Numerical simulation of combined combustion of coal-water and pulverized coal fuel

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Abstract. A numerical method for calculating the processes of co-combustion of coal-water and pulverized coal fuel has been developed. The effect of operating parameters on the processes occurring in the combustion chamber at co-combustion of coal-water and pulverized coal fuel has been studied. It is shown that redistribution of air between two stages of the burner affects significantly the temperature distribution in the volume of combustion chamber. Based on the study, it is shown that the addition of microground coal ensures stable combustion of coal-water fuel at combined burning of these two fuels in a flow reactor.

1. Introduction
Currently, due to the growth in the volume of carbon-containing waste, the problem of their disposal has become quite acute. Such wastes include high-ash and water-logged coal sludge, by-products of coal preparation plants, so-called cakes (flotation enrichment). Based on these waste, various coal-water (CWF) and organic coal-water fuels (OCWF) can be prepared. The most common way to process such waste is incineration. However, the calorific value of such suspensions is usually low. As experience shows, the most efficient and stable combustion of CWF is achieved only when burning in muffle furnace chambers at sufficiently high temperatures [1]. There is an urgent task of developing an effective technology for processing these types of fuels. One of the solutions to this problem can be co-combustion of coal-water fuel with pulverized coal fuel. Finely dispersed pulverized coal (microground coal) has high reactivity, which will ensure stable burning at combined combustion of these two fuels.

This work is aimed at the development and testing of a numerical methodology for modeling the processes of co-combustion of coal-water and pulverized coal fuel.

2. Problem statement and research methods
To study numerically the processes of co-combustion of coal-water and pulverized coal fuel, a setup with a thermal capacity of 5 MW was chosen in [2]. The geometry of the computational region is shown in Figure 1. Microground coal was supplied to the first scroll device together with air. Air for afterburning was fed to the second scroll. The coal-water fuel is supplied by a pneumatic nozzle [3] located at the end of the fire setup in a pipe with a diameter of 80 mm at a distance of 100 mm from the scroll device. The temperature of air and fuels at the inlet is 25°C. The total amount of air is calculated based on $\alpha = 1.2$ for the total flow rate of coal. There are adiabatic conditions on all walls of the reaction chamber.
The operating parameters and flow characteristics chosen for calculations are presented in Table 1. In the first operating regime, only microground coal (without CWF) is supplied; air flow rate on the first scroll is half of the total; and the remaining half of air is supplied to the second scroll. In the second regime, only the fuel supply changes: we add 25% (mass.) of CWF (coal) per nozzle and keep 75% of microground coal in the scroll device. In the third regime, the CWF/microground coal ratio is 50/50% (mass.) by coal. In the fourth regime, the CWF/microground coal ratio is the same as in the second regime, but almost all air is supplied to the first scroll device.

![Geometry of computation region](image)

**Figure 1. Geometry of computation region.**

**Table 1.** Operating parameters and flow characteristics.

| REGIME                      | No. 1 | No. 2 | No. 3 | No. 4 |
|-----------------------------|-------|-------|-------|-------|
| Air flow rate on the first scroll, kg/s | 0.0859 | 0.0859 | 0.0859 | 0.1917 |
| Air flow rate on the second scroll, kg/s | 0.1159 | 0.1159 | 0.1159 | 0.01  |
| Air flow rate on the nozzle, kg/s     | 0.03  | 0.03  | 0.03  | 0.03  |
| Microground coal flow rate, kg/s      | 0.025 | 0.0188| 0.0125| 0.0188|
| CWF flow rate, kg/s                 | 0.0   | 0.0125| 0.025 | 0.0125|

Coal of Kuznetsk deposit was chosen as the microground coal in calculations: the lowest calorific value $Q_r = 24.03$ MJ/kg; humidity $W_r = 5.5\%$; ash content $A_r = 12.47\%$; carbon content $C_r = 60.5\%$; hydrogen content $H_r = 4.1\%$; nitrogen content $N = 1.52\%$; sulfur content $S_r = 0.39\%$; and yield of volatiles per combustible mass $V_{daf} = 41.2\%$. Coal-water fuel is a mixture of coal of grade K and water with a mass ratio of 50/50. Characteristics of K grade coal: lower heat value $Q_r = 25.13$ MJ/kg; humidity $W_r = 0.86\%$; ash content $A_r = 22.22\%$; carbon content $C_r = 64.32\%$; hydrogen content $H_r = 3.38\%$; nitrogen content $N = 0.01\%$; sulfur content $S_r = 0.4\%$; and yield of volatiles per combustible mass $V_{daf} = 28.86\%$.

The proposed complex mathematical model for describing the processes of co-combustion of CWF and microground coal includes: model of motion of a multicomponent non-isothermal gas medium (carrier phase) based on the RANS approach; radiation transfer model based on the discrete ordinate method; model of droplet/particle motion based on the Lagrange approach; model of combustion in the gas phase based on a hybrid model combining chemical reaction mechanisms and turbulent exchange; and model of coke residue burnout. The coal-water fuel sprayed by the nozzle is represented by a discrete set of droplets/particles, which consist of a water complex and coal particles. External moisture, added when preparing CWF, is considered as water. Internal moisture, determined by the technical analysis of fuel, is part of the fuel. In the model, the process of ignition and combustion of a particle occurs in stages. First, external moisture evaporates, and a model of droplet evaporation is used to describe this process. To describe coal burning, a model of ignition and combustion of coal particles is used. According to this model, the particles are heated, the internal
moisture and volatile components of fuel are released, and the coke residue is burnt. Volatile components burn out in the gas phase. The studies were carried out using the universal Ansys Fluent CFD package. The calculation was carried out in a stationary three-dimensional formulation. An unstructured computational grid (765469 cells) was used with local condensation near the nozzle and scroll device.

