

## Effect of thermal radiation on modeling of moist organic dust combustion

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### Abstract

In this paper our last model is extended and thermal radiation is taken to account, which is a dominant mechanism in organic dust combustion. Also effects of devolatilization temperature and particle radius are investigated in this paper. One dimensional model is used to evaluate the flame characteristics. The flame structure is divided into three zones: preheat zone, reaction zone and post-flame zone. Also preheat zone is also divided into four subzones itself: first heating subzone and drying subzone, second heating subzone and volatile evaporation subzone. The obtained results show that the induced thermal radiation from flame interface into the preheat and vaporization zones plays a significant role in the improvement of vaporization process and burning velocity of organic dust mixture, compared with the case in which the thermal radiation factor is neglected. According to results, burning velocity and mass fraction of gaseous fuel strongly depend on radiative heat transfer. By considering radiation effect our results have better agreement with experimental data.

**Keywords:** Organic particles, Thermal radiation, Devolatilization temperature, Particle radius, Burning velocity, Gaseous fuel mass fraction.

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## 1- Introduction

“In this paper our last model [1] is extended and thermal radiation is taken to account, which is a dominant mechanism in organic dust combustion”.

Nowadays greenhouse effect is one of the most challenging issues on human lives, and  $\text{CO}_2$  is one of the important greenhouse gases. By increasing electricity consumption,  $\text{CO}_2$  generation rate increases, and scientists are eager to find new approaches to generate electricity with no  $\text{CO}_2$  production by using solar or biomass power plants [2,3].

From viewpoints of the environment and fuel cost reduction, small scale biomass combined heat and power (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  $\mu\text{m}$  is mainly used, and a combustion chamber length of 3 m is applied [4].

In order to enhance the efficiency of Stirling engines and also to better design of combustion chamber, knowing the combustion mechanism dust particles and interaction between these particles is essential. In spite of this necessity, basic mechanisms of combustion of heterogeneous mixtures consisting of particles and an oxidizer are not well understood yet.

One of the problems in modeling of organic dust combustion is radiation heat transfer. Radiation is often a dominant process in the flame propagation through dust clouds and produces a condition of excess enthalpy in the combustion field. Whereas the radiation behavior in particle cloud combustion is so complicated [5], the influences of radiation are still not well understood. In this paper we extend our last model [1] to calculate effect of radiation in organic dust combustion.

According to our previous model, in this paper, it is also presumed that first the moisture content of the solid particles evaporate, then the dried particles vaporize to yield a gaseous fuel ( $\text{CH}_4$ ). The flame structure is divided into three zones. First zone is preheat zone where the rate of chemical reaction is small. Second zone is an asymptotically thin reaction zone where convection and rate of vaporization of the particles are negligible in comparison with reaction rate. And finally there is a post-flame zone.

It is notable that, the overall equivalence ratio of the initial combustible mixture must be larger than 0.7 to ensure the existence of flame continuity, thus in this article we present results for  $\phi_u > 1$ .

## 2- Theoretical model

In combustion of organic dust particles, the vaporization rate states the differences between the organic dust and gas mixture. Furthermore, the combustion phenomena are not only controlled by the vaporization rate but also by the rate of heat conduction to mass diffusivity. The dimensionless expression of this ratio is represented by the Lewis number ( $Le$ ):

$$Le = \frac{\lambda}{\rho C D} \quad (1)$$

where  $\lambda$ ,  $\rho$ ,  $C$  and  $D$  are thermal conductivity of gaseous mixture, mixture density, mixture specific heat and characteristic mass diffusivity, respectively.

In this article, it is assumed that reaction occurs in thin zone  $O(\epsilon)$  (order of epsilon), whereas preheat and post-flame zones have considerable length. This assumption is based

on high Zeldovich number and  $\varepsilon$  is defined as a reciprocal of Zeldovich number. The Zeldovich number is defined as:

$$Ze = \frac{E(T_f - T_u)}{RT_f^2} \quad (2)$$

where  $E$ ,  $R$ ,  $T_f$  and  $T_u$  are activation energy of reaction, the universal gas constant, flame temperature and fresh mixture temperature, respectively. Vaporization Damköhler number ( $Da_{vap}$ ) is defined as ratio of vaporization time ( $t_{vap}$ ) to characteristic reaction time ( $t_{chem}$ ):

$$Da_{vap} = \frac{t_{vap}}{t_{chem}} \quad (3)$$

Another dimensionless number which has appeared in this study is drying Damköhler number ( $Da_{dry}$ ) that takes the effect of moisture content into account. Vaporization resistance of water within biomass particles is represented here as:

$$Da_{dry} = \frac{t_{dry}}{t_{chem}} \quad (4)$$

The combustion process is modeled as a one-step overall reaction,  $\nu_F[F] + \nu_{O_2}[O_2] \rightarrow \nu_P[P]$  where symbols  $F$ ,  $O_2$ , and  $P$  denote the fuel, oxygen, and product, respectively. And the quantities  $\nu_F$ ,  $\nu_{O_2}$ , and  $\nu_P$  denote their stoichiometric coefficients. Finally the governing equations are written as follow:

