Amirkabir Univ. of Technology
Aerospace Engineering Dept.

The Third Fuel & Combustion Conference of IRAN

Tehran - IRAN Feb. 2010

Iranian Combustion Institute

FCCI2010-1141

Novel analytical model for predicting the heat loss effects on combustion characteristics of premixed flame propagation in biomass particles

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ABSTRACT In this paper the influence of heat-loss and radiation on the pyrolysis of biomass particles by considering the structure of one-dimensional, laminar and steady state flame propagation in uniformly premixed wood particles is analysed. The assumed flame structure consists of a broad preheat-vaporization zone where the rate of gas-phase chemical reaction is small, a thin reaction zone composed of three regions: gas, tar and char combustion where convection and the rate of vaporization of the fuel particles are small and e broad convection zone. The principal attention is focused on the determination of a non-linear burning velocity correlation. Consequently, the impacts of radiation, external heat loss term and particle size as the determining factors on the combustion properties of biomass particles such as burning velocity and flame temperature, are declared in this research.

Keywords Radiation; Heat-loss; Pyrolysis; Flame-Temperature; Burning-Velocity.

INTRODUCTION

Many materials which are commonly known to combust can generate a dust explosion, such as coal and sawdust. However, many otherwise mundane materials can also lead to a dangerous dust cloud such as grain, flour, sugar, powdered milk and pollen The amount of dust accumulation necessary to cause an explosive concentration can vary greatly. This is because there are so many variables – the particle size of the dust, the method of dispersion, ventilation system modes, air currents, physical barriers, and the volume of the area in which the dust cloud exists or may exist.

The effects of heat loss to the environment on combustion have been analytically and numerically investigated in several studies. Lee developed a simple theoretical model to predict the heat loss and flame quenching in a millimetre scale closed vessel combustor. But the heat transfer was between the fluid and the combustor structure, and external heat loss was not considered. Daou and Matalon investigated the effects of heat loss to the structure on premixed flames propagating in channels with constant temperature walls but did not include heat exchange within the micro-combustor's structure. The other aspect is the effects of external wall heat transfer coefficients on combustion in the micro-combustor. Hua numerically investigated the effects of heat conduction within chamber wall, and heat loss through the wall on combustion characteristics in the chamber. The heat loss condition is applied by specifying a constant heat transfer coefficient on the chamber wall. Vican constructed an alumina ceramic “Swiss roll” micro reactor and developed a global energy balance model to analyze effects of equivalence ratio on reactor’s heat loss.

Galgano and Blasi modelled the decomposition of moist wood using the shrinking un-reacted-core approximation for a finite rate of reaction and the effect of convective, conductive, and radiative heat transfer and different physical properties for char, dry wood, and moist wood were studied.

Porterio et al. presented a mathematical model describing the thermal degradation of densified biomass particles. The model used a novel discretisation scheme and combines intra-particle combustion processes with extra-particle transport processes, thereby including thermal and diffusional control mechanisms.

In the resumption of the previous studies, a novel mathematical model is developed in order to estimate the role of heat loss as the considerable heat transfer model on the pyrolysis of biomass dust particles in this research. The heat loss term is added into the energy conservation equation and it is observed that it has a remarkable impact on the temperature and burning velocity behaviour. Moreover, the various radii of the particles including $20, 30$ and $40\,\mu m$ are studied in this research and it is found that the lower radius of the particle results in the higher amount of flame temperature and burning velocity.

MATHEMATICAL MODEL

Governing Equations In this model, the structure of premixed flames propagation in combustible system, containing uniformly distributed gaseous fuel, char, tar and oxidizing gas mixture, is analyzed. In addition, the number and radius of the particles are considered to be known as the primary data and it should be noticed that all external forces such as gravitational field on earth are neglected in this study.

