Propagation of the Reaction Front of Dry Biomass Particles In a Fixed Bed

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Introduction

Global energy consumption is rising due to rapid industrialization and improvement in living standards. Nearly 80 % of the world's energy consumption is fossil fuel based which is causing environmental and health concerns due to increased emissions of CO_2, NO_x and SO_2. After fossil fuels, biomass is the fourth largest source of energy. It supplies about 11-12 % of world's primary energy consumption [1].

Some researchers evaluated the combustion of municipal solid waste (MSW) or biomass in full-scale grate furnaces [2,3]. However, most researchers used laboratory scale fixed-bed units to simulate operation in grate furnaces [4–6] because it is difficult and expensive to obtain detailed in-bed data from full-scale furnaces. Furthermore, experimental and simulated results showed that an analogy exists between combustion in a fixed bed and on a grate [7]. The analogy shows that results from fixed-bed combustion can be applied as a good approximation of moving-bed combustion due to the relatively small horizontal gradients (compared to the vertical) in industrial facilities. The similarities may include: the bed temperature profiles, combustion rates and efficiency, and, gas release from bed surface [8]. Propagation of the ignition flame front is one of the main research topics in the solid fuel combustion in packed beds; it determines the volatiles release rate and affects the combustion thermal output from a given grate area and the stability of combustion [8]. The ignition and propagation of a reaction front in packed bed biomass combustion have been studied experimentally and by modeling in the last decade [3,4,6, 9–11].

In this paper, flame propagation in a fixed bed of burning biomass particles has been considered. After ignition, a reaction front propagates downwards from the surface of the bed against the direction of the combustion air. The heat, generated in the reaction front, is transported against the flow of combustion air and dries and devolatilises the biofuels. This allows the reaction front to propagate [12]. This work is an extension of that by Saastamoinen et al. [4]. The results can also be applied to traveling grates, where the fuel is ignited on top of the bed and the air flows upwards through the grate and the bed.

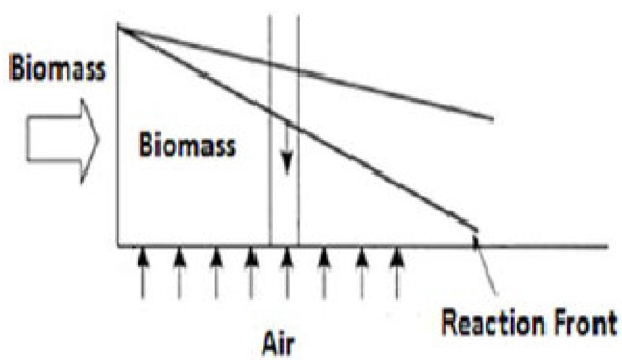

Fig 1.Schematic view of the combustion in bed of solid fuel

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Mathematical Model

Heating of the oxidizing gas flowing against the moving reaction wave and the heating of the solid fuel in the bed are described by the energy equations:

$$\begin{aligned} \rho_g c_g u_g \frac{\partial T_g}{\partial x} &= \frac{\partial}{\partial x}\left(\lambda_g \frac{\partial T_g}{\partial x}\right) + hS\left(T_p - T_g\right) \\ (1-\varepsilon)\rho_p c_p \frac{\partial T_p}{\partial t} &= \frac{\partial}{\partial x}\left(\lambda_{eff} \frac{\partial T_p}{\partial x}\right) - hS\left(T_p - T_g\right) + \dot{q} \end{aligned} \tag{1}$$

where h, S and $\dot{q}$ are convective heat transfer coefficient, W/(m^{2}K), volumetric solid surface area, m^2/m^3, and rate of heat generation per unit volume, W/m^3, respectively. λ_{eff} is effective thermal conductivity of particles that consisting of a conductive and a radiative constituent

$$\lambda_{eff} = (1-\varepsilon)\lambda_p + 4\varepsilon\sigma d_p T_p^3 \tag{2}$$

where ε is the bed voidage, σ the Stefan–Boltzmann constant, d_p the particle diameter, T the temperature and λ_p the thermal conductivity of the fuel [12].