A numerical method for modeling the combustion processes of microground coal was developed and tested by the team of authors [4]. We also simulated the cold task of CWF spraying by a pneumatic nozzle; the results were qualitatively compared with the data of a full-scale experiment. To simulate the flow of droplets of coal-water fuel, the Lagrange method added with a secondary droplet decay model was used. This allowed determining the characteristic angle of flame opening of 20°, velocity of 90–120 m/s and droplet size of 50–300 μm. Further, these data were used in test calculations of CWF combustion and in these calculations. The results of test calculations of CWF combustion were compared with the experimental data of [5]. Good quantitative agreement with the experiment data on temperature and oxygen concentration on the axis of the combustion chamber was obtained.

3. Results and discussion

The results of calculation in the form of a temperature field and oxygen concentration for the first regime of burner operation are shown in Figures 2 and 3. It can be seen that a relatively rapid increase in temperature up to 1800°C is observed in the area of the first scroll device, which is caused by high reactivity of microground coal. Further, the maximum temperatures are localized near the walls of the first stage of the combustion chamber (in the form of a ring) due to flow swirl; coal is concentrated on the wall. The scroll inlet leads to the movement of the pulverized coal bulk in a spiral along the chamber wall. In the second stage, unburned solid carbon is mixed with secondary air and burns out.

![Figure 2](image1.jpg)  
**Figure 2.** The temperature field in the central cross-section of the combustion chamber (1 regime), °C.

![Figure 3](image2.jpg)  
**Figure 3.** The field of oxygen concentration (1 regime), kg/kg.
When CWF is added (Fig. 4 a, b), the temperature in the first stage of the combustion chamber decreases, but at the same time, high temperatures (1500-1800°C) in the form of a ring are kept locally in the region of the first scroll (due to microground coal). The cloud of CWF droplets is located inside the hot gas ring (Fig. 5). This ensures intensive evaporation of water and stable ignition of CWF. It is worth noting that this process without adding microground coal under the same conditions was also calculated. In this case, the active combustion zone is displaced to the second stage, and the first stage cools down completely.

![Figure 4. The temperature field in the central cross-section of the combustion chamber, °C: a) 2 regime, b) 3 regime.](image)

In the fourth regime (Figs. 6 and 7), redistribution of air supply is studied; almost all the air is fed to the first scroll. This leads to a decrease in temperature in the first stage due to the greater amount of cold air supplied. But ignition and combustion of fuel in the first stage is still preserved. In practice, this regime can lead to displacement of the ignition zone.

![Figure 5. The temperature field and motion trajectories of CWF droplets/particles (trackers are colored according to particle velocity), 2 regime.](image)
Figure 6. The temperature field in the central cross-section of the combustion chamber (4 regime), °C.

Figure 7. The field of oxygen concentration (4 regime), kg/kg.

Steam concentration in the central cross-section of the combustion chamber is shown in Figure 8 for the first three regimes. It can be seen that with an increase in the amount of CWF supplied, the amount of steam increases.

Figure 8. The field of steam concentration, kg/kg: a) 1 regime, b) 2 regime, and c) 3 regime.
The results of calculations in the form of gas parameters at combustion chamber outlet are presented in Table 2. In the first regime, due to high reactivity of microground coal, complete combustion of fuel occurs. In the second regime, despite having added more moisture with fuel, the outlet gas temperature is slightly higher than in the first regime. Most likely this is due to the higher calorific value of coal in the CWF composition. This point is confirmed by oxygen concentration, which decreased from 7.7 to 3.6%, since more oxygen was required for combustion. With an increase in the CWF supply to 0.025 kg/s (regime 3), the temperature of outlet gases decreases to 1527°C, which is due to evaporation of more moisture. Despite the fact that in the fourth regime, the combustion intensity in the first stage is low in comparison with the second regime; the parameters of gases at the outlet are approximately the same because of the absence of burnout in the second stage. This is due to the spiral trajectory of coal particle movement in the chamber.

Table 2. Parameters at combustion chamber outlet.

| Regime           | No. 1 | No. 2 | No. 3 | No. 4 |
|------------------|-------|-------|-------|-------|
| Gas temperature at the outlet, °C | 1592  | 1607  | 1527  | 1596  |
| Mechanical underburning, %      | 0.0   | 1.6   | 2.7   | 1.7   |
| O₂, % (mass)     | 7.7   | 3.6   | 3.8   | 3.8   |
| CO₂, % (mass)    | 17.3  | 21.6  | 21.0  | 21.1  |
| H₂O, % (mass)    | 3.2   | 6.0   | 7.8   | 5.9   |

Conclusion

A numerical method for calculating the processes of combined combustion of coal-water and pulverized coal fuel has been developed. The effect of operating parameters on the processes occurring in the combustion chamber at joint combustion of coal-water fuel and microground coal has been studied numerically. It is shown that redistribution of the amount of air between the two stages of the burner affects significantly the temperature distribution in the volume of combustion chamber. Based on the study, it is shown that the addition of microground coal allows stable combustion of coal-water fuel when burning these two fuels together in a flow reactor.

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