

Experimental Research of Oxy-fuel Combustion of Biomass in a Circulating Fluidized-Bed

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Abstract

In this paper a combustion process of agro biomass (wheat straw) and wood biomass (Scots pine) in a circulating fluidized-bed was analyzed. Combustion of spherical biomass pellets ($d = 10$ mm) was conducted in air and O_2/CO_2 mixtures with oxygen concentrations in the range from 21% to 40% vol. at temperature of 850°C in a 12 kW bench-scale CFB combustor. The main objective of this study was to investigate the combustion behaviour of biomass, in terms of particle temperature profiles, ignition time, volatiles combustion time and the total combustion time. The results of tests show that the composition of the oxidizing atmosphere strongly influences the combustion process of biomass fuels.

Nomenclature

21oxy: 21% vol. oxygen + 79% vol. carbon dioxide

30oxy: 30% vol. oxygen + 70% vol. carbon dioxide

40oxy: 40% vol. oxygen + 60% vol. carbon dioxide

Introduction

Nations worldwide are taking initiatives to counteract global warming by reducing their greenhouse gas emissions. The European Union is playing a leading role by setting targets to reduce its greenhouse gas emissions by 20% (from 1990 level), to increase the share of renewable energy to 20% in its primary energy consumption, and to improve energy efficiency by 20%. All three targets will be met by the year 2020. Efforts to increase boiler efficiency and the use of biomass and other solid renewable fuels are well in line with these objectives [1,2].

Biomass is considered as a carbon-neutral fuel in many countries, and its utilization in utility boilers can result in reduction in CO_2 emission since the biomass captures atmospheric carbon dioxide during its growth cycle. Biomass contains more volatiles and low carbon content as compared to coal, which makes biomass a highly reactive fuel. On the other hand, raw biomass have several disadvantages compared to fossil fuels including [3-5]:

- high moisture content (up to 60%),
- irregular shape and size,
- relatively low heating value per unit volume,
- variability of quality and heating value,
- difficulty in controlling the rate of burning,
- rapid burning, necessitating frequent refueling,
- difficulty in mechanizing continuous feeding,
- large volume of area required for storage,
- economic problems associated with transportation and distribution.

Several of these disadvantages are attributed to low bulk density of biomass, especially of agricultural residues. The bulk density of loose wheat straw is approximately 18 kg/m^3 in comparison to lignite coal at 700 kg/m^3 . For

this reason, it generally is only economically feasible to transport unprocessed biomass less than approximately 200 km [6]. To improve the characteristics of biomass fuel for transportation, storage, feeding into boilers and combustion, it may be effective to upgrade the raw biomass by densification and by unifying its size. Biomass densification, which is also known as briquetting or pelletizing of sawdust and other agro residues, has been practiced for many years in several countries. Densification of biomass has the following technical advantages [3-5,7]:

- low moisture content is achieved,
- the rate of combustion can be comparable to those of fossil fuel,
- uniform combustion can be achieved,
- particulate emissions can be reduced,
- the possibility of spontaneous combustion in storage is reduced,
- stability and durability of biomass is improved,
- handling is improved,
- costs associated with the transportation and storage are reduced.

The basic problem often encountered in the use of biomass briquettes or pellets is the cost of densification. Factors that control the densification process are moisture content, particle size, form, fibrous and non-fibrous nature as well as lignin contents.

The dimensions of fuel pellets vary between 3 and 25 mm in diameter depending on the die block that is used in production. The length generally varies between 5 and 40 mm [7]. The standard shape of a biomass pellet is a cylinder but spherical shape is also used e.g. for torrefied pellets [8]. If the product exceeds 25 mm in diameter it is called a briquette. Biomass pellets and briquettes have the potential to be a source of renewable energy if they are made from sustainably harvested biomass or waste agricultural residues. For example, wheat straw represents with about 48% of the production volume in EU the most important part of straw supplying arable crop [9].

