Numerical investigation on burning stability of the coal-dust methane-air mixture in a recuperative burner

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Abstract. The paper is devoted to numerical investigation on combustion singularities of the bi-dispersed coal-dust methane-air mixture in a slot recuperative burner. The aim of the research is to determine the stable combustion conditions of the methane-air mixture depending on the fuel flow rate at the inlet of the burner and on the parameters of the mixture (the particle size and the mass concentration of the coal particles, the percentage composition of inert particles and the methane volume content). The problem was solved by finite difference method. The regimes of stable combustion for the coal-dust methane-air mixture depending on the fuel content and the fuel flow rate at the inlet of the burner the have been defined.

1. Introduction

This paper presents a study on burning stability of coal-dust methane-air mixture (CDMAM) in a recuperative burner. The burning stability depends on the mixture content and the heat recuperation. CDMAM is a methane-air mixture with inert and reacting coal particles and the methane-air ratio is less stoichiometric value. The burning stability depends on the percent composition of inert and the reacting particles, the mass concentration of the coal dust and methane in the mixture and the coal particle size. The researches on the influence of the particles size, the particle mass concentration and the content of the mixture on combustion is presented in [1 – 4].

The authors in [1] showed that the coal-dust methane-air mixture is capable of exploding under the low concentration of coal particles in it. However the coal-dust suspension and the methane-air mixture are not able to explode separately under the same concentrations. The papers [2 – 3] investigate the influence of the fine coal dust powder fraction on the flame propagation rate: under the low initial concentration of reactive gas the presence of the reacting particles in the methane-air mixture increases the flame propagation rate; if the methane-air ratio is close to the stoichiometric condition the particles decrease the flame propagation rate. The paper [4] provides the numerical investigation on the combustion of lean methane-air mixture with monodispersed coal-dust suspension in a recuperative burner. The authors demonstrate that the heat recovery and the presence of the reactive particles support combustion of the 2 % methane-air mixture. The research reveals the influence of the particles size on the burning stability of CDMAM: the increase of the particle radius decreases the maximum value of feed rate at the inlet of the burner which provide the stable combustion.

The aim of the present paper is to investigate the burning stability of the CDMAM depending on the feed rate and the mixture parameters (the size and the mass concentration of coal particles, the inert-reacting particle ratio and methane volume content).
2. Mathematical model

A cold methane–air mixture with the methane mass content $a_{\text{CH}_4}$, the gas phase temperature $T_g$, and overall mass concentration $m_{\text{n,at}} = \sum_{i=1}^{n} \rho_{i,j}$ ($\rho_{i,j}$ - particle mass per unit volume) is fed to a preheated recuperative burner at the rate $u_t$ at the inlet ($x = 0$). The scheme of the burner is presented in figure 1.

![Burner Scheme](image)

Figure 1. The scheme of the burner: I – the inlet tube, II – the inner insert, III – the outlet tube

It is supposed that the particles are divided into reacting ($\rho_{i,1}$) and inert ($\rho_{i,2}$). Other assumptions of the mathematical model correspond to [4]. The mathematical formulation of the problem has the following form:

$$
c_s \rho_g \frac{\partial T_g}{\partial t} + c_s \rho_g u \frac{\partial T_g}{\partial x} = \frac{\partial}{\partial x} \left( \lambda(T_g) \frac{\partial T_g}{\partial x} \right) + \sum_{i=1}^{n} \left[ G_{i} \alpha_{i,j} + \alpha_{i,j} n_i, n_i, S_{i,j} \left( T_{i,j} - T_g \right) \right] +$$

$$
+ \frac{\alpha_s}{h} (T_{1,s} - T_g) + Q_i \rho_i a_{\text{CH}_4} a_{\text{O}_2} k_{03} \exp \left( - \frac{E_1}{R T_g} \right), \quad T_{1,s}(x,t), x < L, \quad T_{3}(x,t), 2L - x, x \geq L. \tag{1}
$$

$$
c_s \rho_g \frac{\partial T_{1,s}}{\partial t} = \lambda_s \frac{\partial^2 T_{1,s}}{\partial x^2} - \frac{\alpha_s}{h_s} \left( T_{1,s} - T_g \left( x,t \right) \right) - \frac{\alpha_s}{h_s} \left( T_{3} - T_{1,s} \left( 2L - x,t \right) \right), 0 \leq x \leq L. \tag{2}
$$