In the models which are presented here, it is assumed that the local absorption of energy in the bed is directly proportional to the local heat flux. Then the heat flux from the burning particles through the bed decays exponentially with distance, $q'' = q_0'' exp(-\alpha X)$, which gives the local heat generation $\dot{q} = \alpha q_0'' exp(-\alpha X)$ [4]. The radiative flux depends on the effective temperature of the flame zone T_f, $q_0'' = k\sigma T_f^4$, where $k(< 1)$is the effective radiation coefficient. T_f depends on the stoichiometry, the calorific value of the fuel, etc [4].

We introduce a coordinate system X attached to the reaction zone

$$X = x - \chi(t) \tag{3}$$

where $\chi(t)$ is the position of the reaction zone and thus, $V_{rf} = \chi'(t)$ is the reaction front velocity. With applying this moving coordinate, these equations are obtained:

$$\begin{aligned} \dot{m}_g'' c_g \frac{\partial T_g}{\partial X} &= \lambda_g \frac{\partial^2 T_g}{\partial X^2} + hS\left(T_p - T_g\right) \\ -(1-\varepsilon)\rho_p c_p V_{rf} \frac{\partial T_p}{\partial X} &= \lambda_{eff} \frac{\partial^2 T_p}{\partial X^2} - hS\left(T_p - T_g\right) + \dot{q} \end{aligned} \tag{4}$$

where we assumed that λ_g and λ_{eff} are constant and cube power of particle temperature is the cube power of reaction temperature.

With introducing below dimensionless parameters

$$\begin{aligned} &\xi = \frac{hS}{\dot{m}_g'' c_g} X = \alpha\Lambda X, \qquad \phi = \frac{\alpha q_0''}{hS(T_{re} - T_\infty)}, \qquad \Lambda = \frac{hS}{\alpha \dot{m}_g'' c_g} \\ &T_p^* = \frac{T_p - T_\infty}{T_{re} - T_\infty}, \qquad T_g^* = \frac{T_g - T_\infty}{T_{re} - T_\infty}, \qquad V_{rf}^* = \frac{(1-\varepsilon)\rho_p c_p V_{rf}}{\dot{m}'' c} \\ &\lambda^* = \frac{\lambda_{eff}}{\lambda_g}, \qquad \beta_g = \frac{\lambda_g hS}{\left(\dot{m}_g'' c_g\right)^2}, \qquad \beta_p = \frac{\lambda_{eff} hS}{\left(\dot{m}_g'' c_g\right)^2} = \lambda^* \beta_g \end{aligned} \tag{5}$$

equation (4) can be presented in dimensionless form as

$$\boldsymbol{\beta_g \frac{\partial^2 T_g^*}{\partial \xi^2} - \frac{\partial T_g^*}{\partial \xi} + T_p^* - T_g^*}$$
$$\boldsymbol{\lambda^* \beta_g \frac{\partial^2 T_p^*}{\partial \xi^2} + V_{rf}^* \frac{\partial T_p^*}{\partial \xi} - T_p^* + T_g^* + \phi e^{-\xi/\Lambda} = 0} \tag{6}$$

By solving the energy conservation equations and with this boundary condition that at $\xi = 0$, the particle temperature is equal with ignition temperature an algebraic equation for the dimensionless reaction front velocity can be obtained

$$V_{rf}^* = \phi\Lambda + \frac{(\lambda^* + 1)\beta_g\Lambda^2 - \lambda^*\beta_g\Lambda - \lambda^*\beta_g^2 + \Lambda^3}{\Lambda^3 - \Lambda^2 - \beta_g\Lambda} \tag{7}$$

that in dimensional form is

$$V_{rf} = \frac{1}{(1-\varepsilon)\rho_p c_p}\left(\frac{q_0''}{T_{re} - T_\infty} + \frac{\lambda_p\alpha\left(hS - \alpha\dot{m}_g''c_g\right) + \lambda_g hS\alpha - \lambda_p\lambda_g\alpha^3 + hS\dot{m}_g''c_g}{hS + \alpha\dot{m}_g''c_g - \lambda_g\alpha^2}\right) \tag{8}$$

Results

The model can be used as a tool to study the influence of combustion characteristics, such as biomass species, particle diameter and density, and air temperature and flow velocity to the fuel bed on the flame front velocities. In some instances the propagation rate of the reaction front where is velocity multiplied by apparent density, $(1-\varepsilon)\rho_p$, of the packed fuel bed is used instead of the velocity of the reaction front. For example figure 1. shows the variation of propagation rate of the reaction front with air flow rate and fig. 3 illustrates the effects of pre-heating the primary air on the propagation rate of the reaction front.

