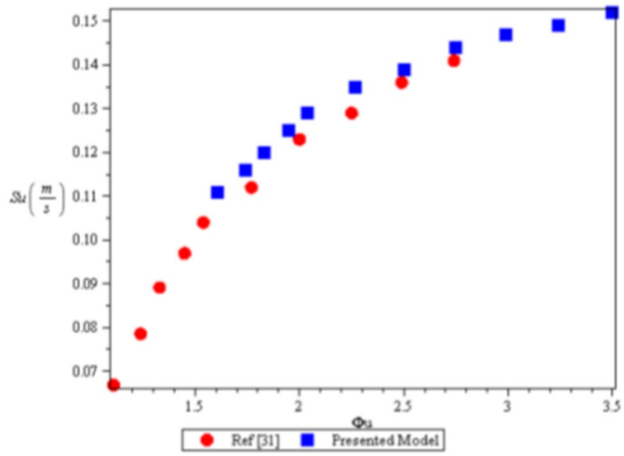

Fig. 2. Comparison between results of this paper and Ref [31]

Result and discussion

The flame temperature without assuming temperature difference is seen to be higher than the flame temperature with temperature difference between gas and dust. Also it is observed that temperature of particles is lower than flame temperatures. Fig. 3 shows effects different assumption of temperature difference on temperature of gas and particle as function of equivalence ratio for different particle radius and R_f=20 . With increase of the particle radius the flame temperatures and the particle temperature are decreased. Also, it can be seen that particle temperature is lower than flame temperatures.

Mass fraction of the fuel particle without temperature difference is lower than with temperature difference. Because heat transfer from gas to particle cause to lower temperature for gas. Also temperature difference assumptions lead to lower φ_g than another assumption.

As the particle radius increases, the burning velocity decreases. It should be noted that the burning velocity with the radius tending to zero equals the burning velocity for a purely gaseous combustible mixture. The assumption of no temperature difference gives higher burning velocity than another assumption. Because the

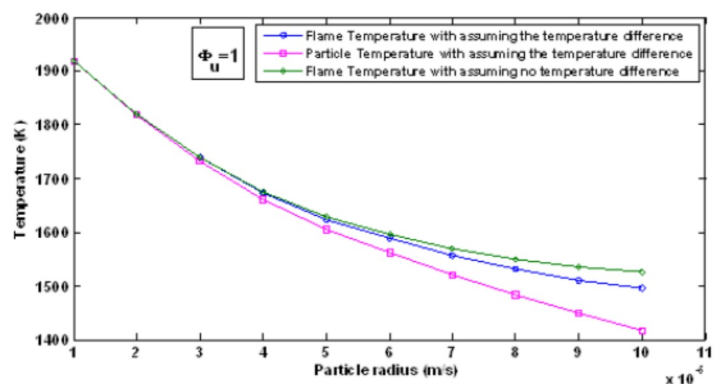

Fig. 3. Comparison between flame temperatures, resulted from both of assumptions, and particle temperature as function of φ_u.

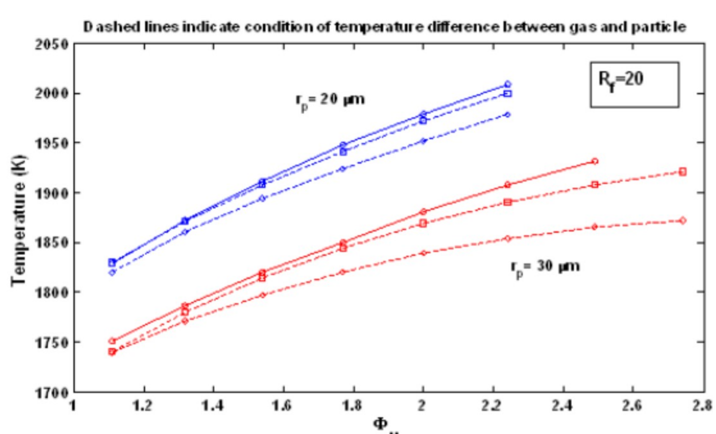

Fig. 4. The effect of φ_u on solid fuel mass fraction with assuming temperature difference between gas and particle

volatile matter and temperature of gas are high in this assumption. Hence, the difference in the gas and particle temperatures affects the burning velocity. It should be noted that the temperature and the burning velocity increase as the equivalence ratio increases (Fig. 6 and Fig. 7). As the image shows, the changes of the burning speed with particle concentration has a reasonable correlation with the data obtained from from the work of Strehlow et al. This indicates that the burning speed increases with the increase of particles concentration. Also considering temperature difference between gas and particle gives the lower flame temperature and burning velocity than another assumption. Also, the flame speed shows similar behavior as equivalence ratio and particle radius changes in different assumptions (Fig. 8).

