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Perturbation Technique to Investigate the Role of Radiation from Flame to Dust Particle

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Abstract: Dust combustion is a very important area due to safety problems related to dust explosion hazards, as well as to utilization of solid fuels. Thus, models describing combustion of metals are necessary to design new and control existing propulsion devices and systems. In this model the flame propagation mechanism is considered by radiation, conduction and convection. Radiation heat transfer from flame to particles surfaces play a major role in dust flame combustion. In this paper by considering the radiation from flame to particles surfaces, investigate the effect of this parameter on temperature profiles and flame speed. Furthermore, results show the role of radiation in high equivalence ratio is more efficient. The new nonlinear differential equations are solved by using perturbation technique. Calculated values are in good agreement with experimental data.

Key word: Dust Combustion, Laminar Flame, Radiation heat transfer, Perturbation technique

INTRODUCTION

Ignition and combustion of solid particles are the issues of interest for many industrial applications. In spite of significant efforts to obtain information about the combustion properties of dusts (Shosin and Dreizin, 2006; Eapen *et al.,* 2005; Kornilov *et al.,* 2006; Shosin and Dreizin, 2003), our knowledge on the fundamental mechanisms of flame propagation in dust clouds is still far from sufficient. This is because of the complex process involved in the combustion of fine solid particles, such as the difficulty of simulating laboratorial conditions especially uniform distribution of suspended particles due to gravity force or low gravity condition (Dreizin, 2003). Due to particle sedimentation and relatively low laminar flame speeds in dust suspensions, microgravity environment is essential for the observation of laminar dust flames in a wide range of particle sizes and fuel concentrations (Sam Goroshin, 2005). The capability of a reduced-gravity environment to facilitate study of dust combustion was realized by researchers long before current microgravity programs were established by the various national Space Agencies. Thus, several experimentalists even built their own, albeit very short-duration, drop tower facilities to study flames in particle and droplet suspensions (Ballal, 1983). Some researchers have been shown that fundamental principles of heat transfer and combustion permits a simplified understanding of aluminum particle combustion in an environment representative of a burning propellant. The model evaluates aluminum particle temperature from insertion into the flame through burnout. An experimental and theoretical modeling for aluminum dust cloud with air as an oxidizer, have been presented by (Goroshin *et al.,* 2000; 1996; 1996). and (Bidabadi *et al.,* 1996; 2008). and combustion particle-laden flows and parameters have been estimated. In present work a mathematical model of combustion of solid particles will be developed. In previous theoretically models (Goroshin *et al.,* 2000; 1996), assumed that radiation heat transfer from flame to particle surfaces was neglected. Thermal radiation is an important, often dominant, heat transfer mechanism in many combustion systems such as combustion in microgravity, ultra lean burning, and fire spreading (Xiao *et al.,* 2005; Spalding, 1957; Turns and Myht, 1991; Guo *et al.,* 1997).

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In the heat transfer equation of the particles, usually convection heat transfer has a great effect comparing to the radiation heat transfer and this parameter is ignored in so that the effect of radiation heat transfer is better focused in this study and because of high gas temperature in combustion chambers the effect of radiation is concluded to the perfect temperature profile of particles. A particle in high fluid temperature can transfer the energy in the form of convection and radiation. In convection the regime of flow around the particle must be identified and then the convection heat transfer factors can be derived. In radiation heat transfer, the position of the particle and flame and also effective area of the particles need to be known. The ultimate objective of the combustion research is to develop a comprehensive model which can adequately combine all the effective processes on the combustion. It is clear that many parts of this theory need to be developed or incorporated from existing models such as external heat and mass transport affected by forced convection in temperature gradients ,heterogeneous processes ,chemical kinetics ,etc. In this article the term of radiation heat transfer has been added to the previous model and its effects on the combustion of fine aluminum particles will be investigated. Therefore we use perturbation technique to obtain the flame speed and temperature profile. Because of the importance of radiation in two-phase combustion having fine particles further examination of the radiation term is needed (Yarin and Hetsroni, 2004).

