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Combustion Analysis of Mixed Secondary Fuel Produced from Agro-Biomass and RDF in a Fluidized Bed

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Abstract: In recent decades, there has been growing interest in the thermal conversion of various alternative fuels, such as biomass and waste-derived fuels. One of the technological solutions for the so-called direct co-combustion of fuels is to create mixtures of various fuels, called mixed secondary fuel. However, mixed secondary fuel has different properties compared to primary fuels. Due to this, by properly selecting the types and proportions of mixtures, it is possible to eliminate their potentially negative impact on both combustion technology and the natural environment. In this paper, we decided to prepare mixed secondary fuel by mixing sunflower husk pellets with RDF (refuse-derived fuel) in a ratio of 1:1 and then analyze the combustion process of the produced fuel in fluidized bed conditions. The results obtained on the basis of the presented research indicate that the mixed secondary fuel eliminated the impact of alkali metal compounds on reducing the melting point of ash and, consequently, on the combustion process of the mixed secondary fuel. An additional benefit is the reduction of emissions of harmful compounds into the atmosphere occurring during the combustion of municipal waste and compliance with the concept of the circular economy.

Keywords: biomass; refuse-derived fuel; mixed secondary fuel; circular economy; pellet; fluidization; combustion

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1. Introduction

Over the past few years, fuel and energy markets and energy policies around the world have changed significantly [1–5]. As a result of the pandemic and the slowdown in the global pace of economic development, there has been a systematic increase in fuel prices and increasingly frequent concerns about the security of energy supply [4,5]. A global transformation of the energy system is becoming inevitable. To achieve lasting changes, including a significant reduction of greenhouse gas emissions or a reduction of our dependence on fossil energy resources, appropriate actions are necessary [6]. In addition to renewable energy sources, there is a possibility of implementing other alternative fuels, such as fuels from waste, in the global energy sector on a much larger scale. In Poland [7], the Regulation of the Minister of the Economy of 16 July 2015, with regard to allowing waste to be stored in landfills (*Journal of Laws of 2015*, item 1277) [8], introduced criteria allowing waste to be stored in facilities intended for this purpose. Pursuant to this regulation, collected municipal solid waste and waste generated during the dumping of municipal solid waste cannot be stored in landfills for waste other than hazardous and neutral if their heat of combustion is higher than 6 MJ/kg. However, this waste can be recovered. One way is the thermal transformation process.

The use of biomass and waste fuels in combustion and co-combustion processes allows for the acquisition of satisfactory energy effects, thus becoming a good complement to fossil fuels. These fuels are characterized by a high level of availability, ensuring the continuity of supply and the ability to reduce the emissions of harmful compounds into the atmosphere. The impact of biomass and waste fuels on reducing CO_2 emissions is particularly important.

The combustion of biomass results in emissions that are considered CO_2-neutral. Similarly, in the case of biodegradable waste, its thermal conversion may also qualify as recovery from renewable energy sources.

However, it should be remembered that biomass fuels and fuels from waste are characterized by variable physicochemical properties that are unstable over time, which may lead to a number of technical problems [9].

Biomass is a fuel that can be imported or supplied locally and may include the following:

1. Waste from forestry, wood processing (e.g., sawdust) [10,11], and agriculture (e.g., wheat chaff);
2. Waste from the paper and sugar industries, as well as waste from food production, e.g., husks (e.g., almonds, sunflower seeds, olives, walnuts, palm kernels, and cocoa);
3. Dedicated energy plants, including woody plants with a fast growth rate, such as herbaceous plants and millet, which are agricultural plants and can be grown solely for the purpose of using them as biomass fuel [12].

On the one hand, the versatile nature of biomass allows it to be used in all parts of the world [13]. On the other hand, this diversity makes biomass an extremely difficult fuel. The main reason is that some types of biomass have a very high content of alkalis, mainly potassium and chlorine, which can cause problems during combustion. The rational use of solid biomass of non-forest origin requires prior identification of its fuel properties. The most important components of biomass include chlorine, potassium, sulfur, nitrogen, and silicon. One of the most significant elements causing problems when combusting biomass is chlorine. In some types of biomass, it occurs in large amounts, e.g., in straw, which may cause corrosion. The high percentage of silicon together with potassium and chlorine plays an important role in the strong ash deposition on heat transfer surfaces at high or moderate combustion temperatures. The main sources of these problems are as follows:

(1) The reaction of alkali compounds with silica to produce alkali metal silicates that melt or soften at low temperatures (temperatures may be lower than 700 °C, depending on the composition of the biomass);
(2) The synthesis reaction of alkali compounds with sulfur, during which alkaline sulphates are formed on the heat exchange surfaces of the combustion chamber [14]. Alkaline compounds play a key role in both processes, and potassium is the dominant source of alkali in most biomass fuels [15,16].

Potassium compounds contained in ash easily settle on heat exchange surfaces, forming deposits. For example, on the surfaces of superheaters, a deposit is formed, which consists mainly of the following: CaO, $CaSO_4$, and K_2SO_4 and hardens under the influence of temperatures >500 °C, thus increasing the heat transfer resistance. Chlorine compounds contained in biomass additionally increase the contamination of the heat exchange surface and significantly increase the risk of high-temperature corrosion in the superheater.

Next to biomass, the second type of fuel with huge potential is RDF (refuse-derived fuel). This is a type of alternative fuel resulting from the processing of municipal waste—MSW (municipal solid waste) and selected industrial waste [17]. Depending on its composition, RDF has a calorific value in the range of 10–25 MJ/kg (in working conditions), which makes it attractive as a fuel or co-fuel in many industrial processes. Its composition varies depending on the region. Various socio-economic parameters (population, lifestyle, per capita income, and education) and weather conditions influence the quantity and quality of waste generated. The most common ingredients in RDF fuels produced from MSW are as follows: paper/cardboard (40–50%), plastics (25–35%), textiles (10–14%), and wood (3–10%) [17]. This composition may vary depending on the type of input, geographical location, season, and processing technology. Each category of waste components (textiles, wood, paper, or plastics) is characterized by huge variability at the level of material or chemical compound [18]. Natural materials are used to produce textile products, e.g., cotton, but also synthetic materials, such as polyester [19]. Natural fibers consist mainly of cellulose, which is a natural biomass polymer, while synthetic fibers are mainly produced from poly-

mers based on fossil raw materials [20]. The same is true for paper/cardboard waste, as the raw materials used to produce paper can be divided into two categories: woody materials such as coniferous and deciduous tree fibers, and non-woody materials, such as grasses, cereal straws, corn stalks, bamboo, and pomace. The typical content of biopolymers in RDF fuels is 50–65%, which is expressed as energy. Therefore, fuel from waste is attractive as an alternative fuel, while being partially renewable and carbon-neutral.

