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Influence of Grinding Methodology and Particle Size on Coal and Wood Co-Combustion via Injection Flame Opening Angle

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Abstract: Today, more than 61% of the world's electricity is generated by burning fossil fuels. The search for reducing the negative impact of such thermal power plants on the environment does not stop for a minute, one of the solutions to this problem is the partial replacement of coal with biomass. This method has proven itself most effective over the past five years. Co-pulverized combustion of coal and biomass has not found wide practical application, since the processes of grinding, mixing and subsequent spraying of such mixed fuels have not been fully studied. This study compares the influence of the method of grinding, mixing coal and biomass on the processes of spraying mixtures with a change in the pressure of the atomizing air. The results of the research showed that the joint grinding of coal and biomass contributes to the achievement of the minimum size of coal and wood and, as a result, leads to an increase in the opening angle of the torch, which will significantly improve the efficiency of flame combustion in the furnace space at the station. The most effective spray pressure of the mixed fuels was established, which was 3 bar. An analysis of the results obtained during the course of the research allows us to conclude that the mixing of coal and sawmill waste, followed by joint grinding in a ball mill, contributes to the effective grinding of biomass and coal particles to a finely dispersed state, which subsequently leads to a significant increase in the opening angle of the torch at any concentration of the mixture composition fuels.

Keywords: coal; biomass; mixed fuel; spraying; fuel preparation

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1. Introduction

The consumption of electric energy in Russia has been steadily growing recently. The country consumes 1107.1 billion kWh of electric energy annually, which is about 5% of the world consumption [1,2]. From 2010 to the present, the demand for electric energy has increased by more than 8%, which is due to the increasing technological growth, but contributes to an increase in the cost of fossil fuels.

In 2021, global coal production increased by 5.7% after the recovery of global demand [2]. China has been the largest coal mining country for several years, where 3.969 Mt of coal fuel is produced annually. China consumes about a quarter of the world's energy resources, which is 35% more than the United States annually.

Large coal-producing countries such as China, India, the USA, and Russia are the world's largest sources of greenhouse gas emissions [3]. According to the calculations of the Global Carbon Project, an international research project on monitoring greenhouse gas emissions, in 2021, carbon dioxide emissions worldwide increased by 4.9% compared to 2020, and amounted to 36.7 billion tons [4]. This is due to recent events, for example, the freezing of wind and solar energy sources throughout Europe, which did not allow for the provision of heat and electricity to most consumers, as well as the systematic refusal

of European countries to purchase hydrocarbons from the Russian Federation, which significantly reduces energy reserves and certainly leads to a shortage in energy supply for both ordinary consumers and manufacturing enterprises.

The annual increase in environmental pollution by emissions gradually leads the world to irreversible climate change; therefore, the urgent issue is to reduce the anthropogenic impact of harmful greenhouse gases, which are mainly formed as a result of thermal power plants operation powered by fossil fuels. People's dependence on fossil fuels is undeniable due to many factors. Firstly, 36% of the world's electricity is generated by coal combustion [5].

In Russia, coal mining is one of the largest economic sectors, providing jobs for about 200,000 people across the country [6]. Coal reserves in the country are enormous; today, they account for about 20% of world indicators [7].

The increase in the cost of traditional fuel, a considerable part of which is the transport component, the difficulties associated with the gasification of remote settlements, the need to dispose of wood waste all push countries to assess the prospects for using their own fuel resources.

According to the EPA review, 291.9 million tons of wood waste is generated annually in the world [8]. Wood is considered a universal renewable resource with a high potential to mitigate the effects of energy enterprises. Wood waste and the by-products of the wood-working industry can be used to produce a wide range of useful industrial products [9,10]. The use of wood waste for energy production includes the incineration of waste in the form of sawdust, pellets, pallets, and briquettes. However, the energy value of such fuels for the production of electricity and heat at large power plants is significantly inferior to traditional energy coals despite the high environmental efficiency of such carbon-neutral fuels.

Scientists and power engineers around the world continue to search for a way to efficiently dispose of waste and significantly reduce the environmental impact of coal-fired thermal power plants [11].

Based on the above, the complete abandonment of coal worldwide is currently impossible. Therefore, it is proposed to replace part of the coal with a carbon-neutral wood biomass. In previously published works [12], it has been proven that replacing coal with 25% percent of recycled wood reduces emissions of harmful anthropogenic gases by more than 64%, and replacing coal with 50% of biomass leads to a reduction in SO_x emissions by more than 90%.

The introduction of technologies for the combustion of fine mixed fuels at the production level entails the need to solve a number of important tasks: the development of fuel preparation systems (joint or separate); the possibility of the joint combustion of mixed fuels in burner devices; a system for storing and transporting such fuels to power plants.

At pulverized coal power plants, coal and biomass are crushed to form particles of a suitable size for pneumatic feeding into the burner. Grinding methods can be divided into two categories:

- crushing of a mixture of biomass and coal using a conventional vertical roller mill;
- grinding of coal and biomass separately using special mills [13,14].

When preparing coals and wood biomass separately from each other and then mixing them, sufficiently high energy and technical characteristics of mixed fuels are achieved, but these characteristics can be significantly improved due to their long-term joint mixing and grinding.

In power plants running on pulverized coal, the particle size of the pulverized mixture is an important parameter affecting the combustion efficiency, ash content, and combustion stability. As a rule, coal is crushed in such a way that 80% of the product particles pass through sieves with a particle size of 75 microns [15]. As such, there are no requirements for the size of biomass particles. Based on the above, it can be concluded that the joint or separate preparation of mixtures, with the grinding of particles to a suitable size, is an urgent problem at the moment.

The size of the dust plays an important role in matters of fuel atomization in the boiler furnace. The smaller the size of the coal dust, the larger the reaction surface area, which means that combustion conditions are significantly improved, since fuel combustion is a heterogeneous process occurring on the surface of the particle. At thermal power plants, pneumatic nozzles are usually used to spray pulverized coal fuel. In the work of the authors [16], the possibility of using flat, rotating and vortex injectors was considered. When using a flat nozzle, the fuel jet is sprayed in the form of a flat fan. The advantage of this type of nozzle is that it keeps a stable angle during spraying. Vortex nozzles are easy to manufacture and operate; they allow for spraying fuel with a thin layer.

In our work, a pneumatic nozzle was used to spray dry mixed fuels. The advantage of injectors of this type is their reliability, the ability to control fuel consumption and the ability to achieve good spraying quality even at a low pressure of the spraying agent.

The issue of joint or separate preparation and combustion of coal and biomass was mentioned by the authors of [17]. The most promising technology was considered to be the co-combustion of pellets with coal in pulverized coal boilers, in which biomass is prepared in an autonomous feeding and grinding system.

