EXPERIMENTAL STUDY OF THE PROCESSES OF IGNITION, COMBUSTION, THERMAL DECOMPOSITION OF COMPOSITE FUEL FROM SAWDUST AND ANTHRACITE

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This study investigates the ignition, combustion, and thermal decomposition processes of composite fuels produced from pine sawdust and anthracite coal through mechanochemical activation. The research aims to optimize the co-combustion of low-reactivity coal and biomass by analyzing the non-additive effects of composite formation on fuel reactivity and combustion efficiency. Experimental methods include synchronous thermal analysis (STA) to evaluate thermal decomposition stages, ignition delay measurements in a vertical tube furnace, and flare combustion tests in a 50 kW semi-industrial burner to assess practical performance.

The results show that composite fuels outperform physical mixtures in combustion characteristics. Thermogravimetric analysis reveals a three-stage decomposition process for composites, with overlapping stages of volatile release, coke residue oxidation, and anthracite carbon combustion. The composite achieves stable torch combustion, while the equivalent mixture fails to stabilize. Ignition delay times for composites are significantly lower than for mixtures or pure components, with the optimal ratio reducing ignition time by 20–30%. Mechanochemical activation generates paramagnetic centers on particle surfaces, accelerating ignition through radical-initiated reactions.

The findings highlight the superiority of composite fuels in improving combustion efficiency, particularly for low-reactivity coals like anthracite. This study lays the groundwork for developing advanced solid biofuels applicable to co-firing systems, advancing sustainable energy solutions and biomass waste utilization.

Key words: Coal, biomass, anthracite, mechanical activation, composite fuel.

1. Introduction

The planet's reserves of annually renewable plant materials amount to approximately 1830 billion tons, equivalent to 640 billion tons of oil. The energy potential of biomass makes it an important renewable resource of the future [1, 2], since, according to forecasts, by 2050 humanity will be able to obtain up to 38% of fuel and up to 17% of electricity from it [3, 4]. In addition, the processing of waste, such as forestry and agricultural industry residues, will help solve urgent social and environmental problems [5, 6].

Renewable plant resources are an almost inexhaustible source of biopolymers that can be processed into useful materials or used in power plants to generate energy. In recent years, countries such as Russia, the USA, the EU and Japan [7, 8] have been actively developing scientific research and technological developments [9] aimed at the efficient use of natural resources, including liquid and solid biofuels. One of the promising areas in thermal power engineering is the combined combustion of coal and biomass (co-firing), which is already successfully used in European countries. This method allows the utilization of agricultural and industrial waste without requiring significant changes in power plants and increases the efficiency of the combustion process to 35–40% [10].

Research has shown that co-firing optimizes the use of existing energy resources, reduces electricity generation costs, and lowers greenhouse gas emissions. This area is currently actively supported by government programs to transition to sustainable energy and reduce carbon footprints.

This study builds upon the authors previous research on the combustion and thermal decomposition of composite fuels, particularly focusing on the co-processing of coal and biomass. Earlier works by Kuznetsov *et al*. have explored the kinetics of thermal decomposition and combustion of mechanical activated coal [11, 12], the ignition of pine sawdust in vertical tube furnace [13, 14], and the combustion characteristics of coal-wood composites [15]. These studies demonstrated that mechanochemical activation enhances fuel reactivity by generating paramagnetic centers on particle surfaces, which accelerate ignition and combustion processes. Notably, the authors' prior work on sawdust-coal composites revealed significant non-additive effects in ignition and combustion behavior, particularly for low-reactivity coals like brown coal [16]. The current study extends this research to anthracite, a coal type with even lower reactivity, aiming to further elucidate the mechanisms underlying composite fuel performance.

In this study, experiments were conducted using pine sawdust (which has a high combustion heat) and anthracite to create mixtures and composites with varying component ratios, optimizing the combustion process and improving efficiency. The use of modern mills, such as the DESI-11 disintegrator, enables achieving the required grinding level.