$$
c_k \rho_{i,j} \frac{\partial T_{i,j}}{\partial t} + u c_k \rho_{i,j} \frac{\partial T_{i,j}}{\partial x} = \alpha_{i,j} S_{i,j} \left( T_g - T_{i,j} \right) + Q_i G_i - G_{i} c_{i,j}, i = 1, 2. \tag{3}
$$

$$
\frac{\partial \alpha_{\text{H}_4}}{\partial t} + \frac{\partial}{\partial x} \left( D(T_g) \frac{\partial \alpha_{\text{H}_4}}{\partial x} \right) - k_{13} \rho_{i,j} a_{\text{CH}_4} a_{\text{O}_2} \exp \left( - \frac{E_1}{R T_g} \right), \tag{4}
$$

$$
\frac{\partial a_{\text{O}_2}}{\partial t} + \frac{\partial}{\partial x} \left( D(T_g) \frac{\partial a_{\text{O}_2}}{\partial x} \right) - \frac{\mu_{\text{O}_2} V_{\text{O}_2}}{\mu_{\text{CH}_4} V_{\text{CH}_4}} k_{13} \rho_{i,j} a_{\text{CH}_4} a_{\text{O}_2} \exp \left( - \frac{E_1}{R T_g} \right) \tag{5}
$$

$$
p = \rho_{i,j} R T_g = \text{const}. \tag{6}
$$

$$
\frac{\partial \rho_{i,j}}{\partial t} + \frac{\partial}{\partial x} \left( \rho_{i,j} u \right) = \sum_{i=1}^{N} G_i. \tag{7}
$$

$$
\frac{\partial \rho_{i,j}}{\partial t} + \frac{\partial}{\partial x} \left( \rho_{i,j} u \right) = -G_i, \quad i = 1, 2. \tag{8}
$$

$$
\frac{\partial n_{i,j}}{\partial t} + \frac{\partial}{\partial x} \left( n_{i,j} u \right) = 0, \quad i = 1, 2. \tag{9}
$$

$$
r_{i,j} = \frac{3 \rho_{i,j}}{4 \pi \rho_{i,j} n_{i,j}}, \quad i = 1, 2. \tag{10}
$$

$$
T_g(x,0) = T_{g,b}(x), \quad T_{1,s}(x,0) = T_{1,s,b}(x), \quad T_{1,s}(x,0) = T_{1,s,b}(x), \quad \rho_{i,j}(x,0) = \rho_{i,j,b}(x), \quad a_{\text{CH}_4}(x,0) = a_{\text{CH}_4,b}(x), \quad a_{\text{O}_2}(x,0) = a_{\text{O}_2,b}(x), \quad u(x,0) = u_{g,b}(x), \quad n_{i,j}(x,0) = n_{i,j,b}(x). \tag{11}
$$
\[ T_s (0,t) = T_{g,v}, \quad T_k (0,t) = T_{k,v}, \quad a_{CH_4} (0,t) = a_{CH_4,v}, \quad a_{O_2} (0,t) = a_{O_2,v}, \]
\[ u (0,t) = u_v, \quad \rho_{k,v} (0,t) = \rho_{k,v}, \quad n_{i,v} (0,t) = \frac{\rho_{k,v}}{V_{i,k} \rho_k^0}, \quad \frac{\partial T_s (0,t)}{\partial x} = 0. \]
\[ \frac{\partial T_s (L,t)}{\partial x} = 0, \]
\[ \frac{\partial T_s (2L,t)}{\partial x} = \frac{\partial a_{CH_4} (2L,t)}{\partial x} = \frac{\partial a_{O_2} (2L,t)}{\partial x} = 0. \]