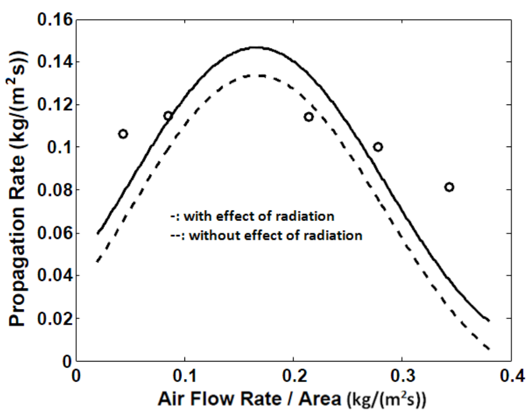

Fig. 1. Measured and calculated propagation rate of the reaction front for different air flow rate. Measured results are for a mixture of spruce and pine and almost dry (2.1% wet basis) from [13].

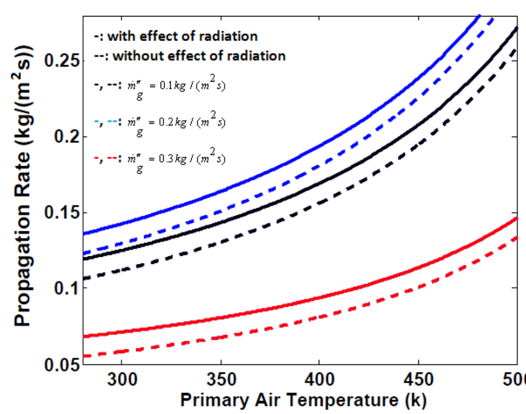

Fig. 2. Effect of primary air temperature on the propagation rate of the reaction front.

Both the experimental and simulated results indicate that the ignition flame front rate initially increase rapidly with an increase of the air-flow rate and then decreases. This can be explained as follows: in the reaction front, a balance between heat generation by volatiles combustion or char oxidation, heat transfer to unburnt fuel, and convective cooling by the primary air is achieved. At low-primary air-flow rate, the amount of heat transported by the air is relatively small as compared with heat generated by fuel oxidation and heat conduction to underlying fresh layers of fuel. The heat produced by fuel combustion linearly increases with the primary air-flow rate, which causes the reaction flame front rate to increase rapidly. However, the amount of heat required for heating the gaseous phase also linearly increases with the air-flow rate. At a high-gas-flow rate, the increase of the heat transported by the air-flow eliminates the increase of the heat produced by the fuel oxidation, which causes the ignition flame front rate to decrease. Ignition could not be obtained when the total amount of heat transported by the gas flow and by the heat conduction is larger than the heat generated by fuel combustion [8]. The model indicates that the propagation rate increased with increasing the primary air preheating temperature.

Conclusions

The paper presents a model for biomass combustion process in fixed bed for calculation propagation rate of reaction front in fixed bed combustor. Equation (8) shows that the for dry biomass particles main factors affecting the reaction velocity are fuel volatile content, air flow rate through the bed, primary air temperature, bulk density of the fuel bed and properties of particles. Results show that the velocity of the reaction front (ignition front) increases first with increasing air velocity, reaches a maximum, and then drops slightly until the reaction extinguishes, Fig. 1. Model predicts that reaction velocity is very sensible to primary air temperature and dependence to the effective thermal conductivity and also bed porosity is also important but with changing of particle diameter, air thermal conductivity and convective heat transfer coefficient change slowly.

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