In addition, studying the effect of various parameters on the combustion process, such as temperature, feed rate, and component ratio, can form the basis for further improvement of technologies. Effective implementation of these methods can lead to a wider use of biomass in energy systems, which in turn will contribute to the economic and environmental development of regions. Thus, work in this area is a contribution to a sustainable future and the development of renewable energy sources. The research was carried out using waste from the city's woodworking enterprises, which are generated in large volumes, such as pine sawdust, as well as coal enrichment waste, which have low reactivity and are difficult to ignite. Pine sawdust, selected for the experiments, has one of the highest combustion heats among woodworking waste - 21.1 MJ/kg, which is confirmed by literary data [17]. Pine sawdust is an excellent choice due to its high calorific value (one of the highest among wood species), making it ideal for energy production, as well as its abundance in woodworking waste since pine is extensively processed in Russia, generating large amounts of sawdust; it also has favorable combustion characteristics with lower ash content compared to hardwoods, reducing residue after burning, and is widely available as sawmills and woodworking industries produce millions of tons of pine sawdust as by-products—additionally, Russia, which has the world's largest forest reserves with over 40 million hectares of pine forests, ensures a stable and sustainable supply of this valuable biomass material. A free-impact mill, the DESI-11 Disintegrator, with a capacity of 4 kilograms per hour and a rotation speed of 7.5 thousand revolutions per minute for each disk, was chosen as an activator mill.

The paper proposes three research methods: synchronous thermal analysis for monitoring the process of thermal-oxidative destruction, ignition of dust suspension in a vertical tubular furnace and flare combustion in a two-stage burner with tangential fuel supply. Thermogravimetric analysis (TGA) allows studying the effects of slow thermal decomposition in fuel samples (at a rate of 10–30°C/min), it does not accurately reflect the real processes of ignition and combustion of pulverized coal fuels in the combustion chambers of boiler plants. Therefore, the study of the processes of ignition and initial stages of combustion of particles of the studied sample under conditions as close as possible to real combustion devices is of great interest. In addition, during mechanically activated grinding, newly formed active centers on the particle surface relax over time, which potentially leads to short-term preservation of highly reactive properties in solid fuel particles after grinding. This necessitates the study of the chemical activity of fuels under conditions of rapid thermal decomposition. To meet these requirements, the most suitable method is to study the ignition and combustion of a dust suspension by introducing it in portions into a vertical tube furnace. And to assess the influence of composite formation on the combustion process, it is necessary to compare not only the ignition of samples, but also the combustion of the mixture and the composite on a semi-industrial burner. Thus, the work presents complex studies of the processes of thermal decomposition, ignition and combustion of composite fuel samples, as well as mixtures of its components.

2. Experimental setup and measurement methods

The study employed anthracite coal from the Kuznetsk Basin (Russia), exhibiting typical properties of low-volatile fuels with less than 8% volatile matter and more than 85% fixed carbon content. The biomass component consisted of pine sawdust sourced from woodworking industry waste in Novosibirsk, Russia.

Proximate analysis revealed fundamental differences between the materials: the anthracite contained 2.1% moisture, 8.5% ash, 7.3% volatile matter, and 82.1% fixed carbon, while the pine sawdust showed higher volatile content 75.4% with 10.2% moisture, 0.8% ash, and 13.6% fixed carbon. Ultimate analysis further highlighted the contrast in composition, with the anthracite dominated by carbon 89.2% and the sawdust richer in oxygen 45.2%.

Prior to experiments, both materials were mechanically processed using a DESI-11 disintegrator to achieve a uniform particle size distribution below 100 μm, ensuring consistent reactivity in subsequent combustion tests.

2.1. Thermal Decomposition Process Study

The thermal decomposition process study was performed using a synchronous thermal analyzer STA 449F1 Jupiter® in accordance with the manufacturer's guidelines, compliant with ISO 11357-1 and DIN 51007. The calibration procedure for the temperature and sensitivity of the device was carried out using a standard calibration set, which included the following high-purity substances: In, Sn, Bi, Zn, Al, Ag, Au. Calibration was carried out under the same conditions that were subsequently used in the experiments (heating rate, atmosphere, sample holder, crucible material, temperature range, etc.). The melting temperature of the standard substances was taken as the temperature of the onset of the T_{onset} peak.

