Straw Pellets Burning in a Fixed Bed with Low Ash Agglomeration

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Abstract. Melting of the straw pellets' ash leads to bed agglomeration with incomplete burning out and even to burning extinguishing. The aims of the work are to study the ash agglomeration during the combustion of straw pellets in a fixed bed at different primary air velocities, which differs by being carried out at various thicknesses of the pellets bed, and to substantiate the mode of burning with minimized ash agglomeration. The aims are achieved by: batch burning of straw pellets with recording bed temperatures; determining the mass fraction of agglomerated ash; determining the ash fusibility temperatures; analyzing the chemical composition of ash and calculating the agglomeration indices; determining energy loss because of incomplete carbon burnout. The most important results are: experimental evidence that decreasing the primary air velocity, combined with lowering the pellets bed thickness, resulted in lower maximal temperatures in the bed and decreased bottom ash agglomeration; when maximal bed temperature decreased the chemical composition of bottom ash changed with ash indices shifting to lower slagging and agglomeration. The practical significance of the obtained results is that at maximal bed temperatures ranging from 1061 to 915°C, the content of agglomerated bottom ash, having initial deformation temperatures of 1065–1045°C, was 0.03 of ash mass. This is a so-called low-temperature mode of burning where the maximal temperature in the burning bed is lower than the initial deformation temperature of the formed bottom ash, thus preventing its melting and agglomeration, and is recommended for straw pellets combustion in a continuously operated burner with acceptable energy loss because of incomplete carbon burnout.

***Keywords*:** straw pellets, bottom ash, ash composition, ash melting, ash fusibility, initial deformation temperature, ash agglomeration.

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Arderea peleții de paie care ard într-un pat fix cu aglomerare scăzută de cenușă

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Rezumat. Topirea cenușii peleților de paie duce la aglomerarea în pat cu ardere incompletă și chiar la stingerea arderii. Scopul lucrării este de a studia aglomerarea de cenușă în perioadă de ardere peleților de paie într-un pat fix la viteze ale aerului primar diferite, care diferă prin faptul că este realizat la diferite grosimi ale patului de peleți și de a fundamenta modul de ardere cu aglomerare minimă de cenușă. Obiectivele sunt atinse prin: arderea lotului de pelete de paie cu înregistrarea temperaturii patului; determinarea fracției de masă a cenușii aglomerate; determinarea temperaturilor de fuzibilitate a cenușii; analiza compoziției chimice a cenușii și calcularea indicilor de aglomerare; determinarea pierderii de energie din cauza consumului incomplet de carbon. Cele mai importante rezultate sunt: dovezi experimentale că scăderea vitezei aerului primar, combinată cu scăderea grosimii patului de pelete, a dus la temperaturi maxime mai scăzute în pat și scăderea aglomerației de cenușă de fund; când temperatura maximă a stratului a scăzut, compoziția chimică a cenușii de fund s-a schimbat cu indici de cenușă deplasându-se la zgură și aglomerare mai scăzute. Semnificația practică a rezultatelor obținute este că la temperaturile maxime ale stratului cuprins între 1061 și 915°C, conținutul de cenușă de fund aglomerată, având temperaturi inițiale de deformare de 1065–1045°C, a fost de 0,03 din masa de cenușă. Acesta este un așa-numit mod de ardere la temperatură joasă în care temperatura maximă în patul de ardere este mai mică decât temperatura inițială de deformare a cenușii de fund formată, prevenind astfel topirea și aglomerarea acesteia și este recomandat pentru arderea peletelor de paie într-un arzător cu funcționare continuă, cu pierderi acceptabile de energie din cauza arderii incomplete a carbonului.

Cuvinte cheie: pelete de paie, cenușă de fund, compoziția cenușii, topirea cenușii, fuzibilitatea cenușii, temperatura de deformare inițială, aglomerarea cenușii.

Сжигание соломенных пеллет в стационарном слое с низкой агломерацией золы

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Аннотация. Плавление золы соломенных пеллет приводит к агломерации слоя, неполному выгоранию и даже погасанию горения. Целью работы является изучение агломерации золы при сжигании соломенных пеллет в неподвижном слое при различных скоростях первичного воздуха, отличающееся тем, что осуществляется при различных толщинах слоя пеллет, а также обоснование выбора режима горения с минимальной агломерацией золы. Поставленные цели достигаются за счет: периодического сжигания соломенных пеллет с регистрацией температуры слоя; определения массовой доли агломерированной золы; определения температур плавкости золы; анализа химического состава золы и расчета индексов агломерации; определения потерь энергии из-за механической неполноты выгорания углерода. Наиболее важными результатами являются: экспериментальное подтверждение того, что снижение скорости первичного воздуха в сочетании с уменьшением толщины слоя пеллет приводит к снижению максимальных температур в слое и уменьшению агломерации золы; при снижении максимальной температуры слоя изменяется химический состав золы, а индексы золы смещаются в сторону более низкого шлакования и агломерации. Практическая значимость полученных результатов заключается в том, что при максимальных температурах слоя от 1061 до 915°C содержание агломерированной золы, имеющей температуры начала деформации 1065–1045°C, составляет до 0,03 массы золы. Этот режим горения можно назвать низкотемпературным, при котором максимальная температура в горящем слое ниже, чем температура начала деформации образовавшейся донной золы, что и предотвращает ее плавление и агломерацию, и рекомендуется для сжигания соломенных пеллет в непрерывно действующей горелке с приемлемыми потерями энергии из-за механической неполноты выгорания углерода.

Ключевые слова: соломенные пеллеты, донная зола, состав золы, плавление золы, плавкость золы, температура начала деформации, агломерация золы.

INTRODUCTION

At energy production for industrial and domestic needs, biomass pellets have become widely used, their global production amounted to 44.2 million tonnes in 2023. In the EU countries, the maximal consumption of pellets, mainly wood pellets, was 34.6 million tonnes in 2021 [1].

Wood pellets burning technologies have long reached technical excellence, but straw pellets burning requires new technologies, which are in the research and development stage [2].

With the UN Framework Convention on Climate Change, the signatory countries have committed themselves to reducing anthropogenic greenhouse gas emissions. At the same time, it was envisaged to preserve and increase the effectiveness of sinks and reservoirs of greenhouse gases, including forests and agricultural lands [3]. EU climate policy is focused on a target to make Europe a net-zero emitter of greenhouse gases by 2050 [4]. Among the tools for achieving EU climate neutrality are the expansion of the renewable energy usage [5] and implementation of circular economy principles [6]. The cascade usage will be introduced in bioresources handling, particularly of wood, where higher-value applications are prioritized before using biological resources for energy and fuel generation [7]. It can be expected that availability of roundwood for energy needs will decrease.

Currently, high-quality wood pellets for non-industrial (domestic and commercial) use, classified as A2 and A1, are primarily produced from stemwood and whole trees without roots [8], which should have an initial deformation temperature of ash above 1100 °C and 1200 °C [9].

Considering the decreasing wood availability for energy production, the use of annual agricultural biomass, particularly cereal straw is an urgent task. In Ukraine, several factories have been built supplying straw pellets mainly for use as fodder and bedding for animals. The quality of straw pellets would pose a problem for most boiler systems due to the high potassium (K) and chloride (Cl) content of straw, which leads to fouling of the boilers and ash melting [10].

Pellets according to standard [11] can be made from biomass as it is delivered from fields and forests. The pellet manufacturer must specify the standardized characteristics of the pellets, including on nitrogen, sulfur, and chlorine content, as well as reference data on the actual values of ash fusibility temperatures, which should be determined according to [12] testing ash, obtained in accordance with the requirements of [13].

An important direction is the non-industrial use of straw pellets, particularly in the Steppe zone, where grain crops are intensively cultivated and wood resources are limited. Small residential and commercial heating boilers with a heat capacity of up to 500 kW, manufactured according to standard [14], are considered in [15] as non-industrial consumers of straw pellets. Fixed bed combustion of wood pellets at high temperatures is mainly carried out in residential and commercial heating boilers with a heat capacity of up to 500 kW. When burning wood with an oxygen excess of $\lambda \approx 1.4...2.0$ the furnace temperature ranges from 1100 to 1300 °C, with local values reaching up to 1600 °C [16].

Cereal straw, as a raw material for producing pellets, is characterized by its unfavorable properties. The content of ash and individual ash related elements in straw can vary widely [11], but [15] sets limits on chlorine, nitrogen, and sulfur content for non-industrial straw pellets. Using natural straw, as delivered from the fields, to produce non-industrial straw pellets is practically impossible because the minimum chlorine content in natural straw equals the maximum allowable chlorine content in non-industrial straw pellets [17]. The initial deformation temperature of straw ash can range from 775 to 1225 °C, with the most likely value of 925 °C [18]. The burning of pellets made of natural straw can most likely be complicated by ash agglomeration in boilers intended for wood pellets combustion.

