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Study of Ash Sintering Temperature and Ash Deposition Behavior during Co-Firing of Polish Bituminous Coal with Barley Straw Using Non-Standard Tests

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Abstract: The need to reduce CO₂ emissions forces the use of biomass as a fuel in the conventional energy conversion process implemented by combustion. Burning biomass alone can be problematic because of the high potential for slugging and fouling on boiler heating surfaces. Therefore, co-firing of biomass with coal is used. This article presents the results of a study of biomass blends of barley, straw, and hard coal biomass from the Polish Makoszowy mine. The sintering of ash from biomass-coal blends was studied by experimental non-standard methods, such as the fracture stress and the pressure drop test. The results were confirmed with the result of thermodynamic modeling using FactSage 8.0 software. Additionally, ash deposition tests were performed in a 3.5 m boiler. The tests conducted showed a significant effect of the addition of biomass to hard coal on the formation of ash deposits on the heating surfaces of the boiler. In addition, the usefulness of non-standard methods in the assessment of the degree of fouling and slugging hazard was confirmed.

Keywords: FactSage analysis; coal; biomass; sintering; pressure drop method; mechanical method



Citation: Król, K.; Nowak-Woźny, D.; Moroń, W. Study of Ash Sintering Temperature and Ash Deposition Behavior during Co-Firing of Polish Bituminous Coal with Barley Straw Using Non-Standard Tests. *Energies* **2023**, *16*, 4424. <https://doi.org/10.3390/en16114424>

Academic Editor: Pavel A. Strizhak

Received: 15 May 2023

Revised: 25 May 2023

Accepted: 29 May 2023

Published: 30 May 2023



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1. Introduction

The use of biomass for energy production is one possibility for its management. Both forest and agro biomass can be used in dedicated installations (thermal conversion plants, biogas plants) as well as in installations using coal (co-firing) [1].

Biomass in large-scale power and CHP coal-fired plants is efficient and profitable and requires moderate additional investment. During co-firing up to 5–10% of materials is biomass (in energy terms), only small changes are required in the combustion plant (i.e., mainly storage, transport, control of the combustion process, management of combustion residues) [2]. In general, the efficiency of biomass combustion in dedicated installations is lower than in the case of coal co-firing in power plants or combined heat and power plants. The experience of many EU countries, especially in Scandinavia, indicates that rational management of biofuels makes it possible to build an energy system that uses biofuels for both eclectic and thermal energy production [3].

An area offering great opportunities for the implementation of coal and biomass co-firing in Poland are local district heating systems. These units include both power plants operating in cogeneration systems and dedicated district heating plants that burn coal or biomass. The transformation process of an energy system and a move away from coal creates opportunities for the use of biomass in these units [4,5]. Biomass as a local fuel source allows for the fuel needs of such plants to be met, while at the same time, the seasonality of heat production (mainly the autumn–winter period) allows proper preparation for the heating season. The use of biomass also has a beneficial effect in reducing CO₂ emissions into the atmosphere. Co-combustion of biomass reduces CO₂ and NO_x emissions from

coal-fired energy systems [6–8]. In contrast, the studies presented in [9] indicate a positive effect of biomass co-combustion on the firing rate.

Many scientific publications point to the specific properties of biomass as a fuel, especially in terms of ash properties. The articles [10,11] point out the different chemical composition of ash, which differ significantly from coal ash. Biomass, depending on its origin, is a complex inorganic–organic mixture with a polycomponent, heterogeneous and variable composition, containing intimately associated solid, liquid, and gaseous phases of different origins. Another identified problem is the increase in chlorine content in biofuels [12,13], which promotes the formation of chlorine compounds that accelerate the slagging and fouling process or the intensity of chlorine corrosion. An issue that is being intensively studied is the effect of biomass combustion on the amount of ash produced and the rate at which it settles. An increase in biomass content of burned blends has been found to affect the amount of ash formed [14], and the rate of its deposition on heated surfaces [11,15]. This is due to the high concentration of alkali metals present in the composition of biomass [16], leading to the formation of compounds with low melting points. A higher proportion of alkali compounds also affects the reduction in the temperature of ash sintering temperature [16]. The lower softening temperature of the ash causes it to have a greater tendency to combine and settle in superheating pipes. In addition, it indicates that coal and co-firing biomass have the property of strongly adhering to surfaces [15].

It should also be remembered that the composition of biomass fuels varies significantly depending on the type of crop, farming practices, harvesting time, storage, etc., and the composition of coal varies depending on the location of the mine. At the same time, scientific research indicates that there is no unequivocal tool available to assess the properties of ash produced from the co-firing of coal and biomass. Therefore, it is important that co-firing tests implemented on both the laboratory and pilot scale be conducted for each specific fuel mixture as part of its evaluation for use in boilers [15].

The article aimed to identify areas of risk of slagging and fouling for coal and biomass blends. The main research tools were standardized and non-standardized methods based on ash analysis supported by numerical simulations conducted with FactSage software 8.0.

In the article presented here, the tests used bituminous coal from the Polish Makoszowy mine and barley straw biomass. All completed research work was performed for both initial fuels and their blends. The proportions of biomass in the blends are 10, 25, 50%, which allowed for observation of the behavior of ash across whole range of the most frequently used biomass amounts. The scope of the completed work included the performance of basic physicochemical analyzes of fuels, oxide analysis, and non-standard laboratory tests that determine the ash sintering temperatures [17]. The tests used a fracture stress test and a pressure drop test, which were then verified using ash phase modeling with FactSage 8.0 software. Baseline studies were verified by laboratory-scale co-firing tests performed in a 3 m flow reactor, where the rate and size of accumulations formed on the heating surfaces of the boiler.

2. Materials and Methods

The following were used as fuels: one type of bituminous coal (BC) from the Polish Makoszowy mine, which is often used in Polish power plants; one type of biomass, barley straw (BS)—popular in Poland; and their blends. Meanwhile, such blends of coal ash (BC) and barley straw (BS) ash as 90 wt.% BC ash/10 wt.% BS ash, 75 wt.% BC ash/25 wt.% BS ash, 50 wt.% BC ash/50 wt.% BS ash were used to study the ash sintering temperature during biomass co-combustion. On the other hand, such blends of Bituminous coal (BC) and barley straw (BS) were used to test deposition rates: 93 wt.% BC and 7 wt.% BS, 86 wt.% BC and 14 wt.% BS, and 67 wt.% BC and 33 wt.% BS.

The coal and biomass ashes were prepared in accordance with European standards [18–20]. For the presented study, ash with a grain fraction of 200 μm corresponding to a consistency of polydisperse dust that is in accordance with the current rules used for bituminous coals was

selected [21]. Samples of 200 μm were obtained after sifting through a sieve analysis. A detailed description of the ash preparation process for the study can be found in [22], among others.

