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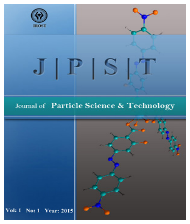

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Effect of Radiation Heat Loss and Ventilation on Dust Explosions in Spherical Vessels

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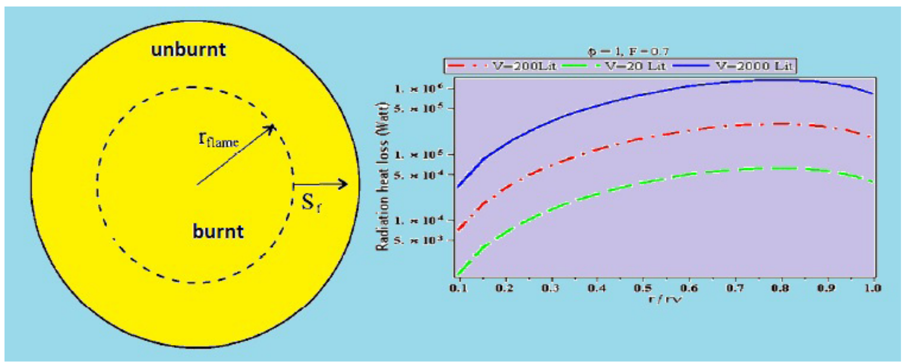
HIGHLIGHTS

- Flame propagation through a coal dust-air mixture in a spherical vessel was analyzed.
- Effect of venting devices and the radiation heat loss on flame propagation speed, flame temperature and pressure were studied.
- Influence of dust concentration and dust volatility on explosion parameters has been analyzed.
- The pressure-time curves that are generated with this model show a good similarity with those measured in practice.

GRAPHICAL ABSTRACT



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ABSTRACT

The flame propagation through a coal dust-air mixture in a spherical vessel was studied by means of a one-dimensional, Arrhenius-type kinetics and quasi-steady model. The model includes the evaporation of the volatile matter of dust particles into a known gaseous fuel (methane) and the single-stage reaction of the gas-phase combustion. Effect of venting devices as safety idea and the radiation heat loss, as very affecting phenomenon on flame propagation speed, flame temperature and pressure were studied. The radiation heat losses occur between the reaction zone and the surrounding wall. Influence of dust concentration and dust volatility on dust explosion parameters has been analyzed. The pressure-time curves that are generated with this model show a good similarity with those measured in practice. The model can represent a useful framework to be employed in organic dust combustion. This research can be valuable in the development of alternative fuels; and it can be used by the fire safety and control industry.

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1.Introduction

Combustion of the heterogeneous mixtures consisting of particles and an oxidizer is important in many areas of engineering. The risk of ignition and explosion of organic cloud particles, is always have raised as a critical challenge in industries such as agricultural, chemical, food, grain storage, coal mining and, etc. Scientists have sought for develop methods for modeling the combustion of organic particles and the prevention of their explosions in industries. Bio powder and organic particles are the suitable options for production of alternative fuel.

The flame propagation through a dust cloud can be modeled by different models. For example, Essenhigh and Csaba [1] presented a model of coal dust flame propagation considering the incoming radiating heat from the walls to the particles. They neglected any other form of heat transfer. Smoot et al. [2] assumed conductive heat transfer as dominant mechanism in modeling of coal dust flame. Mitsui et al[3] Cassel et al[4]modelled flame propagation in which the ignition of a particle was assumed to take place at the surface .