A straw with improved properties, achieved through leaching of ash-related components with atmospheric precipitation, can be used for pellet production [19], but this approach is limited by the scarcity of precipitation, particularly in the Steppe zone. Artificial washing of straw with water [20] or acid solutions [21] was performed with significant water consumption, ranging from 0.00525 to 0.065 L/g [17], which will create the problem of disposing or purifying large volumes of contaminated washing water.

Production of better pellets from a mixture of different types of biomasses was studied. The agropellets made from wheat crop residue, shavings, and a mixture of wheat and rapeseed straw, failed to meet established requirements. The combustion of these agropellets, having deformation temperatures DT = 980 °C and DT = 960 °C, proved unsuccessful, leading to the extinguishing of the fire in the residential space heater after 30 minutes of operation [22]. It was found that only the hogweed and the mix of wood shavings, synthetic, and textile waste can be used for production of pellets complying with ENplus B-class wood pellets quality requirements [23].

Blending of wheat straw with wood for pelletizing can slightly reduce slagging problems. However, only for a blend with high wood content (90 wt %) a distinct reduction of slagging was observed [24, 25, 26].

Increasing the melting temperatures of straw ash can be achieved by adding kaolin, limestone, lime, dolomite and others [27]. Adding 1 % lime during straw burning resulted in minimal slag and sinter formation. The disadvantage of the lime application was a significant reduction in heat output of 5 – 10 % and increased emissions of carbon monoxide and particulate matter. During pellets production, the addition of 1 % CaO to wheat straw increased the deformation temperature from 915 to 1097 °C, and adding 2 % increased it to 1193 °C [28]. Adding limestone ($CaCO_3$) to rice straw proved more effective than adding lime (CaO); specifically, adding 1 % $CaCO_3$ increased the deformation temperature of the ash from 1063 °C to 1110 °C [29].

The kaolin was regarded as the best additive for handling and capturing the problematic alkali-containing species during biomass combustion, with its ability to convert alkali-containing species to high melting point potassium aluminum silicates [30]. A laboratory study of reactions involving K_2SO_4 or KCl and kaolin revealed their high melting products, as well as HCl and SO_3 [31].

The use of pellets with added kaolin led to an increase in the emission of CO and particulate matter, HCl, SO_2, and an increase in the risk of high-temperature corrosion. Besides, because of the additive's abrasiveness, there was a distinct increase in the wear of the dies and the rollers during pellets production [24].

Effects of combustion duration, combustion temperature 600 – 1000 °C, addition of CaO on residual K content, and fusibility of biomass pellet ash were investigated. At the same combustion temperature, the residual content of K ions in ash decreases as the combustion time increases [32].

According to published certificates, straw pellets having an ash content of 8 wt % were characterized by different deformation temperatures of 950 °C and 1000 °C [33]. It follows that individual batches of straw pellets can be characterized by an increased ash deformation temperature, which is higher than the most probable values, but lower than the ENplus requirements. There is a practical interest in burning these straw pellets, as they are, in heating boilers, given their slightly better properties.

Attempts have been made to burn straw pellets in heating boilers with burners designed for wood pellets burning. Pellets made of barley straw with 6.6 % ash and an initial deformation temperature of 980 °C could not be burnt in a retort burner with top fuel supply or in a horizontal cylindrical burner; however, combustion was stabilized in an underfeed retort, although with a significant CO emission of about 6000 ppm [34].

In paper [35], studies on burning straw pellets in two heating boilers were described. The boiler, equipped with a retort burner, operated for only an hour when burning straw pellets, and during this time its heat output decreased from 72 % to 39 % of the rated heat output. Agglomerates of sintered ash formed on the bed surface of burning straw pellets, making combustion difficult and resulting in unburned pellets being discharged from the burner into the ash box. Subsequently, the ash clusters blocked combustion. The boiler, equipped with a burner with movable grate-bars, worked stably for 6 hours continuously when burning straw pellets, providing 56 % of rated heat output. At that time, the average carbon monoxide CO emission was 1800 mg/m^3, with individual peak values reaching up to 5000 mg/m^3. These CO emissions meet the requirements of EN 303–5 [14] for 3rd class boilers with automatic fuel loading. Direct application of the obtained results is hindered by the absence of data on the properties of the burned pellets, on the operating modes of the burners, and on the efficiency of combustion.

The emissions and ash behavior at 18 kW boiler, equipped with an underfeed retort burner designed for wood pellets, when burning 8 mm wheat straw pellets was studied [36]. Adjustments to the air supply could not fully prevent ash sintering. Despite the effort, at straw pellets burning the achieved heat output decreased by 22 %, but the efficiency of the system did not exceed 50 %.

In paper [37], a study was described on the burning of straw pellets in a burner with water-cooled jacket around the combustion chamber, thus supporting a fixed bed of fuel at relatively low temperatures – below 1000 °C. There was an indication of sintering particles on the chamber wall and also, they develop in the bed. The drawback of such an approach, authors [37] supposed, was that gases were rapidly cooled and condensate and tar occurred on cooled chamber walls.

It can be assumed that, at straw pellets burning under the influence of high temperatures, volatile ash components evaporated from the particles of hot fuel and were carried out with flue gas from the furnace. The possibility of such a nature of processes was indicated by study of the chemical composition of the ash after burning wood chips in a 20 MW steam boiler [38]. When comparing the chemical composition of the bottom ash, taken from the grate, and the fly ash, captured in the fiber filter, it was found that the bottom ash had a lower content of potassium and chlorine, but a higher content of aluminum and silicon compared to their content in the fly ash. For these ash samples the authors found that the fusibility index of bottom ash was $T_{AF} = (1200 - 1220)$ °C, and that of fly ash $T_{AF} = (1360 - 1380)$ °C.

Similar studies were carried out at straw burning in the steam boiler furnace [39]. Repeatedly measured in the oxidizing atmosphere, the initial deformation temperatures for bottom ash were in the range 830 – 910 °C, and for fly ash 650 – 790 °C; that is, the initial deformation temperatures of the bottom ash were higher by 40 – 290 degrees than that of the fly ash. The above-mentioned papers [38, 39] described opposite findings regarding the fusibility of bottom and fly ash, but conditions of burning were not reported.

The analysis of published papers revealed that the known methods of improving straw properties, changing method of straw pellets burning have limited application possibilities or only partly solve the problem of ash agglomeration, or may even create new problems. There are features that can contribute to decreasing ash agglomeration at straw pellets combustion. This is the approach of [36] to adjust the intensity of the air supply. It is also worth to consider the emission of potassium during solid biofuels combustion, which was noted in papers [32, 38, 39]. As to straw pellets combustion this phenomenon possibly can lead to change in bottom ash composition and its fusibility.

The aims of the work are to study the ash agglomeration during the combustion of straw pellets in a fixed bed at different primary air velocities, which differs by being carried out at various thicknesses of the pellets bed, and to substantiate the mode of burning with minimized ash agglomeration.

MATERIALS AND METHODS

Experimental approach. Straw pellets, industrially produced from wheat straw in presses with cylindrical dies, had a nominal diameter of

D0 = 8 mm and an actual diameter of 8.2 mm, were used for study. The presence of a fine fraction has a negative effect on the pellets' combustion [2]. In the paper [40], the mechanism of fine particles' role in the origin of fuel agglomerates in a fixed bed in a boiler furnace was described. Different content of fine particles in individual experiments can have an uncontrolled effect on research results. That is why, the delivered pellets were scattered on a sieve with round holes of 3.2 mm to remove the fine fraction. For the coarse fraction of pellets, the total moisture content M_{ar} was determined according to ISO 18134–2:2017, ash content A_d — [13], bulk density *BD* — ISO 17828:2015. According to ISO16993:2016 the low calorific value *LHV* of straw pellets was calculated based on the reference data of the *LHV* of cereal straw [11]. The length of the individual pellets, remaining on the sieve with holes of 3.2 mm, and their length distribution were determined following standard ISO 17829:2015.

