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Burning stability of the coal-dust methane-air mixture in a recuperative burner

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Abstract. The physical mathematical model of combustion of the coal-dust methane-air mixture in a recuperative burner has been developed. The influence of the particles (inert and reacting) on the burning stability of coal-dust methane-air mixture with low concentration of methane has been determined. The regimes of stable combustion for lean methane-air mixture with coal suspension depending on the fuel flow rate at the inlet of the burner and the fuel content have been defined.

1. Introduction
In this paper we investigate the problem of combustion of the coal-dust methane-air mixture in a recuperative burner. In early papers [1-2] the aim was to investigate combustion of gas mixtures in a U-shaped recuperative burner. Combustion of a lean methane–air mixture in a slot burner with an inert inner insert was investigated in [3]. It was demonstrated that the combustion of a methane-air mixture (volume fraction of methane is 2.3% and up) might be initiated and supported by heat recovery. Under the normal conditions, the volume fraction of methane must be above 5.2 % to support the burning of the mixture [4]. A methane-air mixture is a by-product generated during coal mining. The mixture contains impurities and dust particles. The burning characteristics of such mixture differ from characteristics of a pure methane-air mixture. Coal dust can react in the air by itself, but under certain conditions. However a coal-dust methane-air mixture is able to ignite under the conditions at which coal dust and methane do not ignite separately. In the research [5] the authors showed that combustion of coal-dust in the air under the normal conditions is impossible without adding the small amount of methane or without preheat of the burner walls. The addition of methane to coal-dust-air mixture stabilizes the flame front. The presence of inert particles in a coal suspension can also change the nature of the burning process. Thus combustion of a coal-dust methane-air mixture in a recuperative burner is a complex process of heat transfer and chemical reactions.

This paper provides a numerical simulation on combustion of methane-air mixture with suspended coal dust in a fantail burner with an inert inner insert. The aim of the research is to determine the stable combustion conditions of the methane-air mixture depending on the content of the mixture (particle size and percentage composition of the inert particles) and the fuel flow rate at the inlet of the burner.

2. Mathematical model
A cold methane–air mixture with the methane mass content \( a_{CH_4,v} \), the gas phase temperature \( T_{g,v} \), and the overall mass concentration \( m_{dust} = \sum_{i=1}^{N} m_{dust,i} \) is fed to a preheated fantail burner at the rate \( u_v \) at the
The mathematical formulation of the problem has the following form:

The energy equation for gas phase:
\[
c_{g}p_{g} \frac{\partial T_{g}}{\partial t} + c_{g}p_{g} u \frac{\partial T_{g}}{\partial x} = \frac{\partial}{\partial x} \left( \lambda(T_{g}) \frac{\partial T_{g}}{\partial x} \right) + \sum_{j=1}^{N} \left[ Gc_{T_{k,j}} + \alpha_{k,n_{k,j}} S_{k,j} (T_{k,j} - T_{g}) \right] + \frac{\alpha_{s}}{h} (T_{1,s} - T_{g}) + Q_{p} a_{CH4} a_{O2} k_{01} \exp \left( \frac{-E_{1}}{RT_{g}} \right), \quad T_{1,s} (x,t), \quad x < L,
\]

The energy equation for inner insert:
\[
c_{s} \rho_{s} \frac{\partial T_{s}}{\partial t} = \frac{\partial}{\partial x} \left( \lambda(T_{s}) \frac{\partial T_{s}}{\partial x} \right) + \alpha_{s} h_{s} (T_{s} - T_{g}) - \frac{\alpha_{s}}{h_{s}} (T_{s} - T_{g} (2L - x,t)), \quad 0 \leq x \leq L.
\]

The mass balance equation of methane in the mixture:
\[
\frac{\partial a_{CH4}}{\partial t} + u \frac{\partial a_{CH4}}{\partial x} = \frac{\partial}{\partial x} \left( D(T_{g}) \frac{\partial a_{CH4}}{\partial x} \right) - k_{01} p_{g} a_{CH4} a_{O2} \exp \left( \frac{-E_{1}}{RT_{g}} \right).
\]

The mass balance equation of oxidizer in the mixture:
\[
\frac{\partial a_{O2}}{\partial t} + u \frac{\partial a_{O2}}{\partial x} = \frac{\partial}{\partial x} \left( D(T_{g}) \frac{\partial a_{O2}}{\partial x} \right) - \frac{\mu_{O2} v_{O2}}{\mu_{CH4} v_{CH4}} k_{01} p_{g} a_{CH4} a_{O2} \exp \left( \frac{-E_{1}}{RT_{g}} \right) - \frac{\mu_{O2} v_{O2}}{\mu_{C} v_{C}} \sum_{i=1}^{N} G_{i} p_{g}.
\]

The perfect-gas law:
\[
p = p_{g} R_{g} T_{g} = \text{const}.
\]