The physical mechanisms of two-phase flow were studied lower than gas flows. Whereas considerable researches have been done on the spray reactions, but the study of the reaction of two-phase flow were considered very low. The solid phase has a greater thermal inertia than the gas phase. Therefore the temperature difference between the gas phase and the solid occurs. Temperature difference between the particle and the gas changes reactive characteristics such as reaction temperature, gas velocity and reaction components. Many studies have been conducted on the flame propagation in the cloud of particles. Elkotb et al. developed a theoretical model to determine the ignition characteristics of organic dust [5]. Liu et al. [6] investigated the flame propagation through the hybrid mixture of coal dust and methane in a combustion chamber. Proust [7] declared a few fundamental aspects about ignition and flame propagation in dust clouds. In another study, Proust [8] measured laminar burning velocities and maximum flame temperatures for combustible dust air mixtures such as mixtures of starch-dust air, lycopodium air mixtures and sulphur and flour air mixtures. Eckhoff clarified the differences and similarities between dust and gases [9]. Combustion of flammable dust clouds is seriously studied in the last fifty years, and a lot of experimental data is obtained [10,11]. Bidabadi [12] studied flame propagation among cloud particles according to the temperature difference between the particle and gas in the planar flame. In another study, Bidabadi et al [13] investigated the effect of Lewis number and heat loss on the combustion n of organic particles. Effect of radiation on combustion of organic particle cloud was analyzed by Bidabadi [14].

In mining and industeries that use coals, knowledge of the explosion hazard is critical scienice. Many research have been done on the subject of the explosion hazard of powder and flammable dust and several books published in this field[15-20]. Many industrial processes include a gas explosion hazard. The effects of an explosion can be limited e.g. by gas explosion venting systems.

2.Modelling

In this paper the thin-flame model [22] was modified and developed for investigation of spherical flame propagation. The problem can be considered as a real situation like a deflagration in a spherical enclosure. In this paper, the thin model [22] was modified for the particle combustion and has been presented and discussed. The qualitative agreement with experimental data has been found. It is supposed that coal particle devolatilized completely and homogeneous combustion reaction happened. The model presented a useful framework to be implemented in coal combustion situations. The effect of coal volatile matter and dust concentration were investigated. The effect of radiation heat loss on flame temperature and flame speed was evaluated.

During an explosion, the content of the vessel is assumed to consist of a spherical inner region of completely burnt mixture, encapsulated by an outer region of completely unburnt mixture. The regions are separated by an infinitely thin spherical flame front. The flame front is then a surface where a discontinuous transition takes place from unburnt to burnt mixture and propagates radially from the point of ignition towards the vessel wall. The unburnt as wel1 as the burnt mixture are treated as ideal gases. The specific heats of both the unburnt and the burnt mixture are the same and remain constant during the explosion. Here, the mass consumption rate of the unburnt mixture can be expressed by Arrhenius equation for reaction rate. But in previous thin model it obtained as function of burning velocity. that is different from The transition of the unburnt into burnt mixture occurs through a single-step, irreversible chemical reaction which can be described by a global reaction rate expression. The temperature of the unburnt mixture, continually increases as a consequente of the compression, which is assumed to be adiabatic. The burning velocity remains constant during the explosion. Point ignition at the centre of the dust cloud occurs with a negligible energy input.

Lewis and von Elbe [23] give an approximate expression which relates the mass fraction of burnt mixture in the vessel to the fractional pressure rise. Based on this equation, the fraction of unburnt mass can be expressed as

$$\frac{m_u}{m_{uo}} = \frac{P_e - P}{P_e - P_o} \tag{1}$$

And differentiation of equation (1) with respect to time yields:

$$\frac{dP}{dt} = -\frac{P_e - P_o}{m_{uo}} \frac{dm_u}{dt} \tag{2}$$

The mass consumption rate of the unburnt mixture in thin model expressed as [24]

$$\frac{dm_u}{dt} = -\frac{4\pi r_f^2 \delta\omega}{Y_f} \tag{3}$$

That Y_f, ω and δ respectively, are evaporated fuel mass fraction, fuel combustion rate and flame thickness. We consider a single step kinetic model chemical reactions ass Arrhenius method. These parameters calculated as

$$Y_f = F.Y_{sf} \tag{4}$$

$$\omega = A\rho Y_f \exp(\frac{E}{RT_f}) \tag{5}$$

$$\delta = \frac{\lambda}{\rho c_p S_u} \tag{6}$$

Where the F is mass ratio of volatile matter to solid fuel. It assumed that all of volatile matter evaporated to gaseous fuel (methane) and burned in the flame zone. Y_{sf} is solid fuel mass fraction. S_u is obtained as [25,26]

$$S_u = \sqrt{\frac{2\lambda A}{\rho CpZe^2} exp(-\frac{E}{RT_f})} \tag{7}$$

And Y_{sf}

$$Y_{sf} = \frac{m_s}{m_{tot}} = \frac{\frac{4}{3}\pi r_p^3 n_s \rho_s}{\rho_{uo}} \tag{8}$$

