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Vortex combustion characteristics of mechanoactivated coal-biomass composite fuels

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Abstract. This experimental study investigates the combustion characteristics of mechanoactivated coal-biomass composite fuels (70% Kuznetsk bituminous coal / 30% sawdust) in a vortex combustion chamber. The setup employed a seven-section muffle combustion chamber with optical access, incorporating a two-stage burner with tangential and snail-type swirlers to ensure stable combustion initiation. Three distinct combustion phases were observed: chamber preheating (100 s), stable operation (reaching 1500°C), and natural cooling. Mechanochemical pretreatment significantly improved fuel performance, demonstrating complete O_2 consumption (minimum residual 1.9 vol%) and 70% burnout within the first meter of the chamber. Composite fuels outperformed raw mixtures, exhibiting higher steady-state temperatures (>1400°C across all regimes), reduced ignition delays, and a 30% reduction in activation energy (from 200 to 60 kJ/mol). The technology achieved stable oil-free ignition, with CO_2 peaking at full O_2 depletion while maintaining CO/H_2 emissions below 3%. These results validate mechanoactivation as an effective method for optimizing coal-biomass co-combustion in industrial boilers. Further research is required to refine temperature regimes, excess air ratios, and particle residence times. The study contributes essential data for advancing sustainable combustion systems utilizing renewable biomass resources.

1 Introduction

Global reserves of annually renewable plant-based biomass are estimated at 1,830 billion tons, equivalent to 640 billion tons of oil (compared to 4.5 billion tons of global oil production in 2017). This substantial energy potential positions biomass as a leading renewable energy resource for future energy systems. The widespread availability and sustainable nature of biomass make it a viable alternative to conventional fossil fuels. Projections indicate that biomass could supply up to 38% of global fuel demand and 17% of electricity generation by 2050 [1–2].

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The utilization of underused biomass resources—including forest industry byproducts (bark waste, lignin, sawdust, wood chips) and agricultural residues (cereal straw, bagasse, sunflower husks)—presents opportunities to address both socioeconomic challenges and environmental concerns [3].

Mechanochemical processing has emerged as an efficient method for modifying the physicochemical properties of biomass. This approach offers environmental advantages while enhancing material reactivity through:

Increased specific surface area:

Structural modification of lignin and cellulose polymers;

Accelerated kinetics in subsequent chemical processes (e.g., combustion).

Implementation of biomass in pulverized coal boilers requires specific fuel preparation: drying, grinding, blending.

Particle characteristics critically influence combustion efficiency, with optimal biomass particle size exceeding that of coal due to lower density and higher volatile matter release rates [5].

However, excessive particle dimensions may elevate unburned carbon levels [6–7]. Current practice typically determines these parameters empirically, lacking theoretical foundation. Mechanical activation addresses this gap by:

Enhancing mass transfer through increased reactive surface area;

Reducing ignition activation energy (from 200 kJ/mol to 60 kJ/mol);

Generating active sites and deformed molecular structures.

Previous differential scanning calorimetry studies confirm that mechanochemical treatment significantly improves fuel reactivity and combustion kinetics [8]. This study experimentally investigates the production and combustion characteristics of mechanochemically processed coal-sawdust composite fuels.

2 Experiment

The experimental setup is illustrated in Fig. 1. The combustion chamber consists of seven muffle sections with an inner diameter of 110 mm and a length of 150 mm. The muffle walls are made of a refractory mixture ("Mertel") with the addition of plasticizing agents. A central circular channel in each section accommodates a quartz viewing window, providing optical access to the combustion zone. The solid fuel burner comprises two stages. The first stage is a tangential mixing chamber, where an axial ignition-protection device is installed. A propane-butane-air mixture was fed into the primary tangential swirler, which has two tangential inlets for primary air. The fuel was fed from a hopper into the air stream of a snail-type swirler, with mass flow rate controlled by a weighing system (measurement error: ±1 g). Airflow to the tangential and snail swirlers was regulated using orifice plates and differential pressure sensors, ensuring a measurement error of no more than 4%.

