

Article

The Impact of Fuel Type on the Output Parameters of a New Biofuel Burner

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Abstract: Intensified action aimed at reducing CO₂ emissions and striving for energy self-sufficiency of both business entities and individual consumers are forcing the sustainable development of environmentally friendly and renewable energy sources. The development of an appropriate class of equipment and production technology is not without significance in this process. On the basis of a proven design for a combustion burner for ecological fuels, a new biofuel burner, also dedicated to prosumers' energetics, was built. The aim of the study was to determine the effect of the type of biofuel on a burner's output parameters, especially gaseous emissions, during the combustion of four types of fuels, including three types of biomass. The combustion temperature was measured for lignite, wood pellets, straw pellets, and sunflower pellets. An analysis of exhaust gas composition was performed for lignite and wood pellets. The results of exhaust emissions and combustion temperatures were compared with the burners currently in use. The use of a new burner might contribute to cleaner combustion and reducing the emissions of some gaseous components.

Keywords: biofuel burner; combustion; ecological fuels; energy management; cleaner combustion

1. Introduction

Declining reserves of fossil fuels [1,2] and a marked increase in their prices combined with the emission of dangerous and harmful carbon dioxide into the atmosphere are just some of the factors that cause interest in renewable energy sources [3,4]. In addition to energy from water, wind, or solar radiation, biomass is the most commonly used source of renewable fuel [5,6]. Its importance as a clean, inexpensive, and renewable source of energy is clear, particularly when it is produced from agricultural and forestry remains [7,8].

The moisture content of biomass has a significant impact on the content of flammable parts in ash and slag [9,10], the combustion efficiency [11,12] and the place of ignition [13,14]. A high content of water vapor in the flue gas reduces the temperature in the furnace, thus reducing the combustion temperature [15,16]. Delivering to the burner a fuel with proper grinding and humidity [17,18], maintaining the appropriate level of air gradation, and even guaranteeing optimal temperature and burning time [19,20] are the parameters guaranteeing correct ignition, complete and total combustion, as well as low emission of pollutants in the exhaust gases [21,22].

Biomass resources can be a fuel for a number of large steam power plants as well as for small production plants [23,24]. Combustion can be carried out using devices and installations designed exclusively for biomass, but also as an auxiliary fuel for coal combustion [25,26]. As in the case of coal, biomass is burned in boilers with a dust or grate furnace [27,28].

Knowledge of the parameters affecting the combustion process positively and unfavorably allows for improvement and proper selection of fuel for a given type of furnace chamber [29,30].

Also, the design of burners for various fuels has become a research priority, searching for optimal flame structure and temperature distribution to assure the most effective combustion [31,32].

Similar strategies are involved in the construction of burners for biofuel combustion. Biomass burning boilers should contain two separate spaces: one for degassing and one for burning a complete part of volatile fuel products [33,34].

The ecological fuel burner consists of a furnace assembly, air preparation and supply unit, fuel tank connected by a screw conveyor with a combustion chamber, and ash gutter with auger assembly of ash extractor (the invention is protected by Polish Patent No. 221180—Boiler for ecological fuels, especially brown coal). The combustion chamber is cylindrical and has left-handed or clockwise openings through which the air is forced through the air preparation and supply unit. In addition, the combustion chamber has, in the upper part, a hot exhaust outlet connected to a heat exchanger. Outside of the combustion chamber there is a hopper, which is connected with a combustion chamber using a screw conveyor. In addition, in the lower part of the combustion chamber there is an ash gutter with blast nozzles, and below the ash gutter there is a screw conveyor of ash extraction. The combustion chamber is partially surrounded by a water cooling unit with heat recovery. The main advantage of the burner is the possibility of using ecological fuel (such as wood chips, briquettes from sawdust, and other fuels), which is rarely used due to the high water content. The pre-drying and drying system that takes place during the transport of fuel to the combustion chamber increases the energy value of the fuel and the vortex motion in the chamber allows for effective combustion. Another advantage is the high combustion efficiency of 94% (in the case of brown coal).