The sample weight was 10 mg. The experiments were conducted in the temperature range from 30 to 1000°C in a synthetic air atmosphere (80% argon, 20% oxygen), the gas flow rate was 10 ml/min. Open corundum crucibles were used, the heating rate was 10°C/min. The experimental data were processed using the Proteus analysis and NETZSH Thermokinetics 3.1 software packages. The result of experimental data processing is presented as a set of thermal analysis curves. The TG curve describes the dependence of the sample mass change on temperature. The derivative thermogravimetric (DTG) curve is a derivative of the TG curve (rate of mass change), it allows one to separate overlapping steps in the thermal decomposition process and to establish the temperature at which the weight change occurs most rapidly. The differential scanning calorimetry (DSC) curve represents the dependence of heat flow on temperature and allows to evaluate the thermal effects occurring in the sample during its heating.

Figure 1 shows the curves of the thermal decomposition process of pine sawdust. The TG curve describes the dependence of the change in sample mass on temperature. The DTG curve is a derivative of the TG curve (rate of mass change), it allows to separate overlapping stages in the process of thermal decomposition and to establish the temperature at which the weight change occurs most rapidly. The DSC curve represents the dependence of heat flow on temperature and allows to evaluate the thermal effects occurring in the sample during its heating. The process can be divided into two stages: the first involves the release of volatiles 300–350°C, and the second is the decomposition of the coke residue 380–420°C.

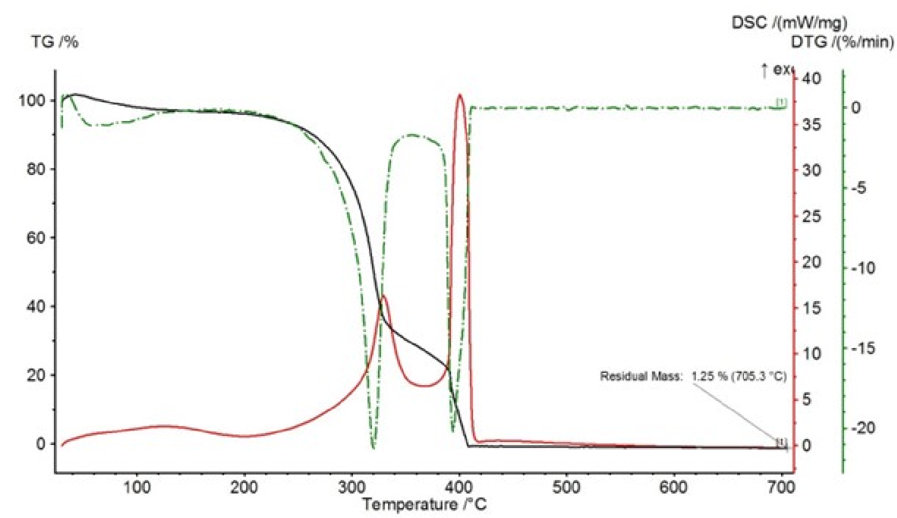

Fig. 1. Thermal decomposition of pine sawdust.

Figure 2 shows the decomposition curves of anthracite. In this case, it is clear that the process of thermal-oxidative destruction occurs in one stage - the decomposition of carbon, which occurs in the range from 500 to 680°C.

