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EFFECT OF COAL DUST ON THE AIR-METHANE MIXTURE COMBUSTION IN THE SWISS-ROLL BURNER

by

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The 2-D numerical model has been developed to simulate the combustion of lean coal-methane-air mixture in "Swiss-roll" burner and investigate the effect of coal particles content and mixture feed rate on the stable burner operation. Five homogeneous and three heterogeneous chemical reactions are considered. The Eulerian model for gas phase and the discrete particle model (Lagrangian) for particle phase taking into account the radiation are used in this study. Simulations are performed for the two turns "Swiss roll" burner with heat insulated outer wall, channel width of 6 mm and inner wall thickness of 2 mm. It is shown that the presence of coal particles in a lean methane-air mixture expands the range of stable operation of the "Swiss-roll" burner. It is found that an increase in the content of coal particles reduces the combustion time of the particles by increasing the combustion temperature, changes the shape of the reaction zone, and shifts it to the burner inlet.

Key word: *Swiss-roll burner, coal particles, lean methane-air mixture,
combustion, feed rate*

Introduction

There are many potentially useful fuels that are not currently used as energy sources. These sources include lean methane-air mixtures with a small content of coal dust, which may be a product of mine production. One of the effective ways to extract the combustion energy of lean methane-air mixtures containing coal dust can be the usage of recuperative type burners [1-3], since the efficiency of heat recovery burner significantly exceed the efficiency of the system without heat recovery [4].

The operation stability of the recuperative type burners depends on the concentration of the fuel, the geometric dimensions of the burner, wall material and the feed rate of the mixture [5, 6]. The effect of the CH_4 concentration in the methane-air mixture, the mixture feed rate and the channel sizes on the stable operating modes of the U-shaped recuperative burner in the 1-D approximation is analyzed in the works [7, 8]. A study based on numerical 1-D calculations and a simplified model of coal combustion [9, 10] shows that the presence of small reacting coal particles in a methane-air mixture leads to an expansion of the range of stable combustion in U-shaped recuperative burners, while inert particles, on the contrary, reduce this range. Reducing the size of the reacting particles also broadens the range of stable

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combustion. But 2-D modeling shows that even in an idealized combustion chamber the behavior of combustion cannot be properly described by 1-D models [11].

Investigation of the coal-methane-air mixture combustion in the recuperative spiral *Swiss-roll* burner considering five reactions in the gas phase and three reactions on the surface of particles is performed in [12] based on the numerical modeling 2-D approximation. It is shown that an increase in the concentration of coal particles expands the range of stable operation of the burner and leads to the fact that the reaction zone is shifted to the inlet part of the burner.

The aim of this work is to study stable combustion conditions for a lean methane-air mixture containing fine coal particles in a double turns *Swiss-roll* burner, depending on the parameters of the initial mixture taking into account the radiation process.

Statement of the problem

The cold coal-methane-air mixture enters the burner, the outer walls of which are thermally insulated, with a feed rate, U_{in}, and a temperature of 300 K at a pressure of 1 atm, fig.1. The width of the burner channels is constant and equal to 6 mm. The thickness of the inner walls of the burner is 2 mm. The mixture flowing into the burner, due to the heat recuperative effect from hot combustion products through the inner walls of the burner heats up to a temperature, at which the components react chemically. The heat released during this process is used to replenish the heat lost by the combustion products, which has gone to the heating of the cold mixture entering the burner.

The gas mixture, consisting of oxygen, CH_4, coal volatile substances, CO, CO_2, water vapor, hydrogen, and nitrogen, is a multicomponent viscous ideal incom-

Figure 1. Scheme of *Swiss-roll* burner;
1 – initial mixture, 2 – product of reactions,
3 – reaction zone, 4 – inner walls,
5 – outer wall

pressible gas. The decomposition reaction of CO_2 and four oxidation reactions occur in the gas phase involving CH_4, the volatile substance of coal, CO, and hydrogen. Here we use the reduced reaction mechanism for the simulation of methane-air combustion, which can adequately predict temperature and main species profiles [13]. On the surface of the coal particle, three oxidation reactions occur with the participation of oxygen, CO_2, and water vapor, resulting in the formation of CO.

It is assumed that coal contains 8% of ash, 12.9% of volatile substances, and 79.1% of carbon. The coal particle size is 4 μm. The methane-air mixture at the inlet to the burner contains 2% CH_4, which corresponds to the mass fractions: oxygen is 0.2298, nitrogen is 0.759, CH_4 is 0.01122.