The aim of the study was to determine the effect of the type of biofuel on a burner's output parameters, especially gaseous emissions, during the combustion of four types of fuels, including three types of biomass. The new biofuel burner is compared with the old burner for use with ecological fuels. The combustion of lignite, wood pellet, straw pellets, and sunflower pellets was analyzed, mainly having in mind the flame behavior, temperature distribution, and gaseous emissions.

2. The Design of a New Biofuel Burner

The construction of a new biofuel burner was created on the basis of the invention described above. The idea for a new version of the burner called a new biofuel burner was to reduce the burner's dimensions while maintaining the thermal efficiency of the device.

Differences and similarities between the burner for ecological fuels and the new biofuel burner are summarized in Table 1.

Table 1. Comparison of the new and old designs of burners for ecological fuels.

Construction Element	New Biofuel Burner	Burner for Ecological Fuels
Hopper	100 kg	300 kg
Drying of the fuel	using the heat of combustion	additional fan placed at the hopper
Fuel feeding	screw feeder driven by a motoreducer	screw feeder driven by a motoreducer
Supply of combustion air	through openings in the combustion chamber	through right- or left-handed holes in the combustion chamber
Preparing the combustion air	The fan placed in the upper part of the combustion chamber	The fan placed on the side of the combustion chamber
The outlet of hot exhaust gases	in the axis of the screw feeder	when the holes are left-handed-on the left side; when the holes are clockwise-on the right
Control of the device	control panel	control panel

The new biofuel burner is smaller, simpler in design, and contains fewer components—which reduces the risk of device failure. What distinguishes it from the previous version is a built-in fuel degassing system and ash cooling system protecting against slagging (sinking).

The new biofuel burner is equipped with a fuel drying system that uses warm air from the combustion process. Since the drying is achieved by means of the hot air being the byproduct of a system, it increases the thermodynamic effectiveness of the device. A fan that causes a swirl movement of gases is placed in the upper part of the combustion chamber, where volatile parts of the fuel appear. Similarly to the first solution, the new biofuel burner is equipped with a charging hopper, a screw feeder embedded in the pipe, a cylindrical combustion chamber with a water jacket, and an automatic ash extraction system. The schematic picture of the burner is shown in Figure 1. A biofuel burner, due to its dimensions, can be placed on the trolley to create a mobile system for the production of process steam, in the event of the failure of a regular source of steam in large industrial plants. Also, the small dimensions of the new burner extend the application towards a wider range of consumers with smaller heating power needs.

