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Analytical Study of Biomass Cloud Particles considering the Lewis number effect

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ABSTRACT: In this paper, the effect of Lewis number on the structure of one-dimensional flame of biomass combustion is analyzed. This effect can be observed by considering the non-unity Lewis number in the governing equations. the value of the characteristic Zeldovich number is too large and the equivalence ratio is larger than unity $\phi_u \geq 1$ The flame structure consists of three different zones which are, a preheat vaporization zone a reaction zone that consists of gas and Char combustion and a convection zone. The obtained results from the present model declare that the temperature and burning velocity profiles are extremely affected by the various Lewis numbers.

Keywords: Biomass particle, Lewis number, Burning rate.

INTRODUCTION

Biomass is a clean and renewable source of energy and currently represents nearly 14-15% energy consumption. In fact, the necessity of biomass varies significantly across regions of the world. Biomass is becoming a more and usable fuel in the developed countries and because of the diversity of this general source of energy, so many scientists all around the world focus their studies on the different aspects of mathematically, numerically and experimentally modeling of biomass and organic fuels (Chen et al., 1998; William et al., 2001; Backreedy et al., 2002). The selection and design of any biomass combustion system is mainly depended on the characteristics of the fuel (Chopra and Jain, 2007).There are wide ranges of biomass fuels such as wood, short-rotation woody crops and herbaceous species which are studied for at least 20 years. Also the study of biomass/coal co-firing because of the greenhouse emission is the goal of combustion scientist (Senneca, 2007). SO2 and NOx are alternatively biomass pollutant which can be pyrolysed or gasified producing a liquid fuel or a gas-like fuel such as carbon monoxide. Pyrolysis actually is the thermal destruction processes of organic materials and it is pursued by heating in the absence or shortage of oxygen. Fuel moisture content, fuel volatile content, and in the case of combustion on the fuel bed, air flow rate through the bed are the critical factors affecting the ignition velocity. Saastamoinen et al. (2001) experimentally and theoretically studied the ignition wave propagation against the air flow in different packed beds of wood fuels and considered the extra factors such as air temperature, bulk density of the fuel bed and particle size. Lu et al. (2009-In Press) experimentally and theoretically indicated the influence of particle shape and size on the biomass particle dynamics, including drying, heating and reaction rate. Wornat et al. (1996) experimentally studied on the two different type of single particle of biomass char and achieved the burning rates and compare them to the high-volatile bituminous coals. C. Ryu et al. (2006) in their study experimentally investigates the combustion of four biomass materials having different fuel properties in a fixed bed under fuel-rich conditions. Also Y.B. Yang et al. (2004) experimentally and analytically studied on the effect of primary airflow rate and fuel moisture of biomass solid wasted fuel and declare that Primary air has an important effect on the sub-processes combustion: moisture evaporation, devolatilisation and char burning. In addition, they claimed that increasing primary airflow initially increases each of the process rates but causes a decrease in the rates beyond the critical airflow rate. Cetin et al. (2005) experimentally studied on the on the influence of Pressure of combustion area on the char structure and gasification kinetics and in their study some results are achieved by the variation of combustion pressure and they analysis the activation energy and frequency factor in Arrhenius equation. In this article the variation effect of Lewis number in a combustion process of biomass fuel particle considering the Char and Tar formation including the heat of vaporization and devolatization of fuel particles is modeled. The governing equations are solved mathematically and the achieved results are plotted numerically.

Physical Modelling

In this process biomass, cloud particles ignited right after the vaporization of their moisture and Char material is generated at the same time and react with oxidizer. During the combustion of biomass particles like wood five volatied material such as CO , CO2 , H2 , H2O and one light hydrocarbon are produced. It is assumed that the rate of gas burning velocity and porous material burning velocities has the same value. the rate of flame propagation is depended on the 1-the rate of the heat exchanged from the flame, 2- thermodynamical equilibrium of gas phase and solid, in the burned zone

Mathematical Modelling

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

Governing Equations

Mass Conservation Equation:

$$\rho V = cte \qquad (1)$$

Energy conservation equation:

(2)

$$\rho \upsilon C\left(\frac{dT}{dx}\right)=\lambda_u\left(\frac{d^2T}{dx^2}\right)+w_F\left(\frac{\rho_u}{\rho}\right)Q-w_\upsilon\left(\frac{\rho_u}{\rho}\right)Q_\upsilon$$
$$+w_C\left(\frac{\rho_C}{\rho}\right)Q_C+w_T\left(\frac{\rho_T}{\rho}\right)Q_T-w_{de}\left(\frac{\rho_u}{\rho}\right)Q_{de}$$