In terms of RDF fuels, the most common are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) [21]. The quality of RDF fuels can be improved by concentrating only on the appropriate combustible fractions (such as plastics, packaging composites, textiles, etc.) and removing physical impurities (glass, stones, ferrous, and non-ferrous metals). Materials with high chlorine content are undesirable, and their removal is considered a priority [22]. It is also beneficial to collect waste electrical and electronic equipment, thermometers, batteries, paints, and galvanized metals separately, which can reduce the mercury and cadmium content of alternative fuels produced.

Due to the above, it should be emphasized that during the processes of combustion and co-combustion, the physical and chemical properties of fuel mixtures are important and affect the efficiency of the process and the characteristics of the by-products. The selection of appropriate combustion technology for the appropriate fuel mixture is considered an important condition for the effective combustion/co-combustion of biomass and alternative fuels.

Direct co-combustion of fuels is often achieved by creating mixtures of various fuels, called mixed secondary fuel [23]. Currently, the commercial power industry is dominated by the joint grinding of coal and biomass. Examples of mixed secondary fuels are brown coal with wood briquettes and hard coal with sunflower husks. Mixing fuels and using various fuel additives can improve their parameters.

Granulation and briquetting are very often mentioned among the methods of improving the properties of fuels from waste and biomass. In order to further improve the properties of fuels produced from biomass, the authors of the works [24–31] proposed the modification of biomass pellets by using various additives, including materials obtained from waste.

The work [24] examined the mechanical properties and the combustion process of biomass pellets, where coal tar residues from CTR gasification (coal gasification tar residue) were used as a binder. The research analyzed pellets from wheat straw, sawdust, moso bamboo, and XiMeng lignite using CTR as a binder. CTR is a type of toxic, hazardous industrial solid waste generated in the gasification or coking process of coal, consisting of heavy tar oil, coal dust, and other solid particles carried in the gases produced during the pyrolysis of coal. According to studies [24–28], CTR contains carcinogenic polycyclic aromatic hydrocarbons (PAHs). The addition of CTR improves the mechanical properties of biomass pellets produced at ambient temperature and low pressure, which significantly reduces the energy demand for the pelletization process. CTR has also been investigated as a binder in briquette production [29].

Binders such as waste vegetable oil and waste packaging paper, among others, have also been studied in the subject-related literature in terms of their impact on the product and the pelletization process [30,31]. In [31], the properties of forest biomass pellets with the addition of used vegetable oil were examined. The addition of oil significantly increased the calorific value of forest biomass pellets, and at the same time, resulted in a deterioration of their mechanical strength. However, in work [32], the properties of wood sawdust pellets and waste wrapping paper were examined. The calorific value of sawdust and wrapping paper mixtures increased with an increasing share of wrapping paper. The process of pelletizing wrapping paper with sawdust is a cost-effective way to prepare sustainable and CO_2-neutral biofuels from wood sawdust and to dispose of paper waste.

In [33], it was proposed to create moisture-resistant wood pellets by adding a hydrophobic coating, which also contributes to an increase in the calorific value of the pellets.

The hydrophobic coating was obtained by immersing the pellets in paraffin oil, castor oil, mineral oil, and linseed oil. Two coating application methods were tested. In one method, individual granules were immersed in oil for specific times: 1 s, 2 s, 3 s, 5 s, and 10 s. It was found that in all cases, time had no effect on oil absorption, and oil absorption was essentially constant over time. In the second method, a selected mass of pellets was immersed in a beaker filled with oil and stirred for a specified time. In all cases, the weight gain due to oil absorption was smaller when it was carried out by mixing a batch of pellets than when it was carried out by immersing individual pellets. The strength of the granules without added oil was found to decrease by approximately 94% after immersion in water for 60 s, while after 1800 s in all oil-treated cases, no significant reduction in granule strength was recorded. Oil treatment was also found to reduce the formation of fine airborne particles and increase the energy density of wood pellets, thus increasing their heat of combustion by up to 1.2 MJ/kg.

Alternative types of biomass with improved physicochemical properties are used in the industry. These are composite pellets made of plastic and wood fibers. In [34], thermal, chemical, and mechanical analyses of composite fuels were carried out. Fibers of biological origin were mixed with a plastic fraction in the form of granulated solid fuel. The presence of plastic changed the thermal properties of the pellet by increasing the energy value while changing the chemical composition of gases released during the thermochemical conversion of biomass.

Of all available combustion technologies, fluidized bed combustion is often considered the best choice for the combustion and/or co-combustion of biomass, waste, and other low-grade solid fuels due to its fuel flexibility, enabling the combustion of fuels characterized by various particle sizes, densities, calorific values, and chemical compositions.

The aim of this work was to analyze the combustion process of fuel with a modified composition, i.e., mixed secondary fuel made from RDF and agro-biomass in fluidized bed conditions. Based on a literature review, it was concluded that it is possible to use RDF fuel containing paper fractions and vegetable oils to change the properties of the agro-biomass observed in work [9]. The authors of the paper [9] noticed that the combustion of agro-type biomass fuels at a temperature of 850 °C leads to the formation of sinters that threaten the hydrodynamics of the fluidized bed layer. As indicated in the literature reviews [24–32], the addition of materials derived from waste include, among others, CTR and wrapping paper as binders, which improve the mechanical durability of biomass pellets, increase the calorific value, and reduce the energy demand for the pelletization process. Due to the aforementioned information, it was decided to prepare a mixed secondary fuel consisting of sunflower husk pellets and RDF pellets in a 1:1 proportion.

2. Research Material and Research Methodology

The research material consisted of two pellet fuels available on the Polish market: those made from sunflower husks and waste (RDF). The sunflower husk pellets were obtained from the Jaworzno III Power Plant. The RDF pellets were delivered by a Polish company producing this type of fuel. Due to the company's policy, consent to publish its data was not obtained. Both types of fuel had a cylindrical shape and a diameter of 8 mm.