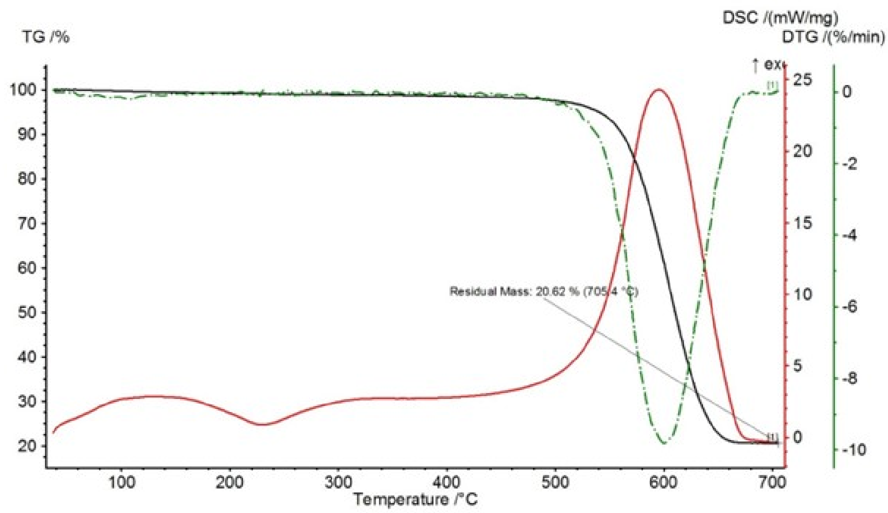

Fig. 2. Thermal decomposition of anthracite

Figure 3 shows the results of comparison of thermogravimetric analysis of composite fuel and mixture. The process of thermal decomposition of mixtures and composites can be divided into several main stages: 300–360°C is the release of volatiles, 380–520°C is the decomposition of coke residue and the reaction of active centers with oxygen, it is worth noting that these 2 processes in the composite are combined, unlike the mixture, which indicates a non-additive addition of characteristics, the third stage is the decomposition of the carbon part of anthracite 520-680°C. There are no significant differences in the decomposition process, since the sawdust and coal particles are in close proximity, lying in the crucible, unlike the dust-air fuel supply in subsequent methods.

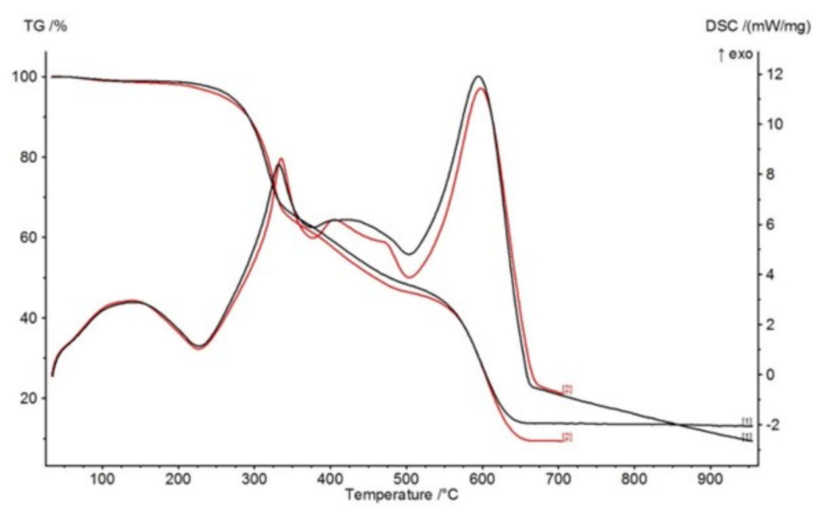

Fig. 3. Comparison of TGA of the mixture and composite. The ratio of components is 50% sawdust, 50% anthracite. The black curve is the composite, the red curve is the mixture.

2.2. Study of the process of self-ignition of samples in a vertical tubular furnace

To study the delay time of the flash of a sample injected with compressed air into a heated volume, a setup was used - a vertical tubular furnace, which is a vertical heat-insulated steel pipe 1 m long, with an internal diameter of 0.4 m, shown in Fig. 4. Electric heating of the pipe is carried out using a system of low-voltage transformers. Along the length of the combustion chamber, photodiodes and thermocouples are located in special holes with a step of 0.1 m, designed to record the flash and temperature, respectively. To stabilize the temperature at the inlet to the reactor, as well as to remove parasitic convective flows and combustion products from the working volume, a small vacuum of about 5 mm of water column is implemented using an air blower and an ejector, the air flow is set depending on the furnace temperature (to stabilize the temperature along the entire length). The trigger mechanism consists of a magnetic valve and a chamber with a volume of 45×10^{-8} m^3. Above the valve there is a powder fuel feeder, where samples weighing from 0.1 to 1 g are poured. Then air is pumped into the chamber and dust is injected into the reactor.