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To utilize agro and wood biomass energy efficiently a range of advanced combustion concepts and technologies have been developed during recent decades, and continue to be developed, such as: direct combustion boilers, co-combustion in pulverized coal furnace, fire grid combustion boilers, bubbling fluidized bed combustion, circulating fluidized bed combustion, pressurized fluidized bed combustion, gasification-combustion boilers in combination with Sterling engines, wood pellet boilers/heaters, small-scale automated biomass combustion devices and so on [3-7].

Circulating fluidized bed (CFB) boilers are ideal for efficient power generation. They are capable of firing a broad variety of solid biomass fuels in small combined heat and power plants (CHP) and large utility power plants. The well known benefits of CFB technology, such as the superior fuel flexibility, inherently low emissions and high availability can be fully utilized for this purpose. Designs of efficient subcritical boilers firing 100% biomass are available to 600 MW_e. Examples of the Advanced Bio CFB (ABC) technology include two power plants in Poland, the Konin power plant (55 MW_e/154 MW_{th}) and the Połaniec power station (205 MW_e/447 MW_{th}). Both plants fire 100% biomass including a considerable share of demanding agricultural residue. The fuel considered for the new Połaniec biomass boiler is comprised of 80% wood biomass and 20% agro biomass [1,2,10]. Biomass residues normally have much lower ash content (except for rice husk with 20% ash) but their ashes have a higher percentage of alkaline minerals, especially potash. These constituents have a tendency to devolatilize during combustion and condense on tubes, especially those of super heaters. These constituents also lower the sintering temperature of ash, leading to ash deposition on the boiler's exposed surfaces.

Biomass firing coupled with oxy-fuel (oxy-biomass combustion) and CCS could be a 'carbon negative' technology. In the oxy-fuel combustion, biomass particles are burnt in a mixture of pure oxygen and recycled flue gas. Because nitrogen is eliminated from the oxidizing gas, the flue gas leaving the combustion chamber is highly enriched in CO₂ which means that the combustion process takes place in an O₂/CO₂ mixture. The main differences are associated with differences in physical properties of CO₂ and N₂ such as [11]:

- density ($\rho_{CO_2}=1.98 \text{ kg/m}^3$, $\rho_{N_2}=1.25 \text{ kg/m}^3$ at $T=273 \text{ K}$ and $p=1 \text{ atm}$),
- specific heat capacity ($C_{pCO_2}=54.3 \text{ kJ/kmol}\cdot\text{K}$, $C_{pN_2}=32.54 \text{ kJ/kmol}\cdot\text{K}$ at $T=1000 \text{ K}$),
- molecular diffusivity ($D_{O_2,CO_2}=3.056\times 10^{-4} \text{ m}^2/\text{s}$, $D_{O_2,N_2}=3.923\times 10^{-4} \text{ m}^2/\text{s}$ at $T=1600 \text{ K}$ and $p=1 \text{ bar}$).

Changes in physical properties of the combustion atmosphere will influence the ignition time and ignition temperature, devolatilization time and volatiles matter combustion time, temperature distribution in a burning solid fuel and the total combustion time for a single particle and pollutant formation [12].

The objective of this study was to investigate combustion characteristics of agro and wood biomass burnt in air and O₂/CO₂ mixtures in a laboratory-scale CFB combustor.

Experimental

Oxy-CFB combustor

Oxy-biomass combustion tests were conducted in a 12-kW bench-scale CFB combustor shown schematically in Figure 1. The facility consists of a combustion chamber (1), a cyclone (2), a downcomer (3) and a loop seal (4).