Where ρ, v, w_F, w_c, w_t and w_υ are the density, the flow velocity, the reaction rate, the reaction rate of char, the reaction rate of tar and the rate of devolitilization respectively and also Y_F and Y_c are the mass fraction of the fuel and the mass fraction of char, respectively. λ is the heat conduction coefficient of both particles and gaseous fuel, Q is the heat release per unit mass of the particles fuel burned in the reaction, Q_v is the heat associated with vaporizing unit mass of fuel and C is the heat capacity of Gaseous and fuel particles combination.
Gaseous fuel conservation equation:

$$\rho v\left(\frac{dY_F}{dx}\right)=\rho_u D_u\left(\frac{d^2Y_F}{dx^2}\right)-w_F\left(\frac{\rho_u}{\rho}\right)$$
$$+w_v\left(\frac{\rho_u}{\rho}\right)+w_{de}\left(\frac{\rho_u}{\rho}\right)-w_T\left(\frac{\rho_T}{\rho}\right) \qquad (3)$$

Where Y is the mass fraction of particles and D is the mass diffusion coefficient Particle mass fraction conservation equation:

$$\rho_S V\left(\frac{dY_S}{dx}\right)=-w_v\left(\frac{\rho_u}{\rho}\right)-w_{de}\left(\frac{\rho_u}{\rho}\right)$$

$$\rho V\left(\frac{dY_C}{dx}\right)=w'_C\left(\frac{\rho_C}{\rho}\right) \qquad (4)$$

The heat capacity (C) is a combination of heat capacity of particles (C_S) and gas (C_P) and it can be evaluated from this expression:

$$C=C_P+\frac{4\pi(r^3C_S\rho_S n_S)}{3\rho} \qquad (6)$$

Where r is the radius of particles and w_v can be described by:

$$w_v=4\pi A n_S r^2(T-T_u)^n \qquad (7)$$

Where A, the Characteristic parameter of vaporization is rate of fuel particles and n is presumed to be constant.

Non-dimensional parameters:

$$m = \frac{\rho \upsilon}{\rho_u \upsilon_u}, \theta = \frac{T - T_u}{T_f - T_u}, y_S = \frac{Y_S}{Y_{FC}}$$
$$z = \frac{\rho_u \upsilon_u C}{\lambda_u} x, y_F = \frac{Y_F}{Y_{FC}}, y_C = \frac{Y_C}{Y_{FC}} \tag{5}$$

Solution: By using the differential equations and asymptotical methods for different combustion zones the equations and non-dimensional equations is solved. The reaction rate is calculated by Arrhenius equ.

Also some parameters such as $\omega_f, \omega_{de}, \omega_c, \gamma, q$ are defined as:

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

The parameters γ, γ' are presumed to be $O(1)$, and the dimensionless form of the boundary conditions for these equations are:

$$\theta = \theta_b = (T_b - T_u)/(T_f - T_u)$$
$$y_F = finite \quad y_C = finite \quad \to z = \infty$$
$$\theta = 0 \quad y_F = 0 \quad y_S = \alpha \quad y_C = 0 \quad \to \quad z = -\infty$$

Where v_u characteristic burning velocity of the flame propagation neglecting the particles is heat of vaporization and α is defined by $\alpha = Y_{FU} / Y_{FC}$. It is assumed that the quantity of q is negligible which means that the heat released due of reaction is more than the heat absorbed due to vaporization of the particles. In this situation instead of θ, the new parameter (θ^0) can be described where $m = 1$.

Burning Velocity Correlation

Using equations (21) and (23), the burning velocity of fuel particles can be obtained as below:

$$\upsilon_u^{\,2} = \frac{2(L_e + b)\lambda_u \varepsilon^2 (\upsilon_F k_F + \upsilon_C k_C + \upsilon_T k_T)}{\rho_u C} \tag{6}$$

And if two parameters T_f and b are presumed to be known, value υ_u can be calculated. For high value of T_f, it is reasonable to assume that $y_{Ff} = 0$ which is resulted to $b = 0$. Flame temperature (T_f) is evaluated by the jump conditions of preheat-vaporization zone and convection zone. The jump condition is written as:

$$\left[\frac{dy_F}{dz}\right]_{0^-} + \left[\frac{d\theta^0}{dz}\right]_{0^-} + \left[\frac{dy_C}{dz}\right]_{0^-} = \left[\frac{dy_F}{dz}\right]_{0^+} + \left[\frac{d\theta^0}{dz}\right]_{0^+} + \left[\frac{dy_C}{dz}\right]_{0^+} \tag{7}$$

RESULTS

In the combustion of the wood particles, it is presumed that the fuel particles vaporize first to yield the methane structure. The chemical kinetic rate parameters are $E = 25000 Cal/mole$ and $B = 5.16\times10^6 mol^{-1}s^{-1}$. Also the kinetic of vaporization of fuel particles are prescribed by these assumptions:

$A = 3.4\times10^{-4}\,(g)_F / [(cm^2)_S\, ks]$, $n = 1.33$.