Before the experiments, proximate and ultimate analyses of the samples were conducted according to Polish standards [23–26]. Additionally, ashes were manufactured according to ASTM E1755-01 (Thermo iCAP 6500 Duo ICP plasma spectrometer, Thermo Fisher Scientific Waltham, MA, USA) to examine their chemical composition.

For the mechanical test, cylindrical specimens with a diameter of 8 mm and a height of 10 mm were heated isothermally for 4 h at a certain temperature T and cooled rapidly to room temperature. The samples were prepared in a hydraulic press at a pressure of 1 atm. The temperature range for isothermal annealing was 500 $^{\circ}\text{C}$ to 1000 $^{\circ}\text{C}$ in 50 $^{\circ}\text{C}$ increments.

In the pressure drop test, a sample in the shape of a cylinder (diameter 10 mm, height: 15 mm) was formed directly in the test tube [22].

The experiment was repeated for five samples prepared from the same ash. The results were calculated as the mean value of the experiment. The standard deviation was calculated.

FactSage 8 thermochemical software with databases was used to complete mechanical and pressure tests. FactSage is based on a combination of the Gibbs minimum free energy determination tool and thermodynamic equilibrium chemical simulation software. A single slag phase was assumed and the FToxid, FTmisc, ELEM, and FactPS databases were used. The atmosphere was excluded [27]. The oxide content of the ashes was entered as input data. Thermodynamic calculations were performed for temperatures from 500 $^{\circ}\text{C}$ to 1100 $^{\circ}\text{C}$, pressure of 0.1 MPa.

Just as important as determining the ash sintering temperature is determining the efficiency of ash deposition during fuel combustion. In an independent test, the efficiency of ash deposition during co-firing of hard coal with biomass was investigated for different proportions of biomass in the fuel mixture (7 wt.%, 14 wt.% and 33 wt.% of biomass). The study was carried out in a 3.5 m diameter flow reactor, in which dust flame combustion conditions were simulated (Figure 1). The slag/ash deposits formed during fuel combustion were collected on a metal probe with a diameter of 15 mm. A thermocouple was attached to the surface of the probe. The test was carried out under single stage combustion conditions, and the duration of one measurement was 45 min.

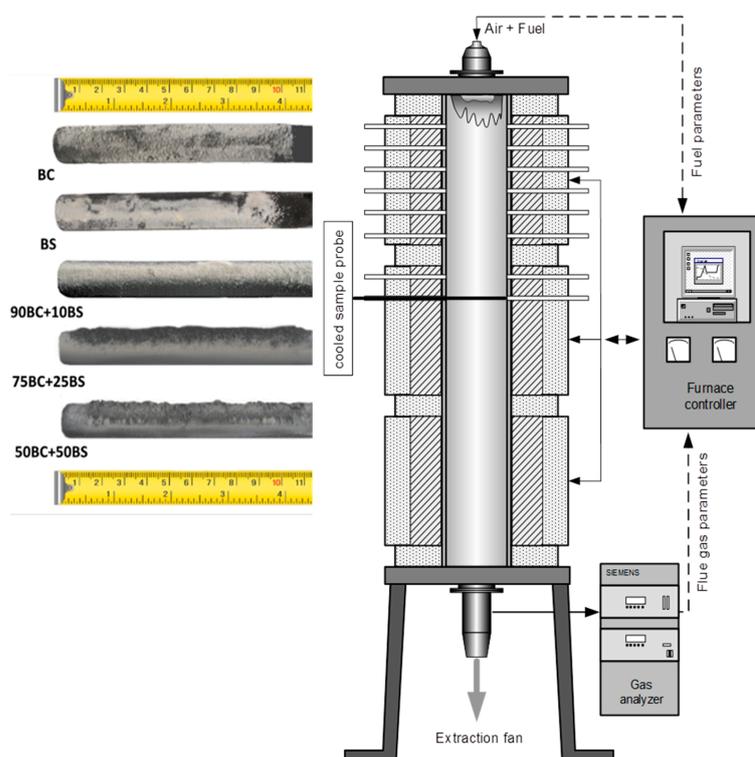


Figure 1. The 3.5 m Entrained Flow Reactor (EFR).

During the test, a constant excess air value of 1.2 was maintained, and the fuel mass rate was kept constant at 5 g/min. The temperature of the experiment was fixed at 1000 °C. The furnace parameters were chosen to maintain laminar flow along the reactor working chamber. The incoming oxidant was separated into a fuel transport air stream (primary) and a secondary air stream fed into the reactor chamber through the honeycomb (flow stabilization). Incident air flow was selected individually according to the fuel flow rate for each fuel. The following research methods were used for the study: Mechanical test, pressure drop test, FactSage 8.0 software, IR methods, and 3.5 m Entrained Flow Reactor (EFR).

The measurement procedure is shown in Figure 2.