The gas continuity equation:
\[
\frac{\partial \rho_{g}}{\partial t} + \frac{\partial (\rho_{g} u)}{\partial x} = \sum_{i=1}^{N} G_{i}.
\]

The mass balance equation for particles of the i-th fraction:
\[
\frac{\partial n_{k,i}}{\partial t} + \frac{\partial (n_{k,i} u)}{\partial x} = -G_{i}, \quad i = 1..N.
\]

The equation of number concentration of the i-th fraction:
\[
\frac{\partial n_{k,i}}{\partial t} + \frac{\partial n_{k,i} u}{\partial x} = 0, \quad i = 1..N.
\]

The equation of radius for i-th fraction:
\[
r_{k,i} = \sqrt{\frac{3 \rho_{k,i}}{4 \pi}, \quad i = 1..N}.
\]

The initial conditions:
\[
T_{g} (x,0) = T_{g,b} (x), \quad T_{s} (x,0) = T_{s,b} (x), \quad T_{k,j} (x,0) = T_{k,j,b} (x), \quad \rho_{k,i} (x,0) = \rho_{k,b} (x),
\]

\[
a_{CH4} (x,0) = a_{CH4,b} (x), \quad a_{O2} (x,0) = a_{O2,b} (x), \quad u(x,0) = u_{g,b} (x), \quad n_{k,j} (0,0) = n_{k,b} (x).
\]

The boundary conditions:
\[
T_{g} (0,t) = T_{g,v}, \quad T_{k,j} (0,t) = T_{k,v}, \quad a_{CH4} (0,t) = a_{CH4,v}, \quad a_{O2} (0,t) = a_{O2,v},
\]

\[
u(0,t) = u, \quad \rho_{k,i} (0,t) = \rho_{k,v}, \quad n_{k,j} (0,t) = \frac{\rho_{k,i}}{V_{k,i} p_{g}} \frac{\partial T_{g}}{\partial x} = 0.
\]
\[
\frac{\partial T_s}{\partial x}(L,t) = 0, \quad (13)
\]

\[
\frac{\partial T_s}{\partial x}(2L,t) = \frac{\partial a_{CH4}}{\partial x}(2L,t) = \frac{\partial a_{O2}}{\partial x}(2L,t) = 0. \quad (14)
\]

Where: \( T \) is the temperature; \( c \) is the heat capacity; \( n \) is the number of particles per unit volume; \( R_u \) – the molar gas constant; \( R_p \) is the gas constant; \( r \) is radius; \( S \) is area; \( V \) is volume; \( Q_{1,2}, E_{1,2}, k_{0,02} \) are the reaction heat; \( \eta \) is the velocity; \( h \) is width of burner canal; \( h_i \) 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 \( T_g = 300 \, K \), \( i = 1..N \) is the number of fraction; \( \lambda = \lambda_u (T/T_g)^{2/3} \) is the thermal conductivity coefficient, \( D \sim \lambda(T) \) is the diffusion coefficient, \( \alpha_s = \lambda_s N t_u / h \) is the gas-inner insert heat exchange coefficient, \( \alpha_{ks} = \lambda_s N u_s / r_k \) is the gas-particles heat exchange coefficient. The heat exchange coefficient of gas and inner insert is determined by Nusselt number, \( N u_s \), [3]:

\[
N u_s = \begin{cases} 
0.979 \left( \frac{h \, Re \, Pr}{x} \right)^{0.33} \frac{h \, Re \, Pr}{x} > 1000, \\
3.78 + \left( N u_s - 3.78 \right) \frac{h \, Re \, Pr}{x} / 900, 100 \leq \frac{h \, Re \, Pr}{x} \leq 1000, \\
3.78, \quad \frac{h \, Re \, Pr}{x} < 100. 
\end{cases}
\]

where \( Pr = c \, \eta / \lambda \) is the Prandtl number, \( Re = \frac{\rho \, h}{\eta} \) is the Reynolds number, \( N u_s \) is the value of Nusselt number, when \( \frac{h \, Re \, Pr}{x} = 1000 \), \( N u_D \) is the diffusion Nusselt number.

The rate of particle mass changing is: \( G = n_i S_j j_i \rho_{O2} \), where \( j_i = \beta_n k_{02} \exp \left( -E_z / R_u T_k \right) / \left[ \bar{\beta}_n + k_{02} \exp \left( -E_z / R_u T_k \right) \right] \) is the heterogeneous reaction rate, \( r_\text{de} \) \( \beta_n = \lambda_n \left( T \right) N u_D / \left( c_s \rho_s r_k \right) \) is the particle mass-transfer coefficient [7]. The rate of mass changing for inert particles \( G_i = 0 \), the radius of an inert particle do not change with increasing temperature.