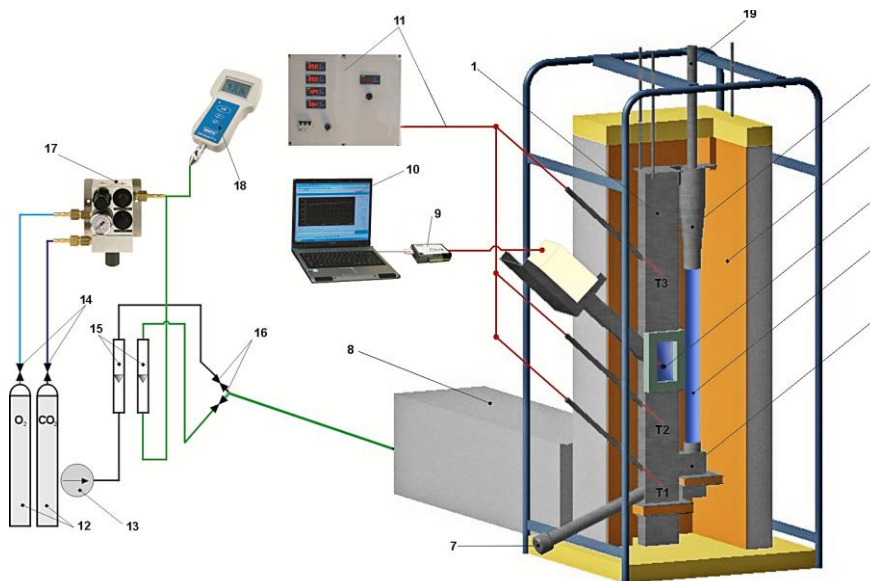


Fig. 1. Schematic diagram of the experimental apparatus for CFB combustion

1 - combustion chamber, 2 - cyclone, 3 - downcomer, 4 - loop seal, 5 - coal particle, 6 - insulation, 7 - drain valve, 8 - preheater, 9 - card, 10 - computer, 11 - temperature measurement and control system, 12 - gas cylinders, 13 - air compressor, 14 - pressure regulators, 15 - rotameters, 16 - valves, 17 - mixer, 18 - gas analyser, 19 - ventilation duct, T1-T3 S-type thermocouples

The electrically-heated rectangular combustion chamber (riser), 680×75×35 mm, is the main component of the unit. The front wall of the riser is made of transparent quartz through which the combustion process can be directly observed. Silica sand (particles smaller than 400 µm) to a mass of 0.3 kg constituted the inert bed. The gases to make up gas mixtures are supplied from cylinders (12) to a mixer (17) and then transferred via a preheater (8) directly into the combustion chamber. Flow rates of gases are controlled by valves (16) and measured by rotameters (15). During combustion tests, the superficial gas velocity was kept at a constant level of about 5 m/s. The temperature was held at 850°C by means of a microprocessor controller (11). S-type thermocouples (T1–T3) measured the temperature at three different levels inside the combustion chamber with an accuracy of ±2°C.

A single biomass pellet (5) was introduced into the combustion chamber and positioned stationary in the bed. To measure the temperatures in the centre and at the surface of the biomass particle a special stand was constructed. It provided a support for two S-type thermocouples. The tip of the first thermocouple was located inside the pellet, while the second thermocouple measured the surface temperature and served as a basket in which the biomass sample was placed. The thermocouples were connected via a card (9) to a computer (10) in order to record the temperature measurements. Ignition time, volatiles combustion time and total combustion time were measured by stopwatch with an accuracy of 0.1s. The intraparticle temperature, the surface temperature, ignition time and volatiles combustion time were measured simultaneously. Video and digital cameras were used to record the progress of biomass combustion.

The experiments were carried out in air (base case) and mixtures of O₂/CO₂ with oxygen concentrations in the range from 21% to 40% vol.

Laboratory method of biomass densification

Figure 2 shows a flow diagram of biomass pellets production. First stage was preliminary size reduction which consisted in cutting biomass into small pieces. Next biomass was milled in a laboratory mill. Then milled biomass was sifted by a series of standard sieves by up to 0.1 mm fraction. Sifted biomass was mixed with potato starch as a binder (about 8% by weight) and water. The mixture was compacted by the stamp hydraulic press to be given a spherical shape. The last stage was the conditioning pellets to remove moisture.

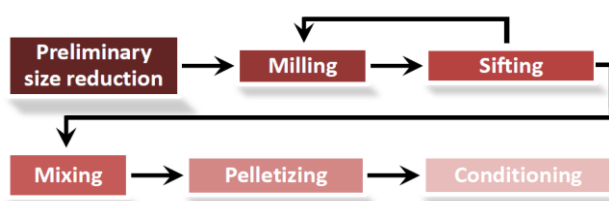


Fig. 2. Flow diagram of biomass pellets production [13]

Biomass tested

10-mm spherical biomass pellets made of wheat straw (Fig.3a) and Scots pine (Fig.3b) were used in this study.