Mass exchange, momentum exchange, and heat exchange due to the mechanisms of convection and radiation occur between the particles and the gaseous medium. The flow of the radiating coal-methane-air mixture is assumed to be stationary and 2-D.
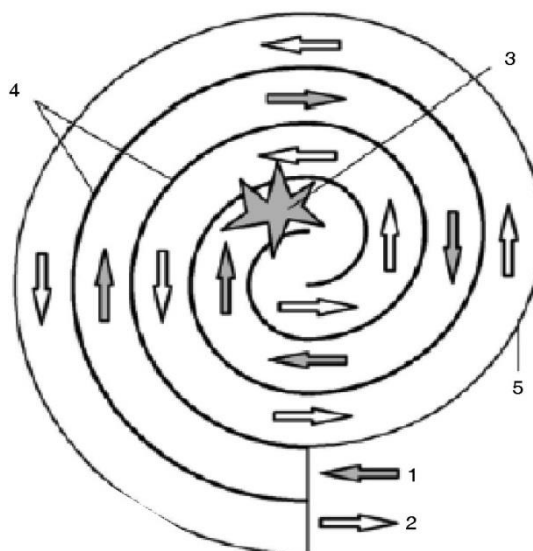
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Model and solution method

The system of equations describing the parameters of the gas phase includes the conservation equations for mass, mass fraction of the components, momentum and energy, which are closed by the ideal gas equation.

The mass rate of ith species production by r^{th} homogeneous chemical reaction in the gas phase obeys the law:

$$R_{r,i} = v_{r,i} A_{r,i} \exp\left(-\frac{E_{1,i}}{R_u T}\right) \prod_{j=1}^{n} \left(\frac{\rho Y_{r,i}}{M_i}\right)^{\eta_{r,j}}$$

The constants of homogeneous reactions are given in tab.1.

Table 1. The rate constants of homogeneous reactions

Reaction	A_i (variable dimension)	$E_{1,i}$ [J·kmole^{-1}]	η_1	η_2
$CH_4 + 1.5O_2 = CO + 2H_2O$	$1.6596 \cdot 10^{15}$	$1.72 \cdot 10^8$	1.46	0.5217
$CO + 0.5O_2 = CO_2$	$7.9799 \cdot 10^{14}$	$9.654 \cdot 10^7$	1	1
$CO_2 = CO + 0.5O_2$	$2.2336 \cdot 10^{14}$	$5.1774 \cdot 10^8$	1	–
$L\left[CH_{8.34}O_{0.212}\right] + 2.979O_2 = CO_2 + 4.17H_2O$	$2.119 \cdot 10^{11}$	$2.027 \cdot 10^8$	0.2	1.3
$H_2 + 0.5O_2 = H_2O$	$1 \cdot 10^{15}$	$1 \cdot 10^8$	1	1

The equations for the particle mass, the particle motion, the particle temperature and the radiative transport equation are used to describe a particle evolution and radiation process.

The model of coal particle combustion is assumed to be as follows. The particle does not change its mass if its temperature is less than the evaporation temperature of volatiles $T_p < T_{vap}$. After reaching the temperature, T_{vap}, the mass of the particle changes according to the law:

$$m_p > \left(1 - f_{v,0}\right)m_{p,0}$$

$$\frac{dm_{vol}}{dt} = -A_0 f_{v,0} m_{p,0}, \quad \frac{dm_{char}}{dt} = 0 \qquad (1)$$

During the entrainment of volatile substances, the particle size changes and is determined:

$$d_p = d_{p,0}\left[\frac{1+\left(C_{sw}-1\right)\left(m_{p,0}-m_p\right)}{f_{v,0}m_{p,0}}\right] \qquad (2)$$

After evaporation of the volatiles, a heterogeneous oxidation reaction takes place between the carbon of the particle and oxygen to form CO_2 and water vapor:

$$\left(1 - f_{v,0} - f_{comb}\right)m_{p,0} < m_p < \left(1 - f_{v,0}\right)m_{p,0}$$

$$\frac{dm_{char}}{dt} = \sum_{i=1}^{3} S_i, \quad \frac{dm_{vol}}{dt} = 0 \qquad (3)$$

The char particle burning rate is controlled by diffusion of the ith oxidizing species to the particle surface and followed by heterogeneous reaction:

$$S_i = A_p p_i \frac{R_{dif,i} R_{kin,i}}{R_{dif,i} + R_{kin,i}} \tag{4}$$

where the diffusion rate coefficient of the ith oxidizing species to the particle surface is:

$$R_{dif,i} = \frac{C_i}{d_p} \left[\frac{(T_p + T)}{2} \right]^{0.75} \tag{5}$$

the kinetic rate coefficient of the ith heterogeneous reaction is:

$$R_{kin,i} = B_i \exp\left(-\frac{E_{2,i}}{R_u T_p} \right) \tag{6}$$

Constants in the combustion model of a particle are given in tab. 2.