The constant rate of the overall reaction is written in the Arrhenius form as:

$$\begin{aligned} K_F &= B\exp(-E/(RT)) \\ K_T &= -\rho K_t \exp(-E/(RT)) \end{aligned} \tag{1}$$

Where B represents the frequency factor, E the activation energy of the reaction, R is the universal gas constant and K_t is the tar reaction rate. Besides the Zeldovich number, which is presumed to be large, is defined as:

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

The subscribes f and u denote the flame and the ambient reactant stream conditions, respectively.

In this analysis, it is presumed that the fuel particle vaporize first to yield a gaseous fuel of the known chemical structure. The vaporization and devolatilization kinetics are assumed to be represented by the following expression:

$$w_\upsilon = An_S 4\pi T^n r^2 \qquad (3)$$
$$w_{de} = A' n_S 4\pi T^n r^2$$

Where A, n and T are the parameter characterizing rate of vaporization, the constant quantity and the gas temperature, respectively. Fig. 1 shows the flame propagation structure.

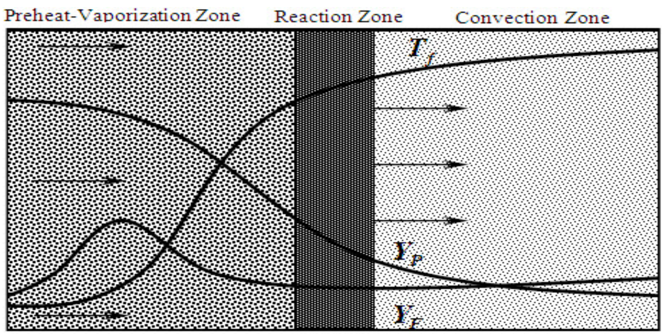

Figure 1. The structure of flame propagation

For the combustion of wood particle-cloud, considering heat loss effects the energy equation derived as:

$$\rho \upsilon C \frac{dT}{dx} = \lambda_u \frac{d^2T}{dx^2} + w_F \frac{\rho_u}{\rho} Q + w_C \frac{\rho_C}{\rho} Q_c + \frac{\rho_u}{\rho} Q_r - w_\upsilon \frac{\rho_u}{\rho} Q_\upsilon - w_{de} \frac{\rho_u}{\rho} Q_\upsilon - \frac{\rho_u}{\rho} Q_L + w_T \frac{\rho_t}{\rho} Q_t \qquad (4)$$

The equation of gaseous fuel conservation is:

$$\rho \upsilon \frac{dY_F}{dx} = \rho_u D_u \frac{d^2 Y_F}{dx^2} - w_F \frac{\rho_u}{\rho} + w_\upsilon \frac{\rho_u}{\rho} + w_{de} \frac{\rho_u}{\rho} + w_T \frac{\rho_t}{\rho} \qquad (5)$$

Where ρ, v, Y_F, Y_c, w_F, w_c and w_υ are the density, the flow velocity, the mass fraction of the fuel, the mass fraction of char, the reaction rate, the reaction of char and the rate of devolitilization respectively, Q_L is the heat loss term and defined as:

$$Q_L = K(T - T_u) \qquad (6)$$

$$K = \frac{b'\lambda}{d^2} \qquad (7)$$

Where b' and d are heat loss coefficient and distance between quenching plates, respectively. The equation governing the mass fraction of particles neglecting diffusion term is written as:

$$\rho \upsilon \frac{dY_S}{dx} = -w_\upsilon \frac{\rho_u}{\rho} - w_{de} \frac{\rho_u}{\rho} \quad , \quad \rho \upsilon \frac{dY_C}{dx} = w_C \frac{\rho_C}{\rho} \tag{8}$$

Where ρ_S and ρ_C are, respectively, the density of fuel particles and char which are considered to be constant.
The equation of state is:

$$\rho T = Cte \tag{9}$$

The general equation of radiation transfer is:

$$\frac{dI}{dx} = +K_a I + K_s I - K_a I_b - \frac{K_s}{4\pi} \int_{4\pi} I(\Omega) P(\theta, \Phi) d\Omega \tag{10}$$

The terms on the right of equation (10) 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.