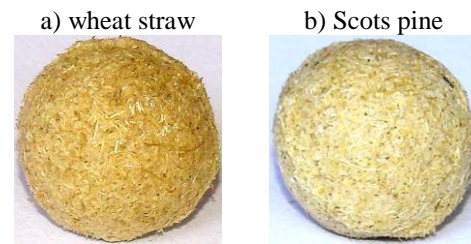


Fig. 3. Spherical biomass pellets (d = 10 mm)

Biomass pellets were produced with a density of about 510 kg/m³ for Scots pine and 300 kg/m³ for wheat straw from loose biomass of bulk density 200 kg/m³ and 20 kg/m³, respectively. Bulk density is defined as the weight per unit volume of a material, expressed in kilograms per cubic meter (kg/m³).

The biomass fuel composition is important with respect to its heat content, emission characteristics and ash-related issues during combustion process. The proximate and ultimate analyses of biomass tested are presented in Table 1. Wood biomass (Scots pine) contains more volatiles and low ash content as compared to agro biomass (wheat straw). The carbon content of wood biomass is higher than that of agro biomass. This explains the higher calorific value of Scots pine. Both biomass fuels tested contains minimal amount of sulfur.

Tab. 1. Proximate and ultimate analyses for biomass

Parameter	wheat straw	Scots pine
Proximate analysis (air-dried basis)		
Moisture (M), %	8.42	6.99
Ash (A), %	6.10	0.55
Volatile matter (VM), %	68.29	76.75
Fixed carbon (FC), %	17.19	15.71
Calorific value (LHV), MJ/kg	15.57	17.63
Ultimate analysis (air-dried basis)		
Carbon (C), %	42.89	47.06
Sulphur (S), %	0.07	0.01
Hydrogen (H), %	5.00	5.32
Nitrogen (N), %	0.66	0
Oxygen (O), %	36.86	40.07

Results and discussion

A single particle of solid fuel introduced to the combustion chamber undergoes several characteristic stages namely:

- heating up,
- drying,
- devolatilization,
- ignition of volatiles,
- volatiles combustion,
- combustion of residual char.

Almost all solid fuels experience these processes but the duration of each process depends on fuel type and its composition (moisture and volatile matter contents, total carbon content), temperature in the combustion chamber, heating rate and oxidizing atmosphere [12].

Figure 4 and 5 show pictures of wheat straw and Scots pine pellets burning in different oxidizing atmospheres. After rapid heating, the ignition of volatiles follows. Burning volatiles form a distinctive long flame. Differences in combustion times that are related to the composition of oxidizing atmospheres can be noticed. At higher oxygen concentrations, the combustion process is more intense and, therefore, the total combustion time is shorter.