And T_f

$$QY_f = c_p(T_f - T_\infty) \Rightarrow T_f = \frac{QY_f}{c_p} - T_\infty \tag{9}$$

That A , E and R represent the frequency factor, the activation energy of the reaction and the universe gas constant respectively. Zeldovich number was defined as Eq. 6 and assumed that the zeldovich number is very high.

$$\mathrm{Ze} = \frac{\mathrm{E}\left(\mathrm{T}_f - \mathrm{T}_\infty\right)}{\mathrm{R}\ \mathrm{T}_f^{\ 2}} \tag{10}$$

The volume of the vessel mixture can be expressed as sum of unburnt and burned gas

$$V_v = \frac{4}{3}\pi r_f^3 + \frac{mRT_u}{P} \tag{11}$$

For adiabatic compression of unburnt mixture $\frac{\rho_{uo}}{\rho_u} = (\frac{P_o}{P})^{1/\gamma}$ and Since $\frac{1}{\rho} = \frac{RT}{P}$, it resulted

$$\frac{mRT_u}{P} = V_v \left(\frac{P_o}{P}\right)^{\frac{1}{\gamma}} \frac{P_e - P}{P_e - P_o} \tag{12}$$

So the flame radius achieved as

$$r_f = R_v \left[1 - \left(\frac{P_o}{P}\right)^{\frac{1}{\gamma}} \frac{P_e - P}{P_e - P_o}\right]^{\frac{1}{3}} \tag{13}$$

$$\frac{dP}{dt} = \frac{12.56(P_e - P_o)\omega r_v^2 \delta}{m_{uo} Y_f} \left(1 - \frac{\left(\frac{P_o}{P}\right)^{1/\gamma} (P_e - P)}{P_e - P_o}\right)^{2/3} \tag{14}$$

$$\dot{m}_{out} = C_{orifice} A_{orifice} \sqrt{\frac{2\rho P\gamma}{(\gamma-1)}\left((\frac{P_a}{P})^{(\frac{2}{\gamma})} - (\frac{P_a}{P})^{\frac{\gamma+1}{\gamma}} \right)} \quad (15)$$

$$\frac{dm_u}{dt} = -\frac{4\pi r_f^2 \delta\omega}{Y_f} + \dot{m}_{out} \quad (16)$$

Where $\dot{m}_{out}$ is flow rate of Exhaust gas from the chamber. For spherical flames, the continuity equation may be combined with the energy equation as,

$$\frac{1}{\gamma P}\frac{dP}{dt} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u) = 0 \quad (17)$$

Where is the radial velocity. For a spherical confinement of radius , and flame radius , the following leading order velocity field is obtained,

$$u = \frac{r}{3\gamma P}\frac{dP}{dt}(\frac{r_v^3}{r^3} - 1), r_f < r \le r_v \quad (18)$$

Note that by taking into account radiation heat loss from flame zone to wall, without absorption by particle and gases the flame temperature can be achieved. Assuming that the gases are optically thin and that the cold surroundings (vessel wall) have a constant temperature, the radiative heat loss can be calculated as:

$$Q_r = 4\pi r_f^2 \sigma (T_f^4 - T_w^4) \quad (19)$$

Where $\sigma = 5.669e-8 \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant, T is the local gas temperature, T_w is the temperature of the cool surrounding wall. Here, the view factor and emission and absorption factor are one. So by heat balance between heat generation (heat of combustion) and heat loss (radiation heat loss), we have :

$$Y_f Q - \frac{4\pi t r_f^2 \sigma (T_f^4 - T_w^4)}{4\pi \rho r f^2 \delta} = c(T_f - T_w) \quad (20)$$

And flame temperature is.

$$T_f = \left(\frac{\pi Q\omega r_f^2 \delta Y_f + 4\sigma\pi r_f^2 T_w^4 + \pi\omega r_f^2 \delta c_p T_w}{\sigma\pi r_f^2} \right)^{0.25} \quad (21)$$

By numerical solution of these equations, flame propagation behavior is obtained.