The authors of [18] determined the characteristics of grinding coal mixtures with different contents of wood pellets. Grinding was carried out using a bench roller mill, the main parts of which are grinding rolls, a rotating table, and a rotating nozzle. The fuel mixtures were crushed for two hours. According to the research results, it was determined that the particle sizes in the mixture increased as the mixing coefficient increased. In addition, wood particles that were not completely crushed accumulated inside the roller mill. Consequently, energy consumption and pressure drop inside the mill increased. The coal present in the mixture was crushed better than sawdust. The authors found that with this method of fuel preparation, it is important to pay attention to the resulting size of the crushed particles for their efficient combustion at coal-fired power plants.

In [19], studies of the joint grinding of coal and biomass in a roller mill were carried out. The authors found that when grinding biomass in a roller mill without preliminary carbonation, the biomass is not crushed to an acceptable size for combustion in pulverized coal boilers (less than 75 microns). The size of the uncarbonized biomass was in the range of 600–1180 microns. As the degree of carbonization increased, the particle size of the crushed biomass decreased. Despite the fact that the requirements for the size of biomass particles are not as serious as for the size of coal, due to its high volatility, the particle size achieved by grinding fuel in a roller mill using the method proposed by the authors of [19] (600–1180 microns) is still not acceptable for spraying in a pulverized coal boiler.

The authors of [15] studied the influence of various mills on the characteristics of particles and processing of wood fuel powder. After grinding wood powder in four types of hammer mills and one knife mill, it was determined that different types of mills produce wood powder with different properties. Sieve analysis and laser diffraction have shown that impact mills grind wood powder with smaller particles compared to knife mills [20].

The effect of co-grinding coal and biomass in a ball drum mill on the processes of ignition, combustion, and spraying of such mixed fuels has not been studied at a fundamental level. Therefore, it is an extremely relevant issue in the energy industry, since this type of grinding is the most common in the energy sector.

The effect of joint grinding of coal and biomass in a ball mill on the processes of ignition, combustion, and atomization of such mixed fuels has not been fundamentally studied. Achieving equally fine particle sizes of coal and wood less than 80 microns with separate grinding requires a lot of energy, so reducing the cost of grinding is an important task. We put forward a hypothesis that the joint grinding of coal and wood waste will lead to a synergistic effect due to the significantly higher hardness of coal compared to wood.

Therefore, this is an extremely urgent problem that we intend to solve in our work.

The main goal of our experimental studies in this work is to compare the effect of the method of preparing mixed fuels based on coal and sawmill waste in a ball drum

mill on the characteristics of their atomization at different pressures of the air agent in a pneumatic nozzle.

2. Methods of Experimental Research

2.1. Methods for Preparing Fuel Mixtures

Wood (pine sawdust) was added to coal during mixed fuel preparation, which remained after business wood sawing at the LLC Dzerzhinskiy LPK timber processing enterprise, Tomsk.

In this paper, the properties of fuels and the characteristics of the spraying of mixed fuels prepared in two different ways are compared: 1. separate grinding followed by mixing; 2. mixing and joint grinding.

In the first method of preparation of mixed fuels, individual components included sawdust, and pieces of coal were pre-ground mechanically to the size of coal particles less than 80 microns and wood particles less than 200 microns, then mixed in the required proportions by weight in a ball drum mill for five minutes [21]. The mill consisted of a five-liter ceramic drum, with grinding balls of the same material and specialized rolls.

In the second method of fuel preparation, coal was used, the average particle size of which did not exceed 3 mm. Sawdust was used directly obtained from the sawmill, previously cleaned of large inclusions. The fuel samples were formed in a different ratio of coal/wood by weight and placed in a ball mill with the addition of grinding bodies equal in weight to the mixture. The mixing and grinding process was carried out simultaneously. The grinding and mixing time was 18 h. After grinding, the mixture was sieved through a sieve of 80 microns and the residue after the sieve was used for research.

The joint grinding of large particles of coal and sawdust made it possible to establish the synergistic effect of their joint grinding. The coal and wood particles were obtained with a particle size less than 80 microns.

2.2. Experiments on the Spraying of Fuel Mixtures

Flare opening studies were carried out using the standard classical method. There are many ways to determine the opening angle of a fuel plume; it can be modeling two-phase flows or visualization, but this is not the goal of the research itself. We decided to go in a proven and accessible way for us to confirm our hypothesis. The purpose of the study of the flame opening angle was that the joint grinding of coal and biomass is most efficient, as it allows to obtain particles of the mixture with close sizes of less than 80 microns, which is a synergistic effect that promotes rapid ignition and combustion, as well as to increase the area of the flame opening angle and the uniformity of the sprayed flow mixtures. Image processing was performed using the ActualFlow program developed by Sigma-Pro (Novosibirsk). This software is used to automate the process of conducting experimental studies using image anemometry (PIV and IPI), storing and processing the obtained data, and visualizing experimental and calculated data.

Experiments on the spraying of mixed fuels were carried out on a stand that allows for simulating the furnace of a boiler unit with a system for spraying dry mixed fuels. The layout of the experimental stand is shown in Figure 1. The pressure of the spraying agent (air) varied from 1 to 4 bar in order to determine its optimal value, at which the spraying angle of the fuel jet would be the largest.

The mixture was supplied from a coal storage unit connected to a spraying pneumatic steel nozzle. The diameter of the nozzle outlet was 3 mm. A laser sheet was used to illuminate the jet of the sprayed fuel. During the moment of illumination of the study area by a laser pulse, the photorecording of the jet was carried out. At least 50 photographs were processed for each composition. The time of the experiment for each composition was 60–80 s. During this time, a stable jet was formed, which made it possible to calculate the spraying angle with high accuracy while spraying various compositions of mixed fuels.

