Influence of mixture content on the minimum sparkplug ignition energy of a coal dust suspension in the air

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Abstract. This paper provides a numerical simulation of a coal-dust suspension sparkplug ignition in the air. The mathematical model is based on the dual-velocity two-phase model of the reacting gas-dispersion medium. The model consists of the continuity equation, the impulse–conversation equation, the gas and the particle energy-conversation equations, the particle burn-out equation and the component mass-conversation equations which take into account diffusion and burn-out. The energy equations consider the thermal conductivity and chemical reactions on the particle surface. The research investigates the influence of particle size on the minimum sparkplug ignition energy.

1. Introduction

The problem of coal-dust sparkplug ignition is the question of the day in coal industry. The researches [1] – [4] investigate ignition features of coal-dust suspension and flame propagation in the air and in a reactive gas. The work [1] suggests the explosion emerging scenarios in mines. It offers assumption about the influence of coal-dust and reactive gas content on the possibility of their mixture to ignite. The paper [2] provides the data on the explosive risk of coal-dust suspension in the air and in a reactive gas. The coal-dust-reactive gas-air mixture is capable of exploding under the low concentration of coal particles in it.

We have investigated the influence of the fine coal dust powder fraction on the flame propagation rate [3]. The presence of the small coal dust particles in the methane-air mixture increases the flame propagation rate under the low initial concentration of reactive gas. If the mixture is close to the stoichiometric condition the particles decrease the flame propagation rate. The pressure growth rate in the volume increases with the presence of coal dust suspension in comparison to its absence.

Papers [5] – [9] are devoted to the problem of sparkplug ignition. The minimum ignition energy of coal-dust suspension in the air depends on coal particle mass concentration [5, 6]. The small particles decrease the minimum ignition energy. The larger particles increase the minimum ignition energy when the mixture is close to the stoichiometric condition, and decrease when the mixture is far from stoichiometric. The large particles do not influence the minimum ignition energy; it is equal to the mixture ignition energy [7].

The research [8] has investigated the radiation transport influence on the sparkplug ignition of the heterogeneously reacting suspension. The study provides the analytic formula to determine the critical activation energy of suspension sparkplug ignition taking into account radiation transport. The motion of suspension during heating is not taken into account in the papers [7, 8]. Later on, the authors have investigated the effect of thermal expansion on the minimum sparkplug ignition energy of the gas [9].
According to the study the thermal-diffusion model of the gas sparkplug ignition understates the minimum activation energy by more than two times.

In the present study we investigate the sparkplug ignition of coal-dust suspension in the air using mathematical models from [7 – 10] and experimental data from [5 – 6]. We have developed the model which takes into account the influence of thermal and dynamic interactions between particles and gas. The aim of the research is to determine the effect of the mixture proportion on the sparkplug ignition energy.

2. Mathematical model

The following assumptions are made: coal dust is uniformly distributed within the volume, the suspension contains $N$–fractions, which mass concentration equals $m_{\text{dust}} = \sum_{i=1,N} m_{\text{dust},i}$. The instantaneous filiform ignition source is located in the center of the volume. The outer boundary of the computational domain is supposed to be infinitely far from the ignition source. The interaction between coal dust fractions and the electrode heat waste are neglected. Other assumptions are the same as in [10].

The mathematical model is based on the dual-velocity two-phase model of the reacting gas-dispersion medium [11]. It consists of the continuity equation, the impulse–conversation equation, the gas energy-conversation equation considering thermal conductivity, the particle energy-conversation equation considering chemical reaction on its surface, the component mass-conversation equations taking into account the particle burn-out and diffusion and the particle burn-out equation. Under the made assumptions the model has the following form:

The gas continuity equation:

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial (\rho_g u_g)}{\partial r} = r \sum_{i=1,N} G_i. \tag{1}$$

The gas impulse–conversation equation:

$$\frac{\partial r (\rho_g u_g^2+p)}{\partial t} + \frac{\partial (\rho_g u_g^3)}{\partial r} = p - r \sum_{i=1,N} \tau_{\text{v},i} + r \sum_{i=1,N} G_i u_{k,j}. \tag{2}$$