Theoretical Analysis:

In the present model after considering the diffusion region for particle combustion, explicit algebraic equations are obtained for predicting the flame speed as a function of the initial particle size, concentration, and heat loss term. Combustion of metallic dust (aluminum in particular) is of interest in the present formulation. Very little detailed information has been reported to date on the combustion mechanism of aluminum particles in oxidation atmospheres, and there is no universally accepted view point on the detailed mechanism of aluminum ignition. According to the ideas of several investigators, ignition occurs due to the heterogeneous reaction of liquid aluminum with the oxidant through an oxide film, while combustion take place in the gas phase where aluminum vapor reacts with the oxidant. In the present formulation, it is assumed that the combustion reaction occurs in gas phase, forming spherical diffusion flame around the fuel particle. Combustion of fine metal particles is given attention in this formulation. An analytical model was constructed to describe a one-dimensional, freely propagation flame in an aluminum particle/oxidizer mixture (Huang *et al.,* 2005). The analysis largely follows the approach of Goroshin *et al.,*(2000). without heat loss to wall and (Bidabadi *et al.,* 1996; 1996). with heat loss to wall, but is extended to consider the heat transfer by radiation from flame to particles.

In a mono-dispersed aluminum particle-laden flow, the flame usually consists of three distinct zones: the preheat, flame, and post flame zone. In the preheat zone, the reaction rate is negligibly small, and the gas is heated by conduction from the flame zone. Also particles are heated by the surrounding gas and radiation from flame until their temperature reaches the ignition point. In the flame zone, particles are ignited and totally consumed. The third zone is the post flame zone where the temperature of gas decreases asymptotically to the ambient temperature at infinity. We can obtain the flame speed; flammability limits and temperature distribution are derived by solving the energy equation in each zone and matching the temperature and heat flux at the interfacial boundaries. The major approximations and assumptions are: (1) the dust cloud consists of uniformly distributed aluminum particles with air; (2) the gravitational effects are neglected; (3) the particle velocity is approximately equal to the gas velocity; (4) collisions and interactions between burning particles are neglected; (5) the Biot number is very small, suggesting a uniform temperature distribution within each particle; (6) the thermal conductivity of the gas, λ , is taken to be constant for simplicity. (7) The reaction rate during diffusive combustion is considered to be constant and equal to an average value (m_s/τ_c). Also supposed that at the ignition point, the particle temperature is close to the auto ignition temperature of a single particle, T_s^i (the ignition temperature during a slow, quasi stationary heating) (Bidabadi, 1996). (Goroshin *et al.,* 2000). shown that the equation governing heat diffusivity in this problem can be transformed into a linear form byintroducing an independent variable x that is related to the spatial coordinate x' as. $x = \int_0^{x'} (\rho/\rho_u)dx$ The gas-phase governing equations for mass and energy conservation can be written as follows:

$$\rho v = \rho_u s_L \tag{1}$$

$$\rho v C_p \frac{dT_g}{dx} = \frac{\lambda d^2 T_g}{dx^2} + w_F Q - \alpha(T_g - T_u) \tag{2}$$

Where ρ, v and T are the gas density, velocity and temperature, respectively. The subscript "g" and "s" donate gas and solid phase, respectively, and subscript "u" is related to the unburned mixture, S_L denotes the flame speed, C_p the specific heat of gas at constant pressure, r the radius of particle, w_F the mass consumption rate of particle, and Q the heat of reaction per unit mass of fuel. The heat transfer coefficient between gas and walls sides is computed in the following way:

$$\alpha = \frac{b'\lambda}{d^2} \tag{3}$$

Where d is the width of the channel and b' is equal to 8 (Jarosinski, 1986). Because of oxygen excess, the decreasing of oxygen concentration in the flame is small and the combustion time of particles in the reaction zone is the same as that for a single particle under initial oxygen concentration (Goroshin, 1996). The equation state for an isobaric system is:

$$\rho T = const \tag{4}$$

Radiation Heat Transfer:

The local radiation flux attenuation rate is proportional to the local value of the number density of particle, n_p, and the radius of the particle, r, transport by this mechanism can be expected to be small for small value of n_s, and when $r_f / r_u \prec\prec 1$, where r_f is the radius of the fuel particle in the flame zone and r_u is the radius of the fuel particle in the preheat zone; strictly speaking the analysis is applicable only within these restrictions (Seshadri *et al.,* 1992). The radiation heat transfer to each particle from flame zone q_r, is given by the Stefan-Boltzmann law

$$q_r = n_p A_{eff} E\sigma(T_f^4 - T_s^4) \tag{5}$$

Where σ, E and T_f are the Stefan-Boltzmann constant, the emissive of the particle that is assumed that the value of emissive for an aluminum particle is 0.3 (Friedman and Macek, 1962). and flame temperature respectively. The effective area of the particles is obtained from $A_{eff} = A_s f_{pf}$ A_s is particle area (The area of a particle which is seen by the flame is half of a perfect area in the preheat zone). To estimate the shape factor (f_{pf}) which has an important role in Stefan-Boltzmann low, we assumes that radiation heat transfer between flame and dust clouds happens between two plates; one of them includes the particles in dust clouds in preheat zone and another is the plate fixed in the centerline of flame. The distance between these two plates is assumed to be equal to the thickness from centerline of the flame. The area of these plates is affected by the experimental setups (Dreizin, 1996; Zhu and Yuasa, 1998).