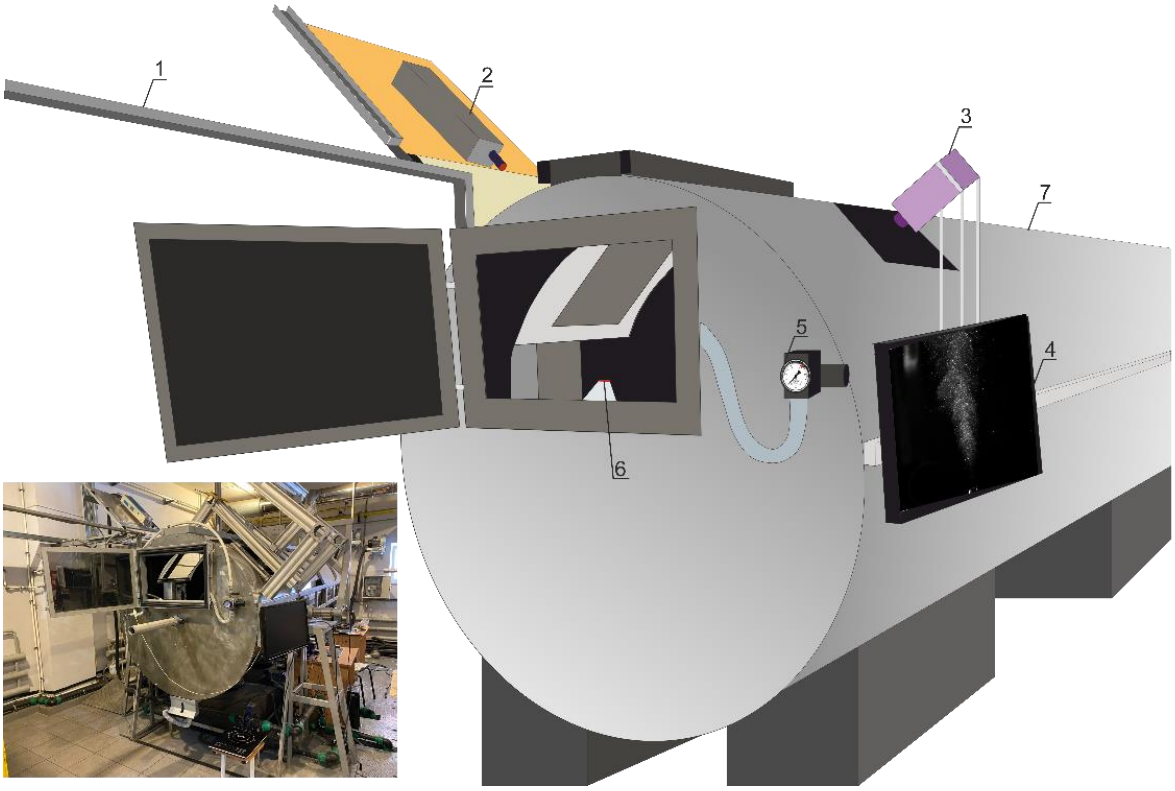


Figure 1. Schematic diagram of the experimental installation to study the spraying characteristics of pulverized mixed fuels: 1—air supply from the compressor, 2—Beamtech NDP15 laser, 3—ImperX Bobcat B2020 cross-correlation camera, 4—monoblock, 5—pressure gauge, 6—pneumatic nozzle, 7—aerodynamic simulator of the combustion chamber.

3. Results and Discussion

The main fuel components and mixtures formed on their basis were analyzed for technical characteristics (humidity, ash content, volatile yield, and calorific value). The studies were carried out in accordance with the methods outlined by ISO 1928-2009 [22] and ISO 589-81 [23]. The results of the technical characteristics of fuels are shown in Table 1.

Table 1. Technical characteristics of fuel.

Fuel (Coal/Wood), %	Calorific Value Q^a_i, MJ/kg	Technical Analysis, %		
		W^a, %	A^d, %	V^{daf}, %
100/0	31.10	3.295	6.843	10.509
90/10	30.68	3.778	5.410	13.582
75/25	28.80	3.944	5.124	21.152
50/50	23.64	6.206	2.148	57.390
Wood 100%	21.70	5.400	0.300	80.300

According to the results of the technical analysis, it can be seen that with an increase in the proportion of wood biomass in the mixture of 50%, the caloric value decreases by 16%, while a decrease in the ash residue of this mixture was established equal to 68%. A significant increase in the yield of volatiles was also found.

To establish the influence of the fuel pressure and the method of its preparation on the spraying angle, studies were carried out on the spraying of dry mixed fuels in an aerodynamic simulator of the combustion chamber. The study of the spray angle was carried out in order to establish the influence of the proportion of the wood component

in the mixed fuel on the flame opening angle. A decrease in the spraying angle leads to an uneven distribution of fuel across the furnace and, consequently, to the least efficient combustion. On the contrary, an increase in the angle leads to a more efficient combustion of such fuel compositions.

For fuel that was prepared separately from each other, a spray study was conducted at several pressures in order to identify the optimal pressure of the spraying agent (air). Figure 2 shows a diagram of the dependence of the jet spraying angle on pressure with different compositions of fuel mixtures.