The constant parameters are presumed are

$\lambda_u = 3\times10^{-4}(cal/cm.s.k), \rho_u = 1.13\times10^{-3}(g/cm^3)$ $\rho_S = 0.72\times10^{-3}(g/cm^3), T_u = 300K, q = 0.01$

It is shown that for $\varphi_u \geq 1$ the equivalence ratio based on the fuel available in the fuel particles (φ_u) are formulated by $\varphi_u = 17.18Y_{Fu}/(1-Y_{Fu})$. Also the effective equivalence ratio in the reaction zone (φ_g) is calculated by $\varphi_g = 17.18Y_{FC}/(1-Y_{FC})$.

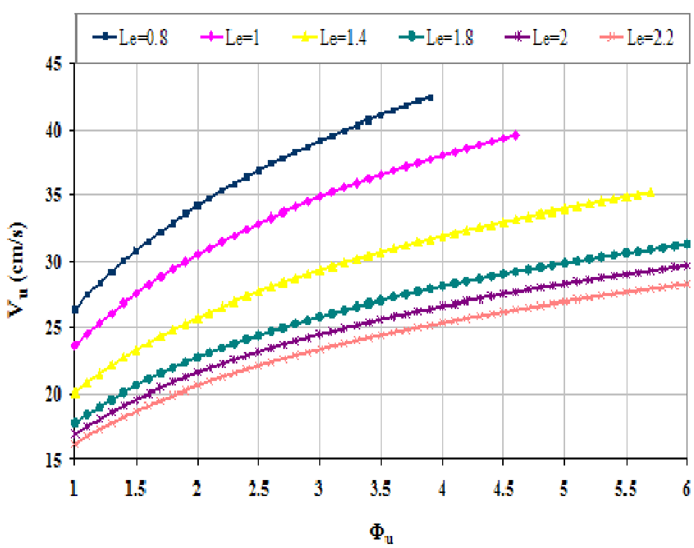

Fig. 1. The variation of burning velocity, neglecting the heat of vaporization, as a function of equivalence ratio for different Lewis numbers at $R = 20\mu m$

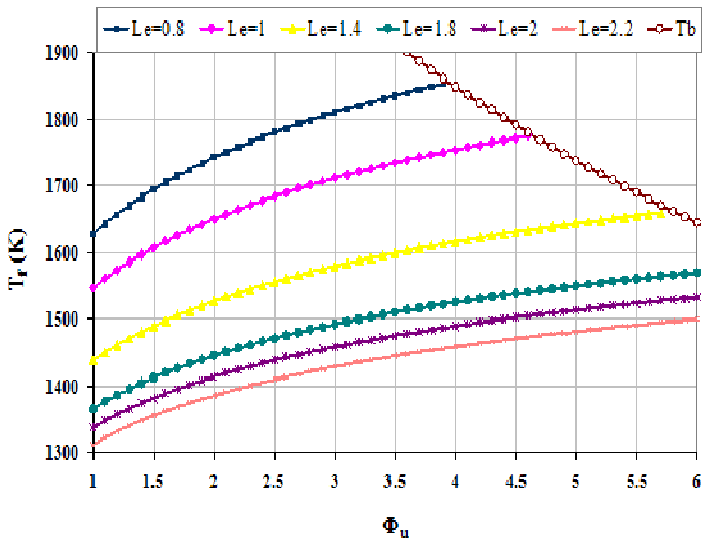

Fig. 2. The variation of flame temperature as a function of equivalence ratio for different Lewis numbers at $R = 20\mu m$