A technical analysis of the fuels was performed in accordance with Polish standards [35–37] for solid fuels, and the results are presented in Table 1.

Table 1. Results of technical analysis of sunflower husk and RDF pellets.

Pellets	Volatile Parts (%)	Moisture (%)	Ash (%)	Solid Combustible Parts (%)	Heat of Combustion (MJ/kg)	Calorific Value (MJ/kg)
Sunflower husk	73.8	8.4	5.5	12.3	19.8	18.3
RDF	74.4	7.4	12.1	6.0	21.3	19.6

It is worth emphasizing the significant differences (more than twofold) in the contents of ash and solid combustible parts between the fuels. The remaining ingredients, i.e., the contents of flammable parts and moisture, were at a similar level. A slightly higher calorific value was recorded for the RDF fuel.

In order to perform the technical analysis and prepare particles of mixed secondary fuel, the sunflower husk and RDF pellets were ground separately in an electric knife grinder. After grinding, the obtained samples were mixed in a previously determined proportion (Figure 1). The next stage of preparing the mixed secondary fuel was the production of pellet particles. The first tests were performed on a hydraulic press without a heating system. The obtained pellets were characterized by very low durability compared to the primary pellets. For this reason, it was decided to use a hydraulic press equipped with a heating system (Figure 2), thus enabling the matrix to be heated to the required temperature. In the described tests, the temperature was set to 100 °C. The high temperature of the pelletization process increased the density and durability of the pellets [38]. The products of the pelletization process were particles with the same diameter as the starting material—8 mm (Figure 3). This time, it was found that the pellets were very easy to produce and their durability and structure were comparable to those of the original pellets.



Figure 1. Pellets after grinding; a mixture of sunflower husk pellets and RDF (refuse-derived fuel) pellets at a 1:1 ratio.



Figure 2. Hydraulic press equipped with a heating system.



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

Figure 3. Pellets with a diameter of 8 mm: (**a**) agro biomass–sunflower husk pellets; (**b**) RDF; (**c**) mixed secondary fuel.

The prepared pellets were again subjected to technical analysis (Table 2) in accordance with the methodology described earlier. It should be noted that as a result of the grinding and pelletization processes at 100 °C, there was a slight drying of the material and, as a consequence, a slight increase in the percentage of volatile parts of the produced fuel in relation to the starting materials (Table 1). The contents of ash and solid combustible parts were between the values determined for both fuels. The determined calorific value of the produced fuel was similar to the calorific value of the sunflower husk pellets (Tables 1 and 2).

Table 2. Contents of moisture, ash, and volatile matter in pellets made from a mixture of 50% sunflower husk pellets/50% RDF pellets.

Pellets	Volatile Parts (%)	Moisture (%)	Ash (%)	Solid Combustible Parts (%)	Heat of Combustion (MJ/kg)	Calorific Value (MJ/kg)
Mixed secondary fuel	77.7	7.03	6.45	8.7	19.73	18.25

3. Analysis of the Combustion Process of the Produced Secondary Fuel in Fluidized Bed Conditions

Before starting the preliminary research, an analysis of the combustion process of the pellets used for this research, i.e., sunflower husk and RDF, was carried out at a temperature of 850 °C in selected hydrodynamic conditions.

The temperature in the fluidized bed boiler chamber is one of its most important operating parameters. The average temperature maintained in the reactor of the fluidized bed boiler during combustion was 850 °C, as this enables optimization of the efficiency of the desulfurization process and ensures low NOx emissions. At the same time, problems with the combustion of agro-biomass in the fluidized bed observed during research [9] were revealed precisely at this temperature.

The construction of the experimental station presented in detail in [9] (Figure 4) made it possible to model the conditions prevailing in the circulating fluidized bed and guaranteed the repeatability of the measurement conditions for each single combusted particle of solid fuel. During each measurement, it was possible to record the experimental data and visualize the investigated process. The station consisted of the following main elements: an inert material container, a downpipe, and a combustion chamber. The station was heated to the appropriate temperature using electric heaters with a total power of 20 kW. During the experimental tests in conditions modeling the fluidized layer, quartz sand with a particle size of 0–0.63 µm was used. Quartz sand with this particle size is used in real boilers with a circulating fluidized bed to form a layer and supplement it.