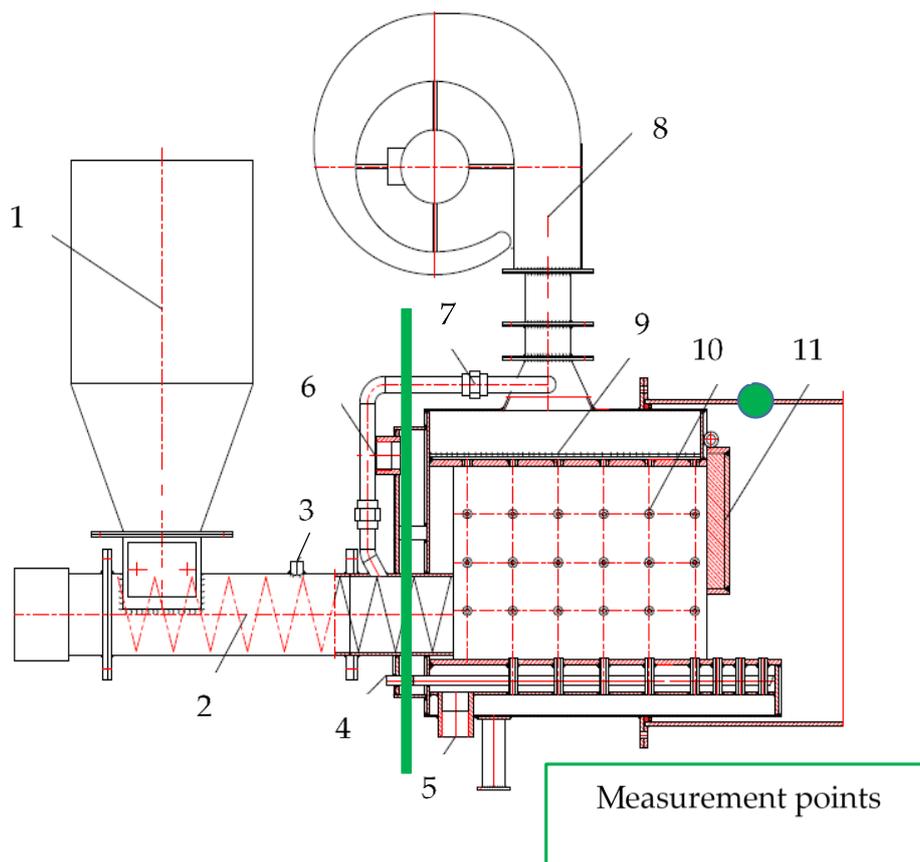


Figure 1. Points for biofuel burner measurements: 1—hopper; 2—screw feeder; 3—fire protection; 4—ash extraction with desludging the burner; 5—burner cooling water inlet; 6—burner cooling water outlet; 7—air supply to the screw; 8—fan; 9—air preparation unit; 10—openings supplying air to the furnace; 11—connection with the boiler.

The fuel can be supplied from the built-in charging hopper or from the storage room adjacent to the boiler room. The fuel is transported by means of a gearmotor (a device consisting of an electric motor and a gear reducer, constituting the drive of the auger, which is connected by means of a collar with a keyway). During transport, the fuel is heated and dried through the air pressed through the pipe into the screw housing. The fuel particles heat up and give off excess water, and further heating triggers the pyrolysis process. Then the fuel is directed to a combustion chamber made of heat-resistant sheet and undergo degassing. After degassing, the volatile parts of the fuel in the vortex motion burn off completely, and the solid parts are pushed into the combustion chamber of the boiler. The burner combustion pressure is approximately 0.024 MPa (0.24 bar). The flue gas under this pressure is directed

to the steam generator or steam boiler, heating the water and evaporating the steam. The burner operation is controlled by means of a control cabinet, thanks to which it is possible to control the fuel supply and the amount of air. To facilitate the operation of the burner, a controller system based on the increase of temperature and pressure was used, which enables the system to select the ratio of fuel and air, thereby ensuring the ideal composition of the combustible mixture.

Most of the biomass burning technologies currently used in burners use air vortex movement [35,36]. These constructions have a rotating combustion chamber and blades that cause a swirl of air in the combustion chamber [37–39]. A biofuel burner has a cylindrical, fixed combustion chamber, and the air vortex is forced by the fan at 1000 Pa pressure. A detailed comparison of the biofuel with other solutions available on the Polish market is presented in Table 2.

Table 2. Comparison of burners available on the market.

Parameter	Biofuel Burner	Burner Scanbio ¹	Burner Kipi ²
Efficiency [%]	94	95	96
Average power consumption [W]	2000	400	600
Fuel consumption [kg/h]	75	67	57
Hopper capacity [kg]	200 kg	No integrated fuel tank—connection required with the warehouse	1800 l
Depth of combustion chamber [mm]	687	700	631
Flue gas temperature (wood pellet) [°C]	1100	220	450

¹ The Scanbio BIOTEC torch is a retort burner controlled by a boiler thermostat. The pellets are delivered to a container inside the device, through a feeder from the fuel storage, then directed to the combustion chamber. The air supply is carried out using a fan. ² The Kipi rotor burner is a solution based on the use of a rotary combustion chamber and a blower, which eliminates the formation of ashes and gangrene.