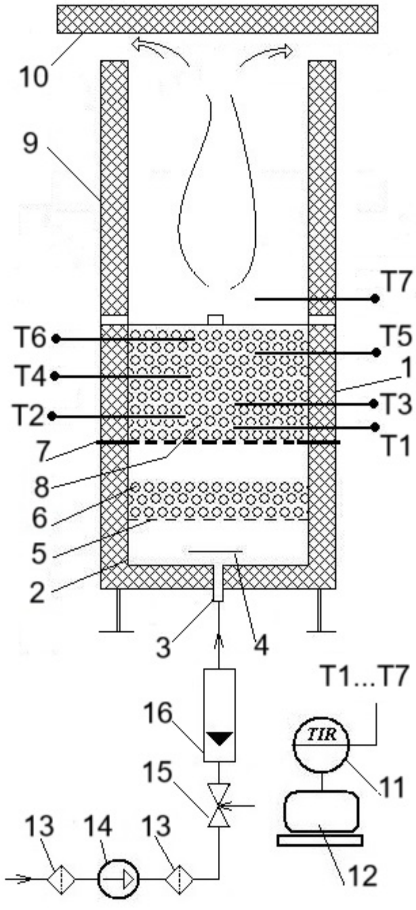
Direct studies of the straw pellets burning in real burners do not allow to single out individual stages of combustion. The idea of the work was to study the periodic burning of pellet portions on a small fixed fire-grate. At that, it was possible to observe the running of individual stages of pellet combustion, study the temperature conditions in the burning fuel bed, and their effect on the properties of bottom ash and its agglomeration.

The results obtained can also be attributed to continuous combustion, which can be considered as a superposition of periodic processes at different stages occurring on sections of the movable fire-grate. The identified conditions for successful combustion of straw pellets, occurring without agglomeration of the formed bottom ash, can be reproduced in the appropriate areas along the movable fire-grate or burner with movable grate-bars.

Experimental installation. In the experimental installation (Fig. 1), periodic burning of straw pellets portions was carried out in a hearth 1, which was made of refractory bricks, which had a cylindrical channel with a diameter of 110 mm and a height of 65 mm. On the outside, the hearth had a heat-insulating layer and a sheet steel shell.

Under the hearth 1 there was an air distribution chamber 2, which was made of stainless-steel sheet, with a primary air supply pipe 3. In distribution chamber 2 above the primary air pipe 3, a reflective disc 4 was installed, as well as a mesh partition 5 with a layer 6 of fireclay gravel of 5 – 10 mm size particles to get a uniform flow of primary air. Outside and below, the air distribution chamber also had fire-proof thermal insulation and a sheet steel shell.

Between the hearth 1 and the air distribution chamber 2, a fire-grate 7 was installed, which was made of heat-resistant sheet steel and had 4.5 mm holes for air passage, the area of the holes was 8.7 % of fire-grate area. The joint between the hearth 1, the fire-grate 7 and the air distribution chamber 2 was sealed with a mullite-silica felt gasket.



1 – hearth, 2 – air distribution chamber, 3 – primary air pipe, 4 – reflective disc, 5 – mesh partition, 6 – fireclay gravel, 7 – fire-grate, 8 – pellets bed, 9 – afterburn chamber, 10 – refractory cover, 11 – temperature meter/recorder, 12 – personal computer, 13 – filter, 14 – blow fan, 15 – control valve, 16 – rotameter, T1 ... T7 – thermocouples.

Fig. 1. Scheme of the experimental installation for studying the straw pellets combustion in fixed bed.

A pellets bed 8 was laid on the fire-grate 7. To measure temperatures in the fuel bed, the type K thermocouples with electrodes of 0.3 mm in diameter were used, which were in protective ceramic casing having an outside diameter of

2.2 mm. Thermocouples T1 ... T7 were placed at heights h of 15, 20, 25, 30, 40, 45, 65 mm above the fire-grate, respectively, with 25 mm penetration into the pellet bed along the hearth radius. At a small bed thickness, the upper thermocouples were above the fuel.

The hearth 1 was equipped with an afterburning chamber 9, which had an internal cross-section of 125 x 125 mm and a height of 240 mm. The afterburning chamber was made of refractory fireclay segments, covered with an insulating layer of mullite-silica felt. In the lower part of the afterburning chamber, there were holes that allowed uncontrolled access of secondary air for afterburning volatile and incomplete combustion products. To prevent radiation cooling of the burning bed of pellets, a refractory plate 10 was installed above the afterburning chamber.

Atmospheric air was taken through the inlet filter 13 by means of a blow fan 14, and through the outlet filter, a control valve 15, and a rotameter 16 was supplied through the inlet pipe 3 to the air distribution chamber 2. During each of the experiments, the selected constant primary air flow through the rotameter 16 was maintained.

Terminals of thermocouples T1 … T7 were connected to a multi-channel temperature controller 11 (readability 1 °C, measurement error ±3 °C), which was connected to a personal computer 12. The updating period of temperatures on the monitor was 5 s; the average minute values of each measured temperature were saved in the device' memory.

Research method. Pellets were burned on a fire-grate at bed thicknesses H of 30, 45, and 60 mm. With the afterburning chamber 9 removed, a portion of pellets having mass m_f, which was enough to provide the accepted bed height, was poured into the hearth 1, leveled on the fire-grate, and the entire installation was slightly shaken for the free pellets to fit in the bed. A metaldehyde tablet divided into 4 parts was placed on the pellets bed and ignified without primary air supply. After metaldehyde catched fire, the primary air was supplied bringing its flow rate to the required one within 1 minute, and then the afterburning chamber 9 was installed. The primary air flow rate corresponded to air velocity, attributed to the full cross-sectional area of the hearth, with fixed values of w = (0.028; 0.056; 0.096; 0.172) m/s.

Secondary air jets flowed freely through holes in the lower part of the afterburning chamber 9, providing flare afterburning of volatile and incomplete combustion products coming out of the pellets bed. At this stage of research, the effect of secondary air supply on the chemical composition of flue gas and the pollutants' emission was not studied.

The combustion process was visually observed, and the time since the start of the primary air supply to the onset of characteristic states was recorded: the completion of the volatile release and the transition to flameless carbon burning out from the char, the appearance of burnouts in the bed of char; and until the end of the visible smoldering of the last particle in the hearth, which was considered as the burning duration τ of the weighted portion of pellets m_f.

The temperatures T1 … T7 in the pellets bed were observed by the graphic display on the monitor. According to the temperature records, the maximal temperature T_{max} reached in the pellets bed, was determined, which could cause melting and agglomeration of the formed bottom ash on the fire-grate.

The intensity of pellets combustion, actually achieved in the experimental installation, was determined as the thermal tension of the fire-grate q_f [41] based on the calculated calorific value LHV of pellets, and the determined duration of burning τ of the weighted portion of pellets m_f:

$$q_f = m_f \cdot LHV \big/ \left(\tau \cdot F\right), \quad [\mathrm{W/m^2}] \qquad (1)$$

where F is the area of the fire-grate within the hearth, equal to the cross-sectional area of the hearth, m^2.

After trial experiments with wood pellets burning, loose bottom ash remained, and after burning straw pellets, a particle of bottom ash was formed from each pellet, which had a shape close to a cylinder with a diameter of up to 1.5 mm smaller than the initial diameter of straw pellets. At high temperatures, the "ash cylinders" of straw pellets could sinter, that is, become hard, and sticked together, forming agglomerates of bottom ash from many neighboring pellets' ash. After the completion of the experiment, the resulting bottom ash, which was on the fire-grate and under it, was transferred to a sieve with slots 7 mm wide, and sifted with light shaking to separate agglomerated ash particles larger than 7 mm from loose ash. In this work, only sticked blocks of particles larger than 7 mm were considered as agglomerates, in contrast to paper [24] in which the ash particles that remained on a sieve with 3.15 mm round holes were considered as agglomerates.

Agglomerates of ash remaining on the sieve and loose ash falling through the slots were weighed on a scale with a readability of 0.01 g. The proportion of agglomerated ash A_{ag} from all bottom ash was determined:

$$A_{ag} = m_{ag} / \left(m_{ag} + m_{al} \right) \tag{2}$$

where: m_{ag} is the mass of agglomerated ash, kg;
m_{al} is the mass of the loose ash, kg.

All collected bottom ash was ground into particles smaller than 50°µm in a mortar. The resulting ash had a black color, which indicated incomplete fuel burnout, and this may cause losses of fuel energy because of the mechanical incompleteness of burning out. Since ash residues have been exposed to high temperatures 900 – 1200 °C in an oxidizing environment, then carbon can be regarded as the only combustible component in the ash residues. Portions of the ground bottom ash, each weighing 1 g, were placed in calcined porcelain crucibles and the residual carbon was burned out by gradual heating to 550 °C in a muffle furnace, following the standard procedure [13]. The burnt ash turned gray. The carbon content in the bottom ash was determined by the relative decrease in its mass during burning out:

$$C_a = \left(m_1 - m_2 \right) / m_1 \cdot 100 \text{, [wt \%]}, \tag{3}$$

where: m_1 is the mass of the dry ash before carbon burning out, kg;
m_2 is the mass of the dry carbon free ash after burning out in muffle, kg.