The values of adjusting parameters were presented below. These values are taken from properties of coal particles. The table 1 presents the values of adjusting parameters.

Table. 1.
The values of adjusting parameters.

$\tilde{A}$	3.4×10^{-5} kg/(Ksm^2)
n	1.333
γ	1.4
E	96 kJ/mol
Q	50 MJ/kg
T_w	300 K
ρ_{uo}	1.35×10^3 kg/m^3
T_∞	300 K
R_{gas}	8.314 J /Kmol
C_{air}	1205 J/kgK
$C_{p,s}$	1256 J/kgK
λ_u	14.6538×10^{-2} J/(msK)
P_a	1bar
P_o	8bar
P_e	1bar

3. Results and discussion

Example of pressure data for weak and moderate coal dust explosion form ref [15]are compared with results of this paper in figure 1. this comparision showes experimental data for a 20 litre chamber explosion test of low volitile bituminouse coal at a dust concentration of 200 g/m^3. The maximum explosion pressure is about 5.5 bar. Figure 1 shows the computed pressure-time patterns for low volatile coal dust with concentration 200 g/m^3 in 20 liter and F=0.35. The predicted pressure, is in agreement with experimental [15] and confirms the validity of the presented model

In this section, the presented figures for the Pressure pattern, flame propagation speed and the other combustion parameters of particles with different concentrations has been presented and discussed. The studied particle is coal. It is assumed that methane is produced from the evaporation of the volatile matter of coal. The overall equivalence ratio of the premixed coal dust-

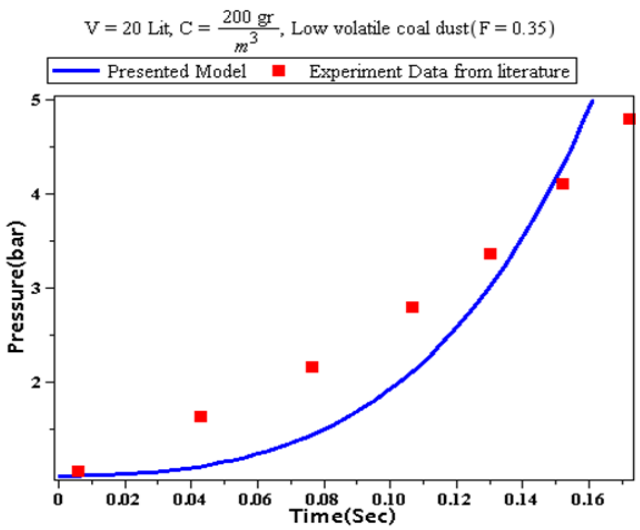

Fig. 1. Comparison between presented simulation and experiment [15].

air is always greater than unity; however, the gaseous equivalence ratio is smaller than unity.

Figs. 2 and 3 respectively show the changes of pressure with the changes of ϕ_u and vessel size. The lower vessel size and higher ϕ_u gives higher rate of pressure change.

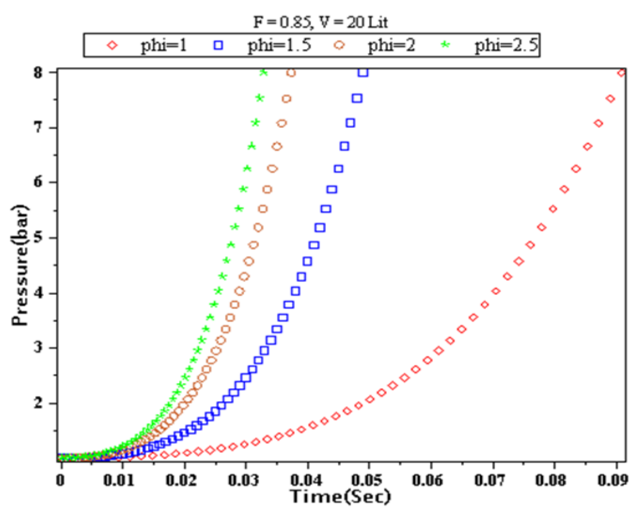

Fig. 2.effect of solid fuel concentration on pressure.

