The influence of the oxidizing atmosphere on the mass loss of biomass pellets combusted in the inert material stream

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Abstract. Biomass is a renewable energy source with high growth potential due to wide availability around the world. Wood pellets are commonly used biomass for modern energy production, however, due to the growing demand, the issue of sustainable development has encouraged many entrepreneurs to produce pellets from non-wood biomass. On the one hand, the versatile nature of biomass enables its use in all parts of the world, on the other hand, this diversity makes biomass a complex and difficult fuel. Especially because of the high percentage of alkali (potassium) and chlorine in some types of biomass that can generate problems during combustion. The production and use of pellets from various types of biomass, therefore, opens up opportunities and challenges for existing technologies. In recent years, fluidized combustion technology has been considered as one of the main directions of development of professional energy in the world. Fluidized bed boilers also allow the implementation of the dynamically developing oxy-combustion technology, which perfectly fits the prevailing trends due to the key advantages of increased energy conversion, as well as the possibility of direct sequestration of carbon dioxide. During experimental research, the mass loss of individual biomass pellets of various origin combusted in a laboratory reactor with a circulating fluid layer under various conditions of the furnace chamber (oxidizing atmosphere and intensity of inert material stream) was analyzed. The obtained results allow stating that the large variety of biomass offered by suppliers requires a thorough knowledge of its properties and determination of its impact on the process and installations when used in the power industry.

1. Introduction

In many countries around the world, also in the case of the largest energy producers, such as the USA, China, India and most of the European Union (EU) countries, energy production by burning solid fuels dominates [1]. Due to the increasing population and technological progress, global primary energy consumption is growing, which in 2018 increased almost twice as fast as the average rate recorded since 2010 and amounts to approximately 14.3 billion tonnes of oil equivalent, which is over 599 EJ (exajoules), (average growth rate was 2.3% per year) [2,3]. The growing awareness of the harmful effects of fossil fuel combustion products on the environment is a stimulus for the creation of international conventions that oblige to take effective measures to reduce emissions of harmful substances through the use of modern energy production technologies and increasing the use of energy from renewable sources. The most important is the Paris agreement-2015, which is the world's first binding treaty to reduce climate change [4]. The sustainable development goals of the United Nations also underline the importance of energy. ‘Affordable and clean energy’ in Goal 7 and ‘Climate action’ in Goal 13, highlight the significance of new and renewable energy to transform the world [5].
the unconventional energy sources available, such as hydro, solar, wind etc. biomass is the only sustainable option based on elemental carbon [6]. Biomass can be transformed into solid, liquid and gas using modern technologies, and thus becomes an efficient and clean fuel for all sectors, such as heat, energy and transport fuel [7]. Direct combustion of firewood is the main source of energy among rural developing countries in Asia and Africa. 2.5 billion of the world's population still relies on this traditional use of biomass as a primary energy source [2]. Wood chips are more popular in developed countries due to the availability of automated heat and energy production systems. European countries such as the United Kingdom, the Netherlands, Denmark, Belgium and Germany are the largest consumers of renewable energy for heating homes, mainly from biomass and pellet waste [13]. Biomass in the form of pellets is now also widely used for the production of electricity. Biomass pellets are characterized by higher quality parameters, in addition, due to their regular shape and standard size, they allow compact storage, convenient operation and automatic supply in large operating units [14]. Wood pellets are commonly used biomass for modern energy production, however, due to the growing demand [15], the issue of sustainable development has encouraged many entrepreneurs to produce pellets from non-wood biomass. On the one hand, the versatile nature of biomass enables its use in all parts of the world, on the other hand, this diversity makes biomass a complex and difficult fuel [16,17]. Especially due to the high percentage of alkali potassium and chlorine in some types of biomass that can generate problems during combustion [18,19]. The production and use of pellets from various types of biomass, therefore, opens up opportunities and challenges for existing technologies. The technology that is considered the most beneficial for biomass combustion is the fluidized bed combustion technology that allows the combustion of low-quality fuels and reduces the emission of environmental pollutants generated during combustion. Fluidized bed boilers also allow the implementation of the dynamically developing oxy-combustion technology, which perfectly fits the prevailing trends due to the key advantages of increased energy conversion, as well as the possibility of direct sequestration of carbon dioxide [20]. The impact of the combustion atmosphere in fluidized bed systems in which various types of coal are burned has been thoroughly investigated in recent years by many researchers [21-24], in which the advantages of oxy-combustion have been confirmed. In general, the experimental results combustion of biomass in oxygen and nitrogen mixtures showed that NOx emission at low O2 concentration is lower than during combustion in the air atmosphere. NOx emissions increase with the increase of O2 concentration in the oxidant due to the temperature increase in the furnace. So far, few researchers have analyzed oxy-combustion in fluidized bed reactors fueled with 100% biomass, so further research is needed. experiments using only biomass fuels. The aim of the work [25] was to study oxy-combustion of three types of biomass fuels: agro, forestry and energy plant in a 20 kWth unit with a bladder fluidized bed (BFB), the impact of the combustion atmosphere and oxygen concentration in the oxidant on gas emission and temperature profiles were analyzed. In contrast, work [26], unlike the abovementioned, was devoted to the analysis of the combustion of a single biomass particle in a fluidized bed in various oxidizing atmospheres. This study used spherical biomass "briquettes" (willows, Salix viminalis). The results of the experiment indicate that the composition of the oxidizing atmosphere strongly influences the combustion process of biomass fuels. The replacement of N2 in the combustion environment by CO2 resulted in a slight ignition delay and lower maximum mass loss during the combustion of biomass. Increasing the amount of oxidant shortened the combusting time. This experimental work involves the analysis of the mass loss of individual pellets combusted in a laboratory fluidized bed reactor.