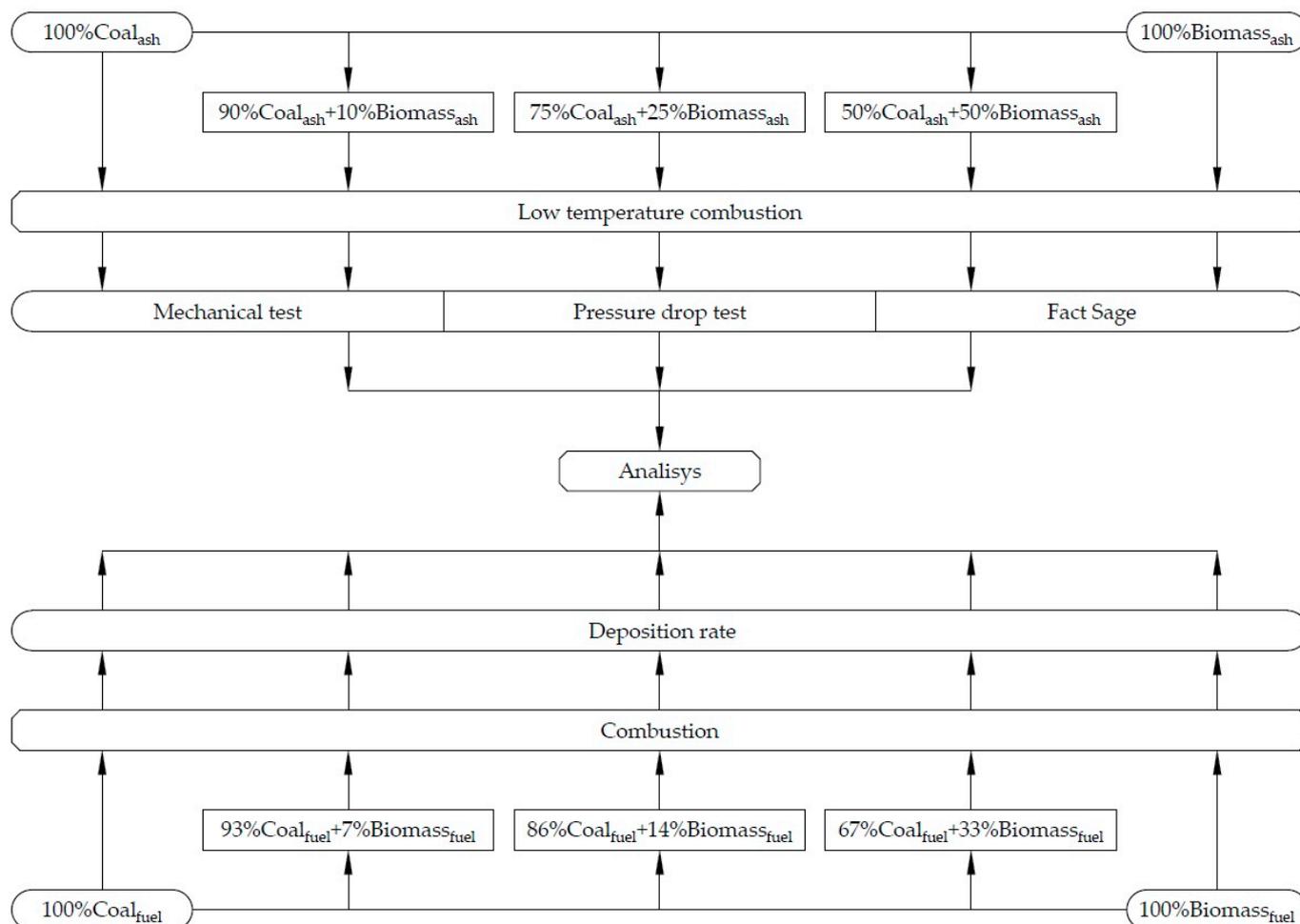


Figure 2. The measurement procedure.

3. Results and Discussion

3.1. Samples Analysis

The proximate and ultimate analysis of the tested fuels and their blends is shown in Table 1.

As expected, the addition of barley straw to Bituminous coal caused an increase in moisture (M), volatile matter (VM), hydrogen (H) and oxygen (O), while a decrease in ash content (A), fixed carbon (FC), fuel ratio (FR) [28], coal (C), hydrogen (H), nitrogen (N), sulphur (S), oxygen (O) and a higher heating value (HHV). In contrast, the content of chlorine (Cl) changes only slightly as a result of the similar content in the tested coal and biomass.

Table 1. Basic properties of the biomass and coal samples and their blends (on an air-dried basis).

Samples	Proximate Analysis					Ultimate Analysis						Heating Values
	M	A	VM	FC	FR	C	H	N	S	O	Cl	HHV
	wt. %	wt. %	wt. %	wt. %	–	wt. %	wt. %	wt. %	wt. %	wt. %	wt. %	MJ/kg
100%BC	2.0	17.3	26.9	53.8	2.00	65.4	3.7	1.3	1.2	8.6	0.51	27.8
93%BC + 7%BS	2.5	16.7	29.4	51.5	1.88	64.2	3.8	1.2	1.1	10.0	0.51	27.0
86%BC + 14%BS	2.9	16.0	31.9	49.2	1.77	62.9	4.0	1.2	1.0	11.4	0.50	26.2
67%BC + 33%BS	4.1	14.3	38.7	42.8	1.45	59.6	4.4	1.0	0.8	15.3	0.49	23.9
100%BS	8.5	8.2	62.7	20.6	0.33	47.8	5.7	0.4	0.1	28.9	0.45	16.1

The biomass combustion/co-combustion process differs from that of coal alone in that, in the case of coal combustion, most of the energy comes from burning coke residues. It should also be noted the mineral content of biomass and biomass–fuel blends [22]. Biomass has a low mineral content, but its composition is more aggressive (high content of alkaline elements and chlorine) than coals. In combustion systems, the risk of slagging and fouling increases, which reduces the efficiency of the combustion process.

Counteracting the adverse effects of biomass on the combustion system involves proper organization of the combustion process, the use of protective coatings, and other protective measures.

It can be seen that the addition of biomass increases the proportion of oxygen compared to coal alone. This changes the combustion area to that of the coke residue, which is characteristic of coal fuels. Shifting the combustion process to the upper zones of the chamber promotes an increase in the temperature of the flue gas along the height of the combustion chamber. This adversely affects the temperature of the ash sintering.

The results of higher temperatures in the upper zones of the combustion chamber are a greater risk of slagging and fouling processes in the boiler. Therefore, the correct determination of the ash sintering temperatures becomes a particularly important issue. The classic Leitz test reports much higher sintering temperatures than those found in reality [22]. Therefore, non-standard methods such as the pressure drop method and the mechanical test method seem to be more useful [22].

The present article focuses on the study of the sintering process of ash from coal and biomass blends, using physical methods (pressure drop test, mechanical test), chemical methods (oxide indices), and simulation methods (FactSage analyzes) compared to the pilot scale experiments in 3.5 m boiler. The aim of the research is to develop a reliable and reproducible method for determining the sintering temperature of biomass ash. This is important in the design stage of biomass combustion/co-firing boilers.

The oxide composition of the ash from the tested materials (determined by the Thermo iCAP 650 Duo ICP [22]) is presented in Table 2.

On the basis of the oxide composition of the ash, the oxide indices were determined. On the basis of oxide contents, the predictive factors for the ash deposition tendency are stated. The main are basic to acidic oxides (B/A), Babcock index (Rs), bed agglomeration index (BAI), fouling index (Fu), fouling factor (Rf), and slag viscosity index (Sr). Indices and the formulas are presented in [22,29,30]. The definitions used for this determination are listed in Equations (1)–(6).

$$\frac{B}{A} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{P}_2\text{O}_5}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}, \quad (1)$$

$$\text{BAI} = \frac{\text{Fe}_2\text{O}_3}{\text{Na}_2\text{O} + \text{K}_2\text{O}}, \quad (2)$$

$$\text{Rs} = \left(\frac{B}{A}\right) \cdot \text{S}^d, \quad (3)$$

$$F_u = \left(\frac{B}{A}\right) \cdot (\text{Na}_2\text{O} + \text{K}_2\text{O}), \quad (4)$$

$$R_f = \left(\frac{B}{A}\right) \cdot (\text{Na}_2\text{O} + 0.659 \cdot \text{K}_2\text{O}), \quad (5)$$

$$S_r = \frac{\text{SiO}_2 \cdot 100}{\text{Fe}_2\text{O}_3 + \text{SiO}_2 + \text{CaO} + \text{MgO}}, \quad (6)$$

It should be noted that the use of indicators is limited due to the statistical nature and the fact that the indices were developed for coal ash [22,29,30]. The ranges of the slagging and fouling indices are shown in Table 3 and are marked in gray scale to highlight the difference in value to improve visibility.