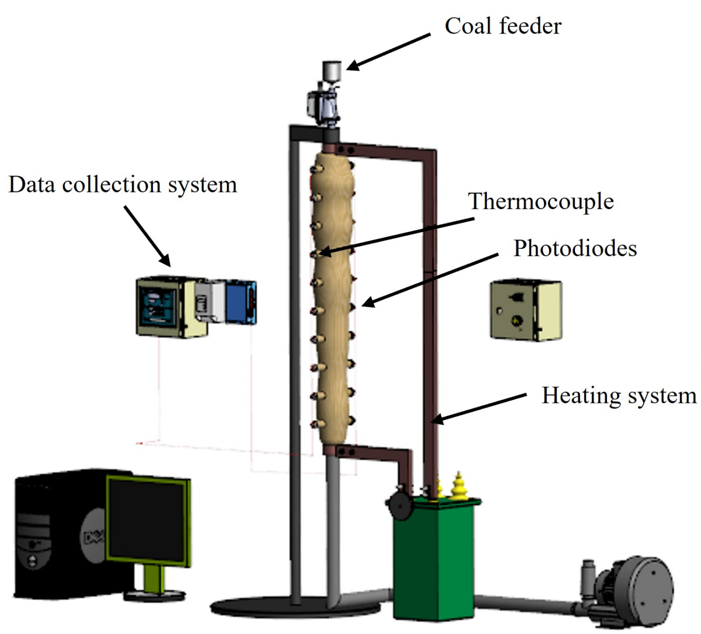

Fig. 4. Vertical tube furnace.

The ignition control system consists of photo sensors, an excitation circuit, a signal processing circuit, a data acquisition unit and software for signal processing. The flame detector has a photodiode with a lens focusing the flamelight in the spectral band between 400 and 1100 nm. on a special window. This technique allows us to determine the minimum dust ignition temperature, as well as the ignition time depending on the reactor temperature. Photodiodes and the opening of the magnetic valve are recorded by the ADC Lcard. As a result, the time between the opening of the valve and the first signal on the photodiode is recorded. As a result of the experiments, dependences of the flash delay time on the coal content in the sample were obtained. In experiments on ignition of dust suspension in a vertical tube furnace, it was not possible to ignite a sample consisting of 100 percent anthracite. The results of comparing the flash delay time (the graph shows the average time value calculated from a series of experiments for each sample) on the coal content in the sample are shown in Fig. 5.

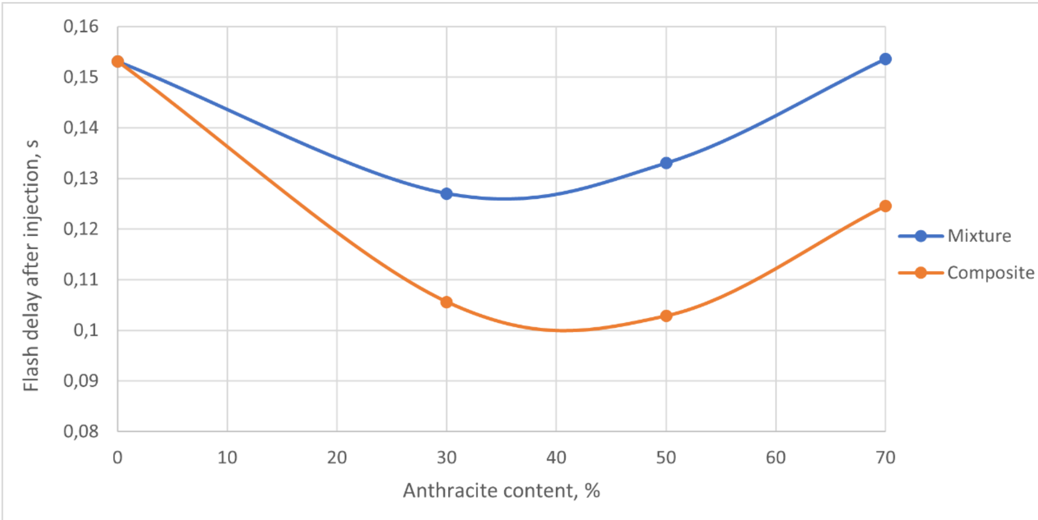

Fig. 5. Flash delay time of the mixture and composite depending on the anthracite content in the sample.