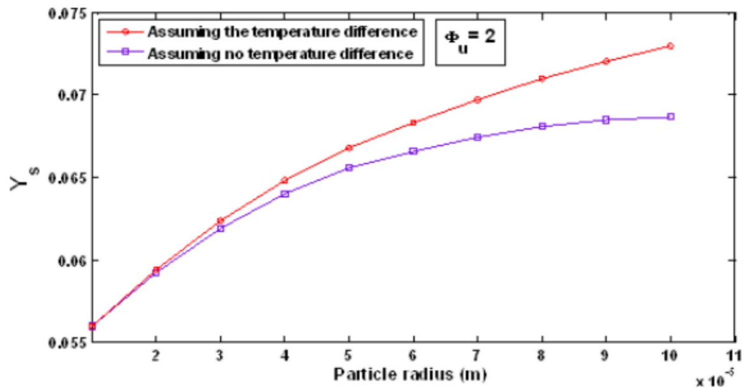

Fig. 5. The effect of φ_u on φ_g with assuming temperature difference between gas and particle

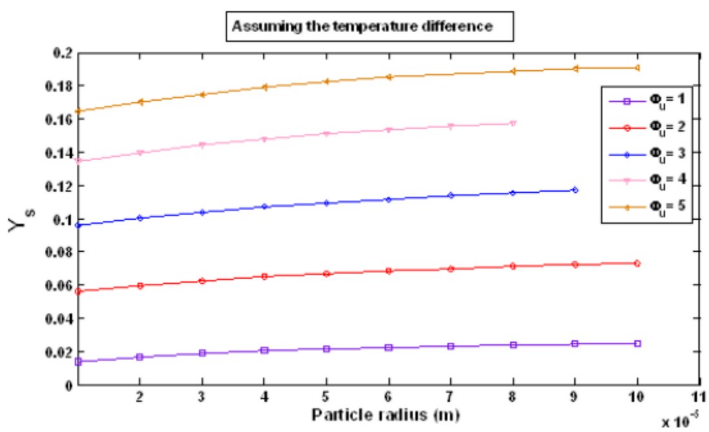

Fig. 6. The effect of particle radius on burning velocity as function of φ_u in both of assumptions

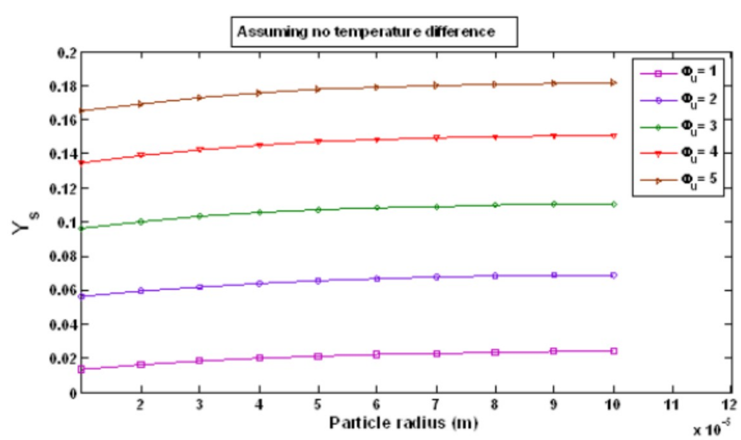

Fig. 7. The effect of particle radius on flame temperature as function of φ_u in both of assumptions

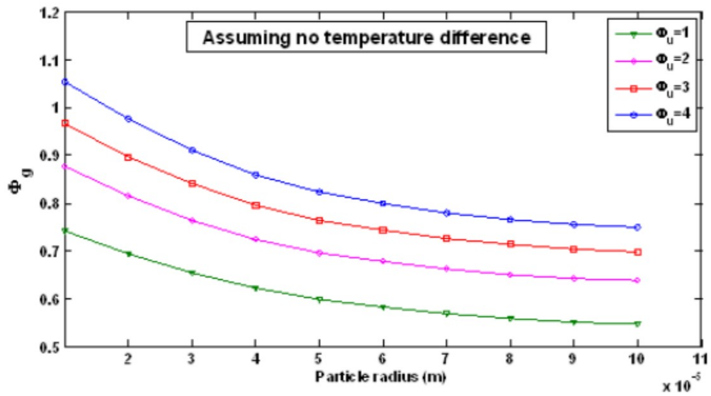

Fig. 8. The effect of particle radius on flame speed as function of φ_u in both of assumptions

In this figure, three different dust–air mixtures with the same concentration and with dissimilar particle sizes are compared with each other. The results indicate that the absorbed radiation intensity increases with the reduction of particle size. This is an expected finding, because radiation intensity has an inverse relationship with particle diameter.

From presented results it concluded that:

It is shown that the assumption of the temperature difference leads to lower flame speed. Also flame speed increases as particle radius decreases and φ_u increases.

It is declared that the burning velocity increases with increasing equivalence ratio for both of assumptions. The assumption of temperature difference gives lower burning velocity. Particles with lower size yield higher burning velocity in both assumptions. The assumption of the temperature difference correspond to greater mass fractions of the particle fuel in the both of assumptions; for all values of φ_u . It observed that the gaseous equivalence ratio, φ_g, decreased by assuming the temperature difference between dust and gas. Also φ_g increases as φ_u increases and particle size decreases.

- The flame temperature is studied as functions of the equivalence ratio. It is shown that the particle temperature is lower than the flame temperature. The lower temperatures are gained in flame with greater particle sizes.

Conclusion

In this investigation, the effects of the temperature difference between gas and particle on premixed spherical flames propagating through coal dust particles are analyzed. An important point about the worth of this research is investigation of real state of flame (spherical flame). The results of the presented model have good agreement with data published in literatures. Taking into account the difference in temperature difference results the lower gaseous fuel and higher mass fraction of solid fuel. It is observed that the burning velocity, flame speed and flame temperature decreased with assumption of temperature difference. In addition, it is shown that the particle temperatures are lower than flame temperature. The amount of burning velocity increases with the increase of equivalence ratio and decrease of particle size.

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