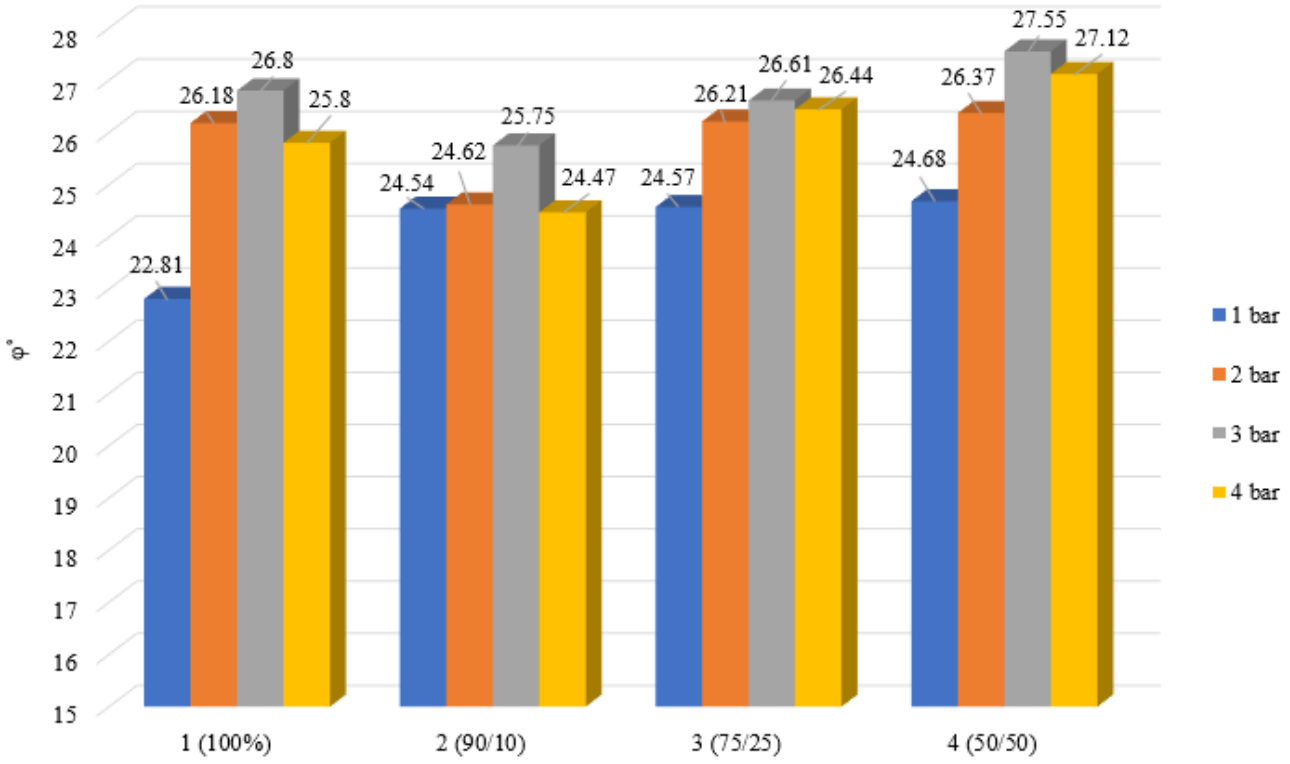


Figure 2. Dependence of the jet spraying angle on pressure with different compositions of fuel mixtures prepared separately (1—100% Coal/0% Wood; 2—90% Coal/10% Wood, 3—75% Coal/25% Wood, 4—50% Coal/50% Wood).

From the analysis of Figure 2, the following conclusions can be drawn:

1. For coal without the addition of sawdust (waste sawmilling), with increasing pressure, the opening angle of the torch increases. The largest value of the flame opening angle is observed at a spray mixture pressure of 3 bar. With a further increase in pressure, the flame opening angle does not increase.
2. At a pressure of 2 bar, the flame opening angle is practically the same for homogeneous coal and for any mixture with a wood content of 25% to 50%. A decrease in the opening angle of the torch is observed only at a ratio of components in the charcoal mixture of 90%/10%.
3. An increase in pressure to 3 bar showed a significant increase in the flame opening angle for coal without additives. For other mixed fuels at this pressure, the flame opening angle is maximum for a mixture of coal and wood in a ratio of 50%/50%.

Since an increase in the flame pressure to 4 bar did not lead to an increase in the flame opening angle, it was decided to conduct all subsequent studies at an effective pressure of 3 bar.

Figure 3 shows a typical image of the spraying angle while spraying a wood–coal mixture at a pressure of 1 bar.

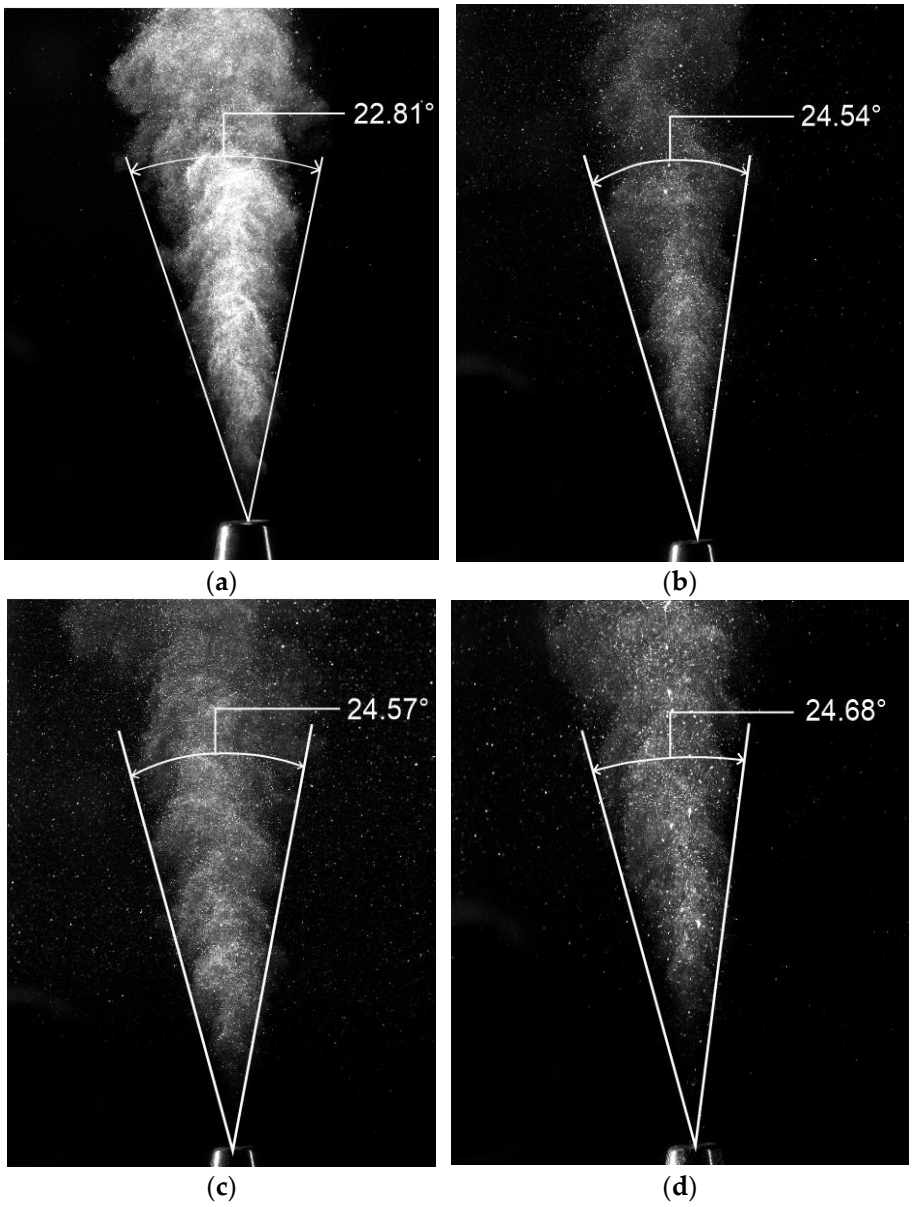


Figure 3. The jet spraying angle while spraying a wood–coal mixture at a pressure of 1 bar ((**a**) coal 100%_wood 0%; (**b**) coal 90%_wood 10%; (**c**) coal 75%_wood 25%; (**d**) coal 50%_wood 50%).

An analysis of Figure 3 makes it possible to visually establish the effect of sawdust on the process of co-spraying with coal. Increasing the proportion of the woody biomass in the mixture from 10% to 50% leads to a slight increase in the flame opening angle at a pressure of 1 bar. For example, when 10% biomass was added to coal, the flame opening angle increased by 7% compared to the coal dust flame opening angle without additives. An increase in the proportion of sawdust in coal from 25% to 50% does not lead to a significant increase in the flame opening angle and does not exceed 7.5%. An analysis of Figure 3 allows us to see that the fuel mixtures are sprayed in waves.