The effects of radiation heat loss and the ratio of evaporated gashouse fuel to solid fuel (F) on spherical flame propagation have been investigated in Figs. 4. As can be seen, the loss of radiation heat leads to the reduction of rate of pressure change and flame propagation speed. The time of flame propagation is increased to approximately double value with radiation. The reason for this deceleration can be found in the temperature reduction caused by thermal radiation (Fig. 5). The higher 'F' and ϕ_u results the higher flame temperature at the beginning of flame propagation and higher temperature decrease (Fig. 6).

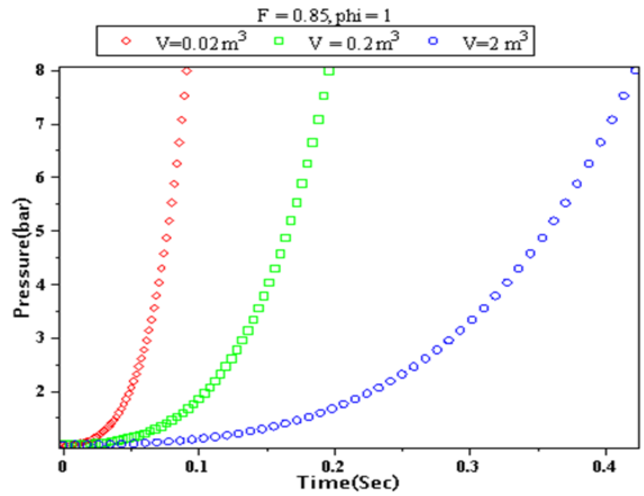

Fig. 3. Effect of vessel size on pressure.

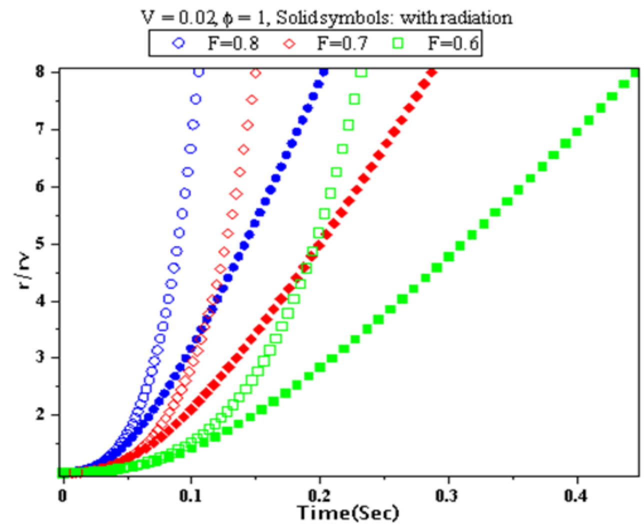

Fig. 4. Effect of radiation heat loss on flame propagation

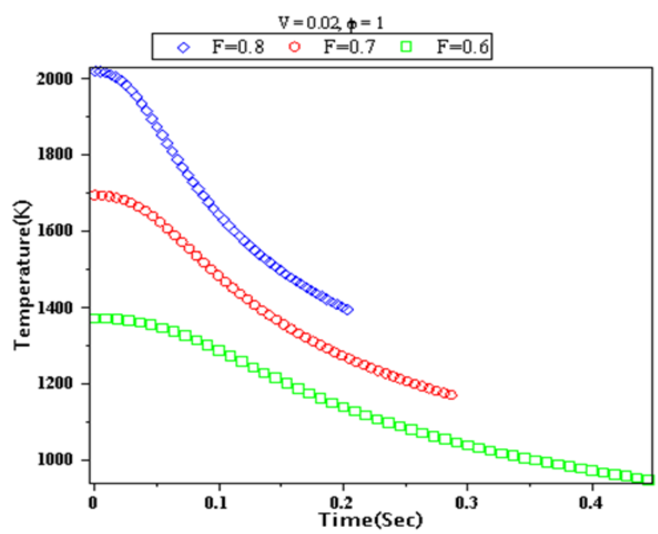

Fig. 5. Effect of radiation heat loss anf fuel volitility on flame temperature.