Table 2. Constants in the combustion model of a particle [14]

Reaction	B_i [kg·m^{-2}s^{-1}Pa^{-1}]	$E_{2,i}$ [J·kmole^{-1}]	C_i [s·K$^{-0.75}$]
$C_{<s>} + 0.5O_2 = CO$	$5.00 \cdot 10^{-3}$	$7.40 \cdot 10^{7}$	$4.13 \cdot 10^{-12}$
$C_{<s>} + CO_2 = 2CO$	$6.35 \cdot 10^{-3}$	$1.62 \cdot 10^{8}$	$1.69 \cdot 10^{-12}$
$C_{<s>} + H_2O = H_2 + CO$	$1.92 \cdot 10^{-3}$	$1.47 \cdot 10^{8}$	$4.12 \cdot 10^{-12}$

The system of equations for the gas phase is solved numerically by the Patankar method using an upwind scheme of second-order accuracy for the convective terms of the equations. The system of equations for particles was solved by an improved Euler method of second-order accuracy. To solve the radiative transport equation the discrete ordinate approach is used. The implementation of difference schemes is implemented using the ANSYS FLUENT package. The chemical rate constants are taken from [14, 15]. The algorithm for obtaining a numerical solution of the initial system of equations includes three stages: the solution of the system of equations for a gas phase not taking into account chemical reactions and particles, specifying the temperature of the inner walls of 1000 K and solving the system of equations for the gas, taking into account chemical reactions in a gas phase without particles, and joint solution of the system of equations for gas phase and particles, taking into account chemical reactions for gas and particles.

Results and discussion

Figure 2 shows dependencies of volume averaged temperature and maximum temperature on the mixture feed rate. Neglecting the radiation process overestimates the maximum temperature up to 2% and volume averaged one up to 10%. Concentration of coal dust affects the nature of temperature *vs*. the mixture feed rate, fig. 3. At a low content of coal particles, the maximum temperature decreases monotonically with increasing the mixture feed rate. The volume averaged temperature first increases and then falls, while at a high content of coal particles both the maximum temperature and the volume averaged temperature increase monotonically. An increase in the feed rate of the mixture leads to the fact that the reaction

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zone is elongated and shifted from the burner inlet to its center. The isolines of the mass fraction of CH_4 with step of 0.0012 are shown in fig. 4. Isoline number 1 corresponds to the value of 0.012, and isoline number 2 does to the value 0.0012. An increase in the concentration of coal dust in the mixture from 1.67 g/m^3 to 16.67 g/m^3 raises the temperature in the burner, since coal is an additional source of chemical energy, fig. 3, points 1 and 2. As a result, CH_4 reacts with oxygen faster, which occurs near the burner inlet, figs. 4(d), 4(e), and 4(f).
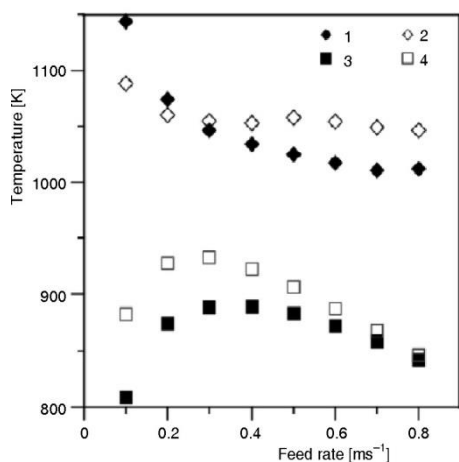

Figure 2. Temperature of mixture *vs*. feed rate,
ρ_s = **1.67 g/m^3;** *1, 2 – radiation,*
3, 4 – no radiation, 1, 3 – maximum temperature,
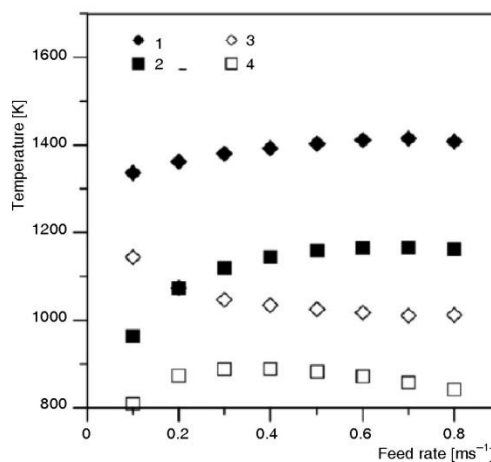*2, 4 – volume averaged temperature*