Neglecting the loss of ash because of its components' evaporation during pellets' combustion, and making up the material balance for 1 kg of burned pellets, it was determined the mass of carbon remaining in the bottom ash and the loss of pellets' energy q_4 caused by the mechanical incompleteness of combustion:

$$q_4 = \frac{100 - M_{ar}}{100} \cdot \frac{A_d}{100} \cdot \frac{C_a}{100} \cdot \frac{HC_c}{LHV} \text{, [\%]}, \tag{4}$$

where: HC_c = 33.9 MJ/kg is the heat value of a carbon.

Determining the ash fusion temperatures. The weighted test portions from the analytical sample of pellets' biomass were burnt in the muffle furnace at gradual heating to 550 °C, preventing the ignition of volatile compounds, according to the standard method [13]. Ash portions from parallel tests were combined and ground into particles smaller than 50°µm in a mortar. Samples of the bottom ash, obtained after burning straw pellets in an experimental installation under different conditions, after determining the carbon content, were used to determine their fusibility temperatures.

In determining the temperature characteristics of straw ash fusibility, the procedure of the ASTM D1857 [42] in the oxidizing environment was selected, taking into account recommendation of [43] that the fusibility of ash, obtained after biomass burning in heat-generating plants, should be determined under oxidizing conditions, mainly due to their similarity to the combustion process, and thus more accurately reflecting possible ash behavior. Additionally, the recommendation of [44] as to advisable reducing the height of the test pyramids of ash to 12 mm to prevent them from tilting was taken into account. For visual observation of the test pyramid melting, the video camera displaying a magnified image of the test pyramid on the monitor was applied.

To measure the temperature of the muffle furnace at heating of tests pyramids of ash, K-type thermocouples with ceramic casing having 3 mm outside diameter were applied. The main thermocouple was located on the longitudinal axis of the furnace at the level of the ash pyramid apex at a 15 mm horizontal distance from it. Thermocouples were connected to a temperature controller-recorder (readability 1 °C, error ±3 °C) which provided a temperature indication and data transmission to a computer. The maximum achievable temperature in the muffle furnace was 1275 °C.

According to ASTM D1857 [42], the following temperatures were determined: the initial deformation temperature (IDT); the softening temperature (ST).

This standard does not envisage the determination of the shrinkage starting temperature (SST) and does not offer characteristic features of the shrinkage start. The ISO 21404 [12] defines SST as the muffle furnace temperature at which the image area of the test ash sample is 95% of the sample image area at which ash was burned, which in this study was 550 °C.

Assuming that during the initial period of ash pyramid heating, all dimensions of the pyramid will experience the same shrinkage, then a decrease in the pyramid image area to 95 % would correspond to a decrease of the pyramid height to $\sqrt{0.95} = 0.975$. For each ash sample, at least two experiments were carried out, and as the result the mean value and standard deviation were taken for the determined temperature.

The chemical composition of the mineral part in straw pellets before burning and that of the straw pellets ash, were measured by means of an X-ray fluorescence analyzer "ElvaX Plus" (Elvatech, Ukraine), which intended for quantitative elements measurements from Na till U. Results were expressed by the relative content by weight of the 11 main ash components: chlorine Cl and oxides SO_3, P_2O_5, SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2 with normalization to 100 %.

Analytical approach. The use of indices, which are calculated based on ash chemical composition, has become widespread. Comparing them to their critical values, it is possible to judge the negative impact of ash properties on the processes in the furnace and in the radiative and convective passes of the boiler. Having the data from the carried-out experiments, it was possible to determine the following indices, reflecting fusibility, agglomeration and fouling of ash: chlorine content in biomass – Cl, wt % [45]; base to acid ratio – $B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5) / (SiO_2 + Al_2O_3 + TiO_2)$ [46]; silica-alumina ratio – $S/A = SiO_2 / Al_2O_3$ [47]; bed agglomeration index – $BAI = (Fe_2O_3) / (Na_2O + K_2O)$ [46]; fouling index – $Fu = (B/A) \cdot (Na_2O + K_2O)$ [46]; slag viscosity index – $Sr = SiO_2 \cdot 100 / (SiO_2 + Fe_2O_3 + CaO + MgO)$ [46]); initial deformation temperature – IDT, °C [48].

RESULTS AND DISCUSSION

The properties of straw pellets. Based on the results of measurements and calculations, the following characteristics of the used straw pellets have been established: total moisture content M_{ar} =10.4 wt %, ash content on dry mass A_d =7.2 wt %, straw pellets' *LHV* =15.15 MJ/kg, bulk density *BD* =550 kg/m^3. The length of the individual pellets ranged from 3.2 mm to 24.1 mm, with an average length of 5.2 mm.

Temperatures in the burning pellets bed. The temperatures change in a bed of pellets having an initial thickness of *H* =60 mm and at a primary air velocity of *w* =0.096 m/s are demonstrated in Fig. 2. The increase in temperatures during the initial period indicated that the ignition of straw pellets propagated gradually from the surface of the bed into deep layers.

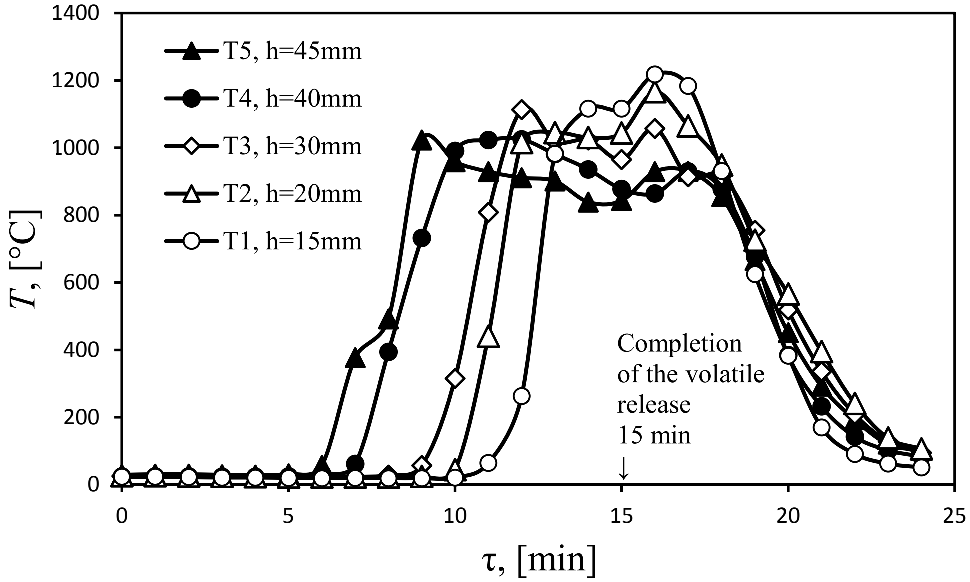


Fig. 2. The temperatures change at heights *h* above the fire-grate in the burning bed of straw pellets having an initial thickness of *H* =60 mm and at the primary air velocity of *w* =0.096 m/s.

Combustion started at the bed surface with its propagation to a depth of 15 mm during the first 5 – 6 minutes, accompanied by short weak flames above the fuel bed. After that, the temperature increase spread to the depth layers, causing the thermal decomposition of pellets, which led to an intensive release of volatile above the bed and their mixing with secondary air, followed by burning with long flame strands in the afterburn chamber. This type of the volatile combustion was observed from the 5th minute and lasted until the 15th minute. During the period of volatile release, the temperatures in the layer increased to 1000 – 1100 °C.

Further, over the fuel bed, the burning of blue flame was observed for a short time, which could indicate the presence of a reduction zone with carbon gasification and incomplete combustion in bed. With the transition to carbon burnout from the char, the bed decreased in height, and in the lower part of the burning bed, the maximal temperature T_{max} = 1218 °C reached for the entire cycle of this fuel load combustion. At the 19th minute, the appearance of bed burnouts was observed; in some areas, carbon burnout was completed; and an ash layer remained. At the 22nd minute, separate smoldering embers were observed in the ash layer, and their smoldering was completed by the 25th minute.

The ash particles formed after the pellet's combustion were black and shaped like cylinders with a diameter of about (6.5 – 7) mm. In some ash particles, ash melting was noticeable with the formation of melt spheres of up to 1 mm in diameter. Inside the bed, the ash pieces fused together to form agglomerates, the content of which was A_{ag} = 0.19 of the total collected ash. The agglomerates and ash pieces, formed outside the agglomerates, were hard but fragile and destroyed when squeezed by fingers.