Where: \( T \) is the temperature; \( c \) is the heat capacity; \( n \) is the number of particles per unit volume; \( R_a \) – the molar gas constant; \( R_i \) is the gas constant; \( r \) is radius; \( S \) is area; \( V \) is volume; \( Q_{1,2}, E_{1,2}, k_{01,02} \) are the reaction heat; the energy of activation; and the constant of the chemical reaction rate for the gas phase and for particle surface; \( \rho \) is the density; \( \rho_k^0 \) is the density of a coal particle; \( a_{O_2}, a_{CH_4} \) are the mass concentration of oxidizer and methane in the mixture; \( \mu_{O_2}, \mu_{CH_4}, \mu_c \) are the molar mass of oxygen, methane and carbon respectively; \( \nu_{O_2}, \nu_{CH_4}, \nu_c \) is the mole number of oxygen, methane and carbon in the reaction; \( u \) is the velocity; \( h \) is width of burner canal; \( h_1 \) is width of the inner insert. Indexes: \( g \) is the gas parameters; \( k \) – the particle parameters; \( S \) is the inner insert parameters; \( b \) is the initial parameters, \( v \) is the parameters at the burner inlet; \( st \) is the values at temperature \( T_s = 300 \) K, \( i \) is the parameters of the reacting particles, \( 2 \) is the parameters of inert particles. \( \lambda = \lambda_v \left( T / T_i \right)^{3/2} \) is the thermal conductivity coefficient, \( D = \lambda (T) \) is the diffusion coefficient, \( \alpha_s = \lambda \cdot Nu_s / h \) is the gas-inner insert heat exchange coefficient, \( \alpha_{k,i} = \lambda \cdot Nu_k / r_k \) is the gas-particles heat exchange coefficient. The heat exchange coefficient between gas and the inner insert is determined by Nusselt number, \( Nu_s \), [4]:

The rate of particle mass changing is: \( G = n_i S_j \mu_{O_2} \), where \( \mu_{O_2} = \beta_{m} k_{O_2} \exp \left( -E_{2} / R_a T_k \right) / \left[ \beta_{m} + k_{O_2} \exp \left( -E_{2} / R_a T_k \right) \right] \) is the heterogeneous reaction rate, \( \beta_{m} = \lambda_{v} (T) \cdot Nu_d / \left( c_g \rho_r r_k \right) \) is the particle mass-transfer coefficient [5]. The rate of mass changing for inert particles \( G_0 = 0 \), the radius of an inert particle does not change with increasing temperature.

The calculation method is presented in [6]. The problem (1) – (14) was solved numerically. The energy equations (1) – (2), the mass balance equations of methane (4) and oxygen (5) were solved by the finite-difference approximation method. The gas continuity equation (7), the energy equation (3), the equation of number concentration (9) and the mass balance equation for particles (8) were approximated by an explicit difference scheme with upwind differences. The spatial step was equal to \( 10^{-5} \) m. The time step was determined by Courant stability criterion.

3. Results and discussion

The initial conditions (11) has been set according to the stable burning parameters of 6% methane-air mixture with mixture feed rate of 0.3 m/s. During the calculation the initial conditions are superseded by the parameters of dust-laden gas with a lower concentration of methane. The calculation is carried out until the stabilization of the burning front. The burning front becomes stable when its coordinate take the steady position. The front coordinate is the area where the methane mass concentration is equal to half of its value at the value of the inlet of the burner.

The calculations were held under thermophysical and kinetic parameters from [4]. Two coal-dust methane-air mixtures with mass concentration of coal dust \( m_{dust} = \sum_{i=1..2} \rho_{k,i} = 0.054 \) kg / m\(^3\). \( m_{dust} = \sum_{i=1..2} \rho_{k,i} = 0.04 \) kg / m\(^3\) and volume content of methane \( (a_{vol} = 2 \%, \ a_{vol} = 3 \%) \) were investigated. The selected values of the mass concentration and the volume content correspond to the
adiabatic temperature $T_{g,ad}= T_{g,b} + \frac{Q_a \rho_{g,b}^t a_{CH_4,vol} + Q_2 m_{dust}}{c_p \rho_{g,b}^t + c_l m_{dust}} < 2500$ K (under the assumption that all particles in the mixture are reacting). During the investigation the content of the mixtures was varied: the radius of the particles ($r_k$) was ranged from $10^{-7}$ m to $10^{-5}$ m, the mass percentage composition of inert particles was ranged from 10% to 30% and the feed rate ($u_b$) was ranged from $10^{-3}$ m/s to 0.5 m/s. The aim of the research was to determine stable regimes of combustion depending on the mixture content and the feed rate at the inlet of the burner.