The flash time of the composite is lower than that of the mixture, which also indicates a non-additive behavior of properties, which occurs due to the appearance of a common surface of coal and sawdust particles as a result of processing, and the ignition time of the composite fuel is lower than that of pure sawdust for each sample. In addition, adding coal to sawdust reduces the flash time compared to pure sawdust (for samples with a biomass content of 70% and 50%), this occurs due to the reaction of oxygen and radical centers on the coal surface, the amount of which is significantly higher than that of sawdust, the reaction of which initiates the combustion of the sawdust component in the sample.

2.3. Flare combustion study

The flare combustion study was conducted on a horizontal burner device, the setup is a chamber furnace with a cooling circuit, in which a vortex burner with three stages is installed. The first stage of the burner is designed to ignite highly reactive initiation fuel, the second stage is designed for solid pulverized fuel of fine fraction composition, and the third stage is designed to ignite large particles of solid fuel.

Ignition of highly reactive fuel is carried out using an ignition device, which is built into the diffuser at the end of the burner device. Thermocouples located in characteristic places are used to obtain temperature readings of the setup, shown in Fig. 6.

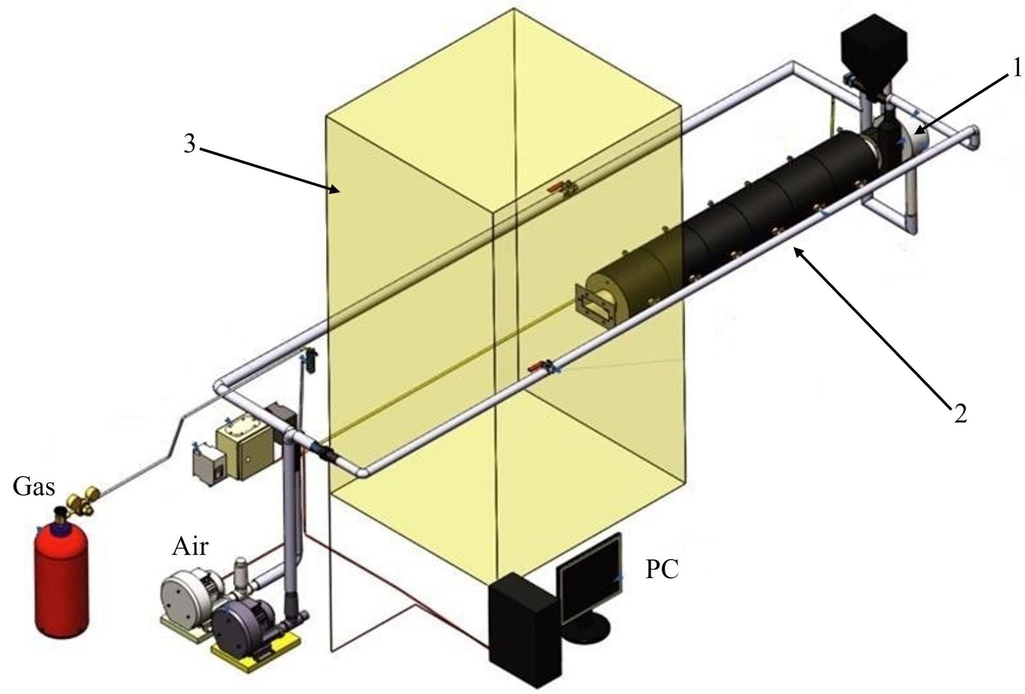

Fig. 6. Experimental setup: 1 - first stage; 2 - second stage; 3 - third stage.