The combustion of straw pellets in a bed of H =30 mm, with a primary air velocity of w = 0.028 m/s showed certain differences (Fig. 3). At a lower primary air velocity, the ignition of straw pellets on the bed surface occurred somewhat faster, but the burning propagation to a depth of 15 mm from the bed surface took longer – 10 minutes. The release and flame combustion of volatile substances were completed in 13 minutes, while at that the temperature reached 684 °C in the bed.

With the transition to the stage of flameless burning of carbon from the char, a maximal temperature T_{max} = 915 °C was reached in the lower part of the burning bed. At the 25th minute, the appearance of bed burnouts with the formation of an ash layer was observed. At the 38th minute, separate smoldering embers were observed in the ash layer, and stopped smoldering by the 44th minute. After the pellets' combustion, most of the formed ash particles were gray on the outside and black on the inside; they were soft and crumbled when touched. In the ash layer, there were few black and harder particles forming separate agglomerates, whose content was only A_{ag} = 0.01 of the ash mass.

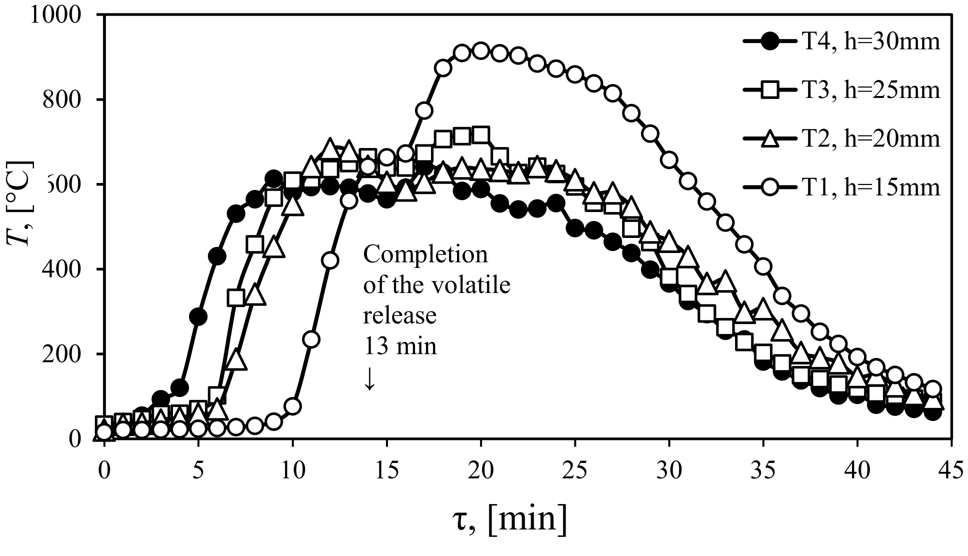
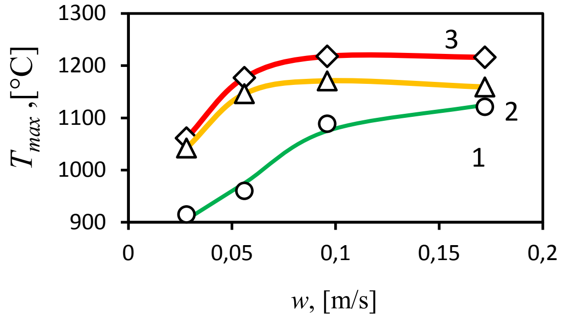


Fig. 3. The change of temperatures at heights h above the fire-grate in the burning bed of straw pellets, having an initial thickness H =30 mm, and at the primary air velocity w =0.028 m/s.

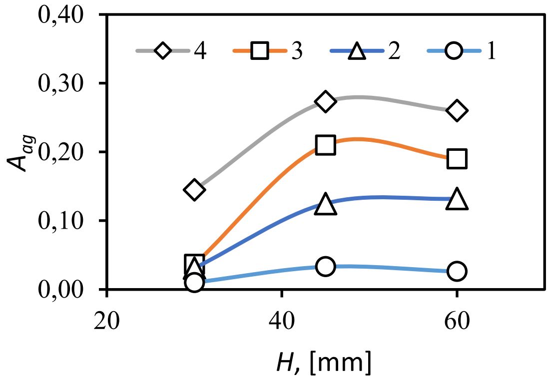
The influence of bed height H and primary air velocity w on maximal temperatures T_{max} at the straw pellets burning. It was proposed to characterize the temperature conditions of straw pellets burning by the maximal temperature, which was achieved in the pellet bed during burning (Fig. 4), as this highest temperature T_{max} determined the possibility of ash fusion with ash particles sticking together and agglomerates forming. The data showed the highest maximal temperatures occurred at higher primary air velocities and greater pellet bed thickness, whereas the lowest maximal temperatures were achieved at the lowest bed thickness combined with lower primary air velocity.



1 – H=30mm; 2 – H=45 mm; 3 – H= 60 mm.

Fig. 4. Maximal burning temperature T_{max} depending on velocity of primary air w at initial thickness H of straw pellets bed.

The influence of straw pellet burning conditions on ash agglomeration. Data in Fig. 5 show that at a low primary air velocity w = 0.028 m/s, agglomerated ash formation was only A_{ag} = 0.01 - 0.03 at the studied bed thicknesses of H = 30 – 60 mm.



1 – w = 0.028 m/s; 2 – w = 0.056 m/s;
3 – w = 0.096 m/s; 4 – w = 0.172 m/s.

Fig. 5. Content of ash agglomerates A_{ag} depending on an initial thickness of the pellets bed H at different primary air velocities w.

Also, low formation of ash agglomerates A_{ag} < 0.05 was observed at a pellet bed thickness of H = 30 mm and moderate primary air velocities $w \leq 0.096$ m/s. Maximal absolute errors in determining the agglomerated ash content were up to 0.0012.

The intensity and completeness of straw pellets burning. Table 1 shows the thermal tension of the fire-grate q_f when straw pellets were burnt under different conditions. The thermal tension of fire-grate, otherworld intensity of the pellets' combustion, was mainly determined by the primary air velocity and, to a lesser extent, by the pellets' bed thickness on the fire-grate. The combustion modes with low ash agglomeration are characterized by a thermal tension of fire-grate of $q_f \leq 172$ kW/m^2, which is two times less than that of intensive combustion with more significant ash agglomeration.

Table 1

Thermal tension of fire-grate q_f, [kW/m^2] depending on the pellets bed thickness H and the primary air velocity w

w, [m/s]	H, [mm]		
	30	45	60
0.172	244	344	359
0.096	172	248	330
0.056	159	188	212
0.028	99	122	121

When straw pellets were burned at a bed thickness of H =60 mm with a primary air velocity of w =0.172 m/s the residual carbon content was C_a =1.97 wt % in the ash; and in cases where pellets were combusted in a thin layer of H =30 mm with a primary air velocity of w =0.028 – 0.096 m/s, the residual carbon content was C_a =2.82 wt %. The loss of the straw pellets' energy q_4 because of mechanical incompleteness of carbon burning out was 0.28 % and 0.41 %, respectively. According to the requirements for boilers [41], fuel energy losses due to mechanical incompleteness of combustion up to 1 % are permissible when burning wood fuels in a fixed bed on fire-grates. Based on the experimental data obtained and mentioned requirements, it can be concluded that modes of straw pellets burning with low ash agglomeration are acceptable in terms of energy loss due to mechanical incompleteness of combustion.

Temperature characteristics of ash fusibility. To arrange the straw pellets burning, it is important to understand the ash transformations that occur when combustion conditions change.

For detailed studies, ashes, formed in experiments with both significant and minimal agglomerates formation, were selected (Tab. 2), that is, those obtained at the highest and lowest maximal temperatures achieved during the burning of straw pellets. The temperature characteristics of the ash fusibility under oxidizing conditions were determined, and the results obtained are given in Tab. 3. The fusibility temperatures of straw pellet ash fell within the range reported by other authors for wheat straw ash [49]. The fusibility temperatures of laboratory ash of straw pellets, obtained according to standard [13], were generally lower than the those of ash after flame burning of the straw pellets in the experimental installation.

The SST-es of ash, obtained after straw pellets burning in the bed at a maximal temperature above 1000 °C, were by 50 – 87 degrees higher than that of laboratory ash, but at the maximal bed temperature of 915 °C, the difference was smaller – 23 degrees.

The IDT of ash obtained after straw pellets burning at a maximal temperature of 1218 °C was almost the same as that of laboratory ash. At maximal bed temperatures of 1171 – 1061 °C, ashes had IDT-es by 26 – 51 degrees higher than that of laboratory ash, and at lowest bed temperature the difference was only 6 degrees.