Figure 4 shows typical images of the results of studies on spraying separately prepared mixed fuels at a pressure of 2 bar.

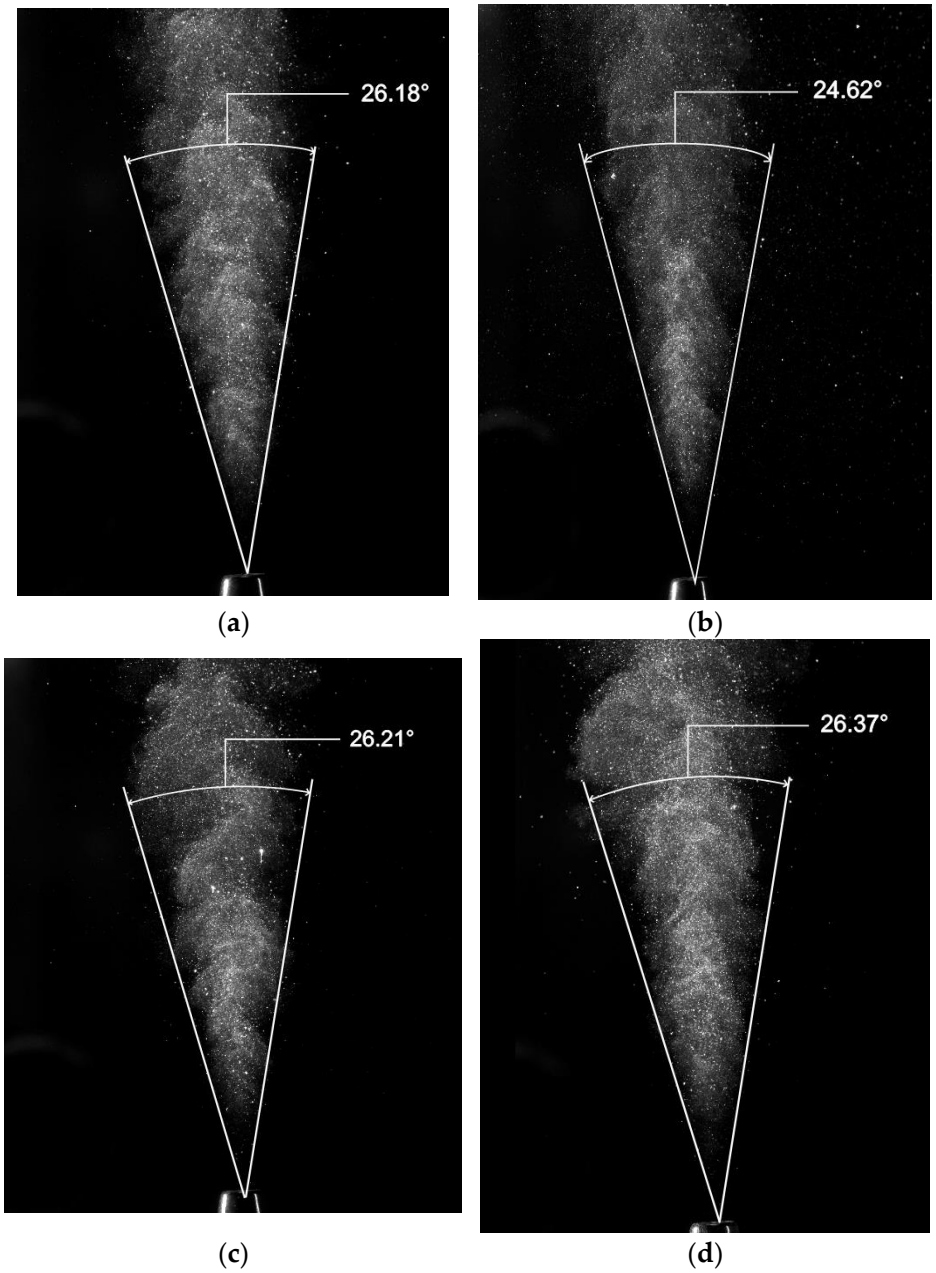


Figure 4. The jet spraying angle while spraying a wood–coal mixture at a pressure of 2 bar ((**a**) coal 100%_wood 0%; (**b**) coal 90%_wood 10%; (**c**) coal 75%_wood 25%; (**d**) coal 50%_wood 50%).

The typical results of spraying coal, and the mixed fuels based on it, with wood waste at a pressure of 2 bar showed that an increase in the proportion of the latter in the mixture led to a minimum increase in the opening angle of the torch by no more than 1%. An analysis of the results allows us to conclude that at a pressure of 2 bar, mixed fuels are atomized, comparable to the atomization of coal without additives.

Typical images of the results of experimental studies on the spraying of mixed fuels performed at a pressure of 3 bar are shown in Figure 5.