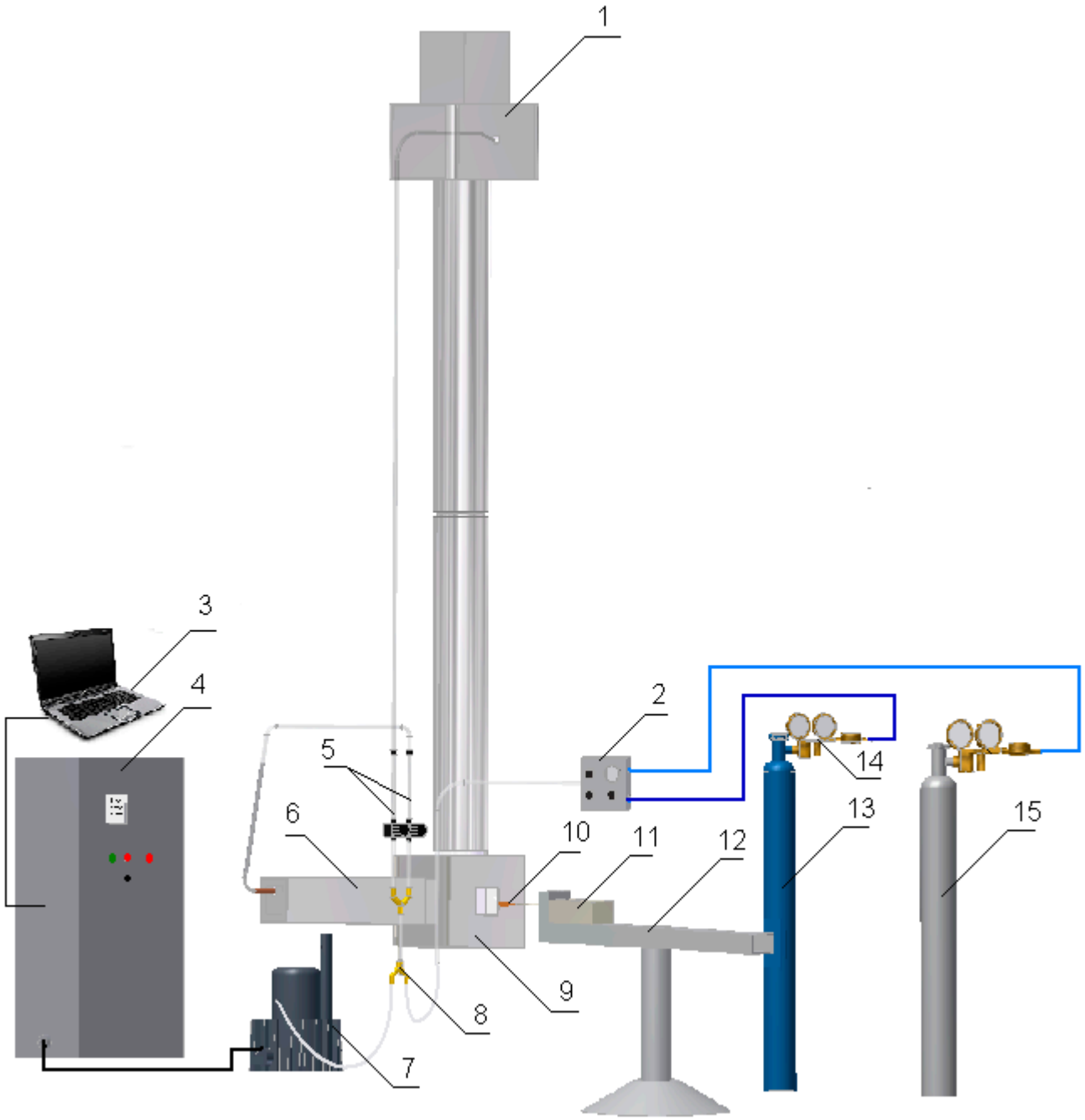

Figure 4. Schematics of the experimental station; (1) quartz sand container, (2) mixer, (3) laptop, (4) control box, (5) rotameters, (6) heater, (7) fan, (8) tee, (9) combustion chamber, (10) particle basket, (11) scale strain gauge, (12) entry platform, (13, 15) technical gas cylinders, (14) reducer.

Inert material, which was the quartz sand, was introduced into the container, where it was heated. After the inert material reached the set temperature, the remaining sections of the station were heated. When the temperatures reached the set values, a previously prepared single particle of fuel was placed on the handle of the strain gauge scale. Subsequently, the inert material's regulating valve was unscrewed to supply the inert material to the combustion chamber. After setting the selected inert material's stream intensity, the fuel particle was introduced into the combustion chamber using the strain gauge balance support. Then, the measurement recording began. When the particle mass value reached zero or remained unchanged, the measurement was stopped. In order to determine the average

mass flow of inert material Gs during the measurement, after each measurement, the mass of used sand collected in the tank located under the combustion chamber was measured.

3.1. Preliminary Research

In the first stage of the research, pellet particles from the agro-biomass and RDF were combusted in an air atmosphere without the flow of inert material, i.e., at Gs = 0 kg/m^2 s at a temperature of 850 °C. This study was intended to enable a comparison of the mass loss of fuel particles combusted at Gs = 0 kg/m^2 s with the results of the mass loss of fuel particles during their combustion in a stream of inert material of Gs > 0 kg/m^2 s.

Subsequently, an analysis of the combustion of both fuels in a two-phase flow with the participation of the inert material was carried out for Gs = 2.5 and 5 kg/m^2 s. The range of inert material concentration adopted in the research is characteristic of a circulating fluidized bed, in the so-called zone of "fast fluidization".

The results of the preliminary research confirm the conclusions obtained in [9]. During the combustion of sunflower husk pellets in a stream of inert material at a temperature of 850 °C, ash softening and the formation of sinters were observed. The results of the experimental tests on the combustion of sunflower husk pellets at a temperature of 850 °C with various concentrations of the inert material are presented in Figure 5.

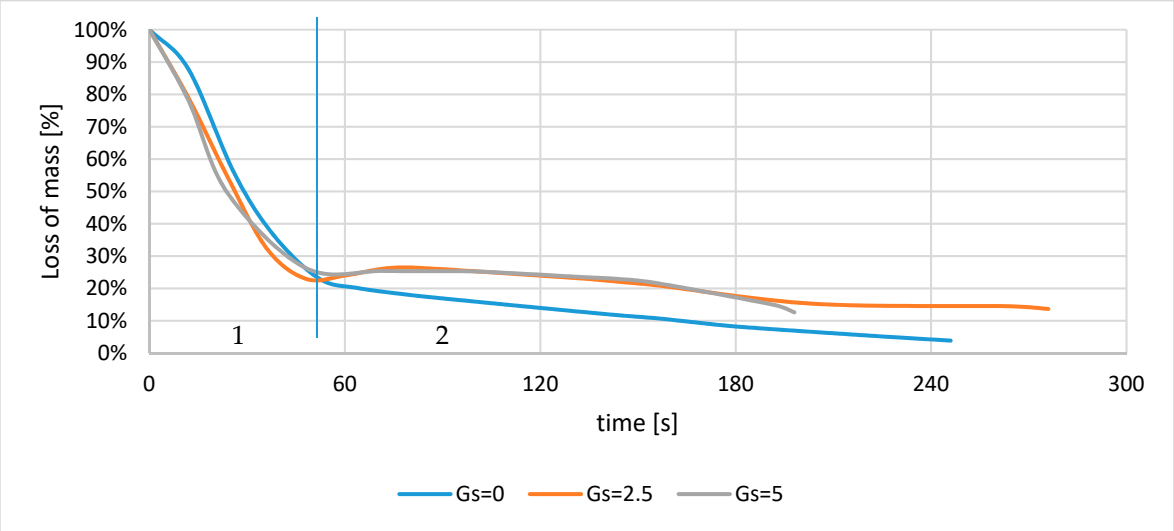

Figure 5. Mass loss of sunflower husk pellets during combustion at 850 °C at different values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s). Combustion stages: (1) combustion of volatile parts, and (2) combustion of char.