Solving equation (10) in all of the described zones using the required boundary conditions yields the following general expression for the radiation transfer.

$$Q_r = K_a I_f e^{K_t x} \tag{11}$$

Where $I_f = \sigma T_f^{\,4} / \pi$. The heat capacity C appearing in the above equation is the combined heat capacity of the gas, C_p, and of the particles, C_s, and can be calculated as:

$$C = C_P + \frac{4\pi r^3 C_S \rho_S n_S}{3\rho} \tag{12}$$

Dimensionless System of Governing Equations Dimensionless parameters are defined as:

$$m = \frac{\rho \upsilon}{\rho_u \upsilon_u} \quad , \quad \theta = \frac{T - T_u}{T_f - T_u} \quad , \quad y_S = \frac{Y_S}{Y_{FC}} \quad , \quad z = \frac{\rho_u \upsilon_u C}{\lambda_u} x \quad , \quad y_F = \frac{Y_F}{Y_{FC}} \quad , \quad y_C = \frac{Y_C}{Y_{FC}} \tag{13}$$

In the above equation, T_f is the maximum temperature of the reaction zone calculated by considering the fact that the vaporization term is negligible. The parameter Y_{FC} is followed by:

$$Y_{FC} Q = C(T_f - T_u) \tag{14}$$

In the above equation, some parameters such as $\omega_F, \omega_{de}, \omega_C, \gamma, q$ are defined as:

$$\omega_F=\frac{\lambda_u\times w_F}{(\rho_u\upsilon_u)^2\times C\times Y_{FC}}\quad,\quad \omega_C=\frac{\lambda_u\times w_C}{(\rho_u\upsilon_u)^2\times C\times Y_{FC}}\quad,\quad \omega_{de}=\frac{\lambda_u\times w_{de}\times Y_{FC}}{(\rho_u\upsilon_u)^2\times C^3\times(T_f-T_u)^2} \tag{15}$$

$$\omega_T=\frac{\lambda_u\times w_T}{(\rho_u\upsilon_u)^2\times C\times Y_{FC}}\quad,\quad q=\frac{Q_\upsilon}{Q}\quad,\ \gamma=\frac{4.836An_u{}^{1/3}\lambda_u\left(T_f-T_u\right)^n}{\upsilon_u{}^2\rho_u{}^{4/3}CY_{FC}{}^{1/3}\rho_S{}^{2/3}},\gamma'=\frac{4.836A'n_u{}^{1/3}\lambda_u\left(T_f-T_u\right)^n}{\upsilon_u{}^2\rho_u{}^{4/3}CY_{FC}{}^{1/3}\rho_S{}^{2/3}}$$

Thus, the dimensionless form of the boundary conditions for these equations is:

$$\begin{aligned}&at\ \ z=\infty\ ,\ \theta=\theta_b=(T_b-T_u)/(T_f-T_u)\quad y_F=finite\quad y_C=finite\\&at\ \ z=-\infty\ ,\ \theta=0\quad y_F=0\quad y_S=\alpha\quad y_C=0\end{aligned} \tag{16}$$

Where $\alpha=Y_{Fu}/Y_{FC}$. In this research, the quantity q, which is the ratio of heat required to vaporize the fuel particles to the overall heat release by the flame, is negligible because it is too small in comparison with other parameters. The quantity m can be considered unity, which is the usual assumption for solving the governing equations. Thus, the governing equations are simplified and rewritten as:

$$\begin{aligned}&\frac{d\theta^o}{dz}=\frac{d^2\theta^o}{dz^2}+\omega_F\frac{\rho_u}{\rho}+\omega_C\frac{\rho_C}{\rho}+\frac{B'}{v_u^2}\exp\left(\frac{C'z}{v_u}\right)+\omega_T\frac{\rho_t}{\rho}-\frac{D'}{v_u^2}\theta^o\\&\frac{dy_F}{dz}=\frac{d^2y_F}{dz^2}-\omega_F\frac{\rho_u}{\rho}+\gamma y_S{}^{2/3}\left(\theta^o\right)^n+\omega_T\frac{\rho_t}{\rho}+\gamma' y_S{}^{2/3}\left(\theta^o\right)^n\\&\frac{dy_S}{dz}=-\gamma y_S{}^{2/3}\left(\theta^o\right)^n-\gamma' y_S{}^{2/3}\left(\theta^o\right)^n\\&\frac{dy_C}{dz}=\omega_C\frac{\rho_C}{\rho}\end{aligned} \tag{17}$$

Where the parameter υ_u is the burning velocity when the heat of vaporization is neglected.