Table 2. Chemical composition of biomass and coal ash and their blends.

Samples	100%BC	90%BC + 10%BS	75%BC + 25%BS	50%BC + 50%BS	100%BS
Oxides	wt. %	wt. %	wt. %	wt. %	wt. %
SiO ₂	51.4	53.0	55.4	59.4	67.5
Al ₂ O ₃	25.5	22.9	19.2	12.8	0.2
Fe ₂ O ₃	6.6	5.9	5.0	3.4	0.2
CaO	4.6	4.6	4.7	4.8	4.9
MgO	3.3	3.1	2.9	2.4	1.5
Na ₂ O	1.0	0.9	0.8	0.7	0.4
K ₂ O	2.6	4.5	7.2	11.8	21.0
P ₂ O ₅	0.5	0.7	1.0	1.6	2.7
TiO ₂	1.1	1.0	0.8	0.5	0.0
SO ₃	3.2	3.0	2.8	2.4	1.5
Mn ₃ O ₄	0.1	0.1	0.1	0.1	0.0
BaO	0.2	0.2	0.1	0.1	0.0
SrO	0.1	0.1	0.0	0.0	0.0

Table 3. The ash deposition indices.

Parameter/Symbol	Value				Fuel					Unit
	Low	Medium	High	Extremely High	100%BC	90%BC + 10%BS	75%BC + 25%BS	50%BC + 50%BS	BS	
Silica content in ash SiO ₂	<20	20–25	>25		51.35	52.97	55.38	59.41	67.46	wt. %
Chlorine content in fuel Cl ^d	<0.2	0.2–0.3	0.3–0.5	>0.5	0.52	0.52	0.51	0.51	0.49	wt. %
Basic to acidic compounds ratio B/A	<0.5	0.5–1.0	1.0–1.75		0.24	0.26	0.29	0.34	0.45	–
Bed agglomeration index BAI			<0.15		1.83	1.11	0.62	0.27	0.01	–
Babcock index Rs	<0.6	0.6–2.0	2–2.6	>2.6	0.29	0.29	0.27	0.23	0.04	–
Fouling index F _u	0.6–2.0		2.0–40	>40	0.86	1.38	2.31	4.24	9.75	–
Fouling factor R _f	<0.2	0.2–0.5	0.5–1.0	>1.0	0.64	0.99	1.61	2.88	6.49	–
Slag viscosity index Sr	>72	65–72	<65		77.96	79.41	81.53	84.88	91.04	–
Mechanical test temperature T(MT)	>1100	900–1100	<900		975	975	925	825	725	°C
Pressure drop test temperature T(PDT)	>1100	900–1100	<900		942	942	878	790	649	°C

^d in dry state. T(MT) sintering temperature from mechanical test. T(PDT) sintering temperature from pressure drop test.

The tested fuels have a high potential for ash deposition because they have a high silica content. Silica reacts with sodium and potassium to form eutectics with low melting points. Chlorine content is high for barley straw and very high for other fuels. Chlorine is responsible for the formation of potassium chloride and the formation of ash deposits on low-temperature heating surfaces [22,29,30]. In contrast, the B/A indices (describing the overall melting behavior) are low for all samples. The tendency of the bed to agglomerate during fluidized bed combustion (BAI index) is high only for BS.

Babcock's index, R_s (providing some information about the increased tendency to deposit on high-temperature heating surfaces), is low for all fuels studied. The viscosity indices are low for all samples tested.

3.2. Pressure Drop Test and Mechanical Test Compared to the FactSage Analyzes

Mechanical and pressure drop tests were performed for the coal and coal and biomass blends tested. The results obtained were compared with the results of thermodynamic simulation using FactSage 8.0 software. The results of the measurements and calculations are shown in Figures 3–7.