During the combustion of the sunflower husk pellets without inert material, Gs = 0 kg/m^2 s, it was possible to distinguish the characteristic stages of particle combustion. The ignition of the volatile parts occurred almost immediately after placing the particle in the combustion chamber and lasted 40–50 s, after which the char remaining after degassing was combusted.

At the end of the curve showing the mass loss, it is possible to read the average ash content remaining after pellet combustion, i.e., 4%, which is almost identical to the value obtained as a result of the technical analysis (Table 1). Pellet combustion in a stream of inert material at Gs = 2.5 kg/m^2 s lasted longer than combustion without inert material by 12%. It was noticed that at this temperature, the phenomenon of ash softening occurred, thus causing the sunflower husk pellet particle to stick to the quartz sand. The mass loss curve (from 48 s) shows a clear increase in mass. The sand stuck to the surface of the combusting particle, increasing its total mass and impeding the flow of the oxidant to the combusting surface of the particle. At the end of the mass loss curve, the final mass of the sinter formed can be seen. This is a percentage of the total pellet mass (Figure 6). Increasing

the inert material flow to Gs = 5 kg/m^2 s resulted in a further shortening of the combustion time of the sunflower husk pellets by 20% compared to combustion without inert material. When increasing the intensity of the inert material stream in the case of the sunflower husk pellets, the coating formed during combustion partially disintegrated. The chemical analysis of sunflower husk pellet ash indicates that the probable reason for the softening of the ash is the high content of potassium oxide. In the case of potassium-rich fuels, the interaction between the ash components and the inert fluidized bed material results in the formation of viscous coatings around the bed particles. The most dominant reaction is the formation of low-melting silicates during the reaction of alkali metals from fuel ash and silicon from quartz sand. The viscosity associated with the presence of a layer of silicates on the surface causes their mutual adhesion, which may ultimately lead to the inhibition of the fluidization process.



Figure 6. Residue after combusting sunflower husk pellets at 850 °C at Gs = 2.5 kg/m^2 s.

Figure 7 shows the results of the analogous experimental tests on the combustion of RDF pellets. The same scope of research was adopted for the biomass fuels tested in work [9].

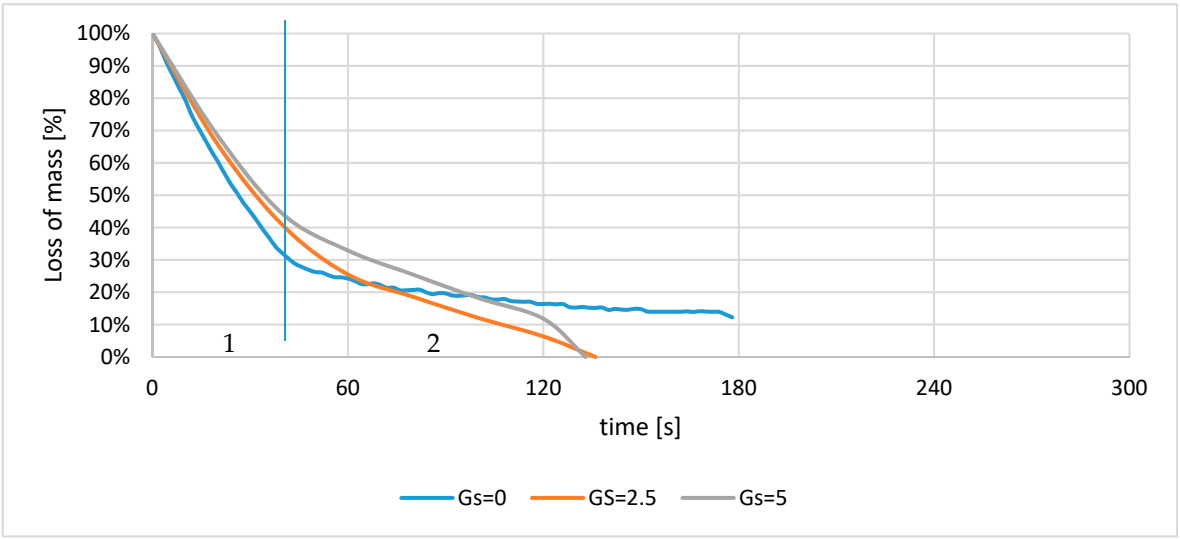

Figure 7. Mass loss of RDF pellet particles during combustion at a temperature of 850 °C at various values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s). Combustion stages: (1) combustion of volatile parts, and (2) combustion of char.

In the analyzed case, the impact of the inert material resulted in a shortening of the combustion time of the RDF pellet particles. The mere presence of the inert material had a greater impact on shortening the combustion time of RDF pellets than on increasing its intensity in the tested range. The increase in the inert material stream did not affect the fuel particle combustion mechanism but led to its intensification. Increasing the intensity of the inert material stream increases the impact of the erosive impact of the inert material

particles hitting the surface of the combusting pellet particle, which accelerates the loss of particle mass and shortens the total combustion time of the pellets. The combustion time for Gs = 2.5 kg/m^2 s was 24% shorter than without the inert material. Increasing the intensity to Gs = 5 kg/m^2 s resulted in a further shortening of the combustion time, but only by 1%.

A comparison of the results of experimental studies on RDF combustion in a fluidized bed with studies on the combustion of biomass fuels of various origins described in work [9] indicates that the kinetics of the combustion of RDF fuels at Gs = 0 kg/m^2 s are similar to the kinetics of the combustion of biomass fuels, regardless of their type. During the tests in the fluidized bed at a temperature of 850 °C, it was noticed that the combustion process of RDF fuels was more similar to the combustion process of forest biomass (Figure 8). Unlike the agro-biomass combustion process, no ash softening was observed during RDF combustion.