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

3. Results and discussion

The initial conditions (11) have been set according to the stable burning parameters of 6% methane-air mixture with the feed rate of 0.23 \, m/s. During the calculation the initial conditions are superseded by the parameters of the dust-laden gas with the lower concentration of methane. The calculations were held under the parameters taken from [6]. The size of the particles ranges from 0.1 to 10 \, \mu m, \, r_k = 10^{-3}.
The mixture feed rate \( u_x \) and the volumetric content of methane \( C_{CH4,vol} \) at the inlet of the burner ranges from 0.1 to 0.5 \( m/s \) and from 1 to 5\% respectively. The dust mass concentration is \( m_{dust} = 0.2 \text{ kg/m}^3 \). We numerically investigate combustion of the methane-air mixture with monodisperse suspension without inert particles and the methane-air mixture with bi-disperse suspension with 10\% of inert particles. The aim of the calculations was to determine the boundary of stable combustion depending on the fuel flow rate at the inlet of the burner and the content of the mixture.

The results of two different calculations are shown in Figures 1-2. Figure 1a shows the temperatures of gas (curve 1), inert (curve 2) and reacting particles (curve 3) for the feed rate \( u_x = 0.2 \text{ m/s} \) and particle radius \( r_k = 10^{-6} \text{ m} \). Pic 1b shows temperatures for the feed rate \( u_x = 0.16 \text{ m/s} \) and particle radius \( r_k = 4 \cdot 10^{-6} \text{ m} \). The temperature of inert particles is close to the temperature of the gas. The reacting particles have the higher temperature due to the combustion. Moreover the largest particles have the higher temperature.

![Figure 1: The temperatures of gas, inert and reacting particles.](image)

Figure 2 provides data about combustion of the monodisperse and the bi-disperse coal suspension. The bi-disperse suspension has 10\% of inert particles. According to the obtained result the presence of inert particles changes the boundary of stable combustion. The inert particles increase the mass of the mixture and pull heat from the area of combustion. The heat transfer leads to the decrease of the feed rate at which the mixture can ignite and burn steady.

The numerical simulation for 1\% methane-air mixture with monodisperse reacting coal-dust suspension showed the possibility of stable combustion when the coal mass concentration is not less than \( m_{dust} = 0.068 \text{ kg/m}^3 \) [6]. In this paper with the help of the model (1)--(14) we numerically investigate the stable combustion of a polydisperse coal-dust suspension when the coal mass concentration \( m_{dust} \) ranges from 0.02 to 0.05 \text{ kg/m}^3. It is supposed that the suspension consists of 4 fractions. The sizes of the fractions are \( r_{k,1} = 6.5 \cdot 10^{-6} \text{ m} \), \( r_{k,2} = 1.3 \cdot 10^{-6} \text{ m} \), \( r_{k,3} = 2 \cdot 10^{-6} \text{ m} \), \( r_{k,4} = 3 \cdot 10^{-6} \text{ m} \). The masses of each fraction are \( m_{dust,1} = 0.4 \text{ m}_{dust} \), \( m_{dust,2} = 0.3 \text{ m}_{dust} \), \( m_{dust,3} = 0.2 \text{ m}_{dust} \), \( m_{dust,4} = 0.1 \text{ m}_{dust} \). It should be noted that the most particles in the suspension are micron in size. The result of the calculation is shown in Figure 3. According to the graph the mixture is able to burn at \( C_{CH4} = 1\% \) and \( m_{dust} = 0.01 \text{ kg/m}^3 \). Moreover the lean gas mixture \( (C_{CH4} = 1\% \) and \( m_{dust} = 0.01 \text{ kg/m}^3) \) burns steady at low feed rate at the inlet. The temperature of the burning front ranges from 1100 to 1300 \text{ K}. Oxygen does not completely burn out at this composition of the mixture. Thus the stable regime of the low-temperature
combustion is implemented, which can be used to burn-out the by-products generated during coal mining.

![Figure 2](attachment://figure2.png)

**Figure 2.** The boundary of stable combustion for coal-dust methane-air mixture. Curves: 1 – monodisperse suspension of reacting particles, 2 – bi-disperse suspension of reacting and inert particles (10% of total mass).

![Figure 3](attachment://figure3.png)

**Figure 3.** The boundary of stable combustion for polydisperse coal-dust methane-air mixture

\[ r_{k,1} = 0.65 \times 10^{-6} \text{ m}, r_{k,2} = 1.3 \times 10^{-6} \text{ m}, r_{k,3} = 2 \times 10^{-6} \text{ m}, r_{k,4} = 3 \times 10^{-6} \text{ m}; a_{\text{vol, CH}_4} = 1\% .\]

4.Conclusions

We numerically investigated burning stability of the coal-dust methane-air mixture in a recuperative burner. We theoretically showed the possibility of the low-temperature burning for the lean gas mixture with the coal-dust mass concentration of 10 kg/m³ and 1% methane volume content. The obtained results provide data about the influence of inert particles on burning stability of the coal-dust
methane-air mixture. The presence of the inert particles decreases the range of the feed rate at the inlet at which the steady burning regime is implemented.

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