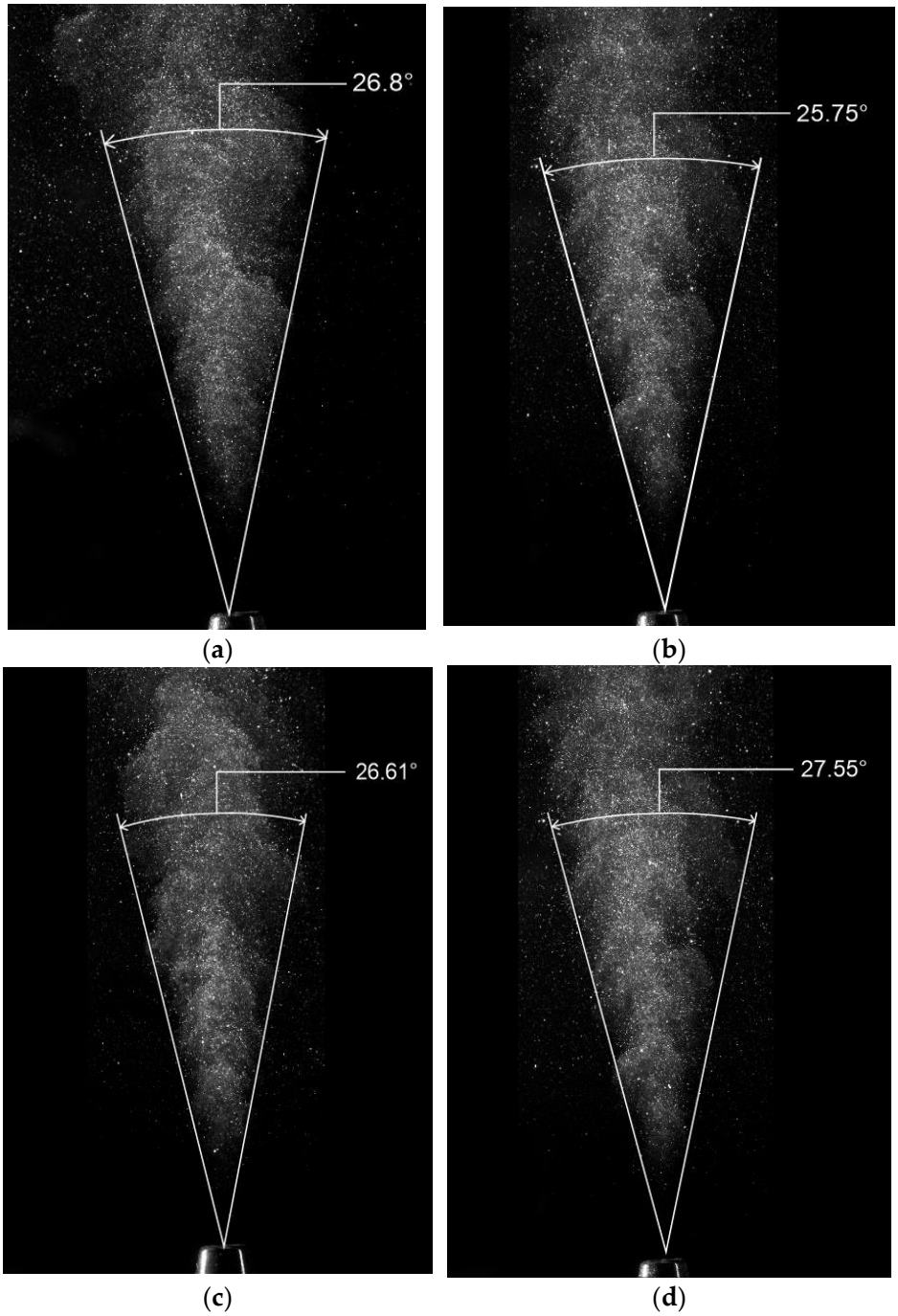


Figure 5. The jet spraying angle while spraying a wood–coal mixture at a pressure of 3 bar ((**a**) coal 100%_wood 0%; (**b**) coal 90%_wood 10%; (**c**) coal 75%_wood 25%; (**d**) coal 50%_wood 50%).

With an increase in pressure to 3 bar, it was found that with a mixture composition of 50%/50%, the flame opening angle increases by 2.7% compared to the coal flame opening angle without the addition of sawdust. For the other two fuel mixtures, we see a slight decrease in the flame opening angle compared to coal, but despite the negative effect, we observe a significant increase in the flame opening angle compared to spraying the same fuel mixtures at a pressure of 1 bar. From the analysis of the obtained results, it can be concluded that at a pressure of 3 bar, the spraying of fuel compositions occurs more evenly and no wave bursts are observed. This effect will have a positive effect on the processes of fuel combustion in the future.

Next, the analysis of the spraying angles of the coal and mixed fuels based on it and biomass at a pressure of 4 bar was performed. The typical images of the research results are shown in Figure 6.

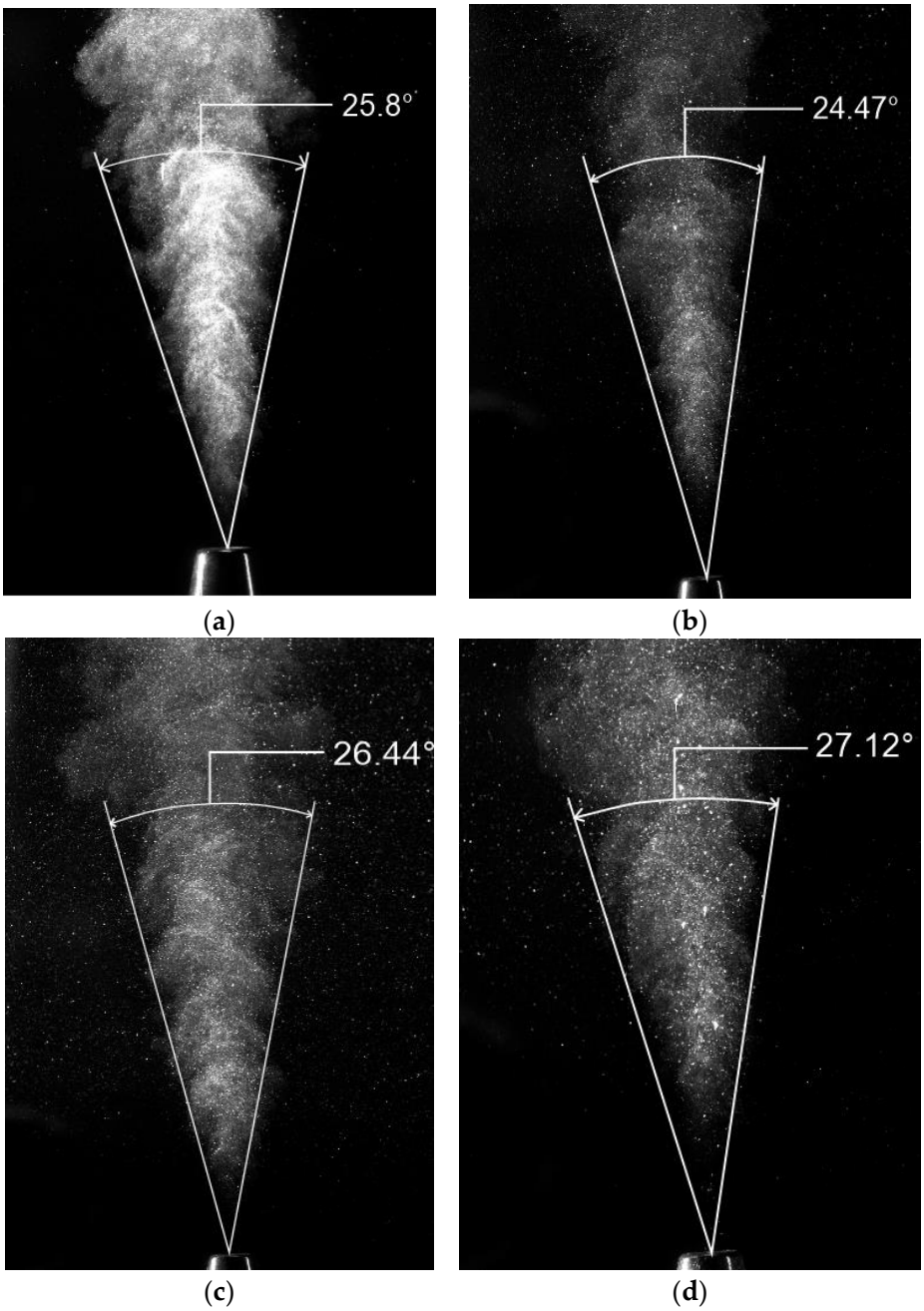


Figure 6. The jet spraying angle while spraying a wood–coal mixture at a pressure of 4 bar ((**a**) coal 100%_wood 0%; (**b**) coal 90%_wood 10%; (**c**) coal 75%_wood 25%; (**d**) coal 50%_wood 50%).