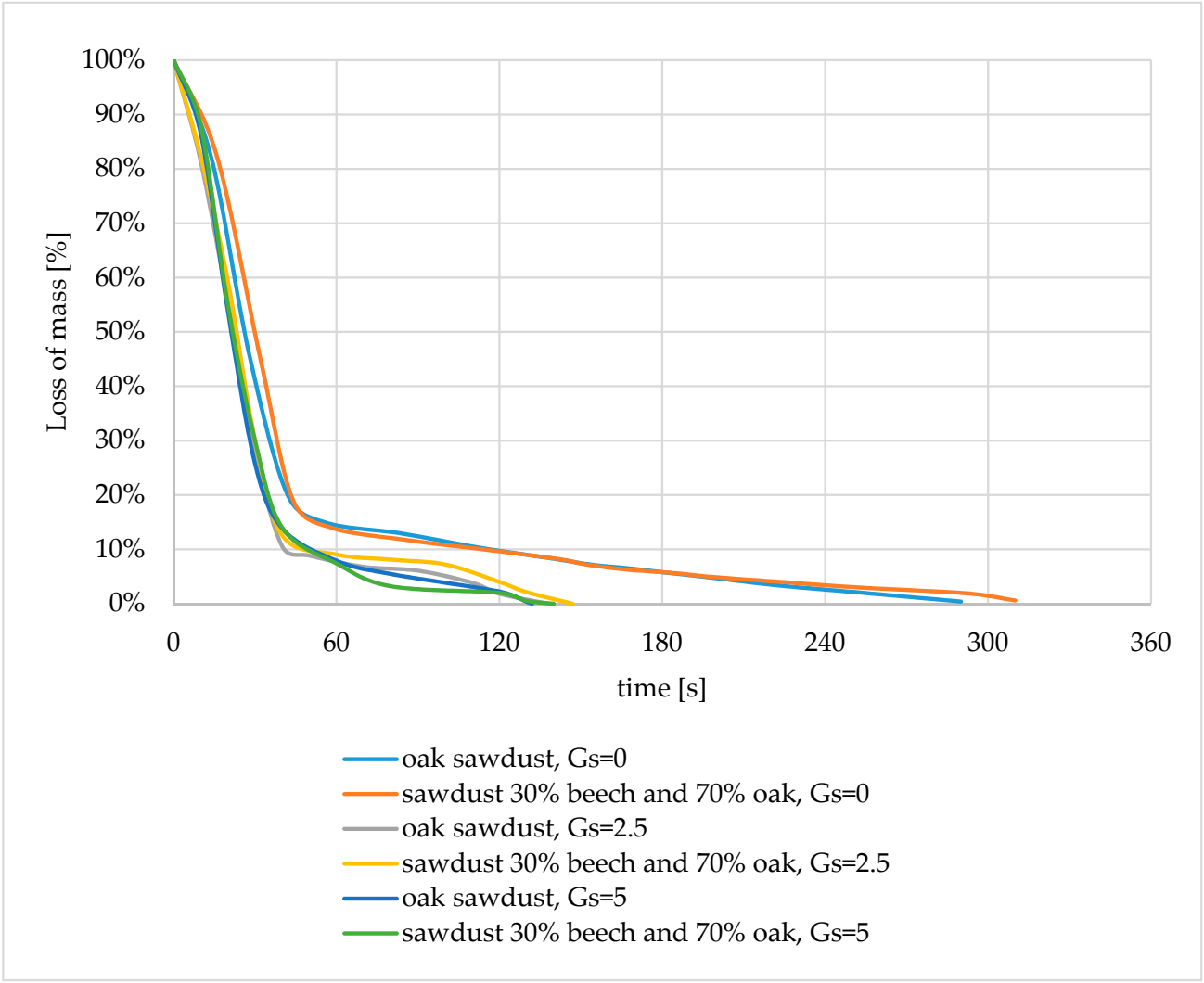

Figure 8. Loss of mass of forest biomass pellet particles: oak sawdust and 30% beech and 70% oak sawdust during combustion at a temperature of 850 °C at various values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s).

3.2. Mixture Combustion Analysis

During the basic tests of the combustion of pellets from the mixture produced, the same scope and research methodology were adopted.

As in the preliminary tests, samples of the mixed secondary fuel were combusted at Gs = 0 kg/m^2 s and at Gs = 2.5 and 5 kg/m^2 s. For each tested case, the experiment

was repeated many times to determine the representative course of mass loss. The results obtained during the experiment are presented in Figure 9. They indicate that the course of the combustion process of the mixed secondary fuel was similar to the course of the combustion of forest biomass fuels presented in [9] (Figure 8) and RDF (Figure 7). The biggest difference in the combustion processes of the forest biomass and RDF fuels was a much greater impact of the increasing inert material stream intensity on the total combustion time of the mixed secondary fuel. In the case of the forest biomass and RDF fuels, increasing the inert material stream resulted in shortening the combustion time by only a small percentage (Figures 7 and 8), while in the case of the pellets made from a mixture of sunflower husk and RDF, the combustion time was shortened by almost 30% (Figures 9–11). The reason for this situation is most likely the technological process of fuel production in laboratory conditions. The structure of the mixed secondary fuel pellets was more susceptible to the influence of the inert material compared to the starting material.