The result of the calculation for the mixture with $r_k = 10^{-6}$ m, $m_{dust} = \sum_{i=1,2} \rho_{k,i} = 0.054$ kg/m$^3$, $a_{vol} = 2 \%$, $u_b = 0.21$ m/s and with 10% of inert particles is presented in figure 2. The temperature of inert particles is equal to the gas phase, the reacting particle temperature is shade higher than the gas. Increasing in the particle size leads to the rise of the particle temperature.

![Figure 2](image1.png)

Figure 2. Temperature distribution of reacting particles (1) and the gas (2) along the burner. $r_k = 10^{-6}$ m, $m_{dust} = 0.054$ kg/m$^3$, $a_{vol} = 2 \%$, $u_b = 0.21$ m/s, 10% of inert particles.

![Figure 3](image2.png)

Figure 3. Temperature distribution of reacting particles (1) and the gas (2) along the burner. $r_k = 4 \cdot 10^{-6}$ m, $m_{dust} = 0.054$ kg/m$^3$, $a_{vol} = 2 \%$, $u_b = 0.18$ m/s, 10% of inert particles.
The parametric calculations provided data about the boundary of stable combustion depending on the particle size and the feed rate for the mixture with the coal mass concentration $m_{\text{dust}} = 0.054 \text{ kg} / \text{m}^3$, the volume concentration $a_{\text{vol}} = 2 \%$ (figure 4). The curve 1 was plotted for the monodispersed coal-dust methane-air mixture without inert particles. The curve 2 corresponds to the mixture with 30% of inert particles. According to the figure 4 the presence of inert particles in the finely-divided coal-dust methane-air mixture influences on the stable combustion more than for the mixture with the large dispersed coal fraction. The maximum feed rate which provides stable combustion decreases in $1.4 \div 1.6$ times with the presence of inert particles which is less than 1 $\mu \text{m}$. The more inert particles in the mixture, the less maximum feed rate which provides stable combustion. The increasing in particles size decreases the influence of inert particles on combustion. For example, the feed rate for the mixture with the coal particle radius $r_k = 10^{-5} \text{ m}$ changes from 0.19 m/s for the mixture without inert particles to 0.15 m/s for the mixture with 30% of inert particles. The figure 4 shows that the boundary of stable combustion for the large particle does not change with increasing in the particle size.

The result of the calculation for the mixture with the coal mass concentration $m_{\text{dust}} = 0.04 \text{ kg} / \text{m}^3$ and the volume concentration $a_{\text{vol}} = 3 \%$ is presented in figure 5. The addition of inert particles leads to the decrease of the feed rate $u_0$ which provide stable combustion. The boundary of stable combustion in the case of $m_{\text{dust}} = 0.04 \text{ kg} / \text{m}^3$ and $a_{\text{vol}} = 3 \%$ does not shift as much as in the case of the mixture with $m_{\text{dust}} = 0.054 \text{ kg} / \text{m}^3$ and $a_{\text{vol}} = 2 \%$. With the addition of inert particles the stable combustion area for the mixture with $a_{\text{vol}} = 3 \%$ is wider than for the mixture with $a_{\text{vol}} = 2 \%$ (the curve 2 in figure 4. is below the curve 2 in figure 5). The less volume concentration of methane in the mixture the more influence of inert particles on the combustion stability for the lean coal-dust methane–air mixture.

![Figure 4. The boundary of stable combustion. Curves: 1 – mixture with monodispersed reacting coal particles, 2 – bi-dispersed reacting and inert (30%) coal particles. $m_{\text{dust}} = 0.054 \text{ kg} / \text{m}^3$, $a_{\text{vol}} = 2 \%$](image)

![Figure 5. The boundary of stable combustion. Curves: 1 – mixture with monodispersed reacting coal particles, 2 – bi-dispersed reacting and inert (30%) coal particles. $m_{\text{dust}} = 0.04 \text{ kg} / \text{m}^3$, $a_{\text{vol}} = 3 \%$](image)
4. Conclusions
In this paper we have numerically investigated the problem on burning stability of coal-dust methane-air mixture in a recuperative burner. The particle size, the methane volume content and the particle mass concentration influence the burning stability of CDMAM. It has been shown that a mixture with high mass concentration of the finely-divided coal fraction burns steady under a wide range of the feed rate at the inlet of the burner. The presence of inert particles leads to the decrease of the feed rate range which provides stable burning of CDMAM. The influence of inert particles on the burning stability decreases with increasing of the methane volume content.

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