The gas energy-conversation equation:

$$\frac{\partial r \rho_g \left( e_g + \frac{u_g^2}{2} \right)}{\partial t} + \frac{\partial r \left( \rho_g u_g \left( e_g + \frac{u_g^2}{2} \right) + pu_g \right)}{\partial r} = \frac{\partial}{\partial r} \left( r \lambda_g \left( T_g \right) \frac{\partial T_g}{\partial r} \right) + r \sum_{i=1,N} \left( G_c t_{k,i} - u_{k,i} \tau_{\text{v},i} + G_t \frac{u_{k,i}^2}{2} + \alpha_{k,i} n_{k,i} S_{k,i} \left( t_{k,i} - T_g \right) \right). \tag{3}$$

The oxygen mass balance equation:

$$\frac{\partial r \rho_{O2}}{\partial t} + \frac{\partial r \rho_{O2} u_g}{\partial r} = \frac{\partial}{\partial r} \left( r D_{O2} \left( T_g \right) \frac{\partial \rho_{O2}}{\partial r} \right) - r \alpha_1 \sum_{i=1,N} G_i. \tag{4}$$

The particle mass balance equation:

$$\frac{\partial r \rho_{k,i}}{\partial t} + \frac{\partial r \rho_{k,i} u_{k,i}}{\partial r} = -r G_i, \ i = 1..N. \tag{5}$$

The particle impulse–conversation equation:

$$\frac{\partial r \left( \rho_{k,i} u_{k,i} \right)}{\partial t} + \frac{\partial r \rho_{k,i} u_{k,i}^2}{\partial r} = r \tau_{\text{v},i} - r G u_{k,i}, \ i = 1..N. \tag{6}$$

The particle energy-conversation equation:
\[
\frac{\partial r \rho_{k,j}}{\partial t} \left( e_{k,j} + \frac{u_{i,k,j}^2}{2} \right) + \frac{\partial r \rho_{k,j} u_{i,k,j}}{\partial r} \left( e_{k,j} + \frac{u_{i,k,j}^2}{2} \right) = -r \alpha_{k,j} S_{k,j} n_{i,j} \left( T_{k,j} - T_{g} \right) + r Q G_{j} - r G_{j} c_{j} T_{k,j} - r G_{j} \frac{u_{i,k,j}^2}{2} + r \tau_{p,j} u_{i,k,j} \], \quad i = 1..N. \tag{7}
\]

The particle number concentration equation:
\[
\frac{\partial r n_{k,j}}{\partial t} + \frac{\partial r n_{k,j} u_{i,k,j}}{\partial r} = 0, \quad i = 1..N. \tag{8}
\]

The perfect-gas law:
\[
p = \rho_{g} R_{g} T_{g}. \tag{9}
\]

The particle radius equation:
\[
r_{k,j} = \sqrt{\frac{3 \rho_{i,j}}{4 \pi \rho_{k}^0 n_{i,j}}}, \quad i = 1..N. \tag{10}
\]

The initial condition:
\[
T_{g}(r, t_{z}) = T_{b} + \frac{Q_{e}}{4 \pi \rho_{k}^0} \exp \left( -\frac{r^2}{4 \lambda_{k}^0 t_{z}} \right), \quad T_{k,j}(r, t_{z}) = T_{b}, \quad \rho_{g2}(r, t_{z}) = \rho_{g2,b}, \quad \rho_{k,i}(r, t_{z}) = \rho_{k,i,b}, \quad i = 1..N. \tag{11}
\]

The boundary conditions:
\[
\frac{\partial \rho(0, t)}{\partial r} = \frac{\partial \rho_{g2}(0, t)}{\partial r} = \frac{\partial T_{g}(0, t)}{\partial r} = 0, \quad u_{g}(0, t) = 0, \quad u_{k,j}(0, t) = 0, \quad i = 1..N, \quad \frac{\partial \rho_{g2}(\infty, t)}{\partial r} = \frac{\partial T_{g}(\infty, t)}{\partial r} = 0. \tag{12}
\]