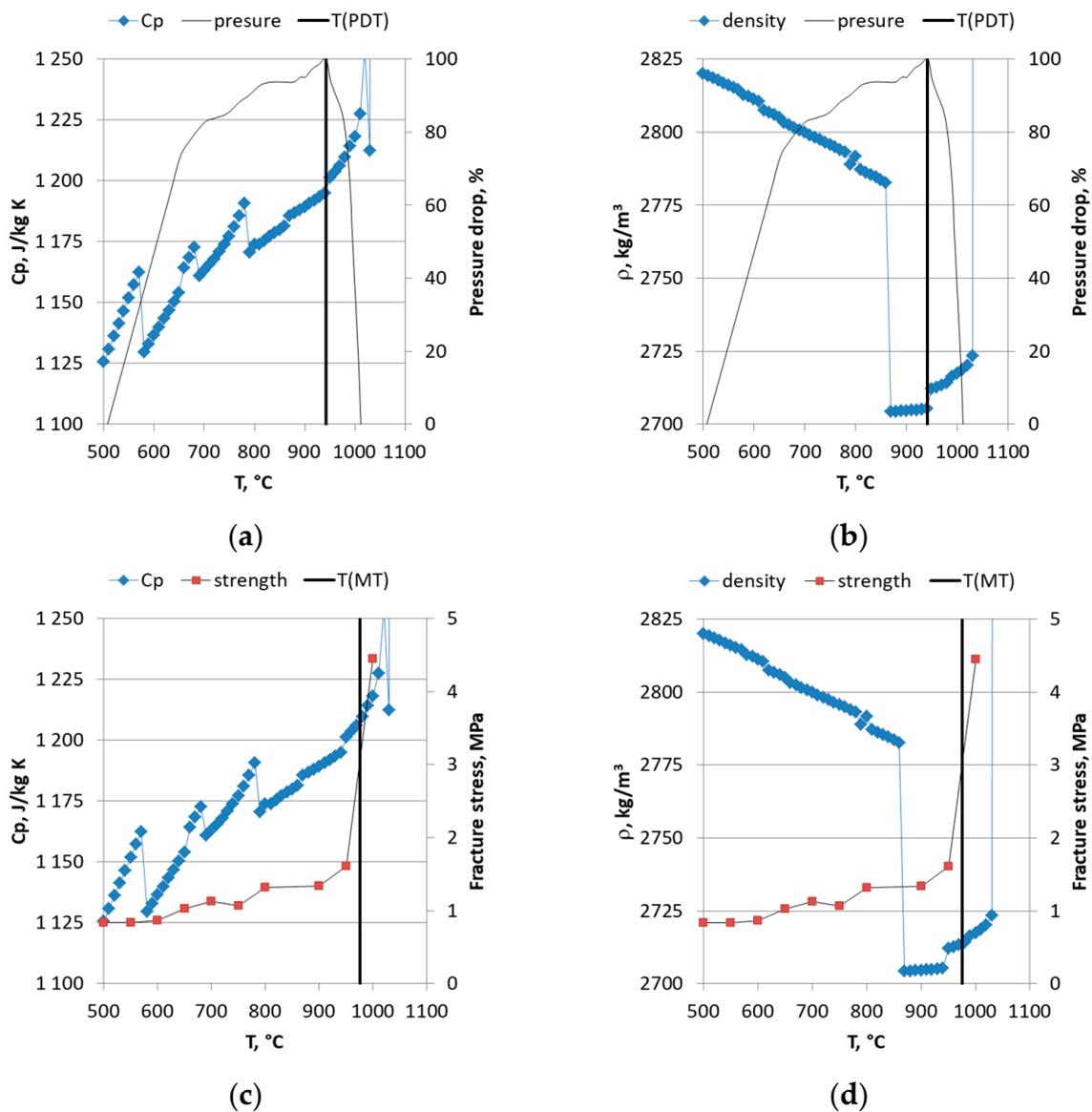


Figure 3. 100%BC: (a) Specific heat (c_p) and pressure drop; (b) density (ρ) and pressure drop; (c) specific heat and fracture stress; (d) density and fracture stress.

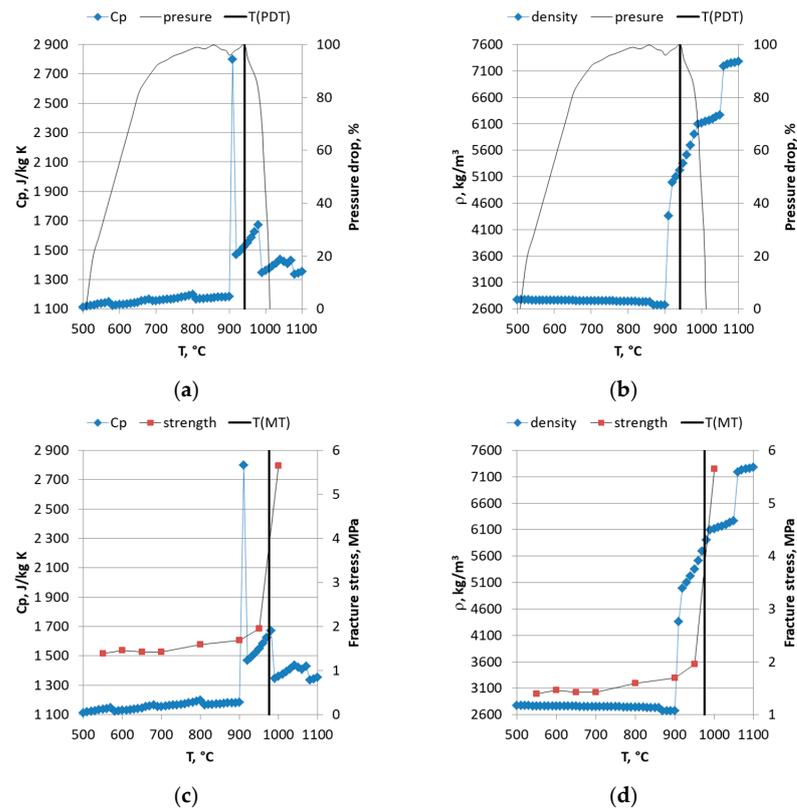


Figure 4. A mix of 90%BC + 10%BS: (a) Specific heat (c_p) and pressure drop; (b) density (ρ) and pressure drop; (c) specific heat and fracture stress; (d) density and fracture stress.

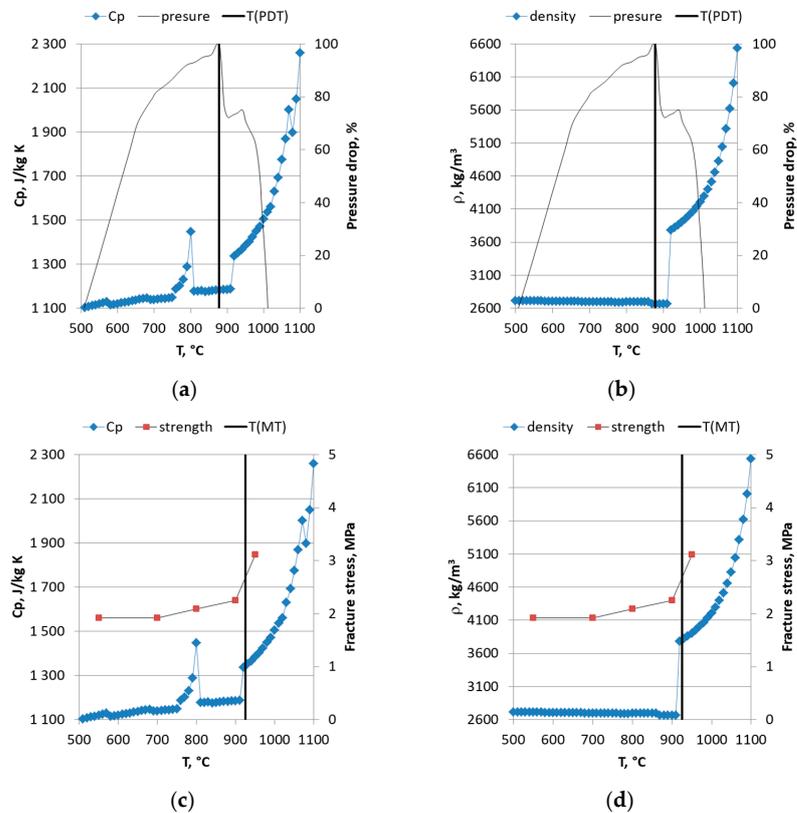


Figure 5. A mix of 75% BC + 25% BS: (a) Specific heat (c_p) and pressure drop; (b) density (ρ) and pressure drop; (c) specific heat and fracture stress; (d) density and fracture stress.