An analysis of Figure 6 allows us to conclude that an increase in pressure to 4 bar again leads to the appearance of wave oscillations in the supply of the fuel mixture. An increase in the opening angle of the torch is also observed only for a mixture with an equal mass of coal and sawdust waste (sawdust). Therefore, we believe that the most effective pressure is 3 bar for spraying mixed fuels, at which the flame opening angle is almost the same for the entire range of charcoal mixed fuels.

A similar study was conducted for the mixed fuels formed by grinding in a ball drum mill for 18 h. The pressure of the feeding agent was chosen to be 3 bar, since at this pressure,

the studies performed earlier showed the most satisfactory results. The typical results of flame opening angles for coal without the addition of wood waste, and mixed fuels based on it, with the addition of wood waste (pine sawdust) are shown in Figure 7.

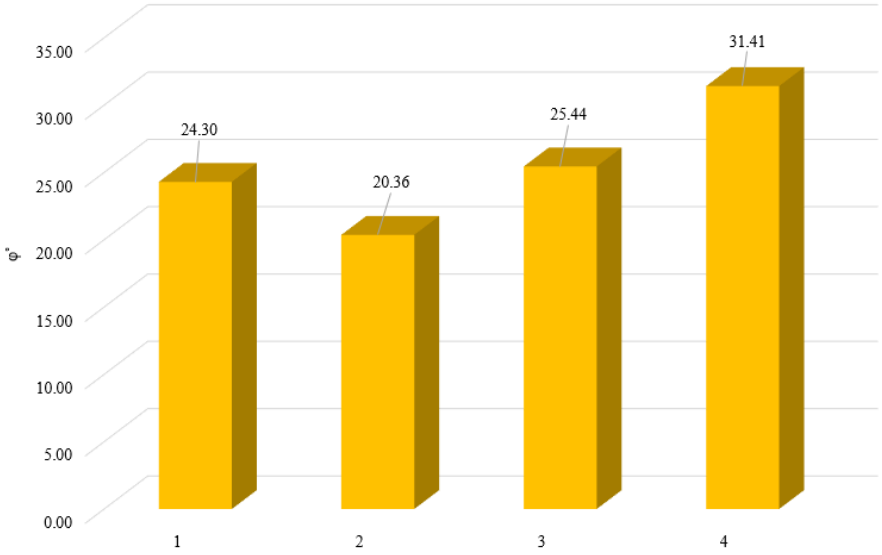
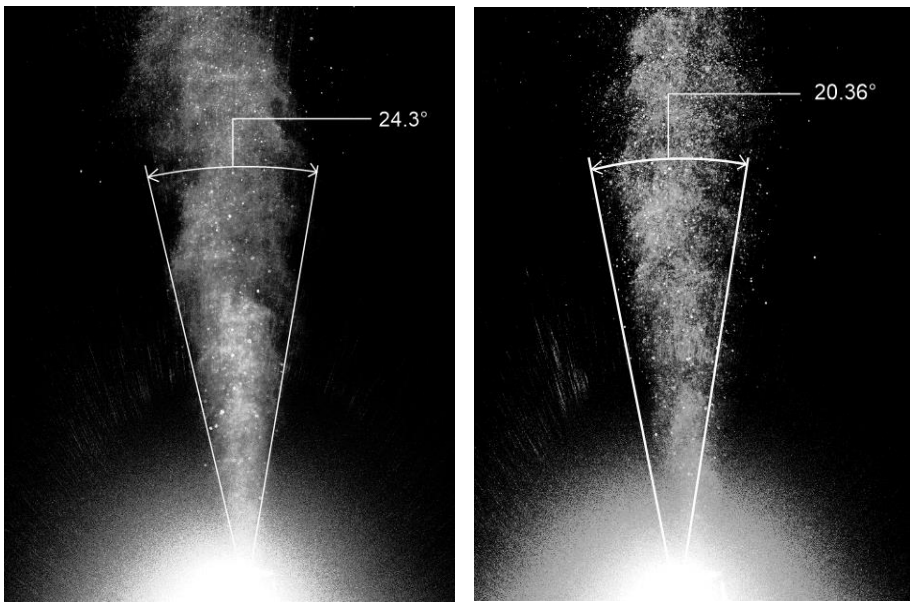


Figure 7. Change in the jet spraying angle of fuel mixtures prepared together at a spraying pressure of 3 bar (1—100% Coal/0% Wood; 2—90% Coal/10% Wood, 3—75% Coal/25% Wood, 4—50% Coal/50% Wood).

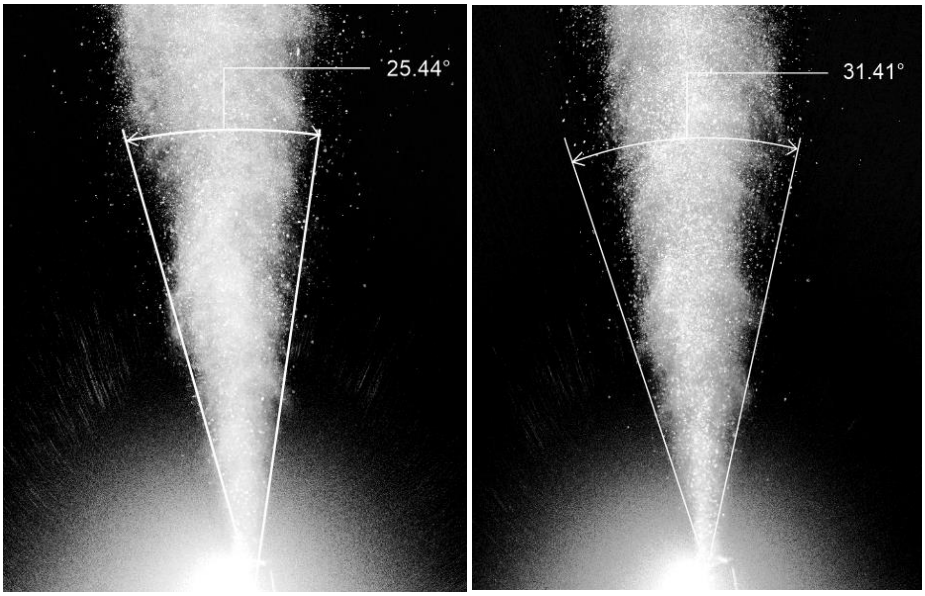
From Figure 7, we can conclude that the flame opening angle for coal without the addition of wood waste with a particle size of less than 100 microns was 24.3°. With the addition of 25% woody biomass, the flame opening angle increased by 4.7%, and with an equal weight ratio of the wood component and coal, the flame opening angle increased significantly by 29.3% compared to the angle with the coal flame opening angle without the addition of sawmill waste. Hence, it can be concluded that the joint grinding of fuel compositions will positively affect the subsequent atomization of such fuels.