3. Materials and Methods

3.1. Materials

The behavior of the following fuels was compared for both the old burner and the new biofuel burner. The fuels use brown coal (lignite), wood pellets, straw pellets, and sunflower seed pellets. The pine pellet, containing an admixture of deciduous trees, was manufactured by King Pellet. The straw pellets made of cereal straw was produced by Polenergia. The physicochemical properties of all fuels used are summarized in Table 3, based on the manufacturer's data.

Table 3. Physicochemical properties of the fuels.

Fuel	Parameter	Value
Lignite [40]	The calorific value	14.882 [MJ]/kg]
	Carbon (by mass)	42.2%
	Hydrogen (by mass)	3.17%
	Sulfur (by mass)	1.18%
	Oxygen (by mass)	12.27%
	Nitrogen (by mass)	0.52%
	Moisture (by mass)	31.82%
	Ash (by mass)	8.84%
Wood pellets	The calorific value	19.4 MJ/kg
	Moisture content	7.8% (measurement 10%)
	Ash content	0.47%
	Diameter	6 mm

Table 3. *Cont.*

Fuel	Parameter	Value
Straw pellets	The calorific value	14.218 MJ/kg
	Moisture content	9.3% (measurement 12.6%)
	Ash content	7.6%
	Diameter	6 mm
Sunflower seed pellets	The calorific value	18 MJ/kg
	Moisture content	9% (measurement 10.2%)
	Ash content	0.5%
	Diameter	6 mm

3.2. Methodology

The subject of the research was a comparison of the combustion of several fuels in a burner for ecological fuels and the construction of a new burner for biofuels (biofuel burner).

The following measurements were made on the same types of fuels for both devices:

3.2.1. Humidity of the Fuel

To determine the humidity of the pellets, a pellet moisture meter Tanel PEL-20 (produced by MERA Poland) with a measuring range 10–20% and accuracy of 0.1% was used.

3.2.2. Flue Gas Analysis

The following measurements were made on the same type of fuel for both devices. For the purpose of determining the composition of the flue gas, an exhaust gas analyzer TESTO 320 basic, with a measuring range of 0–4000 ppm and accuracy of 1 ppm was used.

3.2.3. Temperature Measurements

The apparatus used to measure the temperature was a thermovision camera and a pyrometer. The first temperature measurement was made one hour after lighting, the second after one and a half hours, and the third after an hour and 45 min. The accuracy and range of the measuring devices used are given in Table 4.

Table 4. Accuracy and measuring range of devices.

Device	Measuring Range	Accuracy
Thermal imaging camera	−20–1500 °C	0.1 °C
Video Pyrometer AX 7550	−50–1600 °C	0.1 °C

4. Results and Discussion

Temperature measurements were carried out at the following stages and locations in the burner:

- drying of fuel,
- fuel combustion,
- secondary air,
- inside the combustion chamber 100 mm from the axis of the burner,
- inside the combustion chamber 180 mm from the axis of the burner,
- flue gas outlet to the boiler.

The points of measurements are shown in Figure 1.

The temperature distribution profile across the burner was also determined. A graph showing the temperature distribution in relation to the diameter of the biofuel burner is presented in Figure 2.

It is seen that the temperature inside the combustion chamber is distributed symmetrically. The highest temperatures inside the combustion chamber were noted at the edges of the walls, then, approaching the axis of the screw feeder, they decreased; whereas at the same fuel inlet from the feeder to the chamber a temperature rise was again noted. The laboratory combustion curve from the literature coincides with the results of the measurements carried out on the burner, except for lignite (Figure 2). The results of the measurements of the fuels are presented in Table 5.

Table 5. Temperature of combustion for the fuels studied.