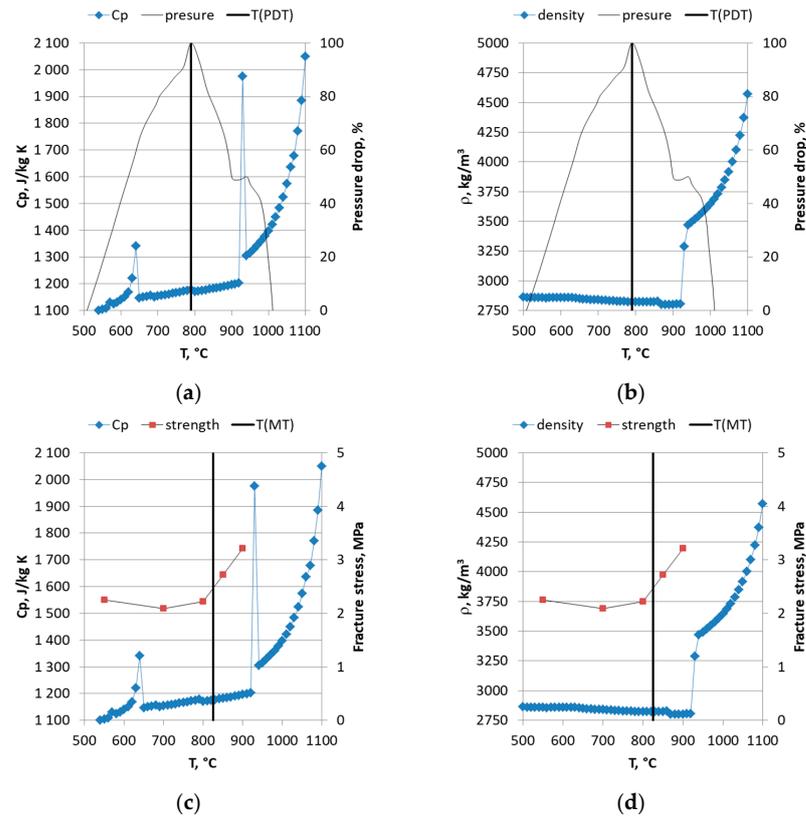


Figure 6. A mix of 50% BC + 50% BS: (a) Specific heat (c_p) and pressure drop as a function of temperature; (b) density (ρ) and pressure drop; (c) specific heat and fracture stress; (d) density and fracture stress.

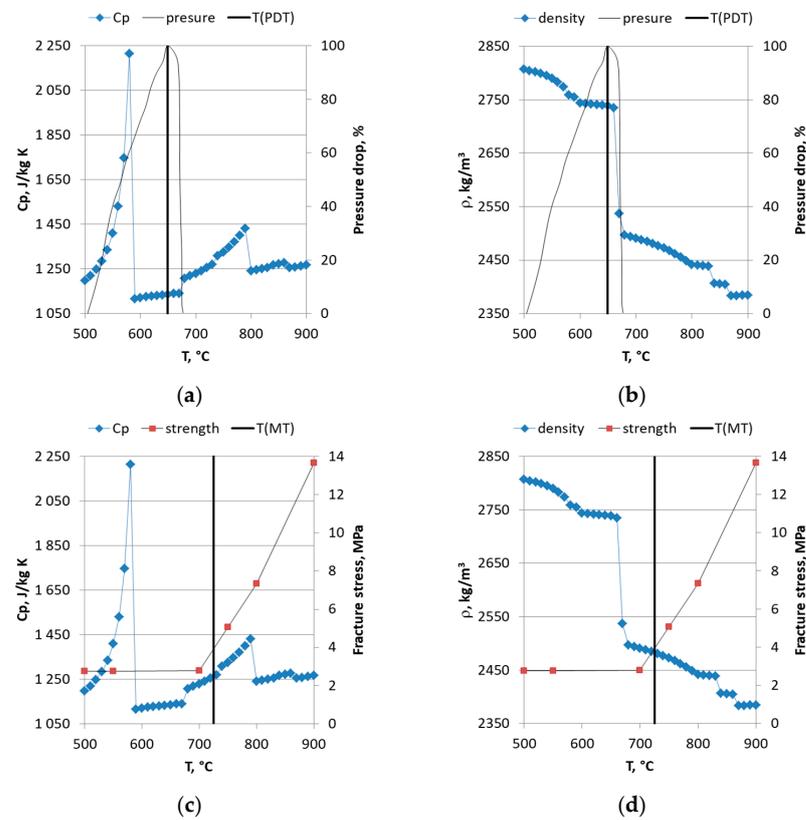


Figure 7. 100%BS: (a) Specific heat (c_p) and pressure drop; (b) density (ρ) and pressure drop; (c) specific heat and fracture stress; (d) density and fracture stress.

In particular, the pressure changes observed during the ash sintering process were compared with the ash density calculated by using FactSage 8.0, as well as with the values of the specific heat capacity c_p values also calculated by using FactSage 8.0.

Analyzing these measured data from the pressure drop test performed during the ash sintering process obtained from Bituminous coal and its blends with barley straw, in comparison with the calculations obtained after using the software (Figures 3–7), it was found that the temperature at which a clear pressure drop begins corresponds to a clear change in the predicted nature of the density–temperature relationship for all samples tested. The mechanical test performed during the sintering process of all samples tested, compared to the calculations obtained after using the FactSage 8.0 software (Figures 3–7), found that the temperature at which a clear increase in fracture stress begins corresponds to a clear change in the predicted nature of the density–temperature relationship.

Discontinuities in specific heat c_p and density are observed in the same temperature range as the drop in pressure in the drop test or the increase in fracture stress in the mechanical test. It should be noted that discontinuities in specific heat c_p are mainly associated with phase transformations, while an increase in fracture stress is rather associated with a change in the microstructure of the materials of ash sample.

Interestingly, the nature of the density changes, determined using FactSage, is different in pure fuels (for both barley straw biomass and Bituminous coal) (Figures 3 and 7) than in their blends (Figures 4–6). In pure fuels, there is a marked decrease in density near sintering temperatures determined by pressure and mechanical methods. On the other hand, in their blends (10, 25 and 50 wt.% of barley straw), the density increases markedly. It is presumed that in blends of both fuels the increase in porosity of the sample itself is mainly responsible for the pressure drop observed in the test. In pure fuels, where a significant decrease in the ash density and a marked decrease in the pressure drop test are observed simultaneously, the dominant effect is the shrinkage of the ash sample during sintering.

We think that for the bituminous coal and barley straw blends, it is unlikely that the entire ash sample will shrink during sintering. It is likely that the change in its microstructure is related to an increase in porosity and the formation of channels that transport the gas phase through the sample. Thus, we can see that for the fuels studied, we do not have a uniform process mechanism responsible for the pressure drop in the pressure method and the increase in fracture stress in the mechanical method. However, what is interesting is the close relationship between the pressure drop in the pressure test and the increase in fracture stress in the mechanical method used to evaluate the sintering temperature measurement and the changes in the density of the solid ash and their specific heat c_p observed in Figures 3–7.