Where: \( \rho \) – density; \( \rho_{g2} \) – oxygen partial density; \( \rho_{g2,b} \) – methane partial density; \( u \) – velocity; \( t \) – time; \( r \) – radial coordinate; \( r_{k} \) – particle radius; \( p \) – pressure; \( Q \) – reaction heat; \( Q_{e} \) – spark ignition energy; \( k_{0} \) – chemical reaction-rate constant; \( T \) – temperature; \( E \) – energy of activation; \( R_{g} \) – the molar gas constant; \( S_{m} \) – cross-sectional area; \( \eta \) – absolute viscosity coefficient of the gas; \( c_{v} \) – gas heat capacity at constant pressure; \( c_{k} \) – gas heat capacity of the coal; \( e_{k} = c_{k} T_{k} \) – the particle internal energy; \( e_{g} = \frac{p}{\rho_{g}} \left( \gamma - 1 \right) \) – gas internal energy; \( \lambda_{g} = \lambda_{u} \left( \frac{T_{g}}{T_{u}} \right)^{0.667} \) – thermal conductivity coefficient; \( D_{g} = D_{u} \left( \frac{T_{g}}{T_{u}} \right)^{0.667} \) – diffusion coefficient [12]; \( \alpha_{i} = \frac{N_{u} k_{g} \lambda_{g}}{2 r_{k}} \) – gas-particles heat exchange coefficient; \( \gamma = \frac{c_{p}}{c_{v}} \) – adiabatic exponent; \( \alpha_{i} = \frac{\mu_{g} \nu_{g} \nu_{g}}{\mu_{c} \nu_{c}} \) – oxygen consumption coefficient in reaction with coal dust; \( \chi_{g} = \frac{\lambda_{g}}{c_{v} \rho_{g}} \) – heat diffusivity. Indexes: \( b \) - initial conditions of the gas parameters, \( z \) –spark characteristics, \( k \) – particle parameters, \( g \) – gas parameters, \( i = 1..N \) – fraction number, numeration begins from largest to the smallest size. The rate of particle mass changing is defined by \( G = n_{k} S_{i,j} \rho_{g2} \), where \( j_{i} = \frac{\beta_{m} k_{o2} \exp \left( -E_{z} / R_{u} T_{k} \right)}{\beta_{n} + k_{o2} \exp \left( -E_{z} / R_{u} T_{k} \right)} \) – heterogeneous reaction.
rate, \( \beta_g = \frac{\lambda_g(T) \nu_{D}}{c_g \rho_g r_k} \) – particles mass-transfer coefficient [13]. The friction force is determined by
\[
\tau = n_k F_v, \quad \text{where} \quad F_v = \frac{C_g S_n \rho_g (u_g - u_k) |u_g - u_k|}{2},
\]
interaction force of a single particle with the gas,
\[
C_g = \frac{24(1 + 0.15 \text{Re}^{0.682})}{\text{Re}}, \quad \text{friction coefficient}, \quad \text{Re} = \frac{2 \rho_k r_k |u_g - u_k|}{\eta}
\]
– Reynolds number,
\[
\text{Nu}_k = 2 + \left( \text{Nu}_1^2 + \text{Nu}_2^2 \right)^{0.5} \quad \text{Nusselt number, where} \quad \text{Nu}_1 = 0.664 \text{Re}^{0.5}, \quad \text{Nu}_2 = 0.037 \text{Re}^{0.8} \ [10].
\]

We have solved the system of equations (1) – (12) using the method from [10]. The spatial step around the ignition source area (up to coordinate \( r = 10^{-3} \) m) was set to \( \Delta h = 10^{-6} \) m. After the coordinate \( r = 10^{-3} \) m the spatial step was defined as geometric progression \( \Delta h_i = 1.005 \Delta h \). The time step was calculated by Courant’s stability criterion.

3. Results and discussion

In this study we used thermophysical and kinetics parameters of the coal dust from [19] to solve the problem. The coal particle size \( r_k \) varied from \( 10^{-8} \) to \( 3 \times 10^{-6} \) m. The number of the fractions and fraction composition in percentages was also varied to evaluate the influence of the changing values on the ignition. The aim of the calculations was to determine the minimum spark ignition energy \( Q \) for each composition when the flame front occurred, propagated by the volume. The dimension of the ignition energy is \( J/m \). To define the energy in \( J \), the anode-cathode spacing has to be taken into account, which ranges from \( 4 \times 10^{-3} \) to \( 6 \times 10^{-3} \) m [5].