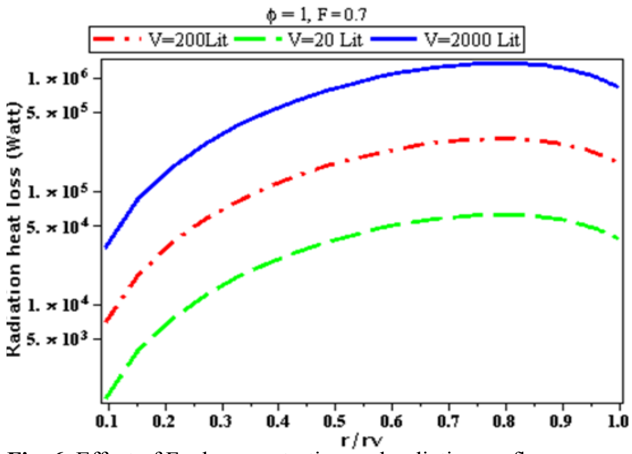

Fig. 6. Effect of Fuel concentration and radiation on flame propagation.

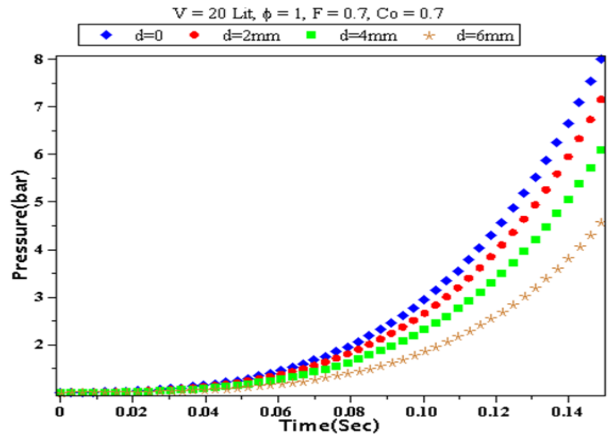

Fig. 8. Effect of vent size on pressure.

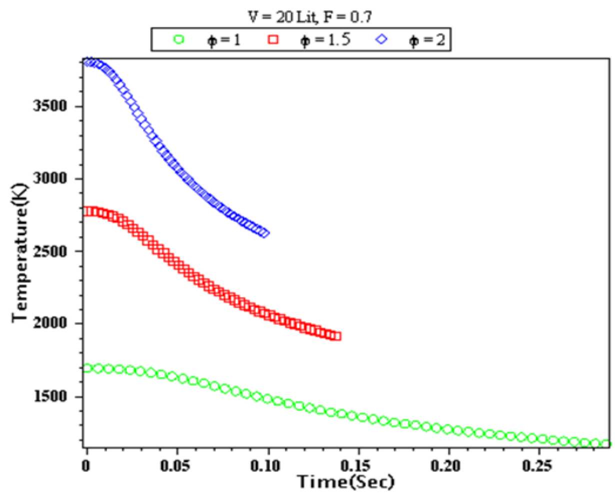

Fig. 7. Effect of vessel size on radiation heat loss.

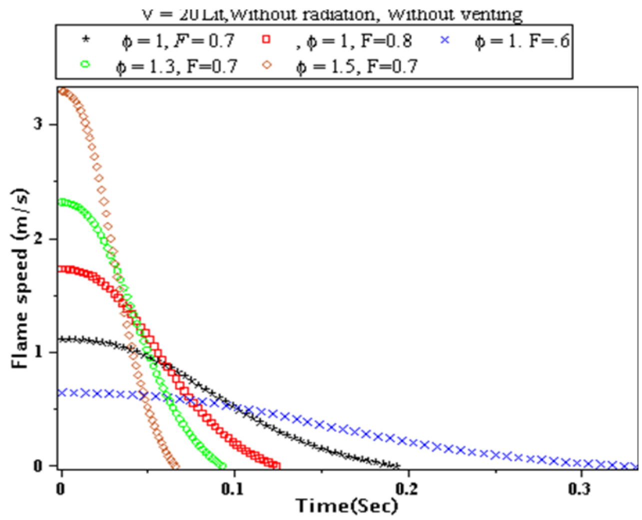

Fig. 9. Effect of fuel concentration and volatility on flame speed.