ANALYTICAL APPROACH

Preheat Zone As pointed out previously, the reaction zone is located at $x=0$. Thus $Z<0$ denotes the preheat zone and $Z>0$ denotes the convection zone. In this zone, when the limit $Z_e\to\infty$, the chemical reaction between the gaseous fuel and oxidizer is assumed negligible. Hence, the first term of the equation (19) can be written as:

$$\frac{d\theta^o}{dz}=\frac{d^2\theta^o}{dz^2}+\frac{B'}{v_u^2}\exp\left(\frac{C'z}{v_u}\right)-\frac{D'}{v_u^2}\theta^o \tag{18}$$

Thus ω_C,ω_F and ω_T are neglected in this zone. Two boundary conditions $\theta^o=1$ at $z=0$ and $\theta^0=0$ at $z=-\infty$ are used for solving this differential equation. Therefore, the dimensionless temperature correlation in preheat zone is derived as:

$$\theta^{o}=\left(1+\frac{B'/v_u^2}{(C'^2/v_u^2)-(C'/v_u)-(D'/v_u^2)}\right)\exp(\kappa z)-\left(\frac{B'/v_u^2}{(C'^2/v_u^2)-(C'/v_u)-(D'/v_u^2)}\right)\exp\left(\frac{C'z}{v_u}\right)\qquad z\le 0 \tag{19}$$

Where

$$C'=\frac{K_t\lambda_u}{\rho_u C}\quad,\quad D'=\frac{\lambda_u\lambda b'}{\rho\rho_u C^2D^2}\quad,\quad B'=\frac{K_a I_f\lambda_u}{\rho\rho_u C^2(T_f-T_u)}\quad,\quad \kappa=\frac{1+\sqrt{1+4D'/v_u^2}}{2} \tag{20}$$

Where D and κ demonstrate the diffusion coefficient and heat loss term respectively. Substituting equation (19) into the third term of equation (17) and using the aforementioned boundary conditions (equation (16)) culminate in:

$$y_S=\left[\alpha^{1/3}-b\left(e\exp(\kappa z)-f\exp(\frac{C'}{v_u}z)\right)\right]^3\qquad z\le 0 \tag{23}$$

Where

$$b=\frac{\gamma+\gamma'}{3}\quad,\quad e=\frac{1}{\kappa}\left(1+\frac{\frac{B'}{v_u^2}}{(\frac{C'^2}{v_u^2})-(\frac{C'}{v_u})-(\frac{D'}{v_u^2})}\right)\quad,\quad f=\left(\frac{\frac{B'}{v_uC'}}{(\frac{C'^2}{v_u^2})-(\frac{C'}{v_u})-(\frac{D'}{v_u^2})}\right) \tag{24}$$

Introducing equations θ^0 and y_S into the second term of equation (17) and integrating this equation from $z=-\infty$ to $z=0^-$ using the boundary conditions in this zone result in the following expression:

$$-\left[\frac{dy_F}{dz}\right]_{0^-}=\left((e-f)(3b\alpha^{2/3}-3b^2\alpha^{1/3}(e-f)+b^3(e-f)^2)-y_{Ff}\right) \tag{25}$$

Reaction Zone This zone is divided in three parts. The first part of the reaction zone is the combustion of the fuel particles, which are converted into the gaseous phase, and the second part is the char combustion resultant of the primary fuel particles and the last part is the tar combustion. In this zone, convection and vaporization terms are neglected against the diffusion term. The reaction rates w_F, w_C, w_{de} and w_T are followed by:

$$w_F=\upsilon_F W_F k_F C_F\quad,\quad w_C=\upsilon_C W_C k_C C_C$$
$$w_T=\upsilon_T W_T k_T C_T\quad,\quad w_{de}=A' n_S 4\pi T^n r^2 \tag{26}$$

In order to analyze the flame structure in this zone, the following parameters are defined:

$$z=\varepsilon\eta\quad,\quad y_F=\varepsilon(b+y)\quad,\quad \theta^0=1-\varepsilon t \tag{27}$$

Where $b=y_{Ff}/\varepsilon$ and $\varepsilon=1/Ze$ are the expansion parameters and the order of unity.