➤ Solid fuel particles conservation:

$$\rho V \frac{dY_s}{dx} = -\rho_u w_{dry} - \rho_u w_{vap} \quad (5)$$

In above equation,  $Y_s$ ,  $V$  and  $\rho$  are mass fraction of organic dust particles, burning velocity and density of the mixture, respectively.  $w_{dry}$ ,  $w_{vap}$  are particle drying rate and volatile vaporization rate which are expressed by:

$$w_{dry} = \frac{Y_s}{\tau_{dry}} H(T - T_{dry})$$

$$w_{vap} = \frac{Y_s}{\tau_{vap}} H(T - T_{vap}) \quad (6, 7)$$

where  $H$ ,  $\tau_{dry}$ ,  $\tau_{vap}$ ,  $T$ ,  $T_{dry}$  and  $T_{vap}$  are the Heaviside function, constant characteristic time of drying and vaporization, mixture temperature and threshold temperature of drying and vaporization, respectively.

➤ Gaseous fuel conservation:

$$\rho V \frac{dY_g}{dx} = \rho_u D_u \frac{d^2 Y_g}{dx^2} - \rho_u w_g + \rho_u w_{vap} \quad (8)$$

where  $Y_g$  and  $D_u$  are mass fraction of gaseous fuel gained from vaporization of organic dust particles and binary diffusion coefficient of gaseous limiting component, respectively.  $w_{chem}$  is rate of chemical-kinetic that is expressed by following relation:

$$w_{chem} = Y_g k$$

$$k = B \exp\left(\frac{-E}{RT}\right) \quad (9)$$

In above equation,  $B$  is frequency factor.

➤ Energy conservation:

$$\rho VC \frac{dT}{dx} = \lambda_w \frac{d^2T}{dx^2} + \rho_u Q w_{chem} - \rho_u Q_{dry} w_{dry} - \rho_u Q_{vap} w_{vap} + Q_{rad} \quad (10)$$

$Q_{dry}$ ,  $Q_{vap}$  are latent heat of drying and volatile vaporization and heat of reaction, respectively. Also,  $Q_{rad}$  is the heat transport by radiation through the cloud of volatile fuel particles, which is defined by following equation:

$$\begin{cases} Q_{rad} = K_a I_f \exp(K_c x) & \text{for preheat and vaporization zones} \\ Q_{rad} = -K_a (I_{bpf} - I_f) & \text{for asymptotically thin reaction zone} \\ Q_{rad} = -\Omega K_a I_{bpf} & \text{for post-flame zone} \end{cases} \quad (11)$$

where:

$$\begin{aligned} K_c &= K_u + K_s & I_{bpf} &= \frac{\sigma T_f^4}{\pi} & I_f &= \frac{K_a}{K_c} I_{bpf} & \Omega &= \frac{K_a}{K_a + K_s} \\ K_a &= \frac{\pi d_p^2 n_s}{4} Q_{abs} = \frac{3}{2} \frac{\varphi}{\rho_p d_p} Q_{abs} \\ K_s &= \frac{\pi d_p^2 n_s}{4} Q_{sca} = \frac{3}{2} \frac{\varphi}{\rho_p d_p} Q_{sca} \end{aligned} \quad (12)$$

In these relation,  $\sigma$  is Stefan-Boltzmann constant.  $d_p$  and  $\varphi$  are particle diameter and mass concentration, respectively. Also,  $Q_{abs}$  and  $Q_{sca}$  are absorption and scattering efficiencies, respectively. If the particles of the mixture are mainly diffusely reflecting spheres, the absorption and scattering efficiencies can be written as follows [6]:

$$Q_{abs} = \epsilon_p, \quad Q_{sca} = 1 - \epsilon_p \quad (13)$$

where  $\epsilon_p$  is the solid particle emissivity.  $C$  is heat capacity of mixture obtained from heat capacity of gas ( $C_p$ ) and particle ( $C_s$ ), which is defined by following equation:

$$C = C_p + \frac{4\pi r_p^3 C_s \rho_s n_s}{3\rho} \quad (14)$$

$\rho_s$ ,  $r_p$  and  $n_s$  are particle density, radius of particle and average number of particles per unit volume, respectively. Flame structure for organic dust particles is shown in Fig.1. According to this figure flame structure is divided into three zone. To calculate effect of moisture content, preheat zone is separated into four subzone.

