COMBINED COMBUSTION OF PULVERIZED COAL AND LIQUID FUEL IN A LOW POWER VORTEX BURNER

by

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In this work we study the process of co-combustion of pulverized coal fuel (coal grinded up to 100 microns) and liquid (diesel) fuel in a new low power burner, where coal-air mixture is fed tangentially together with secondary air, and liquid fuel is atomized by a high velocity steam jet. Temperature profiles and composition of intermediate combustion products along the vertical axis of the burner have been studied. The heat release (power) and the gas composition of final combustion products have been measured. This allowed us to demonstrate the principal possibility of combined combustion of coal dust and diesel fuel in a compact laboratory burner.

Key words: *pulverized coal, diesel fuel, co-burning, superheated steam, vortex combustion*

Introduction

The demand for coal as an energy source currently persists due to its prevalence and cheapness. About 40% of the electricity consumed in the current world balance is obtained by coal combustion, thus its annual consumption exceeds 3.7 billionns of oil equivalent [1]. Unfortunately, coal is also one of the most *dirty* types of fuel, whose combustion of which is accompanied by high emissions of harmful substances, the formation of a large amount of slag and ash with a high content of heavy metals, and toxic contamination of water with radionuclides [2-5]. Nevertheless, according to the forecasts of the World Energy Agency (IEA) [1] and other sources [6-8], even taking into account the tightening of climate and environmental policies, the demand for coal in the future until 2040 will remain stable. Thus, the harmful impact of coal energy on the environment can only be reduced by improving the technologies for its use. Against this background, *clean* coal technologies [9-12] designed to minimize the harmful effects of its use received an impetus for development.

To date, almost all mined coal is subjected to sorting and enrichment. At the stage of coal mining and its sorting, huge reserves of low grade coal and sludge are formed. Coal is enriched mainly with *wet* technologies, and after enrichment there are also large volumes of waste that cannot be used through the traditional methods of coal combustion, but they sometimes contain more than 50% of carbon. At present, more than 25 millionns of coal enrichment wastes have accumulated in dumps in Kuzbass alone. Involvement of such fuel in the fuel and energy balance will allow solving two problems at once: increasing economic efficiency due to the low cost of fuel and reducing the environmental impact on the environment through the disposal of accumulated waste.

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Oil remains the second largest source of energy by 2040. At the same time, the annual accumulation of oil sludge worldwide is 160 millionns, and the annual global accumulation of used lubricating oil along exceeds 20 millionns, highlighting the scale of the environmental threat. If used properly, these energy sources can also be an alternative to high grade fuels, while solving an environmental problem.

One of the most common uses of coal fuel is flaring [13]. Despite the advantages of this approach (smaller dimensions, high combustion efficiency, low emissions*, etc.*), it has a number of drawbacks, such as difficulties in igniting the fuel, which requires additional devices (plasma torches, electroionization burners*, etc.*) and lighting fuels (fuel oil, gas). In addition, power boilers operating on pulverized coal fuel have significant limitations on the possibility of reducing power (*unloading*), determined by the properties of coal (reactivity, volatile yield, ash melting point), since complete particle burnout requires certain temperature conditions and time of staying in the fire zone. In addition, the requirements for operating parameters necessary for ash removal introduce additional restrictions on temperature conditions inside the furnace. Also, during the operation of pulverized coal boilers, their regular shutdown is required to clean the heating surfaces, remove slagging and coking products, and replace heat exchange elements due to abrasive wear. A separate task is the organization of the combustion process itself, including the staged combustion, as well as the use of appropriate environmental systems (ash collectors, desulfurization, denetrification devices*, etc.*) to ensure an acceptable level of emissions of harmful substances, in particular, NO_x. Thus, due to the need to carry out operating procedures and connect a large number of auxiliary equipment, existing approaches and technologies cannot sufficiently ensure the efficient use of pulverized coal in small-capacity plants due to an inappropriate increase in specific capital investments to support operation of such a device.