Using equations (15) and substituting equation (27) in the second part of equation (17), the following expression is extracted:

$$\frac{d^2t}{d\eta^2}=\Lambda(b+y)\exp(-t)\quad,\quad \frac{d^2(t+y)}{d\eta^2}=0 \tag{28}$$

The parameter Λ is determined with the assumption $\omega_C c_C = \omega_F c_F = \omega_T c_T$ as follow:

$$\Lambda = \frac{\lambda_u B\varepsilon^2(\upsilon_F \exp(E_{aF}/RT_F) + \upsilon_C \exp(E_{aC}/RT_C) + \upsilon_T \exp(E_{aT}/RT_T))}{\rho_u {\upsilon_u}^2 C} \tag{29}$$

Λ is presumed to be the order of unity. The first term of equation (28) is integrated once using the boundary conditions, the following expression is extracted:

$$2(1+b)\Lambda = \left(\kappa + \frac{B'/v_u^2(\kappa - C'/v_u)}{(C'^2/v_u^2) - (C'/v_u) - (D'/v_u^2)}\right)^2 \tag{30}$$

Burning Velocity Substituting equation (30) into equation (29) yields the burning velocity expression as:

$${\upsilon_u}^2 = \frac{2(1+b)\lambda_u B\varepsilon^2(\upsilon_F k_F + \upsilon_C k_C + \upsilon_T k_T)}{(\Psi)^2 \rho_u C} \tag{31}$$

Where

$$\Psi = \kappa + \frac{B'/v_u^2(\kappa - C'/v_u)}{(C'^2/v_u^2) - (C'/v_u) - (D'/v_u^2)} \tag{32}$$

In order to calculate the flame temperature, the following jump condition is used:

$$\left[\frac{dy_C}{dz}\right]_{0^-} + \left[\frac{d\theta^0}{dz}\right]_{0^-} + \left[\frac{dy_F}{dz}\right]_{0^-} = \left[\frac{dy_F}{dz}\right]_{0^+} + \left[\frac{d\theta^0}{dz}\right]_{0^+} + \left[\frac{dy_C}{dz}\right]_{0^+} \tag{33}$$

If T_f is large enough, y_{Ff} and b can be considered zero in the process of solving this equation. Introducing equations (18) and (25) into equation (33) concludes the following correlation:

$$(e-f)(3b\alpha^{2/3} - 3b^2\alpha^{1/3}(e-f) + b^3(e-f)^2) - (e\kappa^2 - f(C'/v_u)^2) = 0 \tag{34}$$

Equation (31) shows that υ_u is proportional to:

$$\upsilon_u \approx \exp[-E/(2RT_f)] \tag{35}$$

υ_υ represents the burning velocity concluding the heat vaporization of the fuel particles which are proportional to the following equation:

$$\upsilon_\upsilon \approx \exp[-E/(2RT_{f\upsilon})] \tag{36}$$

Where

$$T_{f\upsilon} = T_f - q(T_f - T_u) \tag{37}$$

RESULT AND DISCUSSION

In the combustion of the wood particles, it is presumed that the fuel particles vaporize first to yield the methane structure. The flame temperature and heat capacity, considering the heat loss effects is calculated via the standard computer program and are shown in Figure 2.