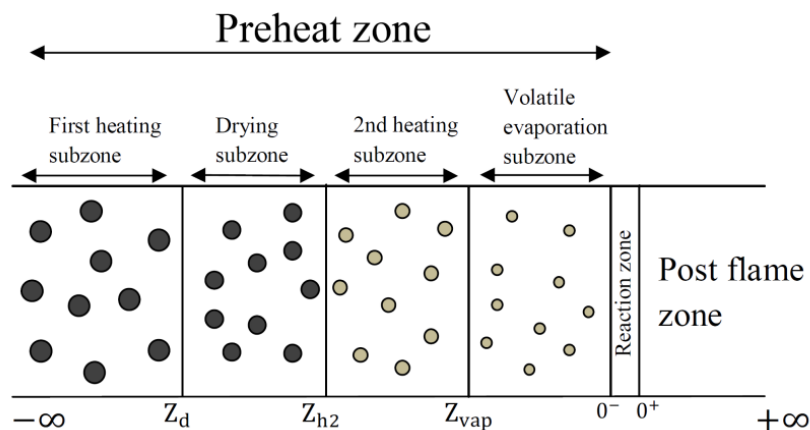


Fig. 1. Schematic figure of combustion regions for presented model.

In order to obtain the flame structure, an analytical method is used to solve the governing equations with existing boundary conditions and a matching condition.

### 3- Results and discussion

To evaluate accuracy of the presented model, the burning velocity is compared with flame velocity which is calculated by Proust [7]. Proust calculated burning velocity of lycopodium as a function of mass particle. As shown in Fig. 2. by considering radiation heat transfer, presented model has more conformity with experimental data in comparison of our previous model [1].

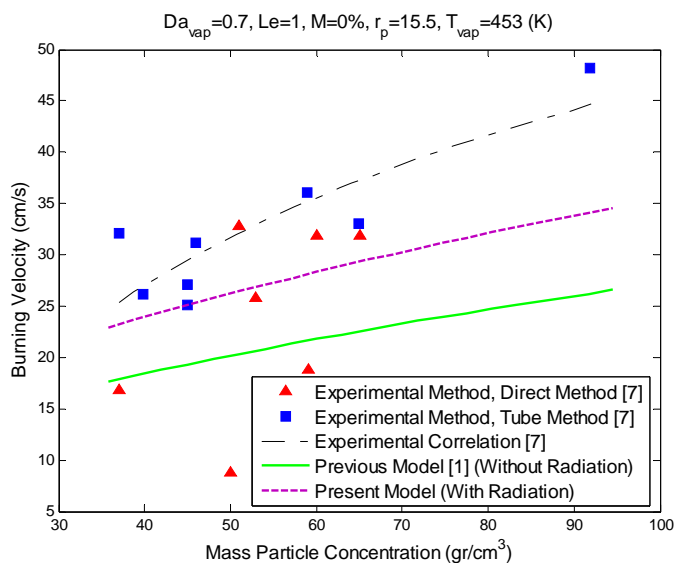


Fig. 2. The variation of burning velocity as a function of mass particle concentration for both present model and experimental data [7].

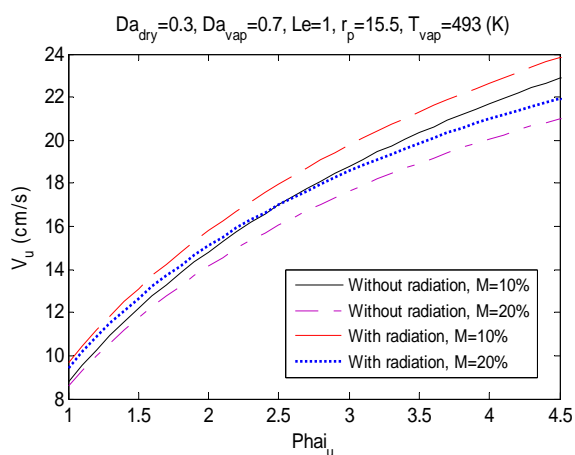


Fig. 3. The variation of burning velocity as a function of  $\phi_u$  (equivalence ratio) for different moisture contents.