Measurement Point	Measurement Number	Temperature of the Lignite Combustion [°C]	Temperature of the Wood Pellet Combustion [°C]	Temperature of Straw Pellets Burning [°C]	Temperature of the Sunflower Pellet Burning [°C]
The air pipe for drying the fuel	I	480	600	440	580
	II	500	621	448	587
	III	502	615	452	584
Fuel inlet to the combustion chamber	I	322	545	360	539
	II	350	604	378	542
	III	348	608	375	542
External wall of the combustion chamber	I	978	1167	904	1087
	II	991	1142	892	1111
	III	1000	1169	897	1100
100 mm distance from the screw	I	408	408	256	370
	II	433	433	249	371
	III	429	429	251	370
180 mm distance from the screw	I	760	760	694	854
	II	799	799	690	859
	III	802	802	694	862
Exhaust gas outlet	I	1064	1209	1002	1201
	II	1103	1250	987	1215
	III	1100	1244	990	1218

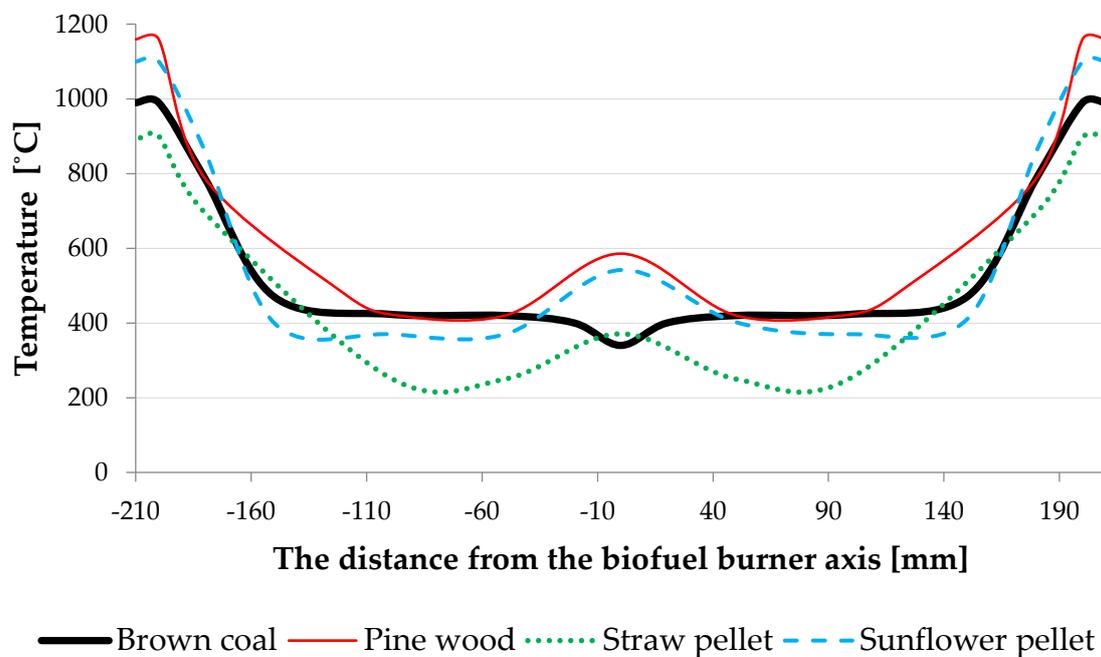


Figure 2. Comparison of the results of combustion of various types of fuels in the biofuel burner.

4.1. The Exhaust Gas Analysis

To determine the emission level of the burner (in the case of brown coal) and check whether it meets the emission standards regarding the content of impurities in the flue, the gas analysis was compared to the requirements of PN-EN 303-5/2012. The results are summarized in Table 6.

Table 6. Results of measurements from the exhaust gas analyzer.

Exhaust Gas Component	Measurement	Requirement of the Standard
O ₂	7.7%	met
CO ₂	9.8%	met
CO	68 ppm 116 mg/kWh	met
NO	5 ppm 14%CO ₂	met
NO _x	12 g/kWh	met

4.2. Summary of Biofuel Burner Characteristics

To determine the total power of the steam generator equipped with the new biofuel burner, it was necessary to calculate the power of the steam boiler, the power of the cooling system of the burner, and the chemical energy of the fuel burned.