Convection Heat Transfer:

For solving the heat transfer equation particularly in convection regime, knowledge about the regime of flow around the particle must be determined because the Nusselt number (Nu), which is one of the important factors in convection heat transfer, depends on the regime flow. Considering fig1 for particle which surrounded by hot gas in preheat zone we can obtained for Nusselt number:

$$Nu = 2 + (0.4\,\mathrm{Re}^{.5} + 0.06\,\mathrm{Re}^{.66})\,\mathrm{Pr}^{.4}(\mu/\mu_s)^{.25} \tag{6}$$

Where, **Re** is Reynolds number, **Pr** is Prantle number, μ_a is the kinetic viscosity. Because of microgravity size of particle and small Re numbers, the Nusselt number is assumed to be equal to 2 for this analysis. (Joulin, 1980; 1987). The heat transfer between each particle and surrounding gas, q_c is given by

$$q_c = Nu \cdot 2\pi r\lambda(T_g - T_s) \tag{7}$$

By considering the heat transfer between gas and particle generally, Eq. (8) obtained.

$$\rho_s v C_s \frac{dT_s}{dx} = n_p 4\pi r\lambda(T_g - T_s) + n_p A_{qw} E\sigma(T_f^4 - T_s^4) \tag{8}$$

Where C_s is the specific heat of particles, $\rho_s = n_p \rho_a 4\pi r^3/3$ is the bulk density of particles (mass of particles per unit volume), and is the material density of aluminum. With these assumptions, the dimensionless governing heat diffusivity equation and the boundary conditions for the problem illustrated in Figure 1 can be written in a dimensionless form:

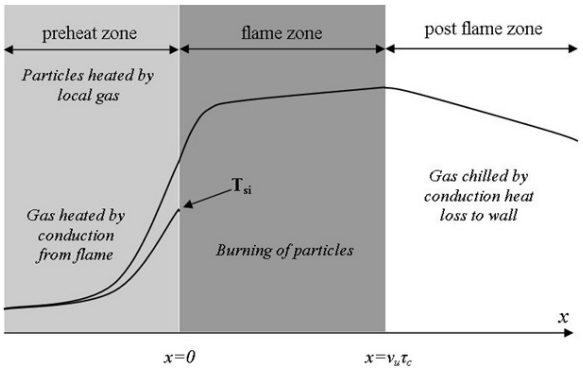

Fig. 1: Structure of dust flame in mono size suspension.

$$\frac{d^2\theta}{dy^2} - k\frac{d\theta}{dy} = k\eta(\theta - 1) + W\begin{cases} 0 & -\infty < y < 0 \\ -\mu k(\theta_s^i - 1) & 0 < y < 1 \\ 0 & 1 < y < -\infty \end{cases} \tag{9}$$

Here a nondimensional gas temperature θ is defined as $\theta = T_g/T_{gu}$ (Subscripts g and u are denoting gas and unburned mixture correspondingly). y is a nondimensional coordinate defined as $y = x/v_u\tau_c$ (where v_u s the flame speed and τ_c total particle combustion time). Parameter k is a nondimensional flame speed, $k = v_u^2\tau_c/\alpha_u$ (where $\alpha_u = \lambda/c_p\rho_{gu}$ Parameter μ is a nondimensional dust concentration defined as: $\mu = BQ/c_p\rho_{gu}(T_{si} - T_u)$, B is dust concentration and θ_s^i is nondimensional ignition temperature of solid particles. The heat loss parameter is the ratio of particle combustion time to time of heat transfer in the channel ($\eta = b'\alpha\tau_c/d^2$).To model the heat loss, it was determined by considering the heat transfer contents to surrounding surfaces. The heat loss term, which is assumed to be linearly proportional to temperature difference between gas and walls (Goroshin *et al.,* 1996), is considered for flame between quenching plats and derived quenching distance. The heat loss parameter (η) covers a range from 0 to 0.02 which η=0 belongs to the adiabatic condition. Spherical aluminum powders with particle sizes $d_p = 5.4\mu m$ were used in calculation. For micron and larger-sized particles, which usually burn under diffusion-controlled conditions, numerous data exists on their burning times. Several d^n-models, with n ranging from *1.5* to *2.0*,

have been proposed. As is stated in (Huang *et al.,* 2006) $\tau_c = 0.7ms$ nd T_u is ambient temperature ($300^{\circ}k$).