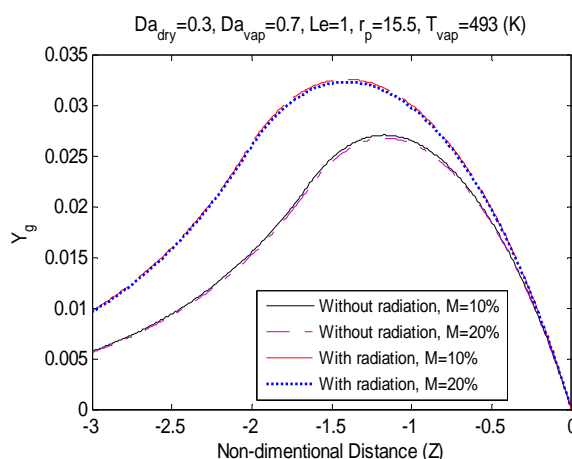
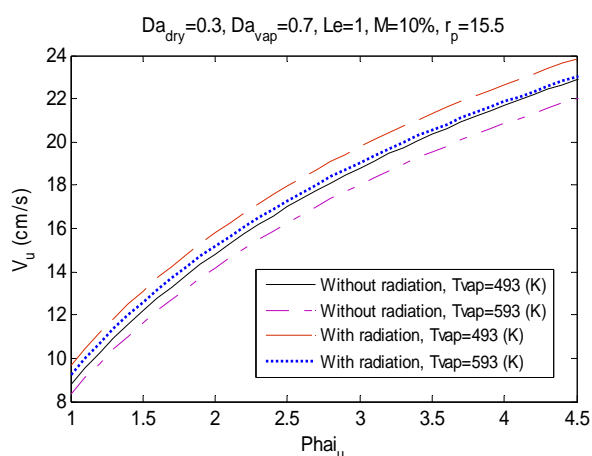


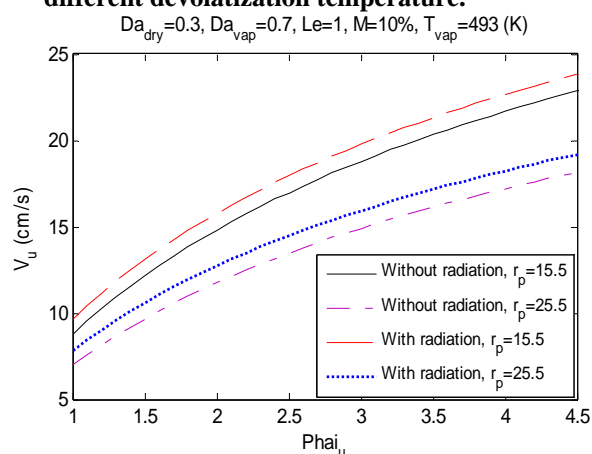
Fig. 4. The variation of gaseous fuel mass fraction as a function of dimensionless distance for different moisture content.

According to Fig. 3. increase in moisture content cause to decrease burning velocity, however by considering radiation, burning velocity increases. As shown in fig. 4. by assuming

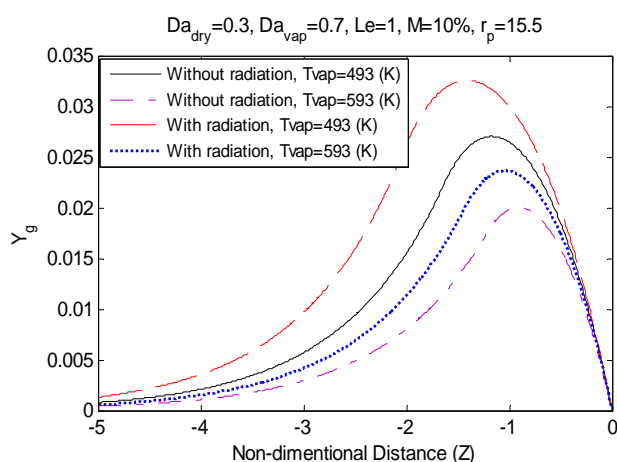
radiation, in equal moisture content, amount of produced gaseous fuel increases. In fact the radiation improves the drying and the vaporization processes of organic dust particles by transferring the heat from the flame interface into the preheat zone.



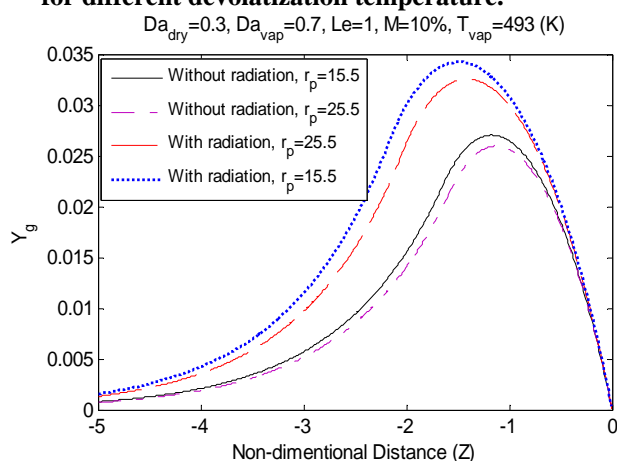
**Fig. 5.** The variation of burning velocity as a function of  $\phi_u$  (equivalence ratio) for different devolatilization temperature.



