

Effect of dimensionless numbers on production of energy from moist organic dust particles

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Abstract

Nowadays Stirling engines are widely used in Baltic countries. Widespread usage of Stirling engines led to many investigations on organic dust combustion to enhance these engines efficiency. However many experimental studies have done in this subject, but lack of an integral analytical model is sensible. In this study we present an analytical model to simulate the combustion process of moist organic dust. 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. Finally, effect of moisture and also effects of some important parameters, like devolatilization temperature, Da_{vap} , Da_{dry} and Lewis numbers are investigated. Increase in moisture content causes a reduction in burning velocity due to moisture evaporation resistance.

Keywords: Organic particles, Moisture content, Analytical model, Da_{vap} number, Da_{dry} number, Lewis number, Devolatilization temperature.

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1- Introduction

Increasing in energy demands and completion of fossil fuels cause human to explore new resources for fulfilling these necessities, also the effective conversion systems have essential role in the future of energy production [1]. Biomass has been known as the major renewable resource [2]. Furthermore, power generation from biomass is a CO_2 -neutral method and help us to conserve our environment for future generations. Biomass is presently estimated to contribute the order **10-14%** of the world's energy supply [3].

Having low energy density, it is not economical to transport biomass fuels to power plants. However, small scale biomass conversion system is suitable for local usage. The Stirling engine is one of the best available technologies for small-scale biomass power production. The Stirling engine can be driven by many kinds of heat sources. It is also called external combustion engine when the heat is derived from fuel combustion. Being an external combustion device and less demanding in operation conditions, the Stirling engine has been incorporated into biomass energy utilization research projects as a viable prime mover [2]. The Stirling engines are fed by micro-scale biomass up to 500 micrometer to enhance their efficiency. Furthermore a dual heat source (solar and biomass) can be used for Stirling engines to increase their conformity with the nature [4].

Generally, combustible particles ignite in two phases: the gaseous phase and the solid phase. Most of the organic particles combust in a gaseous phase, thus investigation of vaporization and combustion mechanism of volatile particles is necessary. So far little research has been done in this area. For example, fundamental information such as structure and movement of combustion zone in a dust particle cloud in a vertical duct is still ambiguous [5,6]. In general, solid particles heat up until they reach evaporation temperature, then volatiles come out of the particles and finally these volatiles combust in reaction zone.

In this paper, it is presumed that first the moisture content of the solid particles evaporate, then the dried particles vaporize to yield a gaseous fuel (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 λ , ρ , C and D are thermal conductivity of gaseous mixture, mixture density, mixture specific heat and characteristic mass diffusivity, respectively. To make the problem simple, previous studies often assumed the Lewis number to be unit [7,8]. However, in this study effect of nonunity Lewis number is investigated.

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 ϵ is defined as a reciprocal of Zeldovich number. The Zeldovich number is defined as:

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

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 ν_F , ν_{O_2} , and ν_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 ρ 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 , τ_{dry} , τ_{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:

$$\rho V C \frac{dT}{dx} = \lambda_u \frac{d^2T}{dx^2} + \rho_u Q_{chem} - \rho_u Q_{dry} W_{dry} - \rho_u Q_{vap} W_{vap} \quad (10)$$

Q_{dry} , Q_{vap} are latent heat of drying and volatile vaporization and heat of reaction, respectively. C is heat capacity of mixture obtained from heat capacity of gas (C_p) and particle (C_s), which is defined by following equation:

$$C = C_p + \frac{4\pi r_p^3 C_s \rho_s n_s}{3\rho} \quad (11)$$

ρ_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.

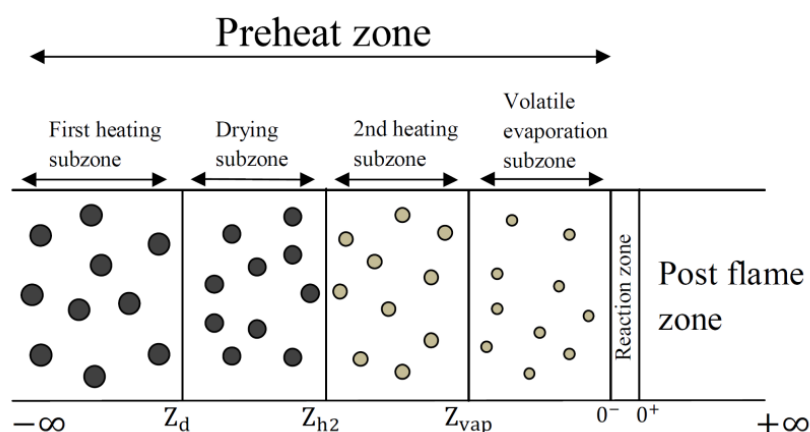


Fig. 1. Schematic figure of combustion regions for presented model.