The current analysis requires the particle ignition temperature (T_{si}) and burning time (τ_c) be specified as input parameters, both of which are a function of particle size. For large particles (D>100μm), most experimental studies (Friedman and Macek, 1962; Zhu and Yuasa, 1998). indicated that ignition is achieved at a temperature near the melting point of aluminum oxide (i.e., 2350 K). It was conjectured that the particle is covered by an impervious oxide shell, and aluminum does not ignite until the oxide shell melts or breaks up near its melting temperature under the effect of aluminum thermal expansion. For nano-sized particles, however, ignition has been observed to occur at temperatures as low as 900 K (Parr *et al.,* 2003). Recent studies (Trunov *et al.,* 2005). also indicate that aluminum particles with diameters of 1 to 100 μm could be ignited over a wide range of temperatures from 1000 to 2300 K. (Trunov *et al.,* 2005). suggested that aluminum oxidation and polymorphic phase transformations of the alumina shell are responsible for these diverse ignition temperatures. The corresponding ignition temperature of particle with average diameter about 5.4 μm is near $2100K$. (Huang *et al.,* 2006). The dimensionless energy conservation equation for the particle phase is:

$$\frac{d\theta_s}{dy} = \frac{\theta - \theta_s}{\xi} + \varepsilon(\theta_f^4 - \theta_s^4) \qquad -\infty < y < 0 \tag{10}$$

Where $\xi = [(r^2 c_s \rho_s / 3\alpha_u c_p \rho_g)] / \tau_c$ is a ratio of the characteristic particle heat exchange time and combustion time of the particle (with r radius) that is close to unity for nonvolatile and Lewis number (Le=1). The parameter ε that donate emissivity is defined as,

$$\varepsilon = \frac{\sigma f_{wf} E T_u^3 r}{2\lambda} \tag{11}$$

The boundary conditions for the above differential equations are as following:

$$\begin{cases} y \to -\infty \Rightarrow \theta = \theta_s = 1, y \to +\infty \Rightarrow \theta = 1 \\ y = 0 \Rightarrow \theta_s = \theta_s^i, \theta\big|_{0^-} = \theta\big|_{0^+}, d\theta/dy\big|_{0^-} = d\theta/dy\big|_{0^+} \\ y = 1 \Rightarrow \theta\big|_{1^-} = \theta\big|_{1^+}, d\theta/dy\big|_{1^-} = d\theta/dy\big|_{1^+} \end{cases} \tag{12}$$

We note that Eq. (10) is a nonlinear differential equation. Next we give the solution of problem (10) under the boundary conditions (12) by perturbation technique.

Analysis of problem by using perturbation technique:

Exact solutions are rare in many branches of fluid mechanics, solid mechanics, and other physics phenomena because of nonlinearities, inhomogeneities, etc. Hence engineering and physics are forced to determined approximate solutions of the problem they are facing. These approximations may be purely numerical, purely analytical, or combination of numerical techniques.

In this work, we use perturbation theory to determine approximate solutions of differential equation that is governed. Perturbation techniques (Rand and Armbruster, 1987; Nayfeh, 1993). are widely applied for obtaining approximate solutions to these equations involving a small parameter ε. These techniques are so powerful that sometimes the parameter ε is artificially introduced into a problem having no parameter and then finally set equal to unity to recover the solution of the original problem.

By using perturbation series we need to expand our differential equation in power series of a small parameter ε. It should be noted that ε is small enough and we can expand our problem in power series of it.

$$\theta_s = \sum_{n=0}^{\infty} \theta_{s_n} \varepsilon^n = \theta_{s_0} + \theta_{s_1} \varepsilon + o(\varepsilon^2) \tag{13}$$

With respect to accuracy that we need for this work, final solution of Eq. (10) is considered up to first order.