The need to find optimal ways to control waste requires the development of new technologies and equipment based on scientific understanding of the processes that determine combustion characteristics depending on the dynamic and thermal conditions implemented in specific burners. The use of vortex technologies in the combustion of low reactive fuel allows process intensification by optimizing aerodynamics of the device: creating complex trajectories to increase the burning time of fuel particles, intensifying mixture formation*, etc.* Thus, the study of transport processes in vortex reacting flows during the combustion of fossil fuels is an urgent scientific problem.

In this paper, we study the combined combustion of liquid and pulverized coal fuel in an original low power (15 kWt) steam-oil burner that implements the principle of burning liquid fuel in a jet of superheated steam with additional tangential supply of pulverized coal. This work is aimed at the development of scientific and technical foundations for creating the low emission methods for co-combustion of low grade liquid and solid hydrocarbon fuels in low power burners to produce cheap energy.

Experimental set-up

In this work, we used an original burner developed at the IT SB RAS, which was made to study the process of combined combustion of coal and liquid hydrocarbon fuels being sprayed with a high velocity jet of superheated steam. The burner scheme is shown in fig. 1. Its feature is the tangential supply of pulverized coal (and secondary air) to the zone of liquid fuel combustion. Due to this, a swirling flow is organized inside the burner; it increases the residence time of coal particles in the combustion area, which ensures more complete and efficient combustion of pulverized coal in the studied device. Liquid fuel is fed to the base of the steam jet, which entrains and atomizes fuel forming a tiny gas-droplet flow, which facilitates

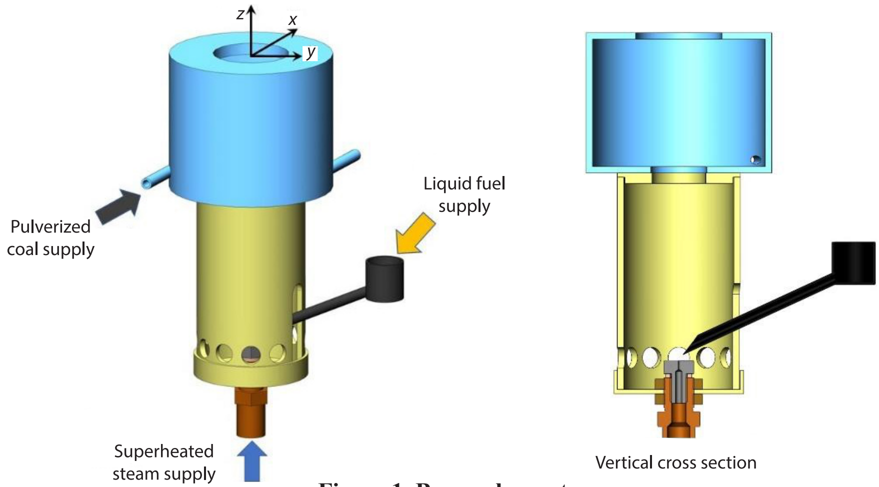

Figure 1. Burner lay-out

liquid fuel ignition and reduces emissions due to the physicochemical effects of steam presence. In this case, the primary air for burning liquid fuel enters the burner from the surrounding atmosphere due to spontaneous inflow through the holes in the burner housing. This method of supplying and burning liquid fuel was previously developed by the authors and showed high efficiency (it provides a high degree of fuel burnout and low emissions) [14, 15].

In the case of the burner under study, liquid fuel serves to provide temperature conditions required for ignition and burnout of solid fuel.

Experimental studies were carried out on a firing test bench, fig. 2. The main elements are steam supply system, fuel supply system, burner, thermocouple (mounted on a co-ordinate moving device), calorimeter, gas analyzer, and control unit. A stable mass-flow rate of liquid fuel is set by a fuel injector and a pump.