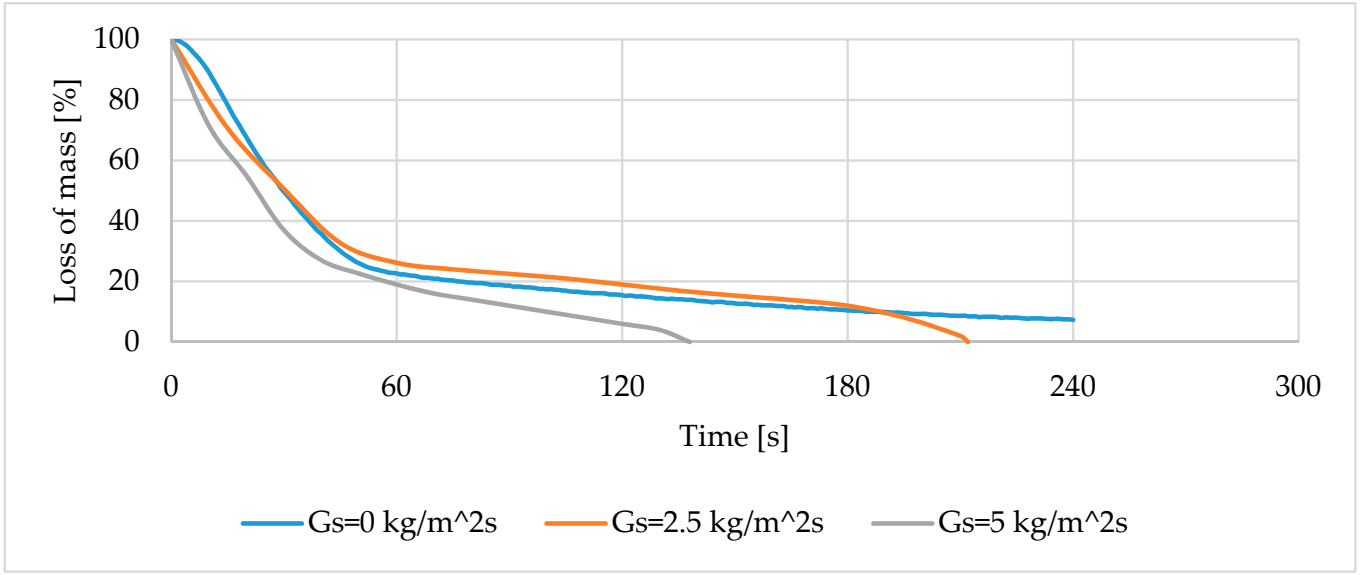

Figure 9. Mass loss during the combustion of mixed secondary fuel pellets at a temperature of 850 °C with different values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s) [39].

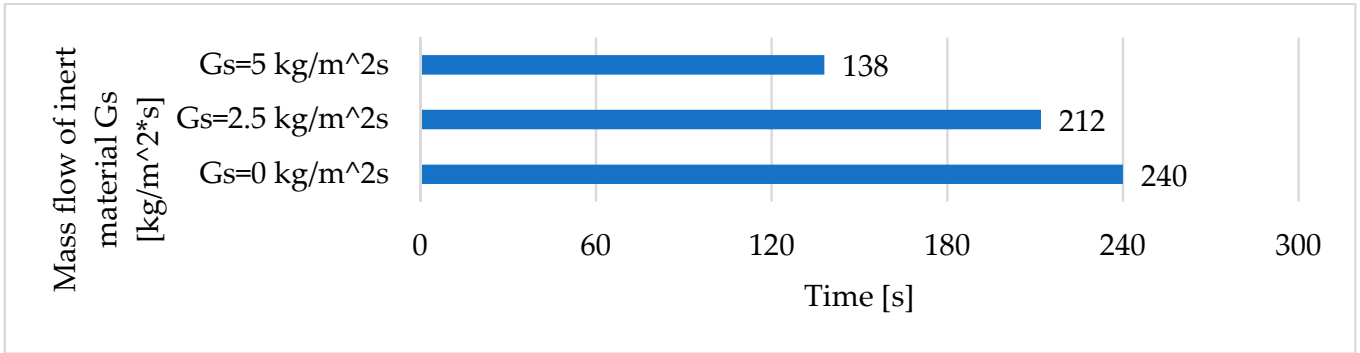

Figure 10. Combustion time of mixed secondary fuel at a temperature of 850 °C with different values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s) [39].

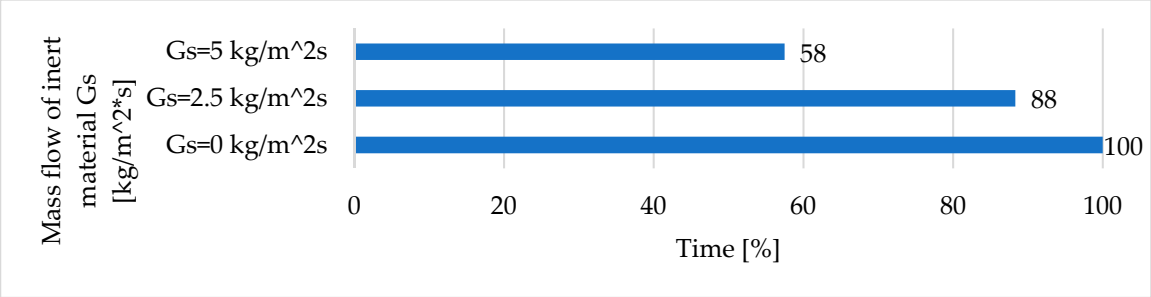

Figure 11. Combustion time of a mixed secondary fuel pellets in a stream of inert material (Gs = 2.5 kg/m^2 s and Gs = 5 kg/m^2 s) compared with combustion without inert material (Gs = 0 kg/m^2 s) at 850 °C [39].

A comparison of the mass loss during the combustion of the mixed secondary fuel pellets with sunflower husk and RDF pellets under the same conditions is shown in Figure 12. A clearly visible difference can be seen in the combustion of the mixed secondary fuel and RDF compared to the combustion of the sunflower husk pellets at Gs = 2.5 kg/m^2 s. The reason for this situation is the elimination of the formation of sinter in the mixture produced. Reducing the biomass content in the fuel sample resulted in a reduction in the contents of metals and alkaline compounds and their impact on the combustion process of fuel particles in fluidized bed conditions.