In the case of characteristic values of exhaust gases, calculations were made only for lignite, because of all the fuels used for testing, only in the case of brown coal are the fuel composition reports generally available. The composition of lignite is presented in Table 3. The results of all calculations are presented in Table 7.

Table 7. Summary of calculation results.

Parameter	Value	Unit
The power of steam boiler	232	kW
The power of the cooling system	20.32	kW
Chemical energy of the fuel	310	kW
The total power of the system	292	kW
System efficiency	94	%
The minimum oxygen mass demand for burning	1.268	kg O ₂ /kg fuel
Minimum oxygen molar demand for combustion	0.03963	kmol O ₂ /kg fuel
Minimum combustion air requirement	0.1887	kmol air/kg fuel
Actual air demand for combustion	0.302	kmol air/kg fuel
Total amount of damped moist exhaust gas	9.6781	kg moist exhaust gas/kg fuel (without ballast)
Composition of moist exhaust gas: CO ₂	0.1599	kg CO ₂ /kg moist exhaust gas
Composition of moist exhaust gas: SO ₂	0.0025	kg SO ₂ /kg moist exhaust gas
Composition of moist exhaust gas: N ₂	0.6909	kg N ₂ /kg moist exhaust gas
Composition of moist exhaust gas: O ₂	0.786	kg O ₂ /kg moist exhaust gas
Composition of moist exhaust gas: H ₂ O	0.0681	kg H ₂ O/kg moist exhaust gas
Flux of part of fuel without ash-ballast	0.019	kg/s
Mass flux of moist flue gas flow	0.18	kg/s
Emission CO ₂	103.63	kg/h
Emission SO ₂	1.62	kg/h
Emission N ₂	447.7	kg/h
Emission O ₂	50.93	kg/h
Emission H ₂ O	44.13	kg/h
Emission of dust	0.0663	kg/h

It can be concluded from Table 7 that, e.g., the ash content in flue gas is as low as 0.01% (mass), which appears rather low as compared with the data for classical burners [41,42].

The latter source [42] also reports higher CO₂ content in exhaust gas (11.6%, while our biofuel-burner has 9.8%). It can be concluded, therefore, that higher air excess is assured by the controlling unit, which also results in better combustion.

The brown coal combustion temperature was 1000 °C. Lignite is one of the fuels containing the highest water concentration. When air is injected into the tube with an embedded worm screw, the

fuel starts to evaporate and the drying temperature is reduced from 500 °C to 340 °C. At the outlet from the burner to the boiler, the flue gas reached a temperature of about 1100 °C. Ash and moisture reduce the heating value of lignite and, consequently, the output parameters of its combustion.

During the combustion of wood pellets made of sawdust from pine wood, the temperature was read at 1160 °C; at the inlet of the pellet to the furnace the temperature reached 585 °C, and the secondary air temperature was 612 °C. In terms of temperature and emission performance, it is the recommended fuel for this type of equipment.

Straw as biomass for combustion is an attractive fuel due to the low price and high availability. The main problem when operating straw-fired machines is the high silicon content. During harvesting and storage, a large amount of sand accumulates, which during combustion leads to sintering, resulting in a shortening of the life of the burner. In addition, ash from incombustible straw substances has a low melting point of about 95–105 °C, which also results in slagging of the furnace. The combustion temperature compared to other fuels is lower, at 993 °C, and the drying temperature during transport is 371 °C. It can be concluded, therefore, that straw is not an appropriate fuel for the constructed burner.

Pellets from the sunflower husks used for measurements were made with an admixture of sawdust from deciduous trees and oak wood, which increases the calorific value and reduces the susceptibility to sintering. The ash obtained from combustion can be used as an organic fertilizer. The fuel inlet temperature for the combustion chamber is 541 °C, 1100 °C combustion, and the exhaust outlet 1211 °C.