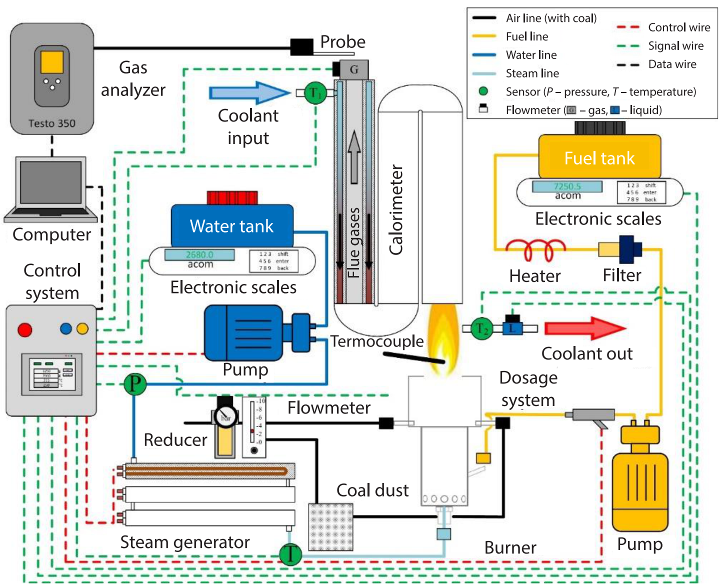

Figure 2. Scheme of experimental set-up

Ground (95% <100 μm) long-flame hard coal was used as a pulverized coal fuel and it was supplied together with secondary air in the form of an air mixture. The same coal was used as in [16]. The characteristics of coal are presented in tab. 1. To supply coal fuel, a device operating on the Laskin nozzle principle was used: a compressed air-flow passed through a container with coal dust, creating an air suspension, which was captured by this flow and fed into the burner along with the air necessary for combustion. The flow was adjusted by changing the parameters of compressed air supply: primary pressure adjustment in the tract with the help of a reducer and secondary air-flow adjustment by a Bronkhorst MASS-VIEW mass-flow meter with a needle valve. To estimate coal consumption, the fuel tank was installed on an Acom PC-100W-10H electronic scale (error limit of 1 g). A standard diesel fuel was used as a liquid fuel.

Table 1. Characteristics of coal dust

W [%]	A^d [%]	V^{daf} [%]	C [%]	H [%]	O [%]	N [%]	S [%]	Calorific value, [kJkg^{-1}]	R90 [μm]
2	21	41	74.5	4.9	17.7	2.2	0.6	20934	100

To study the flame characteristics, the average flame temperature was measured by a thermocouple placed at various points, and this allowed us to obtain the distribution of the time-averaged temperature in the flow. In the studied regimes, the temperature profiles in the external flame along the vertical axis of the burner were measured using a platinum-rhodium-platinum-rhodium thermocouple (0.5 mm in diameter). The working junction of thermocouple was moved using an automated co-ordinate-moving device (spatial step of 10 mm, measurement time at a point of no less than 10 seconds, delay time before measurements at a point of 7 seconds). To study intermediate combustion products, a TEST-1 gas analyzer was used, CO (0-10 vol.%), H_2 (0-40 vol.%), CH (0-20 vol.%), CO_2 (0-20 vol.%), O_2 (0-21 vol.%). A water-cooled probe was used to take a sample from the flame. The released energy was determined with the help of a flow calorimeter. The measurement technique for this device is described in detail in [13]. For the gas analysis of final combustion products, a Testo-350 gas analyzer was applied. Its probe was installed at the calorimeter outlet. The following sensors were installed in the gas analyzer: CO (0-500 ppm), NO (0-300 ppm), NO_2 (0-500 ppm), CO_2 (0-50 vol.%), and O_2 (0-25 vol.%). The following characteristics of operating parameters have been chosen for experimental studies: steam flow rate F_v = 0.6 kg per hour, liquid fuel flow rate F_f = 0.7 kg per hour and coal flow rate F_c = 0.1 kg per hour. The set temperature of superheated steam was T = 250 °C. The flow rates of steam and liquid fuel were chosen on the basis of previous studies by the authors, since the burner is based on the already proven scheme and shape of the ignition chamber [13]. In this regime, a high completeness of fuel combustion with a low content of harmful substances in the combustion products is shown. The coal flow rate was selected empirically to achieve complete fuel burnout in the created design of the burner. The error of gas analyzers measurements was no more than 5%, the thermocouple error was no more than 5%.