In contrast to the tests described in this review, this experimental work consists of analyzing the mass loss of individual pellets combusted in a laboratory fluidized bed reactor. The experiment used biomass of various origins, available on the market and specially dedicated to combustion in the energy sector. The effect of two fluidized combustion parameters were analyzed: the oxidizing atmosphere and the intensity of the inert material stream.

2. Motivations
The aim of the experimental research was to analyze the oxygen combustion process (three oxygen and carbon dioxide mixtures) in CFB technology, selected biomass fuels of wood origin:
oak sawdust pellets and pellets from a mixture of sawdust 30% beech /70% oak and agro: pellets from sunflower husk and from straw dedicated for combustion in the energy sector.

3. Experimental stand and parameters of the experiment
The research was carried out on a specially constructed test stand. The experimental stand made it possible to model the conditions of the circulating fluidized bed. The experimental stand is presented in Figure 1. [22]. During the experimental research, the impact of inert material and oxidizing atmosphere on the mass loss of pellets of two types of biomass was analyzed: wood biomass - oak sawdust pellets and pellets from a mixture of sawdust 30% beech / 70% oak) and agro-pellets from sunflower husk and from straw. Table 1 contains the results of the technical analysis of the tested fuels. The temperature of 850 °C was corresponding to the combustion temperature of fuels in professional fluidized bed boilers. The research was performed in air atmosphere and gas compound: 21% O₂ and 79% CO₂, 25% O₂ and 75% CO₂, and 30% O₂ and 70% CO₂. The research was carried out in a stream of inert material Gs=0 kg/m²s, 2.5kg/m²s and 5kg/m²s. The values of the stream of inert material are characteristic for the upper and middle area of the real zone of the fluidized bed boilers.

Table 1. Results of technical analysis of biomass fuels.

| Pellets                | Volatile [%] | Moisture [%] | Ash [%] | Fixed coal [%] | Combustion heat [MJ/kg] |
|------------------------|--------------|--------------|---------|----------------|-------------------------|
| Oak sawdust            | 79.6         | 8.7          | 1.2     | 10.5           | 18.2                    |
| 30% beech/70% oak sawdust | 77.7       | 8.8          | 1.3     | 10.7           | 17.9                    |
| Sunflower husk         | 73.8         | 8.4          | 5.5     | 12.3           | 19.8                    |
| Straw                  | 71.8         | 8.7          | 12.2    | 7.3            | 16.2                    |

Figure 1. The scheme of test apparatus. (1) vessel of inert material, (2) gas mixer, (3) PC-computer, (4) control panel, (5) rotameters, (6) gas heater, (7) ventilator, (8) T-connector, (9) combustion chamber, (10) coal particle, (11) tensometric branch scale, (12) support, (13,15) technical gases, (14)-reducer [23].

4. Results of the experiment
Fig. 2. presents a comparison of pellets combustion time combusted at different conditions in a circulating fluidized bed. In all cases, according to the theory, a change in the combustion atmosphere consisting of an increase in the concentration of the oxidizer results in the reduction of the total loss of mass of the biomass pellets combusted. Supplying more oxidizer to the combustion area causes acceleration of the combustion process, therefore the loss of mass is accelerated due to the increased concentration of oxidizer and temperature in the area of the combusted particle., which is caused by the occurring chemical reactions. During combusting pellets without inert material, the wood biomass pellets were combusted the longest (pellets of oak sawdust), and straw pellets the shortest. The shortest combusting time of straw pellets may result from its composition. It has the highest ash content (over 12%) and the lowest fixed coal content among the fuels analyzed - Table 1.
In the case of pellets combusting in the stream of inert material \( G_s = 2.5 \) kg/m\(^2\)s, wood biomass pellets were the shortest combusted, the longest combusted pellets from sunflower husk. At this temperature, the phenomenon of ash softening is manifested by the sticking of sunflower husk pellets through quartz sand. The sand forms a durable surface surrounding the incinerated pellet, consequently preventing the oxidizer from entering the combusted pellet. A similar effect was observed when combusting straw pellets at 850°C. The straw pellets combusted at 850 °C were sintered.