Zeroth-order:

The differential equation of the zero order with the boundary conditions is obtained as follows:

$$\frac{d\theta_{s_0}}{dy} = \frac{\theta - \theta_{s_0}}{\xi} \qquad \theta_{s_0}(-\infty) = 1 \tag{14}$$

The resulting differential equation subjected to the boundary condition, θ_{s_0} s obtained as follows

$$\theta_{s_0} = 1 + \frac{M_1 \exp(K_1 y)}{(1 + K_1 \xi)} \tag{15}$$

Where:

$$M_1 = \frac{K_2 \mu \varphi (\theta_s - 1)(\exp(-K_1 - 1)}{\eta (K_1 - K_2)} \tag{17}$$

$$K_2 = \frac{k}{2}\left(1 - \sqrt{1 + 4\frac{\eta}{k}}\right) \tag{18}$$

First – order:

The first order equation is

$$\frac{d\theta_{s_1}}{dy} = \frac{\theta_f^4 - \theta_{s_0}^4 - \theta_{s_1}}{\xi} \tag{19}$$

Subject to boundary conditions

$$\theta_{s_1}(-\infty) = 0 \tag{20}$$

For first order solution, we substitute the zero-order solution θ_{s_0} in Eq.(19) and some simplification along with boundary conditions, the first order solution is obtained as fallow:

$$\theta_{s_1} = M_2 - \frac{M_3 \exp(K_1 y)}{(1 + K_1 \xi)} - \frac{M_4 \exp(2K_1 y)}{(1 + 2K_1 \xi)} - \frac{M_5 \exp(3K_1 y)}{(1 + 3K_1 \xi)} - \frac{M_6 \exp(4K_1 y)}{(1 + 4K_1 \xi)(1 + K_1 \xi)^4} \tag{21}$$

Where:

$$M_2 = \theta_f^4 \xi^4 K_1^4 + 4\theta_f^4 \xi^3 K_1^3 + 6\theta_f^4 \xi^2 K_1^2 + 4\theta_f^4 \xi K_1 + \theta_f^4 - 4\xi K_1 - 6\xi^2 K_1^2 - 4\xi^3 K_1^3 - \xi^4 K_1^4 - 1 \tag{22}$$

$$M_3 = 4M_1 + 12M_1 K_1 \xi + 12M_1 K_1^2 \xi^2 + 4M_1 K_1^3 \xi^3 \tag{23}$$

$$M_4 = 6M_1^2 + 12M_1^2 K_1 \xi + 6M_1^2 K_1^2 \xi^2 \tag{24}$$

$$M_5 = 4M_1^3 + 4M_1^3 K_1 \xi \tag{25}$$

$$M_6 = M_1^4 \tag{26}$$

With respect to accuracy in this work, final solution of Eq. (10) by using perturbation technique up to first order is,

$$\theta_s = \theta_{s_0} + \varepsilon\theta_{s_1} + o(\varepsilon^2) \tag{27}$$

By considering additional condition of $\theta_s(y = 0) = \theta_s^i$ and solving these heat transfer equations in each

flame zone and by matching the heat fluxes obtained from these solutions on the boundary of each zone, the algebraic equation for the nondimensional flame speed (k) is found to be:

$$k = f(\varphi, \varepsilon, \theta_s, \xi, \eta, \theta_f) \tag{28}$$

In solving velocity equation in terms of concentration for non zero value of η, two answers will be gained which the smaller value is unstable (Goroshin and Bidabadi, 1996; Zeldovich *et al.,* 1985). The appearing point of the second answer or in the other words the minimum concentration point is bifurcation point. With the use of this we can compute the lean propagation limit of the flame. In above equation if we neglected from radiative heat transfer to particle and set ε=0, the equation reduces to Bidabadi's model with heat loss (Bidabadi, 1996)

$$\frac{1}{\mu\varphi} = \frac{1}{K_1(1 + K_1\zeta)} \frac{1 - \exp(-K_1)}{\sqrt{1 + 4\dfrac{\eta}{k}}} \tag{29}$$

And if we neglected from both heat loss and radiative heat transfer to particle (i.e. η=0 , ε=0) the equation changes to Goroshin 's model without heat loss (Goroshin *et al.,* 2000).

$$k = \mu\varphi[1 - \exp(-k)]/(1 + k\xi) \tag{30}$$

RESULTS AND DISCUSSIONS

Figure 2 shows the particles temperature as a function of non-dimensional length. Some radiative energy from flame zone will be added to the preheat zone and this on the one hand increases the temperature in the preheat zone which in turn increases flame speed. Also we can draw the key relation of speed in terms of concentration. It is observed that the new model in comparing with the old model belonged to (Bidabadi *et al.,* 1996; 1996). is nearer to the experimental results (Bidabadi, 1996). which can indicate the effect of radiation. Figure 3 shows the dependence of the flame speed on the various dust concentration for $\eta = 0.01$ and, $\varepsilon = 0.001$ the two curves depict the solution of the equations without including radiation term and by radiation term to particle (present article) are compared with experimental result, respectively. As it can be seen the highest flame speed is gained when radiation to particles is considered. Figure 4 shows the dependence of the flame speed k in different values of the emissivity parameter. Flame speed gained here shows that the increase of emissivity parameter ε leads to increase of flame speed and this is because of the increase of radiation per particle received.