According to state standards [17] for boiler plants, NO_x emissions for light liquid fuel are allowed no more than 230 mg/m^3, the allowed CO emissions are not higher than 115 mg/m^3. For coal with a volatile yield of more than 17%, NO_x emissions are not regulated, CO emissions are up to 46000 mg/m^3.

Results

A complex of calorimetric, gas-analytical and temperature measurements of characteristics of coal and liquid fuel combustion in the studied regimes of the created burner operation was carried out.

Three options of combustion were selected for the pilot study:

– Combustion of only diesel fuel without secondary air. Since combustion of diesel fuel is the basis for the functioning of the burner under study, it is necessary to investigate the process of its combustion in a new device.
– Combustion of diesel fuel with secondary air without coal fuel. It is necessary to assess the effect of tangential (vortex) secondary air supply on the process of fuel combustion in the burner under study.
– Combined combustion of liquid and pulverized coal supplied as an air mixture together with secondary air. Basic research regime.

Figure 3 shows typical flame photographs for a new design of a low power swirl burner for co-combustion of coal and liquid hydrocarbon fuels when sprayed with a high velocity jet of superheated steam for three combustion regimes.

It can be seen that when air is supplied, fig. 3(b) due to the flow swirl, the flame decreases. The main combustion takes place inside the burner. The flame becomes less bright. When coal dust is added, fig. 3(c), the flame, on the contrary, becomes brighter, as evidenced by the glow of carbon in the flame. At the same time, there is mechanical underburning of fuel in the form of unburned coal particles deposited around the burner, which emphasizes the need for numerical simulation optimize the regime relations and geometric parameters of the burner.

According to digital visualization, when the flame is swirled with secondary air, the flame becomes narrower, but the form of a divergent cone, typical of other swirling flames, for example [18], is not observed. Therefore, the temperature and products of incomplete combustion were measured on the central axis of the flame. The time-averaged flame temperature profiles obtained by a thermocouple along the central axis of the burner are shown in fig. 4.

Figure 3. Typical photos of the flame in various combustion regimes; (a) combustion of diesel fuel without secondary air and coal: F_v = 0.58 kg per hour, F_f = 0.7 kg per hour, (b) combustion of diesel fuel with secondary air without coal: F_v = 0.57 kg per hour, F_f = 0.7 kg per hour, F_{a2} = 4 kg per hour, and (c) co-combustion of diesel fuel and pulverized coal: F_v = 0.59 kg per hour, F_f = 0.7 kg per hour, F_c = 0.1 kg per hour, F_{a2} = 4 kg per hour

When diesel burns with steam, the maximum temperature reaches 1700 °C at the burner outlet, then it gradually decreases to 900-1000 °C as it is diluted with an influx of atmospheric air. When air is added to swirl the flow (without coal), the zone with the highest flame temperature shifts down (inside the burner), and this is accompanied by a decrease in the size of the external flame. The temperature at the burner outlet rises to ~1750 °C, and then it decreases at a higher rate as compared to the steam-diesel regime, which is associated with faster fuel burnout when the process is intensified due to the air supply. At the same time, when coal is added, the reverse trend is observed: the flame size increases, and the temperature maximum drops to 1600 °C, after which the temperature decreases gradually as the coal particles burn out.

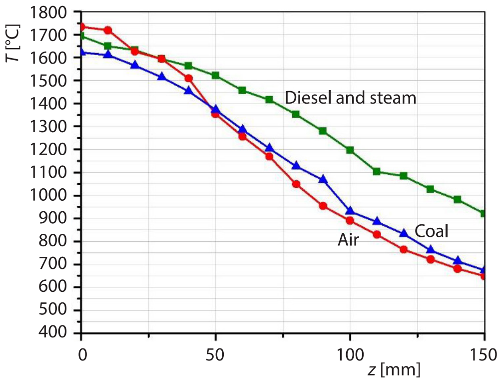

Figure 4. Profiles of the flame temperature along the vertical axis of the burner for three typical regimesm, see fig. 3

The general view of the flame temperature profiles during diesel fuel combustion without secondary air and with it (but without coal) indicates that the flow swirl *locks* the flame inside the burner.