Effect of vessel size on variation of the radiation heat loss against dimensionless flame radius is shown in Fig. 7. As can be seen, with increase of vessel size heat loss increases. But maximum of heat loss is at point 0.8 on horizontal axis in all plots. As a safety idea, vessels have to be protected against extreme pressure by venting devices such as bursting discs. The safety device discharges at P_{set}=1.2 bar the overpressure in a vessel. Latter is important for most vent sizing methodologies and is proportional to the vent area. Fig. 8. shows the influence of venting size on the pressure profiles. Pressure profiles of vented gas registered a decrease in pressure with increasing vent area, as expected.

Flame speed largely depends on the radiation heat loss, the overall equivalence ratio (Φ_u), dust volatility (F factor) and venting (Fig. 9 and 10). Flame speed increase when ventilation diminishes and when Φ_u, increases. The radiation heat loss leads to the reduction of flame temperature and flame speed.

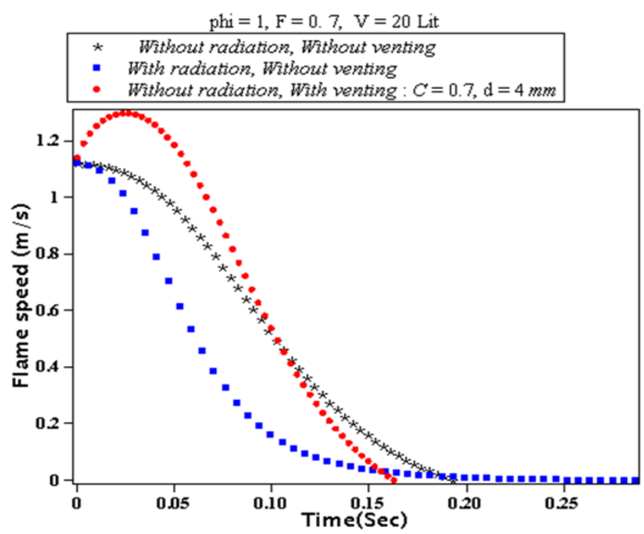

Fig. 10. Effect of radiation heat loss and venting on flame speed.

4.Conclusions

Equations are developed to correlate flame radius, pressure, and time for explosion in a spherical vessel. The development includes an expression for the rate of reaction which appears to be consistent Arrhenius equation. Radiation heat loss to the vessel walls analyzed as a key factor. The developed model indicates that the rate of pressure rise increases with increase of dust concentration and mass fraction of volatile fuel. Because of heat loss to the vessel wall the flame propagation speed and flame temperature is lower than case of without radiation. The model can be used to predict the pressure development of dust explosions for safety purposes. Simulation with this model shows a good resemblance to experimentally observed pressure-time curves.

Nomenclature			
m_{uo}	Unburned mass before flame initiation	F	Mass Ratio of volatile fuel to solid fuel
m_u	Unburned mass before	S_u	Burning velocity
P	Vessel Pressure	C_p	Specific heat
P_e	Maximum Pressure in vessel	E	Activation energy
P_o	Initial pressure in vessel	R	Gas constant
P_a	Atmosphere pressure	Z_e	Zeldovich number
c_{orf}	Orifice coefficient	ρ	density
A_{orf}	Orifice area	T_f	Flame temperature
A	Frequency factor	ω	Reaction rate
Q	Specific Heat of fuel combustion	T_u	Temperature of unburned mixture
δ	Flame thickness	σ	Stefan-Boltzmann constant
Y_f	Mass fraction of volatized fuel	γ	Ratio of specific heat
Y_{sf}	Mass fraction of solid fuel		

References

[1] K. N. Essenhigh, I. Csaba, 9th Symposium (International) on Combustion, New York-London, 1963.