Figure 3. Effect of particle concentration on mixture temperature; *1, 3 – maximum temperature,*
2, 4 – volume averaged temperature,
1, 2 – ρ_s = 16.67 g/m^3, 3, 4 – ρ_s = 1.67 g/m^3

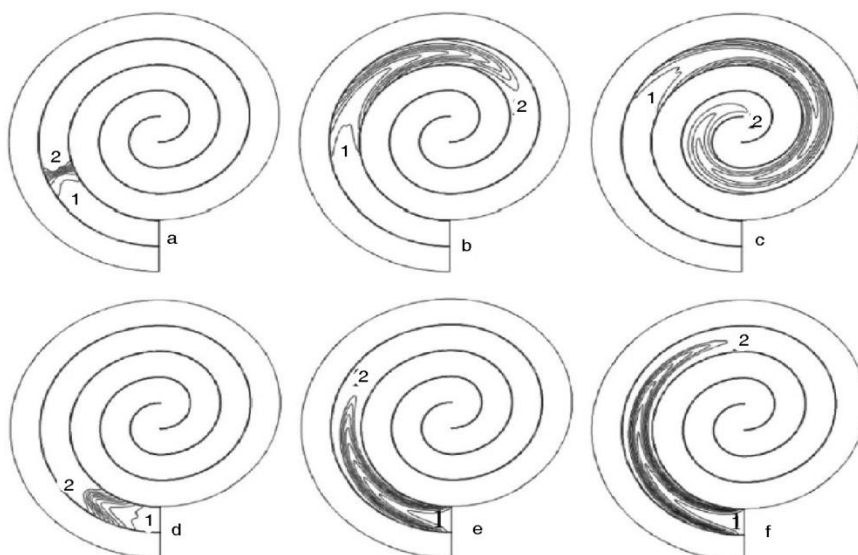**Figure 4. Isolines of CH_4 mass fraction; (a), (b), (c) – ρ_s = 1.67 g/m^3,**
(d), (e), (f) – ρ_s = 16.67 g/m^3, (a), (d) – U_{in} = 0.1 m/s, (b), (e) – 0.4 m/s,
(c), (f) – 0.7 m/s, 1 – Y_{CH_4} = 0.012, 2 – Y_{CH_4} = 0.0012

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The regions of maximum temperature are also elongated and shifted from the burner inlet to its center when the mixture feed rate increases, fig. 5. Wherein the increase in particle concentration makes the maximum temperature zone position less sensitive to the mixture feed rate, fig. 5(b). Calculations show that for a particle concentration of 1.67 g/m^3, the burner operates steadily up to a rate of 0.8 m/s, after which the conditions for heat recuperation are violated. For mixture feed rates above 0.7 m/s, the maximum temperature zones 7 and 8, fig. 5(a), extend beyond the center of the burner, which corresponds to the limit position at when heat recovery does not occur. For a particle concentration of 16.67 g/m^3, the limiting feed rate of the mixture was 1.8 m/s. It is interesting to note that the increase in the mixture feed rate by the same value of 0.1 m/s leads to a shift of the maximum temperature zone by approximately the same angle relative to the center of the burner.
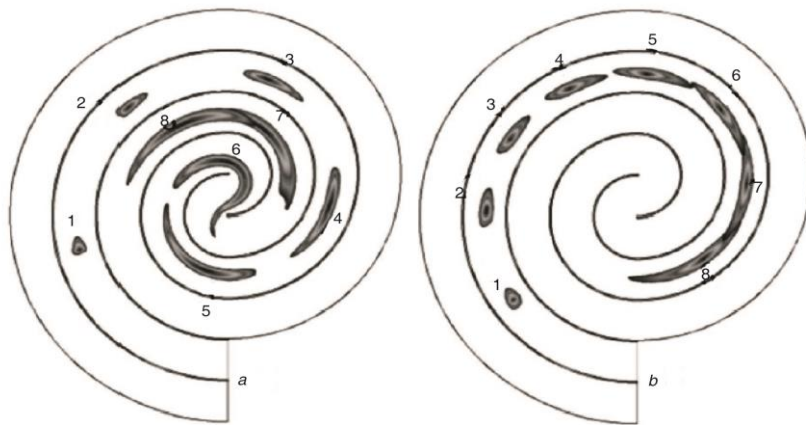