The ST-es of ashes, obtained after straw pellets burning with a maximal temperature in the bed of more than 1171 °C, were lower than that of laboratory ash. At maximal temperatures in the bed of 1089 °C and below, the ST-es of ashes were by 12 – 22 degrees higher than that of laboratory ash.

Thus, the burning of straw pellets in modes with lower maximal temperatures in the bed led to the formation of bottom ash having slightly higher fusibility temperatures. Moreover, at maximal bed temperatures of 1061 – 915 °C, the bottom ash was formed, having IDT-es of 1065 – 1045 °C; that is, higher than the corresponding maximal temperatures reached in the bed during straw pellets burning, and this can explain the small portion of ash agglomerates.

Table 2

Selected modes of straw pellets burning characterized by different ash agglomeration
(Experiment code *H-w* includes: H – bed thickness, mm; and w – primary air velocity, m/s)

Parameters	Values for experiments with codes *H-w*				
	60-0.096	45-0.096	30-0.096	60-0.056	30-0.028
Pellets bed thickness, H, [mm]	60	45	30	60	30
Primary air velocity, w, [m/s]	0.096	0.096	0.096	0.056	0.028
Thermal tension of the fire-grate, q_f, [kW/m^2]	330	248	200	121	99
Maximal temperature achieved in the bed, T_{max}, [°C]	1218	1171	1089	1061	915
Content of agglomerated ash, A_{ag}, [-]	0.26	0.21	0.036	0.03	0.01

Table 3

Fusibility temperatures (mean value± standard deviation)
for straw pellets' bottom ash obtained at different conditions

Fusion temperatures	Laboratory ash, ashing at 550 °C	For experiments with codes *H-w*				
		60-0.096	45-0.096	30-0.096	60-0.056	30-0.028
SST, [°C]	759±12	815±1	835±7	809±6	846±8	782±6
IDT, [°C]	1039±13	1033±1	1090±7	1070±14	1065±7	1045±7
ST, [°C]	1138±4	1100±10	1125±7	1160±0*	1152±4	1150±14

**-results coincidence.*

The mode of straw pellets burning where the maximal temperature T_{max} in the burning straw pellets' bed is lower than the initial deformation temperature of the formed bottom ash, can be referred to as a low-temperature mode, which prevents the fusion and agglomeration of ash.

This is demonstrated by Fig. 6, on which the ash fusion temperatures SST, IDT, ST, and the maximal temperature of the bed T_{max}, depending on the thermal tension of the fire-grate q_f, are presented.

The ashing of an analytical sample of straw pellets in a muffle furnace at 550°C can be regarded as having occurred with near zero thermal tension, and in the Fig. 6, the corresponding fusibility temperatures of laboratory ash are presented on the vertical axis. To the left of the intersection point of the T_{max} and IDT curves lies a zone of low-temperature modes, characterized by T_{max} being lower than IDT, with a low content of agglomerated ash.

The content of ash related macroelements (as of their oxides) in the mineral part of straw pellets before combustion, as well as the chemical composition of laboratory ash, obtained by flameless oxidation of straw pellets in a muffle furnace at 550 °C, and those of samples of bottom ash, obtained after straw pellets burning pellets in an experimental installation, are presented in Tab. 4. These data are generally consistent with the known data [11, 49]. The main components of the mineral part of the studied straw pellets before their combustion were: SiO_2=46.6 wt %, CaO=23 wt %, and K_2O=17.5 wt %, with content of P_2O_5=2.08 wt % and Cl=2 wt %.

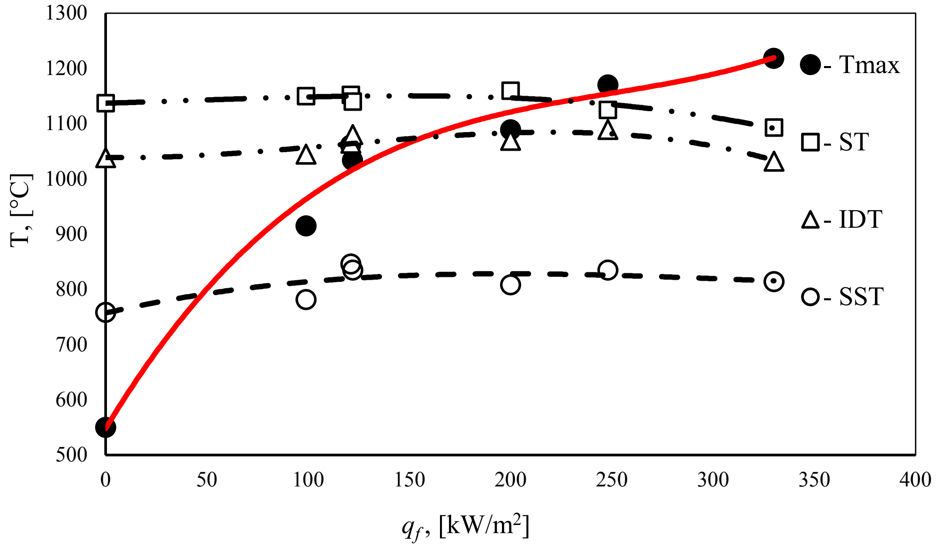


Fig. 6. Dependence of SST, IDT, ST, T_{max} on the thermal tension of the fire-grate q_f

Table 4

Composition of mineral part of straw pellets and ashes, obtained under different burning conditions

Main ash components	Mineral part of pellets before burning	Laboratory ash, ashing at 550 °C	Bottom ash after straw pellet burning in experiments with codes *H-w,* value ± measurement error				
			60-0.096	45-0.096	30-0.096	60-0.056	30-0.028
Cl, [wt %]	2.05±0.07	0.57±0.01	0.07±0.01	0.07±0.01	0.07±0.01	0.34±0.01	0.34±0.01
SO_3, [wt %]	3.22±0.05	2.85±0.02	0.92±0.01	0.92±0.01	0.92±0.07	1.57±0.01	1.39±0.01
P_2O_5, [wt %]	2.08±0.07	2.23±0.03	1.94±0.02	1.10±0.02	1.10±0.02	1.51±0.02	1.24±0.02
SiO_2, [wt %]	46.59±0.14	59.97±0.06	64.95±0.07	65.56±0.07	65.56±0.07	63.71±0.07	63.95±0.07
Fe_2O_3, [wt %]	2.08±0.08	0.76±0.01	0.88±0.01	0.80±0.01	0.80±0.01	0.79±0.01	0.76±0.01
Al_2O_3, [wt %]	0.70±0.06	0.35±0.03	0.65±0.02	0.54±0.02	0.54±0.03	0.27±0.03	0.16±0.03
CaO, [wt %]	23.04±0.11	14.70±0.03	14.31±0.03	15.91±0.03	15.91±0.03	15.84±0.03	16.07±0.03
MgO, [wt %]	2.00±0.17	4.28±0.06	3.68±0.06	3.92±0.06	3.92±0.06	4.15±0.06	4.32±0.06
Na_2O, [wt %]	0.57±0.48	0.14±0.10	0.20±0.10	0.06±0.09	0.06±0.09	0.05±0.09	0.03±0.09
K_2O, [wt %]	17.47±0.08	14.07±0.03	12.30±0.02	11.06±0.02	11.06±0.02	11.69±0.02	11.66±0.02
TiO_2, [wt %]	0.20±0.04	0.08±0.01	0.10±0.01	0.08±0.006	0.08±0.01	0.08±0.01	0.08±0.01

At the flameless oxidation of an analytical sample of pellets in a muffle furnace at a temperature of 550 °C according to the standard procedure, the laboratory ash was obtained, which differed from the mineral part of pellets by an increased content of SiO_2 up to 60 wt %, P_2O_5 up to 2.23 wt %, but a lower content of CaO=14.7 wt %, K_2O=14 wt %, Cl=0.57 wt %, SO_3=2.85 wt %. This indicates that even at oxidization at a low-temperature of 550 °C, there was a loss of some components, in particular K_2O, Na_2O, Cl, and SO_3. These results are consistent with the data of [50] as to significant chlorine loss and moderate sulfur loss even at temperatures below 500 °C. The loss of CaO and Al_2O_3, which are very refractory compounds, cannot be explained by their evaporation at 550 °C, and this requires a separate study.

In experiments with flame combustion of pellets in an experimental installation, which were carried out at temperatures significantly higher than 550 °C, the bottom ash was obtained, which differed in chemical composition from laboratory ash by higher content of SiO_2, and lower content of K_2O and Na_2O. The content of the sum of dolomite oxides (CaO + MgO) depended on the combustion conditions – it was lower than in laboratory ash at the maximal bed temperature of 1218 °C, but at lower maximal temperatures of 1171 – 915 °C it was higher than in the laboratory ash and increased with bed temperature decreasing.