With an increased value of the inert material stream to \( G_s = 5 \) kg/m\(^2\)s, similar to \( G_s = 2.5 \) kg/m\(^2\)s of inert, the longest combusted pellets from sunflower husk, and the shortest pellets from wood biomass. In the case of agro biomass combustion, as in the case of combustion in \( G_s = 2.5 \) kg/m\(^2\)s, during the combusting of pellets from sunflower husk, the formation of a coating was observed, which was partially broken down as a result of the mechanical impact of inert material. On the other hand, the sinter was formed during the combustion of straw was completely broken down.

Analyzing Figure 2., it can be stated that inert material caused a reduction in the total combustion time compared to the combustion time without its participation in each of the analyzed oxidizing atmospheres, and increasing the flux further reduced the combustion time, although to a lesser extent. Which confirms the observations noted in [23]. In the case of both wood biomass, the combustion in the stream of material \( G_s = 2.5 \) kg/m\(^2\)s in each atmosphere is shorter by about 50% compared to incineration without inert material. However, further increase of the inert material stream to \( G_s = 5 \) kg/m\(^2\)s accelerated the combustion process, but only by about 10%. In the case of combusting sunflower husk pellets compared to incineration without inert material, the combustion time in the stream \( G_s = 2.5 \) kg/m\(^2\)s is reduced by about 20-30%. Increasing the value of inert material stream to \( G_s = 5 \) kg/m\(^2\)s resulted in shortening the combustion time in the case of two oxidizing atmospheres of 21% and 25% oxygen by about 10%, while in the case of 30% oxygen concentration, the combustion time was extended by 1%. In the case of straw pellets compared to incineration without inert material, the combustion time in the stream of inert material \( G_s = 2.5 \) kg/m\(^2\)s is reduced by about 35%. Increasing the value of the stream of inert material caused a reduction of the combustion time by about 10%.

![Figure 2. Comparison of pellets combustion time combusted at different conditions in a circulating fluidized bed.](image-url)
5. Conclusions
The analysis carried out as part of the work facilitates the formulation of the following conclusions:
1) Changing the combustion atmosphere is a very important parameter directly affecting the duration of the combustion process and particle surface temperature, and indirectly on the efficiency of combustion and fluidization process.
2) Increasing the concentration of oxidant in the atmosphere of combustion causes the reduction of the time of total mass loss of combusted particles of all tested biomass fuels. According to the theory of providing more oxidizer to the combustion area, it accelerates the combustion process, therefore the mass loss is accelerated.
3) The introduction of inert material into the combustion zone of the particle resulted in the reduction of the total combustion time for all tested fuels in comparison with the combustion time without its participation in each analysed oxidizing atmosphere. In the case of both wood biomass, the combustion in the stream of material $G_s = 2.5 \text{ kg/m}^2\text{s}$ in each atmosphere is shorter by about 50% compared to incineration without inert material. However, further increase of the inert material stream to $G_s = 5 \text{ kg/m}^2\text{s}$ accelerated the combustion process, but only by about 10%. In the case of combusting sunflower husk pellets compared to incineration without inert material, the combustion time in the stream $G_s = 2.5 \text{ kg/m}^2\text{s}$ is reduced by about 20-30%. Increasing the value of inert material stream to $G_s = 5 \text{ kg/m}^2\text{s}$ resulted in shortening the combustion time in the case of two oxidizing atmospheres of 21% and 25% oxygen by about 10%, while in the case of 30% oxygen concentration, the combustion time was extended by 1%. In the case of straw pellets compared to incineration without inert material, the combustion time in the stream of inert material $G_s = 2.5 \text{ kg/m}^2\text{s}$ is reduced by about 35%. Increasing the value of the stream of inert material caused a reduction of the combustion time by about 10%.
4) In the case of the combustion of the sunflower husk pellets in an inert material stream, the ash softening temperature was exceeded and the sample sand was glued through the quartz sand in each analysed oxidizing atmosphere. During the combustion of straw pellets in the flow of inert material, in each analysed oxidizing atmosphere the formation of sinters was observed. During the intensification of the flow of inert material pellets from sunflower husk, the formation of a coating was observed, which was partially broken down as a result of the mechanical impact of inert material. On the other hand, the sinter was formed during the combustion of straw was completely broken down.

Based on the conducted experimental research, it was found that wood and agricultural biomass can be successfully used during oxygen combustion in circulating fluidized bed boilers under several conditions. On the one hand, the versatile nature of biomass enables its versatile use, on the other hand, this diversity makes biomass a complex and difficult fuel, especially due to the high percentage of potassium and chlorine alkali, in some types of agricultural biomass that can generate problems during combustion, lowering the softening and melting ash. Therefore, biomass should be burned under appropriate controlled conditions, adapted to the type and quality of the fuel used.

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