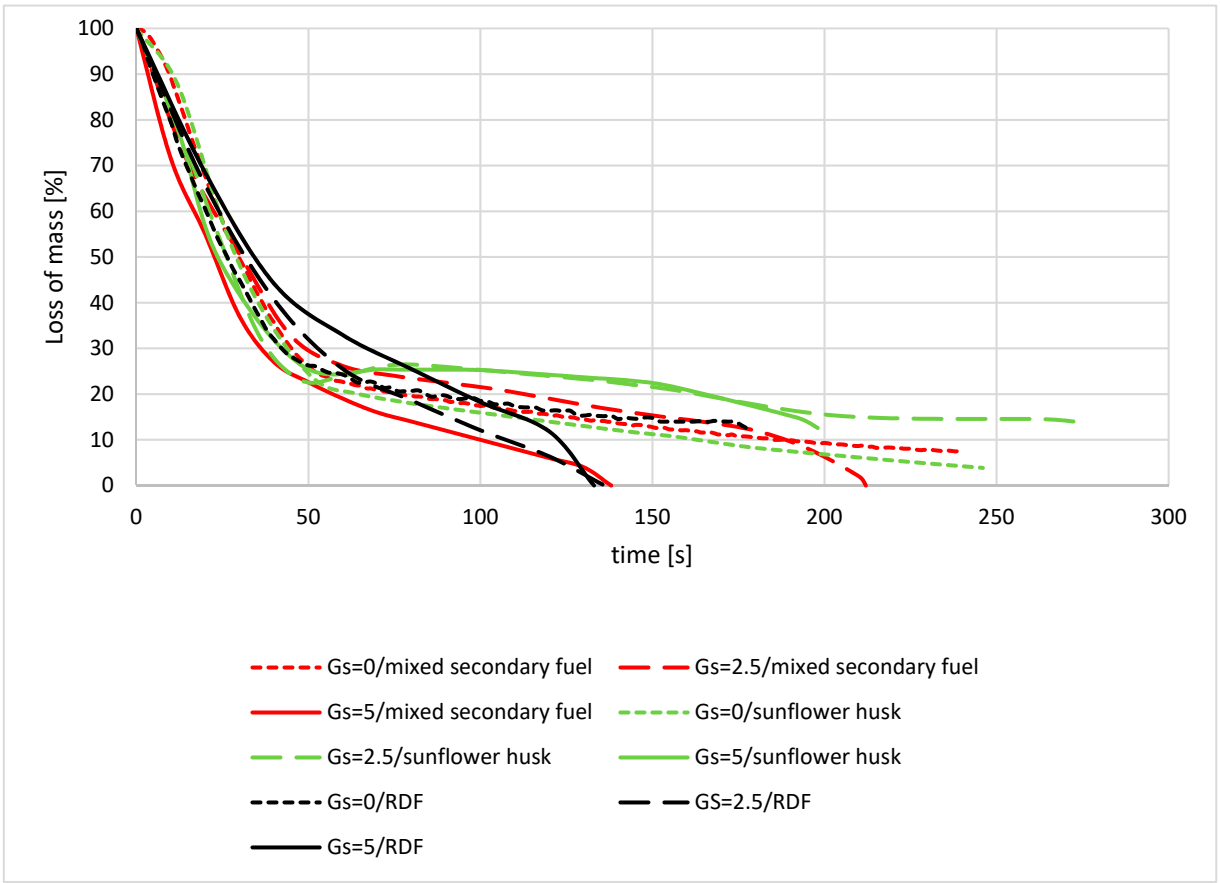

Figure 12. Mass loss during the combustion of mixed secondary fuel pellets, sunflower husk pellets, and RDF pellets at a temperature of 850 °C at different values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s) [39].

The combustion time of the mixed secondary fuel pellets during combustion without the inert material was similar to the combustion time of the sunflower husk pellets, while in the case of Gs = 5 kg/m^2 s, it was similar to the combustion time of the RDF fuel (Figure 13).

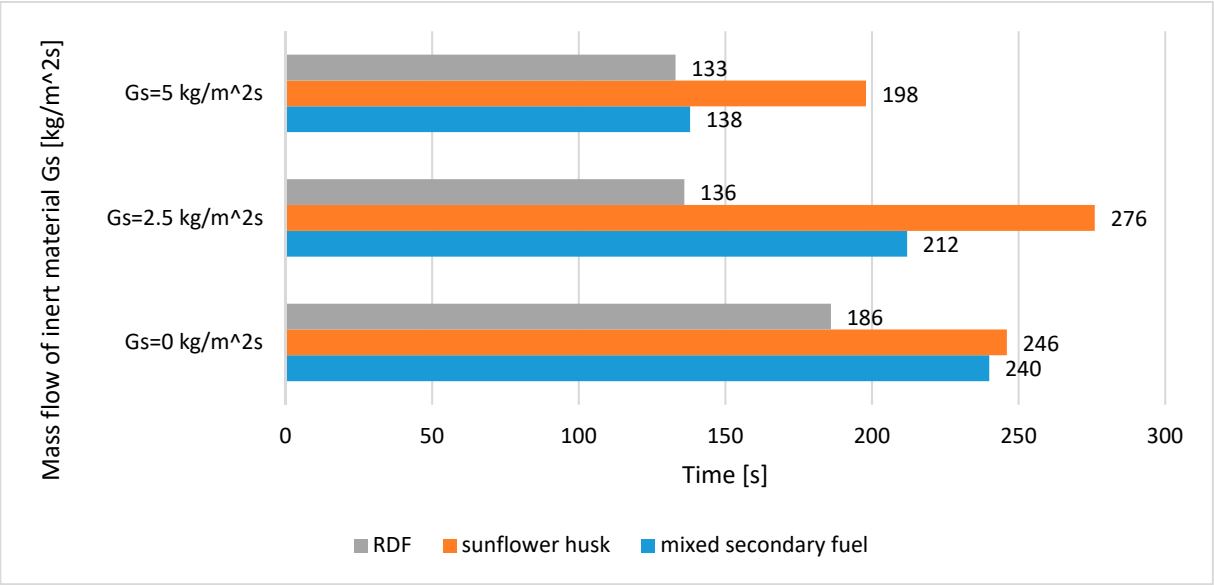

Figure 13. Combustion process of mixed secondary fuel pellets, sunflower husk pellets, and RDF pellets at a temperature of 850 °C at different values of the mass flow of the inert material (Gs = 0 kg/m^2 s, Gs = 2.5 kg/m^2 s, and Gs = 5 kg/m^2 s) [39].

4. Conclusions

The results of the experimental studies carried out on the combustion of mixed secondary fuel under various fluidized bed conditions of allow the following conclusions to be made:

1. The production of mixed secondary fuel is advisable because it eliminates the influence of alkali metal compounds on the melting point of the ash.
2. The combustion process of mixed secondary fuel in fluidized bed conditions is similar in the cases of forest biomass and RDF.
3. The appropriate selection of fuel mixtures can increase the use of fuel with undesirable characteristics while reducing the risk of operational problems or damage to the combustion unit.
4. Due to the heterogeneous composition of RDF fuel and the lack of standardization of its production, its use in mixed secondary fuel will contribute to reducing the emissions of potentially harmful compounds into the atmosphere during its co-combustion.
5. The production of mixed secondary fuel fits perfectly into the proposed concept of the circular economy, reducing the storage of municipal waste with a combustion heat value of >6 MJ/kg.
6. As shown in the literature review, the addition of materials derived from waste that can be a component of RDF fuel include, among others, oils and wrapping paper as binders, which improve the mechanical durability of biomass pellets, increase the calorific value, and reduce the energy demand for the pelletization process.

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