The contents of chlorine and sulfur oxide in the ashes were very low at maximal bed temperatures of 1218 – 1089 °C, which is consistent with the data [50] that at high temperatures chlorine was almost completely released from the ash of all fuels, and about the significant release of sulfur for fuels rich in SiO_2, which are the studied straw pellets.

At maximal temperatures in the pellet bed of 1061 °C and 915 °C, the residual contents of chlorine and sulfur in the ashes were high, but lower than those in the laboratory ash obtained at 550 °C. This result contradicts the data [50] on the complete release of chlorine from the ash of all fuels and a sharp increase in sulfur release at temperatures above 800 °C for fuels rich in SiO_2. It can be assumed that, as at temperatures about 1000 °C the vapor pressure of KCl is low, there was a slow evaporation at low primary air velocities, and during a short period of maximal temperatures (see Fig. 2 and 3), the equilibrium states were not reached.

Indices of fusibility and agglomeration of ash, obtained under different conditions of straw pellets burning, are presented in Tab. 5.

At the Cl<0.2 wt % in biomass, a low tendency of ash to slagging and fouling is expected [45]. When burning the studied pellets having Cl=0.16 wt %, the formed ash may have a low tendency to slagging in the bed and sticking to the heating surfaces of the boiler.

The B/A < 0.5 may indicate a low inclination, and a value within 0.5 < B/A < 1.0 an average inclination to ash agglomeration [46]. For the mineral part in unburned pellets and for a laboratory ash, there was a medium inclination, and for bottom ashes, obtained after pellets combustion, it turned towards a low tendency to agglomeration.

Table 5

Fusibility and agglomeration indices of straw pellets ash

Indices	Mineral part of pellets before burning	Laboratory ash, ashing at 550 °C	Values for bottom ash after straw pellet burning for experiments with codes *H-w*				
			60-0.096	45-0.096	30-0.096	60-0.056	30-0.028
Cl, [wt %] in biomass	0.16	-	-	-	-	-	-
B/A, [-]	0.99	0.60	0.51	0.50	0.50	0.53	0.53
BAI, [-]	0.12	0.05	0.07	0.07	0.06	0.07	0.07
S/A, [-]	67	182	100	121	121	235	400
Fu, [-]	17.95	8.51	6.33	5.52	5.62	6.23	6.21
Sr, [-]	63.2	75.2	77.5	76.1	75.9	75.4	75.1
IDT, [°C]	-	1039	1033	1090	1070	1065	1045

The BAI < 0.15 may indicate a high tendency to agglomeration [46]. For all ashes, the BAI values were less than the critical value, and therefore they were all subject to agglomeration, but index values for the bottom ash were higher than that for the laboratory ash. This indicates that at pellets combustion, a change in the composition of the bottom ash led to a certain decrease in its tendency to agglomeration.

At the S/A (<0.31; >3), low inclination and at (0.3 – 3), high inclination to slagging and fouling can be expected [47]. Silica-alumina ratios of studied pellets' ashes were far above the critical value of 3, and with decreasing maximal temperature at burning, the index values increased, indicating a deviating of bottom ash properties to lower slagging and fouling.

The Fu < 0.6 may indicate a low inclination, and a value within 0.6 < Fu < 40 may indicate an average tendency to fouling of ash [46]. Proceeding from the chemical composition of the mineral part of the pellets and that of laboratory sample of ash, obtained in the muffle furnace at 550 °C, an average tendency to fouling can be expected; but for bottom ash, obtained by pellets flame burning, a decrease of Fu and lower inclination to fouling was found.

The Sr > 72 may indicate a low inclination, and a value within 65 < Sr < 72 may indicate an average tendency to slagging [46]. From the found Sr values for all ash samples, a low inclination to slagging can be predicted, while based on the chemical composition of the pellets' mineral part, an average tendency to slag could be expected.

According to [48] at the IDT < 900 °C, there is a high inclination of ash to agglomeration and slagging, at 900 °C < IDT < 1100 °C - medium inclination, and at 1100 °C < IDT - low inclination. For all ash samples examined, an average inclination to agglomeration and slagging can be expected, but after pellets burning at maximal temperatures in the bed below 1200 °C, bottom ash was characterized by an increase in IDT compared to ash obtained by standard laboratory method. This indicates a certain decrease in the bottom ash inclination to agglomeration at lower burning temperatures.

CONCLUSIONS

1. It was found that a decrease in primary air velocity combined with lowering in the thickness of the straw pellets bed on the fire-grate resulted in lower achievable maximal temperatures in the bed and decreased ash agglomeration.

2. Compared to the laboratory ash sample, the bottom ash of all experiments was characterized by an increased content of SiO_2, and a decreased content of K_2O. The content of the sum of dolomite oxides (CaO + MgO) depended on the combustion conditions – was lower than that of laboratory ash at the maximal temperature of 1218 °C in the bed, and at maximal temperatures of 1171 – 915 °C it was higher than that of the laboratory ash and increased with the burning temperature decreasing.

3. The laboratory ash of straw pellets was characterized by IDT of 1039 °C. The formed bottom ash had a slightly higher IDT than laboratory ash, and its indices were shifted to less pronounced slagging and agglomeration.

4. The mode of straw pellets burning, in which the maximal temperature in the burning straw pellets bed is lower than the IDT of the formed bottom ash, can be conditionally called a low-temperature mode that prevents the ash from melting with its agglomeration. Low-temperature burning of straw pellets has led to acceptable pellets energy loss of 0.41% due to incomplete carbon burnout from the ash. Besides, at low-temperature burning of straw pellets, bottom ash contained more chlorine and sulfur compounds, and therefore a reduction in their emission with flue gases can be expected.

5. For practical implementation in the continuously operated burner, it is worth focusing on the low-temperature modes of the studied straw pellets burning, which were carried out with the thermal tension of the fire-grate q_f =99 – 159 kW/m^2. The main mode can be a combustion at a bed thickness of H =30mm and a primary air velocity of w = (0.028-0.056) m/s, while the maximal temperature in the bed was about 915 – 960 °C, and the portion of agglomerated ash was up to A_{ag} = 0.03.

REFERENCES

[1] Pellets. Bioenergy Europe Statistical Report 2024. Bioenergy Europe. Brussels, 2025, 91 p.

[2] Obernberger I., Thek G. The pellet handbook. The production and thermal utilization of pellets. London, Earthscan Ltd., 2010. 549 p.

[3] United Nations Framework Convention on Climate Change. United Nations, 1992. 33 p.

[4] The European Green Deal. European Commission. COM/2019/640 final. Brussels, 2019. 24 p.

[5] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

[6] A new Circular Economy Action Plan. For a cleaner and more competitive Europe. European

Commission. COM/2020/98 final. Brussels, 2020. 20 p.

[7] Guidance on cascading use of biomass with selected good practice examples on woody biomass. European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Publications Office, 2018. https://data.europa.eu/doi/10.2873/68553

[8] ISO 17225–2:2014. Solid biofuels. Fuel specifications and classes. Part 2: Graded wood pellets. Geneva, ISO, 2014. 10 p.

[9] ENplus. Quality Certification Scheme for Wood Pellets. ENplus Handbook. Part 3: Pellet Quality Requirements. Version 3.0. Brussels. *European Biomass Association. European Pellet Council*, 2015. 10 p.

[10] Elbersen W., Poppens R., Lesschen J. P., Sluis T., Galytska M., Kulyk M., Jamblinne P., Kraisvitnii P., Rii O., Hoekstra T. Pellets for Power: Sustainable biomass import from Ukraine. *Wageningen UR Food & Biobased Research,* 2013. 36 p.

[11] ISO 17225–1:2017. Solid biofuels. Fuel specifications and classes. Part 1: General requirements. Geneva, ISO, 2017. 64 p.

[12] ISO 21404:2020 Solid biofuels. Determination of ash melting behaviour. Geneva, ISO, 2020. 13 p.

[13] ISO 18122:2022. Solid biofuels. Determination of ash content. Geneva, ISO, 2022. 7 p.

[14] EN 303–5:2012. Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – Terminology, requirements, testing and marking. European Committee for Standardization. Brussels. 2012. 81 p.

[15] ISO 17225–6:2014. Solid biofuels. Fuel specifications and classes. Part 6: Graded non-woody pellets. Geneva, ISO, 2014. 10 p

[16] Schütz D. Numerische Simulation und messtechnische Evaluierung der Schadstoffemissionen aus Stückholzfeuerungen. Institut für Feuerungs- und Kraftwerkstechnik der Universität Stuttgart, 2012. 144 s.