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 [9]. Proust calculated burning velocity of lycopodium as a function of mass particle concentration in both direct method and tube method. As shown in Fig. 2, the evolution of burning velocity as a function of mass particle concentration is in reasonable agreement with the experimental data.

It is notable that results of this model are closer to direct method data than to tube method data. The calculated velocities are also less than experimental results. Neglecting some mechanisms, like radiation, cause the calculated burning velocity to be smaller than the experimental data. 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.

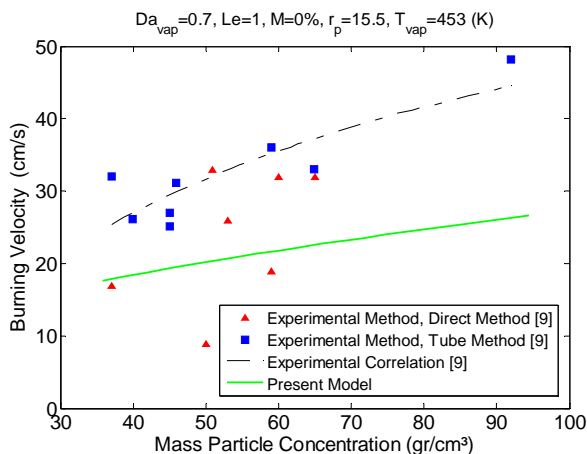


Fig. 2. The variation of burning velocity as a function of mass particle concentration for both present model and experimental data [9].

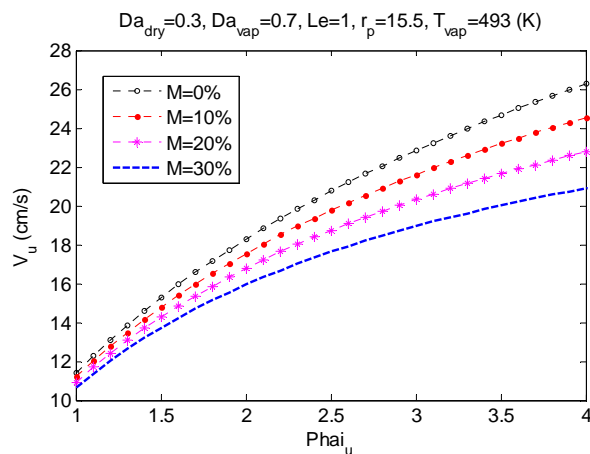


Fig. 3. The variation of burning velocity as a function of ϕ_u (equivalence ratio) for different moisture contents.

According to Fig. 3, the burning velocity goes down when the quantity of moisture content is shooting up from 0% to 30% at $r_p = 15.5 \mu\text{m}$ and $Da_{dry} = 0.3$ and $Da_{vap} = 0.7$ and $Le = 1$. As the moisture content in the particle increase, the moisture evaporation resistance also increases. Therefore, the flame propagation slows down which yields a decrease in the burning velocity. Also increase in equivalence ratio ϕ_u (particle number density), reduces devolatilization resistance. Consequently the burning velocity increases. Clearly any increase in moisture evaporation resistance (Da_{dry}) results in the burning velocity decrease as shown in Fig. 4. Devolatilization temperature (T_{vap}) is one of the essential parameters in behavior of organic dusts. Lower Devolatilization temperature lead to more opportunity for producing gaseous fuel. As a result, as shown in Fig. 5, decrease in devolatilization temperature cause an increase in the burning velocity. An increase in Da_{vap} number results in a decrease in rate of vaporization which means a higher devolatilization resistance for a constant reaction rate. Consequently, the burning velocity decreases as shown in Fig. 6.

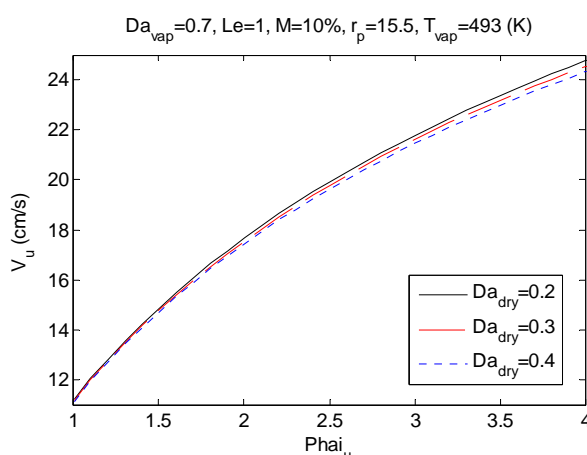


Fig. 4. The variation of burning velocity as a function of ϕ_u (equivalence ratio) for different Da_{dry} number.