By comparing Figures 3 and 4, it can be seen that the sintering temperature determined by the pressure method and the mechanical method (the vertical black line in the figures and Table 3) has the same value, despite the fact that the nature of density changes is different in these cases (decreasing for coal and increasing for a mixture of coal and biomass). However, there are clear points of discontinuity in both the ash density and fracture stress at points characteristic of the pressure method (decreasing pressure) and the mechanical method (increasing fracture stress).

The 25% addition of BS ash to BC ash reduces the sintering temperature determined by the pressure drop test to a value of 878 °C, while the strength method reduces it to a value of 925 °C. In this case, also, we observe a good correlation between changes in pressure drop (pressure drop test) and discontinuities in ash density and their specific heat, as well as an increase in fracture stress (mechanical test) and discontinuities in ash density and fracture stress (Figure 5).

On the other hand, the addition of 50% BS ash to BC ash results in a relatively significant reduction in the sintering temperature determined by the pressure drop test, because of the value of 790 °C, and determined by the mechanical test, because to the value of 725 °C. In this case, too, as before, the correspondence of the temperature ranges of the

discontinuity of ash density and specific heat c_p with changes in pressure in the pressure drop test and changes in fracture stress in the mechanical method is observed.

The sintering temperatures determined by the pressure drop test and mechanical test for the barley straw are the lowest of all samples tested. It is 649 °C for the pressure drop test and 725 °C for the mechanical test. The temperature range of the change in fracture stress and drop in pressure remains consistent with the range of density discontinuities and specific heat c_p .

Analyzing Figure 8, showing the content of the slag phase predicted by FactSage 8.0, it can be seen that the addition of 10 wt.% of BS ash to BC ash does not the dynamics of the formation of change significantly the slag phase. The addition of 25 wt.% of ash from biomass reduces the temperature at which a significant amount of slag phase begins to form from 900 °C to about 800 °C. while the addition of 50 wt.% of ash from biomass drastically reduces the temperature at the beginning of the formation of the slag phase to below 600 °C. These results are consistent with the described changes in the sintering temperature determined by pressure and mechanical methods. The indicated temperatures are consistent with those determined by non-standard methods.

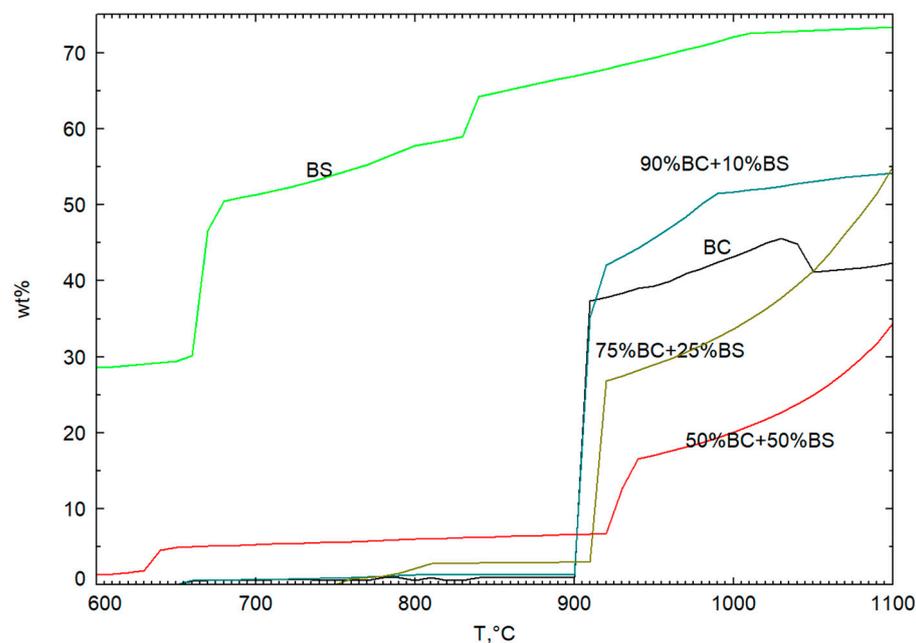


Figure 8. Phases of slag in equilibrium for barley straw ash (BS), bituminous coal ash (BC) and ash blends: 90%BC + 10%BS, 75%BC + 25%BS and 50%BC + 50%BS.

3.3. Deposition Rate Test

The efficiency of the deposition of slag/ash particles in the boiler was determined in the system shown in Figure 1. The deposition process was tested on a measuring probe and the slag/ash deposition rate was calculated as follows.

$$\eta_d = \frac{m_{deposit}}{m_{fuel} \cdot A \cdot t} \cdot 100, \% \quad (7)$$

where $m_{deposit}$ is the mass (g) of slag/ash on the probe, m_{fuel} is the mass(g/s) flow of full, A is the ash content (wt.%) in full, and t is the time of the test. The weight of the slag/ash deposit was determined by measuring the weight of the probe before and after the test.

Based on the results presented in Figure 9, three groups of fuels tested are visible. The first is pure BC and a blend of 90 wt.% of BC with 10 wt.% of BS. The second consists of 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS. The third is pure BS biomass of barley straw. The addition of 10 wt.% of BS to the BC practically changes the deposition rate only in a very narrow range: from 38% for BC to 40% for 90 wt.% BC/10 wt.% BS. A

similar effect of small differences of deposition rate in the group of fuels is observed for the second group of tested fuels, i.e., for 75 wt.% BC/10 wt.% BS and 50 wt.% BC/50 wt.% BS. However, in the second group, the changes in the deposit rate are slightly larger than in the first group of fuels. The deposition rate varies in the range of 90% for a biomass content of 25 wt.% in the blend with BC and 98% for a biomass content of 50 wt.% in the blend with coal. The third group is pure BS biomass for which the deposition rate is 81% and is lower than for the second group of fuels, but higher than for the first one.