Typical images of the results of experiments on spraying a wood–coal mixture prepared together are shown in Figure 8.



(**a**) (**b**)

Figure 8. *Cont.*



(**c**) (**d**)

Figure 8. Change in the spraying angle of mixed fuels prepared together and sprayed at a pressure of 3 bar ((**a**) coal 100%_wood 0%; (**b**) coal 90%_wood 10%; (**c**) coal 75%_wood 25%; (**d**) coal 50%_wood 50%).

An analysis of Figure 8 allows us to conclude that the joint grinding of mixed fuels leads to a significant increase in the opening angle of the flame, with the proportion of the wood component in the mixture of more than 10%. At the same time, we can see the absence of a wave process of spraying; the mixture of coal dust and sawdust is thicker and more uniform throughout the torch jet. This synergistic effect is essential to justify the use of pulverized fuel compositions in power boilers at thermal power plants.

For the clarity of comparison of the opening angles of the flames of mixed fuels, these angles were compared for fuel compositions prepared using various methods and sprayed at a pressure of 3 bar. The comparison results are shown in Figure 9.

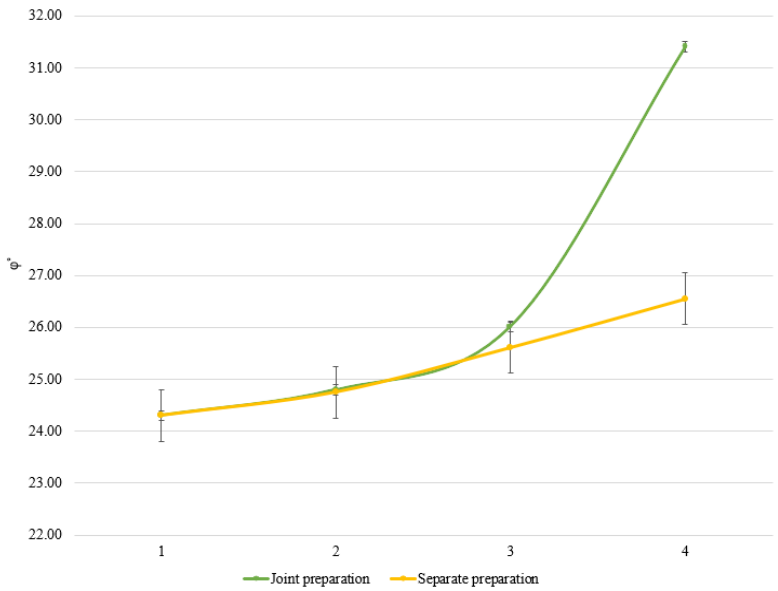


Figure 9. Comparison of changes in the jet spraying angle of different compositions of mixed fuels, fuel preparation methods and at constant pressure (1—100% Coal/0% Wood; 2—90% Coal/10% Wood, 3—75% Coal/25% Wood, 4—50% Coal/50% Wood).

An analysis of Figure 9 makes it possible to visually compare the influence of the grinding method on the process of spraying mixed fuels based on coal and wood waste (pine sawdust). Studies have shown that with the proportion of the wood component in the mixture of up to 25% percent, there is no significant difference in how to grind and mix the fuel components, while the opening angle of the torch practically does not change. This cannot be said about an increase in the wood component in the mixture by more than 25%. The flame opening angle begins to change significantly upward, which is a positive synergistic effect. With a wide opening angle of the torch, the fuel is sprayed more evenly over the furnace.

The analysis of typical photographs of spraying fuel mixtures (Figure 8) during joint grinding showed a denser fuel flow, with a uniform distribution of particles of both the coal and sawdust.

Satisfactory repeatability of experimental results was established when using mixed fuels identical in composition and differing only in the concentration of the main components. It was established that the repeatability of experiments is the highest during stable spraying. The repeatability of the studies was checked for each experiment at least five times.

The results of the calculations of random errors are shown in Table 2.

Table 2. Results of analysis of random measurement errors.

Pressure, Bar	**3**			
Composition of the mixture (coal/wood)	100/0	90/10	75/25	50/50
The average value of the jet spraying angle, $\overline{a}$,	24.297	20.360	25.442	31.410
Random measurement error, $\Delta S_{\overline{a}_i}$	1.146	0.559	1.488	0.377
Standard error, %	4.718	2.746	4.850	1.201

The analysis of the measurement errors showed that the standard deviations of measurements do not exceed 5%, which is a sufficient and reliable result of measurements of flame opening angles. Random errors do not exceed 1.5%, which also indicates the quality of the experimental studies.

The results of the measurement error analysis allow us to conclude that the joint grinding of coal and wood contributes to the production of fine particles, with a size passing through a sieve of 80 microns. This result made it possible to establish a synergistic effect not only for the grinding of mixed fuels, but also obtaining a significant increase in the flame opening angle when spraying mixed fuels with different ratios of coal and wood in relation to each other.

4. Conclusions

Based on the research results, the following conclusions can be drawn that the joint grinding of coal and wood waste leads to a significant synergistic effect; for example, the mixture is more uniform in particle size less than 80 microns. This detected effect will allow the fuel to heat up and ignite more efficiently in the furnace space. Fine particles obtained by co-grinding have led to a new significant effect. Such fuels are atomized more evenly through a pneumatic nozzle, with a significant increase in the opening angle of the flame for a mixture of coal/wood by weight of 50%/50% compared to the atomization of coal alone at the same pressure. The research results confirm the hypothesis put forward at the beginning of the research that the joint grinding of coal fuels and sawmill waste, and their subsequent joint combustion in a pulverized coal burner, is possible and quite effective without significant changes in the design of the burner and the furnace space.

When using the proposed fuel preparation technology, creating a second line for the preparation of wood fuel is not expected, which will significantly reduce the costs for the CHP needs.

Author Contributions: S.Y.: Writing—Review and Editing, Supervision, Conceptualization, Validation, Project Administration. A.M.: Validation, Data Curation, Writing, Investigation. A.B.: Visualization, Investigation. M.V.: Visualization, Investigation. N.Y.: Visualization, Investigation, Research. All authors have read and agreed to the published version of the manuscript.

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