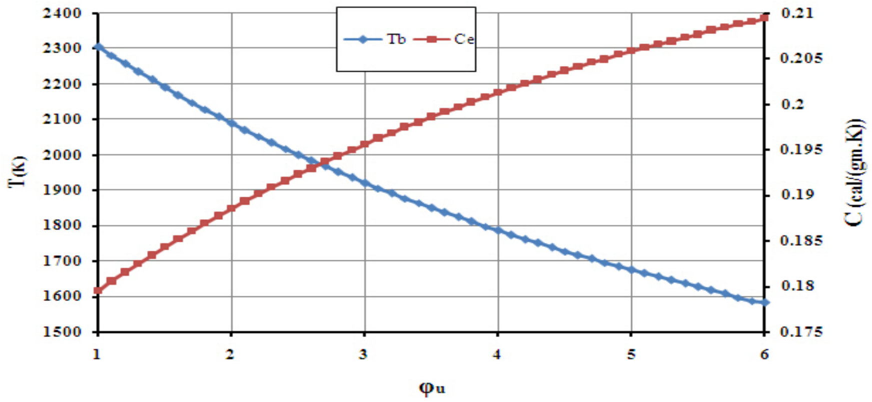

Figure 2. The variation of the adiabatic temperature and heat capacity as a function of equivalence ratio

Figure 3 illustrates the variation of burning velocity υ_{υ}, including the effect of heat vaporization, as a function of equivalence ratio either with or without heat-loss effect. As seen in this figure, the value of burning velocity decreases due to the heat-loss effect in comparison with the case in which the heat-loss term is neglected.

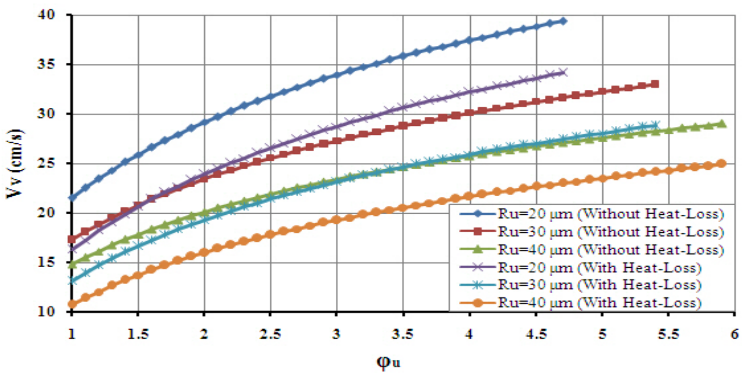

Figure 3. The effect of radiation on the variation of burning velocity υ_{υ}, including the effect of heat vaporization, for different particle radii as a function of equivalence ratio

Figure 4 depicts the flame temperature behavior as a function of equivalence ratio for different radius of the particle either with or without heat-loss impact. This figure demonstrates the considerable effect of heat-loss term on the flame temperature. It must be mentioned that the added heat-loss energy is definitely the main reason for this highlighted decrease in the flame temperature and burning velocity trend.

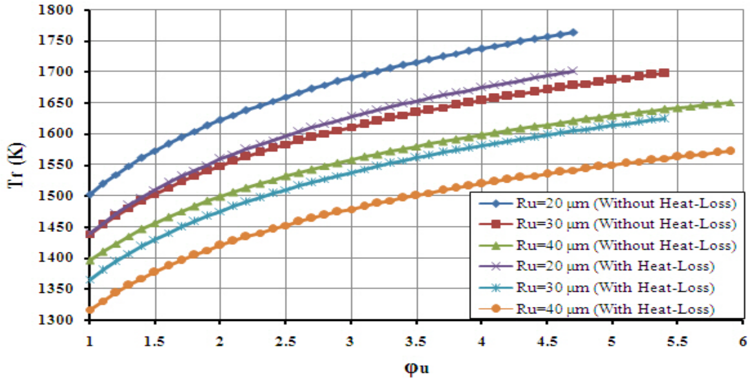

Figure 4. The effect of radiation on the variation of flame temperature for different particle radii as a function of equivalence ratio

It is needed to note that temperature and burning velocity increase due to rising in the equivalence ratio for $\phi_u \geq 1$, while the effective equivalence ratio in the reaction zone is less than unity.