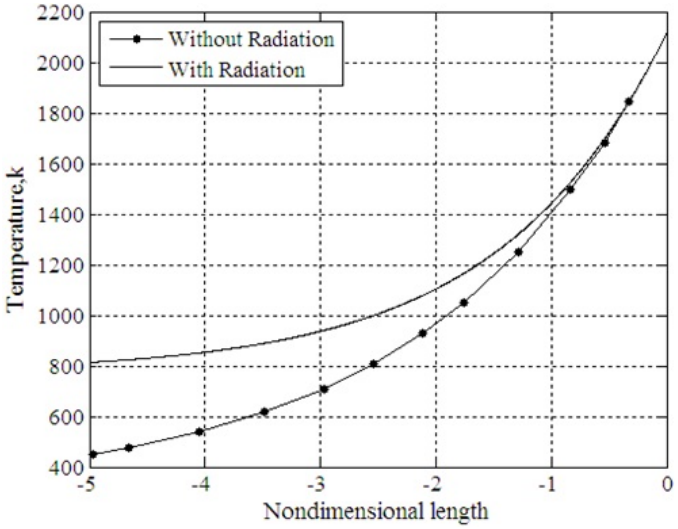

Fig. 2: Comparing the particles temperature profile in preheat zone at φ=0.62

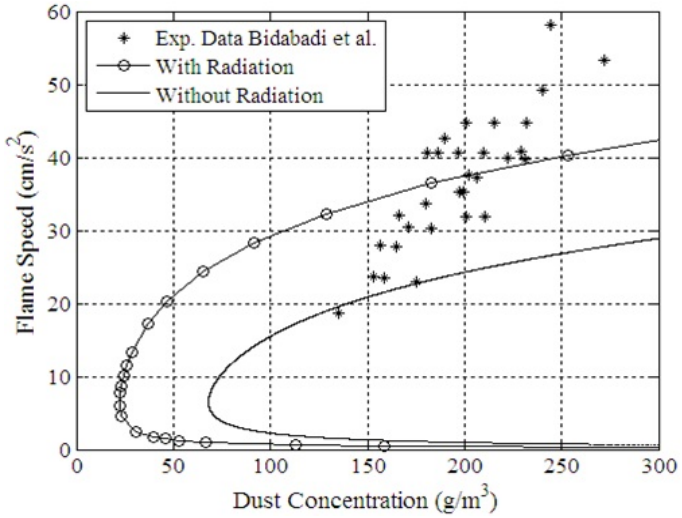

Fig. 3: Dependence of flame speed to dust concentration in various models

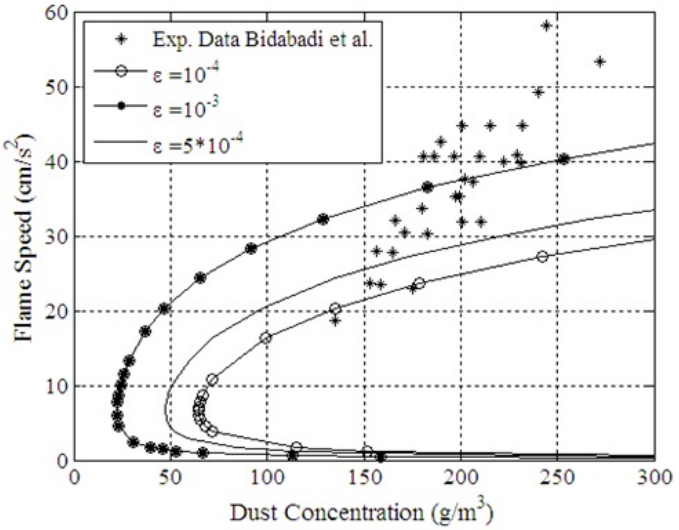

Fig. 4: dependence of flame speed to dust concentration with different value of ε

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