As a result of flare combustion studies in various modes, data on the temperature distribution in the furnace were obtained (Figs. 7, 8).

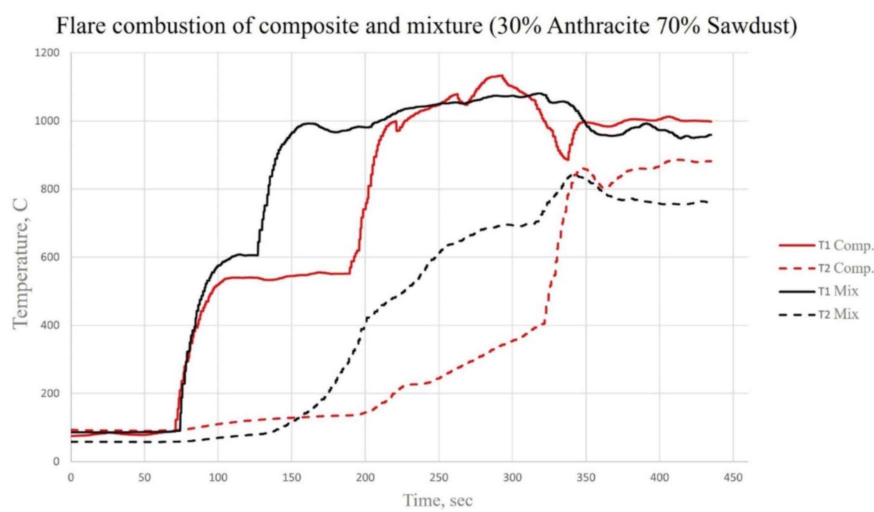

Fig. 7. Temperature curves of the torch combustion process of mixture and composite samples with a component ratio of 30% anthracite and 70% sawdust.

The following results were obtained during flame stabilization in the first part of the test bench for mixture and composite samples:

Mixture of 30 anthracite and 70 sawdust - stable torch combustion, temperature of 1070°C.

Composite of 30 anthracite and 70 sawdust - stable torch combustion, temperature of 1124°C.

Mixture of 50 anthracite and 50 sawdust - unstable torch combustion, temperature reached 903°C.

Composite of 50 anthracite and 50 sawdust - stable torch combustion, temperature of 1200°C.

With the addition of air, the torch broke away from the nozzle and lengthened, and the combustion was distributed deep into the furnace into the combustion chamber. The results obtained from the thermocouples were as follows:

Mixture of "30 anthracite 70 sawdust" - T1 (thermocouple in the first stage) 950°C, T2 (thermocouple in the furnace) - 760°C

Composite of "30 anthracite 70 sawdust" - T1 1000°C, T2 883°C.

Mixture of "50 anthracite 50 sawdust" - unstable combustion of the torch, T1 500°C, T2 482°C.

Composite of "50 anthracite 50 sawdust" - T1 1028°C, T2 860°C.

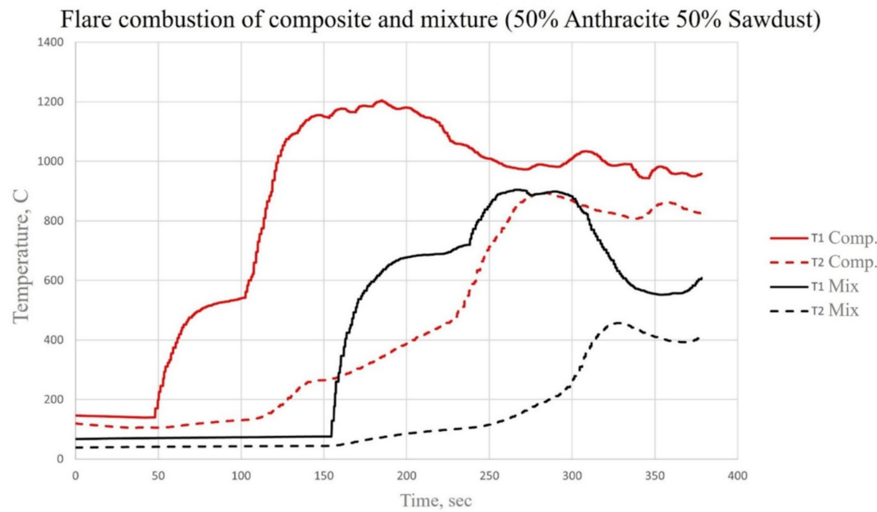

Fig. 8. Temperature curves of the process of flare combustion of samples of the mixture and composite with a component ratio of 50% anthracite 50% sawdust.