Figure 5 shows the results of studying the composition of intermediate combustion products in the flame in the form of profiles along the central axis: O_2, CO_2, H_2, CO, NO, and SO_2. The obtained profiles indicate that when secondary air is supplied, combustion reactions occur mainly inside the burner. Thus, without flow swirl, the maximum concentration of O_2 and the minimum of CO_2 are observed at the outlet at a distance of ~40 mm, while with the flow swirl, the extrema are located inside the burner, and more intense dilution of the external flame with atmospheric air occurs. In the regimes with secondary air supply, the addition of coal affects the course of gasification reaction with the formation of synthesis gas. When coal is introduced, the concentrations of H_2 and CO in the flame increase. For all regimes, NO concentration maxima are located in the zone where the temperatures within the measured area are maximal and NO_x are predominantly formed by the thermal mechanism.

Table 2 shows the measurement results on heat release and composition of cooled products at the calorimeter outlet for the studied regimes. The measurement results were used to verify the mathematical model.

Table 2. Results of the gas analysis of final combustion products and determination of burner power

		S6D7	S6D7Air	S6D7Air + Coal
Steam flow rate, [kg per hour]		0.58	0.57	0.59
Steam temperature, [°C]		250		
Liquid fuel flow rate, [kg per hour]		0.72	0.685	0.71
Air-flow rate, [kg per hour]		–	4	4
Coal flow rate, [kg per hour]		–	–	0.08
Power (together with steam energy), [kW]		9.4	9.1	10.0
O2	[%]	5.6	9.1	8.7
α – excess air ratio		1.36	1.76	1.7
CO	[ppm]	11.7	8.9	36.2
	[mgkW^{-1}h^{-1}]	16.7	17.4	68.7
	[gkg^{-1}]	0.2	0.2	0.8
NO_x	[ppm]	34.8	27.7	48.3
	[mgkW^{-1}h^{-1}]	85.7	88.3	149.6
	[gkg^{-1}]	0.6	0.6	1.1

