Experimental and Numerical Study of Co-firing Peat with Syngas in a Vortex Burner

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Abstract. Experimental and numerical study of co-firing peat with different gaseous fuels in the vortex burner are carried out. At the "lean" operational regimes co-firing peat with syngas is more effective and allows to organize reliable ignition and stable combustion at the values of excess air coefficient up to \(\alpha_\Sigma = 2.7\). In addition, co-firing with syngas requires less initial methane to produce it applying catalytic reforming than direct co-firing with methane. Also, syngas supply into vortex burner allows to reduce combustion temperature and emission of NOx.

1. Introduction
Solid fuel is the largest source of energy for the generation of electricity and heat worldwide. More than half worldwide electricity is produced from solid fuel. Among all solid fuels, coal, oil shale, wood and peat are the most common [1].

In Russia, the main area of application of solid fuel is stand-alone power generation for individual housing constructions, enterprises, small settlements and urban areas. Generation of capacities up to 10 MW, as a rule, is carried out by grate firing in specialized boilers. At higher capacities, this method of combustion is characterized by a large unburned carbon and significant losses of thermal energy through the walls of the boiler. In these cases, pulverized combustion technology is used for energy production [2]. Solid fuel is crushed to a fine state with particle sizes less than 1 mm and fed into the combustion chamber together with the primary air flow. Pulverized technology increases rate and efficiency of combustion, specific heat flux density and uniformity of the temperature distribution in the combustion chamber, reduces emissions of nitrogen oxides.

The main disadvantages of pulverized combustion of solid fuel are associated with the complexity of ignition of air-fuel mixture and flame stabilization. This determines the need to find reliable and effective ways of ignition and flame stabilization, providing reduction of pollutants and high combustion efficiency. The best known and most promising way at the moment is sold fuel co-firing with other different fuels [1, 3-10]. In the literature there are publications on co-firing coal and peat with biomass [1], lignite [3], natural gas [4], oil shale [5], waste fuels [6], syngas [7, 8]. Among other promising ways it is necessary to note coal gasification [9], electrochemical ignition [10] and mechanical activation of fuel (coal) [11].

Using syngas as an additional fuel for ignition and flame stabilization of solid combustion made possible to reduce NOx, CO and CO₂ emissions [7, 8], increase solid particles residence time in the
combustion chamber [8]. Nevertheless, despite all the results obtained regimes and parameters of co-firing solid fuel and syngas are not fully studied. The main questions and problems are connected with co-firing percentage by heat, possible limits of flame blowout, economical and energy efficiency of combustion process. In this paper there are shown experimental and numerical results of co-firing pulverized peat with syngas in a vortex burner.

2. Formulation of CFD Simulation

CFD simulation was carried out for vortex burner scheme of which is shown in Fig. 1 [12]. This vortex burner has three main regions: mixing chamber, where pulverized peat and primary air are mixing into each other; combustion chamber, where ignition and flame stabilization occur; and afterburning chamber, where exhaust gases and unburnt solids leave the burner.

The calculation grid (Fig. 2) of the flow region was multiblock structured; the total number of elements was about 4 million. To calculate the gas flow, Reynolds-averaged Navier-Stokes equations were used, the turbulence was described by $k-\varepsilon$-model. Modeling of peat and gaseous fuel combustion processes was carried out using Eddy Dissipation Model. Radiative heat transfer was not taken into account.

![Figure 1. Scheme of the vortex burner](image1)

![Figure 2. Calculation grid](image2)

To simulate the behavior of particles, the Lagrange approach was used, in which the parameters of each particle or package of particles are calculated. Each individual particle was conventionally represented as a sphere of a certain diameter. The dispersed fraction of hydrocarbon fuel was determined by a set of discrete particle diameters and corresponding mass fractions (Table 1):

| Particle diameter, mkm | 12 | 38 | 62 | 88 |
|------------------------|----|----|----|----|
| Mass fraction          | 0.18 | 0.25 | 0.21 | 0.36 |

Temperature and mass flow rate of pulverized peat were constant for all the calculations and equal to $T_{\text{peat}} = 300$ K and $m_{\text{peat}} = 0.21$ g/s. Total temperature of primary and secondary air were also constant and equal $T_{\text{air}} = 300$ K. Mass flow rate of the primary air $m_{\text{air1}}$ was varied from 0 to 2.5 g/s. Mass flow rate of the secondary air $m_{\text{air2}}$ was varied from 0 to 1.0 g/s. The walls of the computational domain were considered to be adiabatic. Mass flow rate of the gaseous fuel (methane and syngas) was varied from 0 to 0.25 g/s, its total temperature at the inlet boundary condition was equal to $T_{\text{gas}} = 300$ K.
3. Formulation of the Experimental Problem

Experimental stand functional diagram is shown in Fig. 3 [12]. This stand provides organization of co-firing pulverized peat with syngas and other gaseous fuels such as natural gas, methane and propane. All the experiments were carried out for vortex burner described in details in paper [12]. As a solid fuel there was used pulverized peat with a particle size $R_{90} = 56\%$ and $R_{200} = 20\%$, a lower heat value of $LHV = 17.9$ MJ/kg, volatile content $V_d = 64.8\%$ and ash content $A_d = 6.4\%$. During the experiments, peat mass flow rate remained at a constant level of $m_{\text{peat}} = 0.21$ g/s. Methane and propane for co-firing with peat were supplied using gas cylinders; a special catalytic reforming unit was used for the production of syngas [13]. Average composition (by volume) of syngas generated was: $H_2 - 29.42\%$; $CO - 14.32\%$; $CH_4 - 3.8\%$; $N_2 - 49.11\%$; $H_2O - 3.35\%$. The choice of this type of syngas was due to the fact that it allows us to organize a stable combustion in a wide range of operational regimes, including ultra "lean" combustion [14].