**Figure 5. Positions of maximum temperature zones; (a) – ρ_s =1.67 g/m^3,
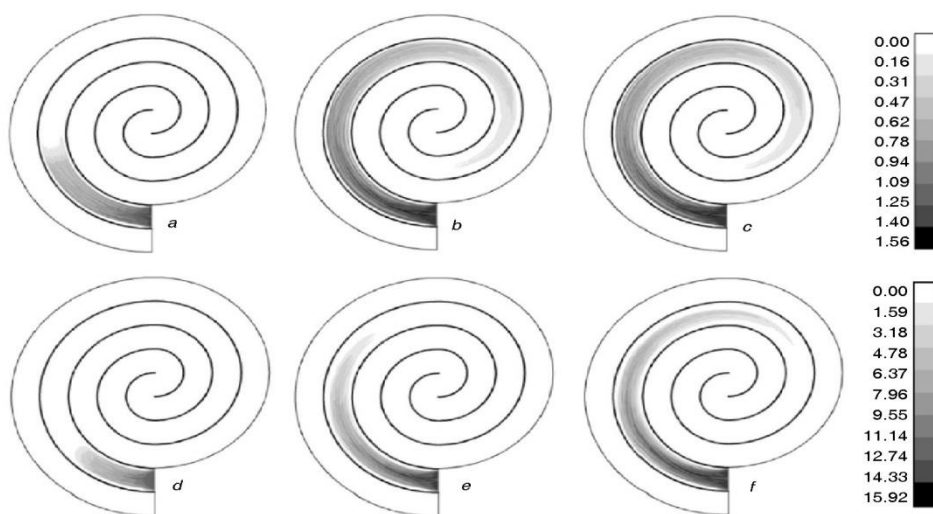(b) – ρ_s =16.67 g/m^3, U_{in} m/s; 1 – 0.1, 2 – 0.2, 3 – 0.3, 4 – 0.4, 5 – 0.5, 6 – 0.6, 7 – 0.7, 8 – 0.8**

**Figure 6. Concentration of coke residue, g/m^3; (a), (b), (c) – ρ_s =1.67 g/m^3,
(d), (e), (f) – ρ_s =16.67 g/m^3, (a), (d) – U_{in} = 0.1 m/s, (b), (e)– 0.4 m/s, (c), (f) – 0.7 m/s**

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Figure 6 shows the fields of coke residue concentrations. The increase in the mixture feed rate increases the area occupied by unburned coal particles. An increase in the concentration of coal dust in the initial mixture narrows the region occupied by the coke residue, figs. 6(d), 6(e), and 6(f). This is because the additional content of coal dust raises the temperature in the burner, thereby accelerating the combustion of particles.

Conclusion

In this paper, we numerically studied how the mixture feed rate and the coal particle concentration affect the reaction zone in the two turns *Swiss-roll* burner operating on lean coal-methane-air mixture. It was demonstrated that the presence of coal particles in a lean methane-air mixture expands the range of stable operation of the *Swiss-roll* burner. It was found that an increase in the content of coal particles reduces the combustion time of the particles by increasing the combustion temperature, changes the shape of the reaction zone and shifts it to the burner inlet, changes the character of the maximum temperature dependence on the mixture feed rate. It was shown that there is an optimum mixture feed rate, at which the volume averaged temperature of the burner has a maximum value.

Acknowledgment

Nomenclature

A_0 – rate constant (50), [s^{-1}]
A_p – particle surface area, [m^2]
$A_{r,i}$ – rate constant of ith species production by r^th homogeneous chemical reaction
C_sw – swelling coefficient, [–]
d_p – particle diameter, [m]
$E_{1,i}$ – activation energy of ith homogeneous reaction, [Jkmole^{-1}]
$E_{2,i}$ – activation energy of the ith heterogeneous reaction, [Jkmole^{-1}]
f_comb – combustible fraction (0.791), [–]
$f_{V,0}$ – fraction of volatiles initially present in the particle (0.129), [–]
m_p – particle mass, [kg]
M_i – molar mass of the ith species, [kg]

p_i – partial pressure of the ith oxidizing species, [Pa]
R_dif – diffusion rate coefficient, [m^{-1}s]
R_kin – kinetic rate coefficient, [m^{-1}s]
$R_{r,i}$ – mass rate of ith species production by r^th homogeneous chemical reaction, [kgs^{-1}]
R_u – universal gas constant, [$\text{Jmole}^{-1}\text{K}^{-1}$]
T – temperature, [K]
Y_i – mass fraction of ith species, [–]

Greek symbols

$v_{r,i}$ – stoichiometric coefficient, [–]
ρ_s – coal dust concentration, [gm^{-3}]
ρ – gas phase density, [kgm^{-3}]

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