The fuel-air mixture was swirled by the snail-type swirler and ignited by a pilot flame generated from propane-butane combustion in the first stage. The chosen swirler geometry (tangential and snail-type) is widely used in solid fuel combustion due to its simplicity and effectiveness (Fig. 6.2).

Flue gas and particulate matter filtration were achieved using a centrifugal-bubbling scrubber (CBS), a wet gas-cleaning apparatus. Temperature data from thermocouples were collected by an 8-channel temperature meter with an integrated RS-485 interface, enabling communication with a personal computer. All control and measurement instruments in the setup were integrated into a unified software system. This software allows experimental data to be recorded in a single file with time-stamped synchronization.

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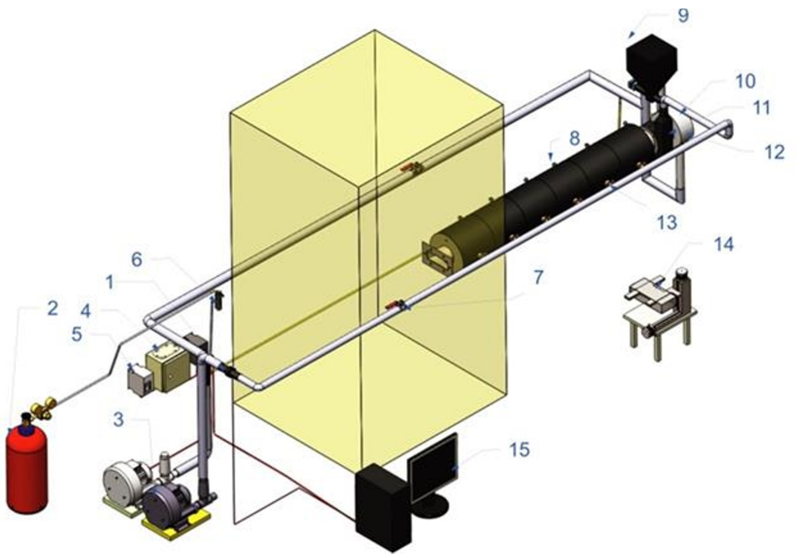

Fig. 1. Experimental setup: 1 – Flow meters, 2 – Gas cylinder, 3 – Air blower, 4 – Frequency converter, 5 – Data acquisition unit, 6 – Rotameter, 7 – Valves, 8 – Thermocouples, 9 – Feeder, 10 – Ignition-protection device (IPD), 11 – Snail-type swirler, 12 – Gas burner, 13 – Viewing windows, 14 – LDA system (Laser Doppler Anemometry), 15 – PC.

3 Results

The experiments were conducted on pre-prepared samples: a composite with an optimal ratio of 70% coal - 30% sawdust. Kuznetsk coal grade D obtained from a boiler house in the city of Berdsk was used in the experiments. For comparison, mixtures of similar composition and sawdust were also studied. The technical composition of the fuel is presented in Table 1.

Table.1. Fuel Characteristics.

Name and designation of indicator	Measurement unit	Coal	Sawdust	Mixture	Composite
Operational moisture, W^r	%	4	0.03	1.0	1
Ash, dry state, A^d	%	18.7	0.6	11.4	9.3
Lowest combustion heat, operational state, Q^r_i	kcal/kg	5677	4620	5381	5413
Sulphur, operational state, S^r	%	0.44	0.23	0.24	0.27
Yield of volatiles, dry ash-free state, V^{daf}	%	40.5	87.4	58.2	57.2

The temperature versus time dependences measured during the experiment shown in Fig. 2 allow us to distinguish three characteristic stages.

Stage 1 – heating up the combustion chamber: Fuel is supplied through the swirler; the gas igniter operates to ignite the coal and further combustion, to heat up the combustion chamber.

Stage 2 – main: fuel is supplied while maintaining a stable mode. The maximum temperature in the reaction chamber reaches 1500 °C.

Stage 3 – final: fuel supply is turned off; the unit is naturally cooled.