![Experimental stand functional diagram](image)

The results of experiments and calculations were summarized using the following dimensionless parameters:

- $\alpha_\Sigma = \frac{m_{\text{air}}}{(m_{\text{peat}} + m_{\text{gas}})} - \text{total excess air coefficient, where } m_{\text{air}} - \text{total air mass flow rate, } m_{\text{gas}} - \text{gaseous fuel mass flow rate, } L_{\text{peat}}$ and $L_{\text{gas}} - \text{stoichiometric coefficients of peat and gaseous fuel respectively; }$
- $\mu = \frac{m_{\text{air cond}}}{m_{\text{air}} - \text{the ratio of the air mass flow rate supplied into combustion chamber of the vortex burner (see details in paper [12]) and the total air mass flow rate } m_{\text{air}};}$
- $\eta = \frac{N_{\text{peat}}}{(N_{\text{peat}} + N_{\text{gas}})} - \frac{\text{fraction of peat in burning mixture by heat, where } N_{\text{peat}} - \text{heat power of peat, } N_{\text{gas}} - \text{heat power of co-firing gas.}}$

For example, operational regime characterized by $\alpha_\Sigma = 1$ and $\eta = 1$ means stoichiometric burning of peat without co-firing. Value $\mu = 1$ means that all the air was supplied as primary air.

4. Results and Discussion

Simulations and experiments were carried out for different values of $\alpha_\Sigma$, $\mu$ and $\eta$. Studies were conducted before the onset of "lean" flame blowout, and the values of $\alpha_\Sigma$, $\mu$ and $\eta$ were measured (or calculated in CFD). Figures 4–9 show the results of numerical simulation of co-firing peat with
methane and syngas just under flame blowout. Volume fractions of unburnt solid particles for calculations with methane are shown in Figures 4 and 6, for calculations with syngas – in Figures 5 and 7. Figures 8 and 9 show contours of total temperature for calculations with methane and syngas respectively.

The numerical results obtained show that co-firing peat with syngas allows to provide stable combustion in conditions of very "lean" air-fuel mixtures (up to $\alpha_\Sigma = 2.71$). In addition, burning syngas instead methane leads to increasing value of $\eta$ to 0.9 and more. Probably, it is caused by presence of hydrogen $H_2$ in syngas composition which is high-reactive gas with high combustion temperature and heat value. At the same time, comparison contours in the Figures 6 and 7 shows more volume fraction of unburnt peat when it is co-firing with syngas. Obviously, it is defined by more total excess air coefficient that leads to decreasing combustion efficiency [15].

The Figures 10 and 11 show a comparison of numerical and experimental results. Analyzing the dependences in Figure 11, we can say that the combustion of peat dust in the operational regime $\mu = 0.53$ to ensure stable combustion there requires energy supply of methane of not less than 56% by
heat. The organization of energy supply of syngas at the same operational regime requires its supply corresponding to only 31% by heat.

Similar values of the required gas supply for the operational regime $\mu = 0.31$ determine the amount of the required methane supply not less than 34%, for syngas – not less than 5%.

In addition, the supply of syngas to the vortex burner made it possible to expand the concentration range of its stable operation to the values of the excess air coefficients $\alpha_\Sigma \approx 2.5..2.7$ (Fig. 10). By comparison, values obtained by co-firing peat with methane or propane are of $\alpha_\Sigma \approx 1.7..1.9$.

![Figure 10](image.png)  
**Figure 10.** Dependence of total excess air coefficient corresponding "lean" flame blowout on ratio of the air mass flow rates: dotted lines - experiments; dash lines - calculations

![Figure 11](image.png)  
**Figure 11.** Dependence of fraction of peat in burning mixture by heat corresponding "lean" flame blowout on ratio of the air mass flow rates: dotted lines - experiments; dash lines - calculations

5. Conclusion

The combustion of peat dust is observed as a multiphase combustion. One of its stages is the combustion of the volatile fraction (about 65% by weight of the initial peat dust), in which co-firing with syngas is much more effective than co-firing with methane and propane. Thus, for the combustion of 1 kg/s of peat dust at the operational regime of $\mu = 0.53$ just under "lean" flame blowout, it is necessary to supply methane not less than 0.1-0.13 kg/s. At the same time, this operation regime requires syngas supply of about 0.23 kg/s. Taking into account that the mass fraction of the initial methane for syngas production applying catalytic reforming is only 0.236, initial methane supply for the combustion of 1 kg/s of peat dust is only 0.054 kg/s. Thus, for co-firing of peat dust with syngas, it requires the initial methane on average 2-2.5 times less than in case of co-firing with pure methane.

Stable combustion of the mixture of peat dust and syngas is possible at the values of excess air coefficient up to $\alpha_\Sigma \approx 2.7$. It provides a significant reduction of the combustion temperature. So co-firing peat dust with methane or propane defines combustion temperature of 1700-1800°C, while co-firing with syngas allows to decrease this temperature to 1100°C. It defines reducing the emission of nitrogen oxides in the exhaust gases of the burner.

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7. References

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