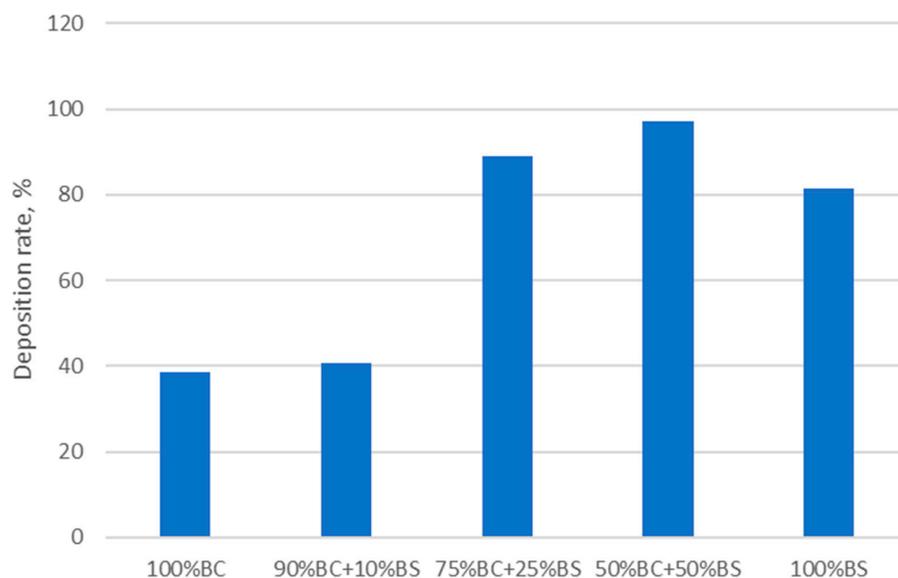


Figure 9. Deposition rate for fuels: pure bituminous coal (100 wt.% BC), pure barley straw (100 wt.% BS) and their blends: 90 wt.% BC/10 wt.% BS, 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS.

In the case of testing samples, the deposition rate of ashes in the combustion of bituminous coal and barley straw and their co-combustion, the addition of barley straw to 50 wt.% increase the deposition rate. Interestingly, in combustion of barley straw alone, the deposition rate is higher than in the combustion of BC coal alone and its co-combustion with 10 wt.% of barley straw, whereas slightly (about 10%) lower than during co-combustion of such blends as 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS [31].

These results are consistent with the results of the pressure drop test and the mechanical test. Figure 10 presents the sintering temperature estimated from these two methods.

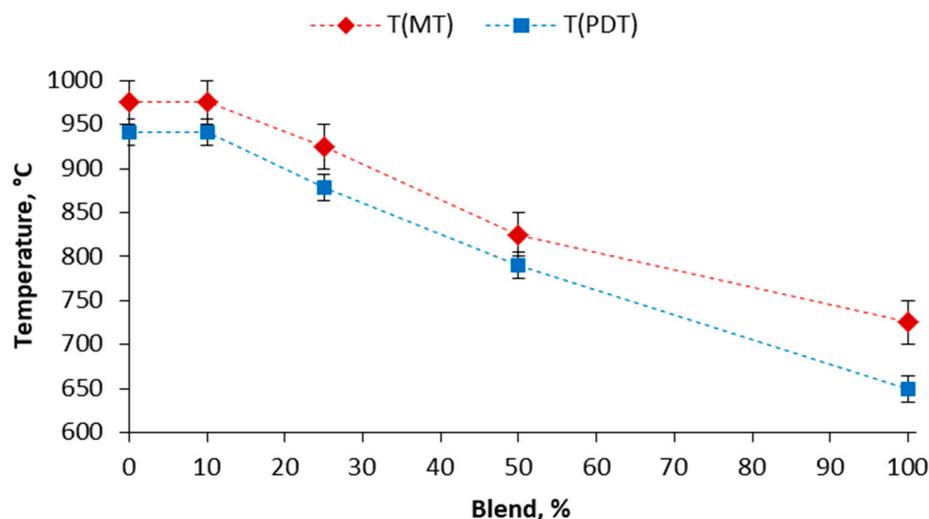


Figure 10. Sintering temperature of the blend determined by the pressure drop test (T(PDT)) and the mechanical test (T(MT)).

The sintering temperatures determined by mechanical test T(MT) and pressure drop test T(PDT) are very close together for bituminous coal BC and its blend with barley straw (BS). It is the lowest for pure barley straw. For blends 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS are between them. It means that the sintering tendency of barley straw is much higher than that of BC and BC/BS blends. It means that during combustion of biomass, many more deposits will be in the bottom part of boiler. This explains why the deposit rate measured in the probe is lower for pure barley straw. The next effect that explains the visible decrease in barley straw the deposition rate in combustion in our experiment (in relation to the deposition rate observed in the co-combustion of fuels 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS) is the low content of mineral matter in the barley straw biomass. The flux of fuel in the presented experiment is the same for all fuels.

4. Conclusions

The presented research is a continuation and supplement to the research presented [17]. Based on previous studies, the pressure drop test and a mechanical test were compared to a thermodynamic simulation performed using FactSage 8.0 software [17], and used as a method for determining the sintering temperature.

The ash sintering process was investigated for the following fuels: bituminous coal from the Polish Mine Makoszowa, barley straw biomass and their blends. The process of ash deposition on measuring probes was also studied in a 3.5 m drop furnace was also studied. On the basis of the conducted research, it was found that;

1. Non-standard methods such as the pressure drop test and the mechanical test well reflect the nature of processes observed during the sintering of the tested ashes with bituminous coal from Polish mine Makoszowa, barley straw biomass and their blends.
2. The characteristic temperature ranges for the discontinuities of the specific heat c_p and density predicted by FactSage 8.0 are consistent with the temperature range of the pressure drop in the pressure drop test and the increase in the fracture stress in the mechanical method.
3. Tested fuel ashes: bituminous coal from Polish Mine Makoszowa (BC), barley straw (BS) biomass and their blends: 90 wt.% BC/10 wt.% BS, 75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS can be divided into three groups due to sintering temperatures.
4. The first group includes BC and 90 wt.% BC/10 wt.% BS. Within this group, the sintering temperatures are the highest and the deposition rate the lowest. The difference of the sintering temperature and deposition rate for BC and 90 wt.% BC/10 wt.% BS are small (<5%).
5. The second group—75 wt.% BC/25 wt.% BS and 50 wt.% BC/50 wt.% BS—is characterized by a much lower sintering temperature and visibly higher deposition rate. This effect is clear. For the BC/BS blends, the slagging/fouling tendency increases.
6. The third group, which is biomass BS, is characterized by the lowest sintering temperature. The deposition rate for BS is lower than for the fuels from the second group, but higher than for the fuels from the first. This effect is a consequence of the low content of ash in BS compared to BC—the flow of mass in our experiment was the same for all fuels.

Author Contributions: Conceptualization, K.K., D.N.-W. and W.M.; methodology, K.K., D.N.-W. and W.M.; validation, K.K., D.N.-W. and W.M.; formal analysis, K.K., D.N.-W. and W.M.; investigation, K.K., D.N.-W. and W.M.; resources, K.K., D.N.-W. and W.M.; data curation, K.K., D.N.-W. and W.M.; writing—original draft preparation, K.K., D.N.-W. and W.M.; writing—review and editing, K.K., D.N.-W. and W.M.; supervision, D.N.-W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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