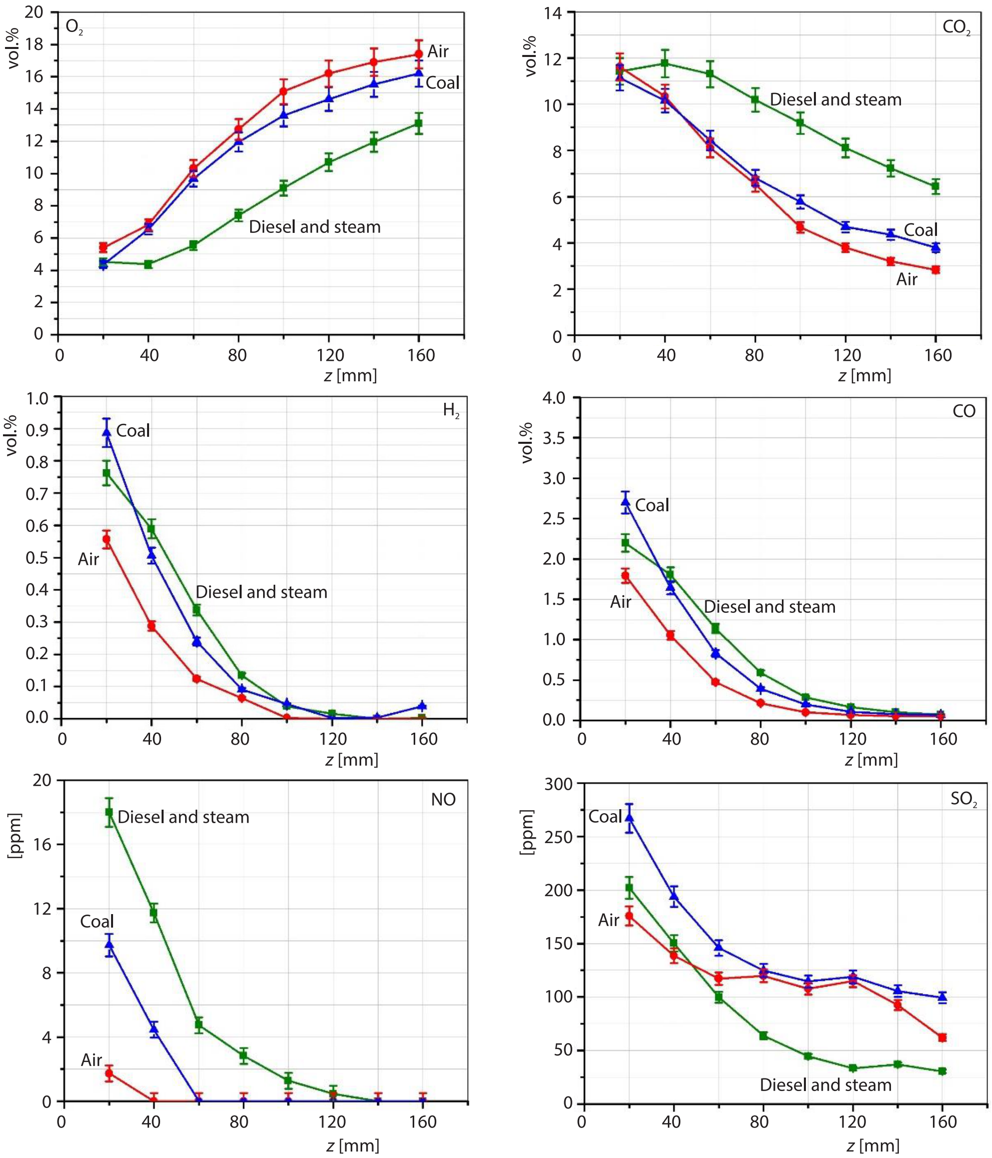

Figure 5. Profiles of gas component concentrations in the flame along the burner axis

Conclusions

A new low power vortex burner for co-combustion of coal and liquid hydrocarbon fuels, which are sprayed with a high velocity jet of superheated steam, has been developed and constructed. The burner implements a method of tangential (vortex) supply of pulverized coal together with secondary air into the area of liquid fuel combustion. Laboratory tests and experimental optimization of operating parameters have been carried out.

The results of calorimetric, gas analytical and temperature measurements of the characteristics of coal and liquid fuel combustion were obtained in the studied operating regimes of the created burner. Three main combustion options are considered: combustion of a single liquid fuel with steam supply. Combustion of a single liquid fuel with steam and secondary air supply. Combined combustion of liquid and pulverized coal fuel under steam gasification conditions. In the regime of diesel combustion with steam, the maximum temperature reaches 1700 °C. When air is added to swirl the flow, the zone with the highest flame temperature moves down (inside the burner), which is accompanied by a decrease in the size of the external flame. The temperature at the burner outlet rises to ~1750 °C. When coal is added, the reverse trend is observed: the flame size increases, and the temperature maximum drops to 1600 °C, after which the temperature decreases gradually as the coal particles burn out. The analysis of intermediate combustion products in the flame showed that in the regimes with the secondary air supply, the addition of coal affects the course of gasification reaction with the formation of synthesis gas and when coal is introduced, the concentrations of H_2 and CO in the flame increase. The principal possibility of co-combustion of pulverized coal and liquid fuels in the developed low power vortex burner is experimentally shown. The information on the main thermotechnical (heat release, flame temperature) and environmental (content of intermediate and final combustion products, including toxic emissions) indicators obtained during the co-combustion of coal and liquid hydrocarbon fuels demonstrates the promise of both the approach and the new design of the low power vortex burner for co-combustion of coal and liquid hydrocarbon fuels, which are sprayed with a high velocity jet of superheated steam.

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