[17] Zhovmir M., Moško,J., Farták J., Jiříček I., Pohořelý M. Complex Study of Straw Suitability for Production of Nonindustrial Straw Pellets. *ACS Omega*, 2023, 8(49), pp. 47100-47112. DOI: 10.1021/acsomega.3c07057.

[18] Hartmann H., Böhm T., Maier L. Naturbelassene biogene Festbrennstoffe – umweltrelevante Eigenschaften und Einflussmöglichkeiten. Technischer Bericht, Bayrisches Staatsministerium für Landesentwicklung und Umweltfragen (StMLU), 2000. 148 s.

[19] Sander B. Fuel Data for Danish Biofuels and Improvement of the Quality of Straw and Whole Crops. *Proceedings of the 9th European Conference on Bioenergy in Copenhagen; Biomass for Energy and the Environment (Vol. 3).* England, Oxford, Elsevier Science Ltd., 1996. pp. 490−495.

[20] Jenkins B. M.; Bakker R. R.; Wei J. B. On the properties of washed straw. *Biomass and Bioenergy,* 1996, 10(4). pp.177−200. DOI: 10.1016/0961-9534(95)00058-5.

[21] Zevenhoven-Onderwater M. Ash-forming Matter in Biomass Fuels. PhD thesis. Department of Chemical Engineering, Åbo Akademi University: Turku, Finland. 2001. 85 p.

[22] Matijašević V., Tekáč V., Beňo Z., Duong V. M. (2025). Assessing the Emissions and Suitability of Agro-Based Pellets for Small-Scale Residential Heating Appliances in Serbia. *Pol. J. Environ. Stud.*, 2025, 34, pp. 1697–1708. DOI: 10.15244/pjoes/188052.

[23] Priedniece V., Sturmane A., Eglitis R., Juhnevica I., Krigers G., Kirsanovs V. Search for Alternative Raw Materials for Pellet Production – a Preliminary Study. *Environmental and Climate Technologies*, 2024, 28(1). pp. 652–669. DOI: 10.2478/rtuect-2024-0051.

[24] Mack R., Kuptz D., Schön C., Hartmann H. Combustion behaviour and slagging tendencies of kaolin additivated agricultural pellets and of wood straw pellets blend in a small scale boiler. *Proceedings of the 26th European Biomass Conference and Exhibition,* 14–17 May 2018, Copenhagen, Denmark, 2018. pp. 408–417. DOI: 10.5071/26thEUBCE2018-2AO.5.1.

[25] Zeng T., Weller N., Pollex A., Lenz V. Blended biomass pellets as fuel for small scale combustion appliances: Influence on gaseous and total particulate matter emissions and applicability of fuel indices. *Fuel*, 2016, 184. pp. 689–700. DOI: 10.1016/j.fuel.2016.07.047

[26] Zeng T., Pollex A., Weller N., Lenz V., Nelles M. Blended biomass pellets as fuel for small scale combustion appliances: Effect of blending on slag formation in the bottom ash and pre-evaluation options. *Fue*l, 2018, 212, pp.108–16. DOI: 10.1016/j.fuel.2017.10.036.

[27] Holubcik M., Jandacka J. (2014). Mathematical Model for Prediction of Biomass Ash Melting Temperature using Additives. *Communications – Scientific Letters of the University of Zilina*, 3A, 2014, pp. 48–53. DOI: 10.26552/com.C.2014.3A.48-53.

[28] Holubčik M.; Jandačka J.; Palacka M.; Vician P. Additives Application to Wheat Straw to Increasing the Ash Fusion Temperature. *AIP Conf. Proc.*, 2016, 1768, No. 020014. DOI: 10.1063/1.4963036.

[29] Chaloupková V.; Ivanova T.; Hutla P.; Špunarová M. Ash Melting Behavior of Rice Straw and Calcium Additives. *Agriculture*, 2021, 11, 1282. DOI: 10.3390/agriculture11121282.

[30] Abioye K.J., Harun N.Y., Saeed A.A.H. A Brief Review of Solving Biomass Ash Deposition with Aluminum-silicate Based Additives and Future Perspective of Kaolin, *Chemical Engineering Transactions, 2023,* 98, pp. 27-32 DOI: 10.3303/CET2398005

[31] Steenary B-M., Lindqvist O. High-temperature reactions of straw ash and the anti-sintering additives kaolin and dolomite. *Biomass and Bioenergy*, 1998, 14(1), pp. 67-76.

[32] Guan B., Liu J., Xia M., Ma C., Yan M., Li J., Zhang J. Ash melting and slagging and residual K ion content in biomass pellet combustion. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2024,* 46(1), pp. 3324-3337. DOI: 10.1080/15567036.2024.2318013.

[33] Pellegreen. https://pellegreen.com.ua/palyvni-pelety (Accessed: 05.02.2023).

[34] Rönnbäck M., Johansson M., Claesson F. ERA-Net Evaluation of technology status for small-scale combustion of pellets from new ash rich biomasses - combustion tests in residential burners. SP Technical Research Institute of Sweden. SP Report 2008:31. Boras. 2008. 43p.

[35] Jandačka J., Holubčik M., Papučik Š., Nosek R. Combustion of pellets from wheat straw. *Acta Montanistica Slovaka*, 2012, 17(4), pp. 283-289.

[36] Backa A., Čajová Kantová N., Nosek R., Patsch M. Evaluating the combustion of various biomass pellets in a small heat source with underfeed pellet burner: Heat output, gas emission and ash melting behavior. *Journal of the Energy Institute*, 2025, 118, 101936. DOI: 10.1016/j.joei.2024.101936.

[37] Lenhard R., Mičieta J., Jandačka J., Gavlas S. Specifics of phytomass combustion in small experimental device. *EPJ Web of Conferences*, 2015, 92, 020147. DOI: 10.1051/epjconf/20159202047

[38] Plešingerová B., Vadász P., Medveď D., Jablonský G., Sučik G., Dzurňák R. Characterisation of Dendromass Ash Fractions Captured in Power Plant with a View to their Further Utilization. *Acta Montanistica Slovaca*, 2023, 28(1), pp. 226–235. DOI: 10.46544/AMS.v28i1.18

[39] Hansen L. A., Frandsen F. J., Dam-Johansen K., Sorensen H.S. Quantification of fusion in ashes from solid fuel combustion. *Thermochim. Acta*, 1999, 326, pp. 105−117. DOI: 10.1016/S0040-6031(98)00596-6

[40] Lyubov V., Malkov A., Alekseev P. Boilers slagging when burning wood pellets. *IOP Conference Series: Materials Science and Engineering,* 2022, pp. 1211 012006. DOI: 10.1088/1757-899x/1211/1/012006.

[41] Teplovoy raschet kotelnykh agregatov. Normativnyi metod. Pod red. Kuznetsova N.V. [Thermal Calculation of Boiler Units. Normative Method. Ed. by Kuznetsov N. V..]. Moscow, Energia, 1973, 296 p. (In Russian).

[42] ASTM D1857-03. Standard Test Method for Fusibility of Coal and Coke Ash; ASTM International: West Conshohocken, PA, 2003. 4 p.

[43] Cajová Kantová N.; Holubčík M.; Trnka J.; Caja A. Analysis of Ash Melting Temperatures of Agricultural Pellets Detected during Different Conditions. *Fire*, 2023, 6, 88. DOI: 10.3390/fire6030088.

[44] ISO 540:2008 Hard coal and coke. Determination of ash fusibility. Geneva, ISO, 2008. 9 p.

[45] Garcia-Maraver A., Mata-Sanchez J., Carpio M., Perez-Jimenez J. A. Critical review of predictive coefficients for biomass ash deposition tendency. *Journal of the Energy Institute*, 2017, 90, pp. 214−228. DOI: 10.1016/j.joei.2016.02.002.

[46] Lachman J., Baláš M., Lisý M., Lisá H., Milčák P., Elbl P. An overview of slagging and fouling indicators and their applicability to biomass fuels. *Fuel Process. Technol.*, 2021, 217, 106804. DOI: 10.1016/j.fuproc.2021.106804

[47] Vamvuka D., Karakas E. Ash properties and environmental impact of various biomass and coal fuels and their blends. *Fuel Process Technol.*, 2011, 92, pp. 570-581. DOI: 10.1016/j.fuproc.2010.11.013.

[48] Ohman M., Nordin A., Hedman H., Jirjis R. Reasons for slagging during stemwood pellet combustion and some measures for prevention. *Biomass and Bioenergy*, 2024, 27, pp. 597−605. DOI: 10.1016/j.biombioe.2003.08.017

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