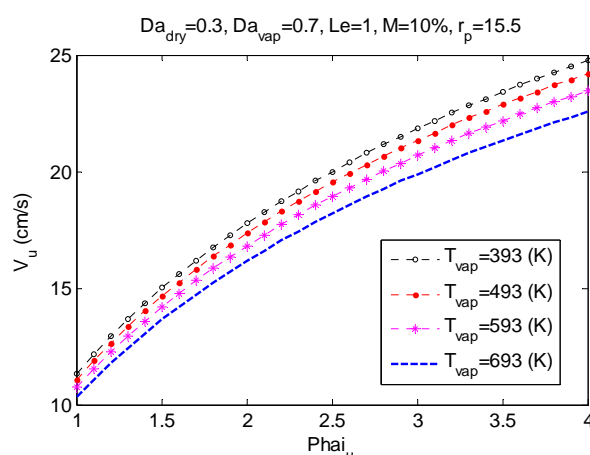


Fig. 5. The variation of burning velocity as a function of ϕ_u (equivalence ratio) for different devolatilization temperature.

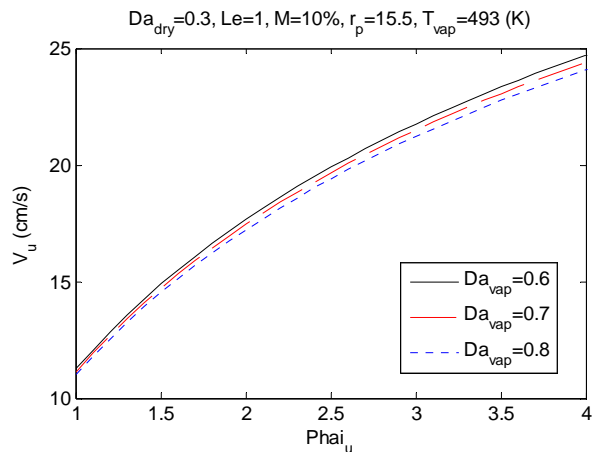


Fig. 6. The variation of burning velocity as a function of ϕ_u (equivalence ratio) for different vaporization Damköhler number.

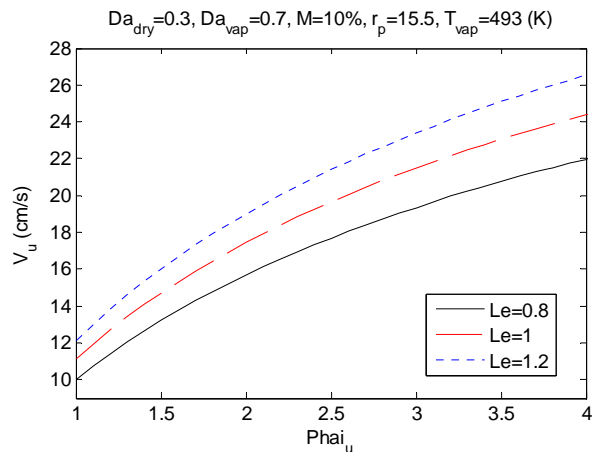


Fig. 7. The variation of burning velocity as a function of ϕ_u (equivalence ratio) for different Lewis number.

Lewis number variation (ratio of thermal diffusivity to mass diffusivity) has a strong effect on burning velocity. Increase in **Le** number associates with the noticeable rise in the thermal diffusivity. This improves the burning velocity as shown in Fig. 7.

4- Conclusion

An analytical model has been presented to determine the effect of moisture content on flame characteristics and also to investigate the effective parameters on organic dust combustion. From results it is understood that increase in moisture content causes the flame velocity to decrease. Other physical characteristics of organic particles also affect the burning velocity. Vaporization Damköhler (Da_{vap}), drying Damköhler (Da_{dry}) and Lewis numbers are the determining factors on combustion of dust particles. It is also seen that an increase in the Da_{vap} or Da_{dry} number causes a reduction in the burning velocity, while increase in Lewis number increases the burning velocity. Increase in T_{vap} , decreases the amount of mass fraction of the produced gaseous fuel, consequently the burning velocity decreases.

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Nomenclature

- B : frequency factor characterizing rate of gaseous fuel oxidation
 C : heat capacity of mixture, Eq. (11)
 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)
 n_p : local number density of particles (number of particles per unit volume)
 Q : released heat per unit mass of consumed fuel particles
 Q_{vap} : heat associated with devolatilizing unit mass of solid fuel particles
 Q_{dry} : heat associated with moisture evaporation from particles
 R : global gas constant
 r_p : radius of the particle
 T : temperature
 T_f : flame temperature
 τ_{chem} : characteristic time of chemical reaction
 τ_{dry} : characteristic time of drying
 τ_{vap} : characteristic time of volatile evaporation
 U_b : 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
 λ : thermal conductivity
 ρ : density of the reactant mixture
 ρ_s : density of a solid particle
 ϕ_u : equivalence ratio based on fuel available in the particles in the ambient reactant stream ($\phi_{fuel,u}$)

Subscripts

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