Calculations of exhaust emissions were made using lignite data as it is the only fuel with an elementary chemical composition report. As a result of combustion in the biofuel, there is emission of moist exhausts, i.e., those in which there is water in the form of water vapor. Gases like N₂, O₂, and H₂O are neutral for the environment because they are present in the air. The CO₂ emissions were determined to be 103.62 kg/h, while those of sulfur dioxide (SO₂) were 1.62 kg/h.

The main design strategy of the new biomass burner design was to reduce its size while maintaining combustion efficiency. Analyzing the measurements made and the temperature values read from the burner controller for ecological fuels (Table 8), it can be concluded that the assumption has been met.

Table 8. Comparison of the combustion temperature of the new and old burner designs with ecological fuels.

Fuel Type	Biofuel Burner—Combustion Temperature [°C] *	Ecological Fuel Burner—Combustion Temperature [°C] **
Brown coal	1089.00	1100
Wood pellets	1234.33	1250
Straw pellets	993.00	1000
Sunflower pellets	1211.33	1200

* Based on our own measurements. ** Based on readings from the control device.

The correctness of the results of the conducted tests was also verified by comparison to the values of fuel combustion in a swirl burner presented in [43], considered as a reference.

The fuel whose combustion guarantees very good burning parameters and favorable economic and ecological estimates is fine brown coal [44,45]. The calorific value of granulate 0–20 mm is 9–15 MJ/kg, and the combustion temperature is around 1100 °C [46]. The ash content is only 4–9%, and the sulfur content is 0.42 ± 0.90% (the sulfur content in bituminous coal is 5–12% and is a factor causing corrosion and shortening the life of the burner and the boiler) [47,48]. For comparison, the calorific value of lignite pea coal (granulation: 20–30 mm) is 10–15 MJ, and that of brown coal (granulation: 40–250 mm) is 10–20 MJ. High-calorific brown coal fine imported from the Czech Republic is also available on the Polish market (granulation 0–10 mm, average calorific value 16.9 kJ/kg, average ash content 13.1%, average sulfur content 0.84%, average humidity 29.7%) [49].

The results of the present investigation show that this classic fuel can be replaced by several types of biofuels when an appropriate burner design is used. For comparison, wood pellets and briquettes are burned at a temperature of about 1250 °C, with a calorific value about 19 MJ/kg. Wood chips and energetic willow have a lower thermal efficiency due to the increased humidity. Their combustion temperature is within the range 900–1000 °C. Cereals and straw briquettes reach temperatures up to 1100 °C with a calorific value of 8–14 MJ/kg. Pellets from sunflower husks reach combustion temperature at 1200 °C, and their calorific value is 17–19 MJ/kg [50]. Ash as a secondary product can be used for soil fertilization in agriculture and horticulture [51,52].

5. Conclusions

In the above study, the object of the research was the comparison of the performance of several fuels in a burner for ecological fuels and a new biofuel burner. Based on the conducted analyses, it can be stated that:

- The fuel that achieved the best burning parameters was wood pellets made of pine. Its calorific value is 19.4 MJ/kg and the combustion temperature was 1235 °C.
- In the case of lignite, the average exhaust gas temperature was 1089 °C; for straw pellets it was 993 °C, and for sunflower pellets 1212 °C.
- The measurements made with the exhaust gas analyzer show that the proposed burner solution meets the emission standards regarding the content of impurities in the exhaust.
- The laboratory combustion curve from the literature coincides with the results of the measurements carried out.
- It should be noted that especially emission of ash from a modernized burner is lower than from a traditional one.

Due to the wide application possibilities of the proposed biofuel burner construction, its installation in industrial plants can be an effective pro-ecological solution through cleaner combustion and the reduction of harmful emissions.

It should be emphasized that the problem of air pollution in heating not only applies to the fuel used; the technique and appropriate combustion technology are also important. The wider introduction of such burners, even on the local scale, will ultimately aid the global struggle for a cleaner atmosphere.

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