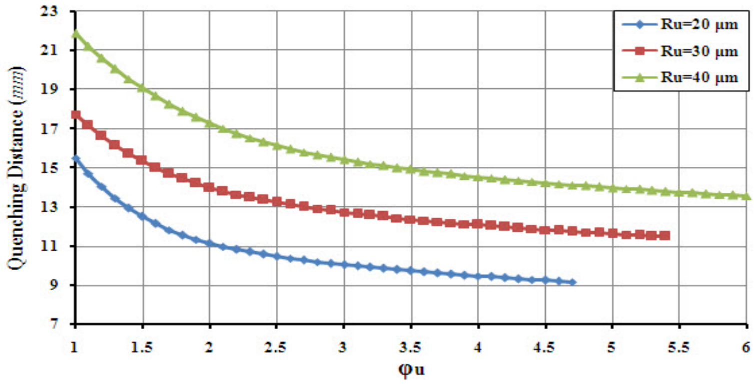

Figure 5. Calculated values of flame quenching distance as a function of equivalence ratio φ_u for the various $R_u\,(\mu m)$

Figure 5 shows the values of flame quenching distance as a function of equivalence ratio for the various $R_u\,(\mu m)$ .This figure shows that for a given value of φ_u the quenching distance decreases with decreasing value of particle size.

CONCLUSION

In this article, the innovative analytical approach is developed for assessing the flame structure and combustion properties of biomass particles. The effects of heat loss from the walls in the structure of premixed flames propagation through biomass dust particles are analyzed. Furthermore, the role of radiation as an effective parameter on the combustion of biomass particles and heat-loss effect are investigated in this research. The initial combustion properties of the biomass particles for instance flame adiabatic temperature and heat capacity of the fuel and air mixture as a function of equivalence ratio are calculated via the standard computer program.
Moreover, associating with the impacts of the heat-loss and different radius of the particles on the combustion properties, it is declared that the lower flame temperature and burning velocity

are gained for either small size of the particles or in the case in which the heat-loss term is applied into the governing equation.

REFERENCES

D.H. Lee and S. Kwon. [2002], Heat transfer and quenching analysis of combustion in a micro combustion vessel, J. Micromech. Microeng. Vol12, pp. 670–676

D.H. Lee, D.E. Park and E. Yoon et al.[2003] A MEMS piston-cylinder device actuated by combustion, ASME J. Heat Transf. Vol125, pp. 487–493.

J. Daou and M. Matalon.[2002], Influence of conductive heat-losses on the propagation of premixed flames in channels, Combust. Flame vol.128, pp. 321–339.

J. Hua, M. Wu and K. Kumar.[2005], Numerical simulation of the combustion of hydrogen–air mixture in micro-scaled chambers. Part I: Fundamental study, Chem. Eng. Sci. Vol60, pp. 3497–3506.

J. Vican, B.F. Gajdeczko and F.L. Dryer *et al.*[2002], Development of a microreactor as a thermal source for micro–electro–mechanical systems power generation, *Proc. Combust. Inst.* Vol29, pp. 909–916.

Galgano, A., and Blasi, C.D.[2004], Modelling the propagation of drying and decomposition fronts in wood. Combustion and Flame,vol.139, pp.16–27.

Porteiro, J., Mıguez, J. L., Granada, E., and Moran, J.C.[2006], Mathematical modelling of the combustion of a single wood particle. Fuel Processing Technology,vol.87, pp.169 – 175.

Bidabadi, M.,Azimi, M. and Rahbari, A. Effects of radiation and particle size on the pyrolysis of biomass particles. Accepted for publication.

Bidabadi, M., and Rahbari, A.[2009], Modelling combustion of lycopodium particles by considering the temperature difference between the gas and the particles. Combustion, Explosion and Shock Waves, vol.45, pp. 49-57.

Williams, M.M.R.[1984], The transmission of radiation through a coagulating aerosol. Journal of Physics D- Applied Physics, vol.17,pp. 509-521.