**Fig. 7.** The variation of burning velocity as a function of  $\phi_u$  (equivalence ratio) for different particle radius.



**Fig. 6.** The variation of gaseous fuel mass fraction as a function of dimensionless distance for different devolatilization temperature.



**Fig. 8.** The variation of gaseous fuel mass fraction as a function of dimensionless distance for different particle radius.

As shown in Fig. 5. and Fig. 6. increase in devolatilization temperature, reduce opportunity of particles to vaporize and change into gaseous fuel. Consequently mass fraction of gaseous fuel at the entrance of reaction zone decrease, finally burning velocity decreases.

As seen in Fig. 7. and Fig. 8. particle radius strongly affects the burning velocity and mass fraction of gaseous fuel. By reducing particles radius, effective surface area increase and clearly improve the devolatilization process. By considering radiation in Figs 5,6,7,8 an increase in vaporization process occurs which is repeated in Fig. 3. and Fig. 4.

#### 4- Conclusion

The present analytical study shows that the induced thermal radiation from flame interface into preheat and vaporization zones plays a significant role in the improvement of vaporization process and burning velocity of organic dust mixture, compared with the case in which the thermal radiation factor is neglected. Interesting results have been also obtained by

considering of the thermal radiation influence as follows. By considering of the thermal radiation from the flame interface into preheat and vaporization zones, due to the fact that an external heat term has been added to these zones, the vaporization process is improved and the burning velocity consequently increases. Therefore, the present model predicts a closer result to experimental data published by Proust [7], compared with our previous study [1].

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## Nomenclature

- $B$  : frequency factor characterizing rate of gaseous fuel oxidation  
 $C$  : heat capacity of mixture, Eq. (14)  
 $C_p$  : heat capacity of the gas  
 $C_s$  : heat capacity of a solid particle  
 $D$  : diffusion coefficient  
 $Da_{dry}$  : drying Damköhler number, Eq. (3)  
 $Da_{vap}$  : vaporization Damköhler number, Eq. (4)  
 $E$  : activation energy of fuel, Eq. (9)  
 $H$  : Heaviside function  
 $k$  : fuel reaction constant rate, Eq. (9)  
 $Le$  : Lewis number  
 $n_p$  : local number density of particles (number of particles per unit volume)  
 $Q$  : released heat per unit mass of consumed fuel particles  
 $Q_{abs}$  : absorption efficiency  
 $Q_{vap}$  : heat associated with devolatilizing unit mass of solid fuel particles  
 $Q_{dry}$  : heat associated with moisture evaporation from particles  
 $Q_{sca}$  : scattering efficiency  
 $R$  : global gas constant  
 $r_p$  : radius of the particle  
 $T$  : temperature  
 $T_f$  : flame temperature  
 $t_{chem}$  : characteristic time of chemical reaction  
 $t_{dry}$  : characteristic time of drying  
 $t_{vap}$  : characteristic time of volatile evaporation  
 $U$  : burning velocity  
 $w_{chem}$  : reaction rate characterizing consumption of gaseous fuel, Eq. (9)  
 $w_{vap}$  : devolatilization rate of solid fuel particles, Eq. (7)  
 $w_{dry}$  : drying rate of solid fuel particles, Eq. (6)  
 $Y$  : mass fraction  
 $Z_e$  : Zeldovich number, Eq. (2)

## Greek Symbols

- $\alpha = 1/Z_e$  : expansion parameter  
 $\epsilon_p$  : is the solid particle emissivity  
 $\lambda$  : thermal conductivity  
 $\rho$  : density of the reactant mixture  
 $\rho_s$  : density of a solid particle  
 $\varphi$  : mass concentration  
 $\varphi_u$  : equivalence ratio based on fuel available in the particles in the ambient reactant stream ( $\varphi_{a,u}$ )  
 $\sigma$  : Stefan-Boltzmann constant

## Subscripts

- $g$  : gaseous fuel  
 $F$  : conditions at the reaction zone  
 $p$  : particle  
 $s$  : solid particles  
 $u$  : conditions in the ambient reactant stream  
 $rad$  : thermal radiation