The curve of the minimum sparkplug ignition energy depending on fraction mass concentration \( m_{\text{dust}, z} \) in percentages is presented in Fig. 1. The total mixture mass is \( m_{\text{dust}} = 0.4 \) kg/ m\(^3\). The value of \( m_{\text{dust}, z} = 0 \% \) corresponds to the monodisperse mixture with particle size \( r_{k,1} = 2 \times 10^{-6} \) m. The value of \( m_{\text{dust}, z} = 100 \% \) - the monodisperse mixture with \( r_{k,2} = 2 \times 10^{-7} \) m. According to the Fig.1, under the constant mass \( m_{\text{dust}} \) the mixtures with the smallest fractions have the lesser value of the minimum ignition energy.

![Fig. 1.](image1.png)

Fig. 1. \( m_{\text{dust}} = 0.4 \) kg/m\(^3\), \( r_{k,1} = 2 \times 10^{-6} \) m, \( r_{k,2} = 2 \times 10^{-7} \) m

![Fig. 2.](image2.png)

Fig. 2. \( m_{\text{dust}} = 0.4 \) kg/m\(^3\), \( m_{\text{dust}, 1} = 0.5 \) kg/m\(^3\), \( m_{\text{dust}, 2} = 0.5 \) kg/m\(^3\)
The more large particles are in the mixture the more minimum sparkplug ignition energy. We conducted several calculations for the mixture with different values of radius of $r_{k,2}$. The calculation result for the fraction ratio $r_{k,1}/r_{k,2} = 1$ and varied radius $r_{k,2}$ is shown in Fig.2. It should be noted that with the increase of fraction radius $r_{k,2}$ the minimum ignition energy rises.

The obtained results show that for the bi-disperse suspension the presence of finely-divided fraction in it leads to significant decrease of minimum sparkplug ignition energy. To show the influence of dispersity on minimum ignition energy of a polydisperse suspension, the parameters of coal particles to make calculations are taken from [1]. The work [1] provides data about dust laden air in mine working: from 40 to 80 % of coal particles have the diameter less than $1.3\cdot10^{-6}$ m, 15 ÷ 35 % less than $2.6\cdot10^{-6}$ m, 5 ÷ 20 % less than $4\cdot10^{-6}$ m and 3 ÷ 10 % of particles have the diameter more than $4\cdot10^{-6}$ m. In this research the investigated suspension has the fractions with the following radiuses: $r_{k,1} = 4\cdot10^{-6}$ m, $r_{k,2} = 2\cdot10^{-6}$ m, $r_{k,3} = 1.3\cdot10^{-6}$ m, $r_{k,4} = 0.65\cdot10^{-6}$ m. The fraction composition in percentages varies within mentioned range. The values of minimum ignition energy spread from 18 $J/m$ for the suspension with 70% of $r_{k,4}$ to 35 $J/m$ for 40 % of $r_{k,4}$.

According to obtained results the presence of the small particles has the significant impact on the minimum sparkplug ignition energy. The number of large particles slightly effect on the ignition energy. The Fig.3,4 show the ignition energy dependence on fraction mass concentration $m_{dust,4}$. The area between curves determines the values of minimum spark ignition energy. The spread of the values for the same $m_{dust,4}$ relates to the different mass value of large particles with the radius $r_{k,3}$. The upper curves on Fig.3,4 correspond to the largest mass of the particles $r_{k,1} = 4\cdot10^{-6}$ m and $r_{k,2} = 2\cdot10^{-6}$ m. The lower curves correspond to the suspension with high content of $r_{k,3} = 1.3\cdot10^{-6}$ m. In Fig.4 the anode-cathode spacing is $4\cdot10^{-3}$ m.

![Fig. 3. The minimum spark ignition energy – fraction mass concentration curve, $m_{dust} = 0.4$ kg/m$^3$.](image3.png)

![Fig. 4. The minimum spark ignition energy – fraction mass concentration curve, $m_{dust} = 0.4$ kg/m$^3$.](image4.png)

The obtained result in this research is in a good agreement with those collected in [5] under the fraction concentration of small particles more than 65%.
4. Conclusions

We numerically investigated the sparkplug ignition problem of bi and poly-dispersed coal-dust suspension. The paper provides data about the effect of particle size and fraction composition in percentages on minimum spark ignition energy. The larger the particles the more energy is needed to ignite the coal-dust suspension. Spread of sparkplug ignition values for bi-dispersed suspension depending on the content is wider than for poly-dispersed.

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