CONCLUSIONS

This article analytically investigates the combustion properties of biomass particles. 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. And also in this paper the variation of burning velocity and the flame temperature via the particles size and thermal properties is shown and illustrated becauseof the extremely dependence to those parameters. It is observed that Lewis number is a determining factor on the combustion properties of biomass particles and the rise in the Lewis number coincides with the reduction in the flame temperature and burning velocity. Similarly, it is declared that the lower flame temperature and burning velocity are gained for larger size of the particles. Consequently, the variation of ϕ_g as a function of ϕ_u elucidates that the quantity of ϕ_g is less than unity and it does not tend to the stoichiometric condition, while ϕ_u is larger than unity. That's why the temperature and burning velocity profiles increase due to increasing the ϕ_u
A characteristic value temperature T_v could be chosen, such that for particle temperature less than T_v, vaporization effects can be ignored and where the gas temperature is larger than T_v the temperature of the particles is presumed to be constant and has a same value with gas. To describing the condition of steady states flame propagation, non adiabatic consideration concepts are employed. The increase in T_v associated with the decrease in the burning velocity which mathematically and physically express that at higher T_v the higher temperature is needed for

starting the vaporization process and the theory declare that since the T_v increase, the mass fraction of the biomass dust particles move towards the reaction zone. It found that excess oxygen would leak from the reaction zone into the convection zone if $\phi_u \geq 1$ and $\phi_g \leq 1$. Similarly it is declared that the lower flame temperature and burning velocity are gained for larger size of the particles. Concluding the high temperature vaporization of the fuel particles in convection zone is continued and presumed one-step reaction between vaporized particles and oxygen is expected to be occurred. Gaseous fuel particle mass fraction at both preheats and vaporization zone decrease and increase respectively when the Lewis number increases. Burning separately with a diffusion flame surrounding the particles in convection zone the variation of ϕ_g as a function of ϕ_u elucidates that the quantity of ϕ_g is less than unity and it doesn't tend to the stoichiometric condition, while ϕ_u is larger than unity. And it declare that the temperature and burning velocity profiles increase due to increasing the ϕ_u .even for the large values of β_2 cloud particles combustion occurred in the reaction zone. The model declare that the increase in T_v reaches to the level which the amount of the gaseous fuel mass fraction and the onset of the vaporization and highest level of the plot move forward the reaction zone and it express the major influence of Lewis number which lead to the flame approaches towards the reaction zone. In the particle cloud combustion including the vaporization of particles, which is happened in the convective, zone the rate of oxidation of H_2 and CO to H_2O and CO_2 can be ignored.

NOMENCLATURE

A : Parameter characterizing rate of vaporization of fuel particles

Y_{FC} : Parameter characterizing rate of vaporization of fuel particles

B : Frequency factor characterizing rate of gas Phase oxidation of the gaseous fuel

C : Heat capacity of mixture

C_F : Molar concentration of fuel

C_P : Heat capacity of the gas

C_S : Heat capacity of a fuel particle

D : Diffusion coefficient

E : Activation energy characterizing the gas-Phase reaction

k : Rate constant of the gas-phase reaction

Le : Lewis Number

n : Temperature exponent characterizing rate of vaporization of fuel particles

n_s : Local number density of particles (number of particles per unit volume)

n_u : Number density of particles in ambient reactant stream (number of particles per unit volume)

Q : Heat release per unit mass of gaseous fuel consumed

Q_v : Heat associated with vaporizing unit mass of fuel

Q_c : Heat associated with charring unit mass of fuel

Q_T : Heat associated with Tarring unit mass of fuel

R : Gas constant
r : Radius of fuel particle
T : Temperature
t : Defined in Eq. 22
v : Velocity
v_u : Burning velocity calculated neglecting heat of vaporization of fuel particles
v_v : Burning velocity calculated including heat of vaporization of fuel particle
W_F : Molecular weight of gaseous fuel
w_v : Rate of vaporization of fuel particles
w_{de} : Rate of vaporization of fuel particles
w_c : Rate of char of fuel particles
w_T : Rate of Tar of fuel particles
w_F : Reaction rate characterizing consumption of gaseous fuel
Y : Mass fraction
y : Gaseous fuel available in the particles in the Ambient reactant stream Defined in Eq. 22
Y_{Fu} : Gaseous fuel available in the particles in the Ambient reactant stream
z_e : Zeldovich number,

Greek Symbols

$\alpha = \frac{Y_{Fu}}{Y_{FC}}$
γ : Defined in Eq
γ' : Defined in Eq.
$\varepsilon = \frac{1}{Z_e}$ Expansion parameter
η : Independent variable defined in Eq. 19
θ : Defined in Eq. 11
θ^0 : Value of θ calculated neglecting heat of Vaporization of particles
Λ : Defined in Eq. 21
λ : Thermal conductivity
ρ : Density of the reactant mixture
ρ_s : Density of a fuel particle
ν : Stoichiometric coefficient
ϕ_u : Equivalence ratio based on fuel available in The particles in the ambient reactant stream
ϕ_s : Effective equivalence ratio in the reaction zone
ω : Defined in Eq. 10

Subscripts

b : Adiabatic conditions after completion of Chemical reactions
F : Gaseous fuel
f : Conditions at the reaction zone

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