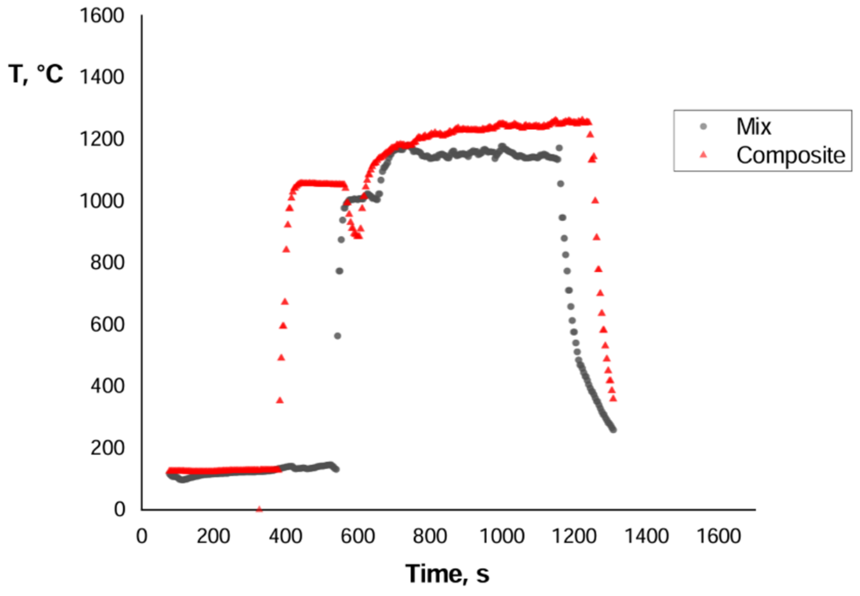

Fig. 2. Change in temperature in the centre of a flow-through vortex combustion chamber during combustion of a composite mixture of the composition "70% coal - 30% sawdust"

Combustion was carried out under challenging thermodynamic conditions with cold (20-30°C) air and fuel supplied to the unit, with 10-30% of the released heat during combustion being removed to the combustion chamber lining and the surrounding space.

After the fuel supply is switched on, the combustion chamber is heated for 100 seconds, and the steady-state mode is reached within 300 seconds. After increasing the fuel consumption, the temperature in the chamber increased. In all experiments, uniform temperature distribution was observed along the experimental setup, with the maximum value reached at the end of the combustion chamber. The temperature on thermocouple T8 during composite fuel combustion in all modes was above 1400 °C.

In experiments with composite and sawdust, complete burnout of O2 is achieved, with the minimum O2 value in the mixture being 1.9 vol. %. When O2 reaches 3%, the concentrations of CO and H2 begin to increase. The concentration of CO2 grows and has a maximum at complete burnout of O2.

When studying the combustion of samples, it was found that, all other conditions of the experiment and technical characteristics of the fuel being equal, different parameters of the flame are observed, namely, the rate of reaching a steady state, the completeness of fuel combustion, the size and distribution of temperature zones strongly depend on the methods used for mechanical processing of the fuel. Comparison of the results showed that, under the same experimental conditions, the temperature distribution along the length of the experimental stand, in a steady state, is higher for composite fuel. In the case of composite fuel, 70 percent of the fuel was burned out in a 1-meter section, which is indicative of these fuel consumptions and kindling processes at industrial thermal power plants. The high reactivity of composites leads to a shift in the ignition zone closer to the beginning of the combustion chamber, a decrease in the time to reach a steady state is observed, this indicator significantly affects the further combustion process in the boiler and reduces the likely carryover of unburned particles.

4 Conclusions

Stable combustion of composite fuels was achieved through mechanical activation grinding and ignition using a gas burner. The study results confirm the applicability of mechanical activation grinding for both gasification and combustion processes. The obtained data on ignition and combustion characteristics of composite fuels support the recommendation of this technology for oil-free ignition systems in boiler plants. For practical implementation and development of efficient gasification processes and equipment for composite fuels, further research is required to optimize key process parameters including temperature regimes, excess air ratios, and residence time of dust suspension in the reaction chamber.

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