As a result of the studies of flare combustion in various modes, data on the temperature distribution in the furnace were obtained. The studies showed more complete combustion of the composite fuel sample, as evidenced by the higher process temperature. In addition, the combustion of the composite more quickly reaches its stable mode. The results obtained correlate for all three methods, the technology for preparing composite fuel has opened up the possibility of igniting a low-reaction type of coal, which opens up wide possibilities for its use.

The conducted study of the ignition and combustion processes of composite fuel based on pine sawdust and anthracite demonstrates significant differences from previously studied systems with brown coal [18]. Unlike brown coal composites, which are characterized by rapid ignition (ignition delay of 50–80 ms at 600°C) due to the high content of volatiles, anthracite mixtures exhibit more inertial behavior, delay of 120–150 ms under the same conditions. This is due to a lower proportion of volatile components and a higher degree of carbonization of anthracite. In addition, if in the case of brown coal, joint thermal decomposition of biomass and coal was observed in a single temperature range 300–500°C, then for anthracite, the processes of sawdust and coal destruction occur more separately, which is confirmed by thermogravimetric analysis data. These results are consistent with the findings of other studies, which also note that the classical ability of composite fuels is highly dependent on the type of coal. For example, the work of Zhou *et al*. [8] showed that the interaction of biomass with brown coal leads to more pronounced synergistic effects compared to anthracite.

The obtained data emphasize the low degree of impact for anthracite-based composites, since it allows to exceed its low power step. This is consistent with the results [16], where it was shown that mechanochemical treatment creates active sites on the particle surface that cause ignition. Thus, the present study makes additional work by demonstrating that even for difficult-to-burn coals such as anthracite, stable and efficient combustion can be achieved to optimize the composition and processing methods of composite fuels.

3. Conclusions

The results of comparative thermogravimetric analysis (TGA) of composite fuel and mixtures with different carbon content show that the thermal decomposition process has several stages. The first stage is the release of volatile fractions; the second stage is the decomposition of the coke residue and the reaction of active centers with oxygen; the third stage is the decomposition of the carbon part of the coal.

When analyzing the flash time of the composite, it was found that it is lower than that of the mixture, which, together with the TGA results, indicates a non-additive behavior of properties, which occurs due to the appearance of a common surface of coal particles and sawdust as a result of processing. In addition, the addition of coal to sawdust reduces the flash time compared to pure sawdust, which occurs due to the reaction of oxygen and radical centers on the coal surface, the amount of which is significantly higher than that of sawdust, the reaction of which initiates the combustion of the sawdust component in the sample. Studies of flare combustion of the obtained composite fuel showed more complete combustion than that of the mixture, as evidenced by the process temperature, as well as gas analyzer data.

The practical application of sawdust-anthracite mixtures and composites in power engineering holds significant promise. The enhanced combustion characteristics, such as reduced ignition delay and improved flame stability, make these fuels suitable for co-firing in existing coal-fired power plants with minimal modifications. The findings of this study provide a foundation for optimizing fuel blends in industrial settings, aligning with global efforts to transition toward sustainable energy solutions.

As a result, it was found that the composite fuel has increased flammability due to the non-additive interaction of the components, which allows for more efficient combustion of solid organic fuel and waste, opening up new possibilities for its use.

Acknowledgements

The study of fuel combustion completeness and identification of environmental characteristics were carried out with the financial support of the Russian Science Foundation (project No. 23-79-01191).

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Submitted: 13.02.2025.
Revised: 21.04.2025
Accepted: 24.04.2025.