[2] L. D. Smoot, M. D. Horton, Propagation of laminar pulverized coal-air flames, Prog. Energy Combust. Sci., 3 (1977) 235-258.

[3] R. Mitsui, T. Tanaka, Simple models of dust explosion, predicting ignition temperature and minimum explosive limit in terms of particle size, Ind. Eng. Chem. Process Design Develop. 12 (1973) 384-389.

[4] H. M. Cassel, I. Liebman, The cooperative mechanism in the ignition of dust dispersions, Combust. Flame 3 (1959) 467-475.

[5] M. M. Elkotb, S. A.El-Sayed, R. M. El-Taher, A. M. E. Abdel-Latif, Organic dust ignition in the high temperature flow behind a shock wave, Process Saf. Environ. Prot. 75 (1997) 14-18.

[6] Y. Liu, J. Sun, D. Chen, Flame propagation in hybrid mixture of coal dust and methane, J. loss prev. process ind. 20 (2007) 691-697.

[7] C. Proust, A few fundamental aspects about ignition and flame propagation in dust clouds, J. loss prev. process ind. 19 (2006) 104-120.

[8] C. Proust, Flame propagation and combustion in some dust-air mixtures, J. loss prev. process ind. 19 (2006) 89-100.

[9] R. K. Eckhoff, Differences and similarities of gas and dust explosions: a critical evaluation of the European 'ATEX'directives in relation to dusts, J. loss prev. process ind. 19 (2006) 553-560.

[10] Z. Chen, B. Fan, Flame propagation through aluminum particle cloud in a combustion tube, J. loss prev. process ind. 18 (2005) 13-19.

[11] Y. Shoshin, E. Dreizin, Particle combustion rates in premixed flames of polydisperse metal—air aerosols, Combust. Flame 133 (2003) 275-287.

[12] M. Bidabadi, A. Rahbari, Modeling combustion of lycopodium particles by considering the temperature difference between the gas and the particles, Combust. Explos. Shock Waves 45 (2009) 278-285.

[13] M. Bidabadi, A. Rahbari, Novel analytical model for predicting the combustion characteristics of premixed flame propagation in lycopodium dust particles, J. Mech. Sci. Technol. 23 (2009) 2417-2423.

[14] M. Bidabadi, A. Shakibi, A. Rahbari, The radiation and heat loss effects on the premixed flame propagation through lycopodium dust particles, J. Taiwan Inst. Chem. Eng. 42 (2011) 180-185.

[15] W. Bartknecht, Dust explosions: course, prevention, protection, Ed. Techniques Ingénieur, 1989.

[16] P. Field, Dust explosions, Elsevier, 2012.

[17] J. Nagy, Development and control of dust explosions (Vol. 8), CRC Press, 1983.

[18] K. L. Cashdollar, M. Hertzberg, Industrial dust explosions, American Society for Testing and Materials, 1987.

[19] R. Eckhoff, Dust explosions in the process industries: identification, assessment and control of dust hazards, Gulf professional publishing, 2003.

[20] W. Bartknecht, The Course of Explosions, In Explosions , Springer, Berlin Heidelberg, 1981.

[21] K. L. Cashdollar, Coal dust explosibility, J. loss prev. process ind. 9 (1996) 65-76.

[22] A. E. Dahoe, J. F. Zevenbergen, S. M. Lemkowitz, B. Scarlett, Dust explosions in spherical vessels: the role of flame thickness in the validity of the 'cube-root law', J. loss prev. process ind. 9 (1996) 33-44.

[23] B. Lewis, G. V. Elbe, Combustion, flames and explosions of gases, Elsevier, 2012.

[24] F.A.Williams, Combustion Theory, 2nd ed., Benjamin- Cummins, Menlo Park, California, 1985.

[25] C. K. Law, Combustion Physics, Cambridge University Press, 2006.