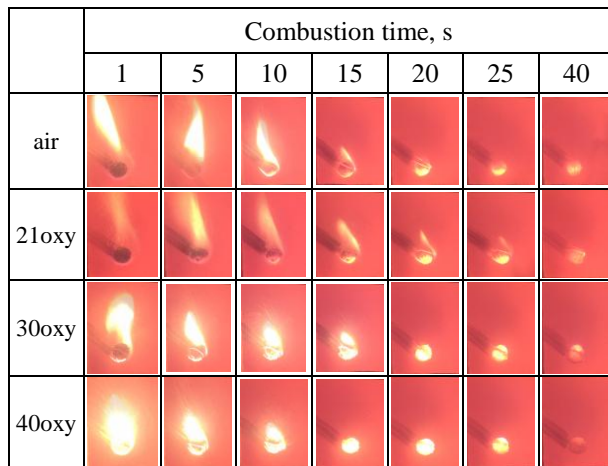


Fig. 4. Combustion of wheat straw pellets in air and O₂/CO₂ mixtures at 850°C

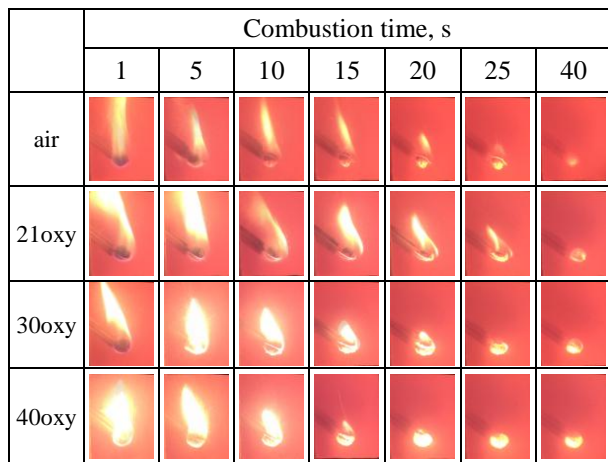


Fig. 5. Combustion of Scots pine pellets in air and O₂/CO₂ mixtures at 850°C

Ignition times for both biomass pellets were below 1 s in all atmospheres tested. Ignition time was characterized by the time required to achieve a visible flame. Volatiles combustion time was the duration of the visible flame (from ignition of volatile matter to the end of combustion of volatile matter) [12]. Volatiles combustion times for biomass pellets are shown in Figure 6. Volatiles combustion times of Scots pine pellets were longer because of higher volatiles matter

content compared to wheat straw. The volatiles combustion time decreases with increasing O₂ concentration for both biomass samples tested.

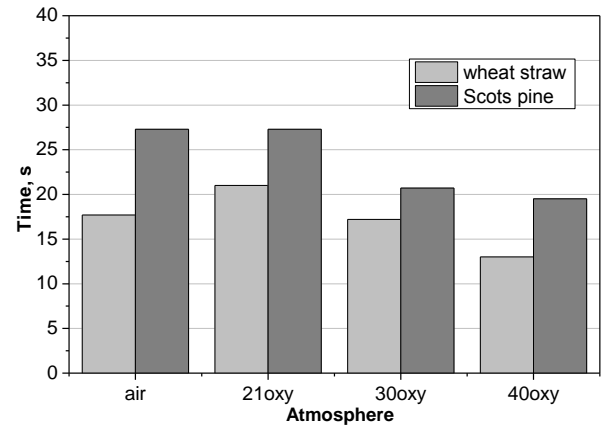


Fig. 6. The arithmetic means of the volatiles combustion times for biomass pellets burning in air and O₂/CO₂ mixtures at 850°C

Figure 7 shows the effect of gas composition on the total combustion time. Scots pine pellets combusted longer because of higher density and calorific value compared to wheat straw. The total combustion time for both biomasses decreases significantly with an increase in oxygen concentration. The total combustion time for biomass pellets in 40oxy atmosphere is approximately 42% shorter than that for combustion in air.

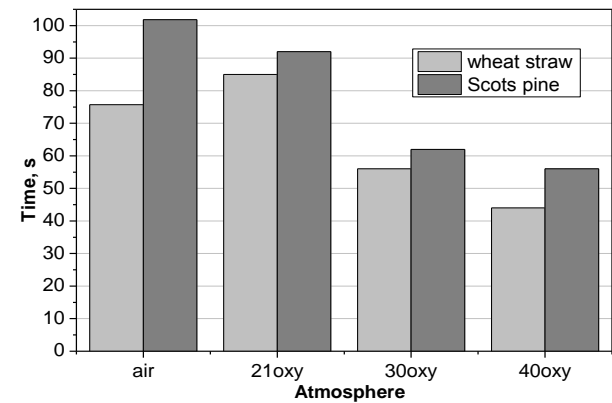


Fig. 7. The arithmetic means of the total combustion times for biomass pellets burned in air and O₂/CO₂ mixtures at 850°C

Figure 8 shows temperatures measured at the surface and in the centre of biomass pellets burned at 850°C in air. For both biomass samples, after an initial delay, the centre temperature exceeds the surface temperature and is approximately 100°C higher during the course of combustion. Lower surface temperatures can be explained by intensive heat transfer between burning coal particles and bed material. When the flame approaches its point of extinction, the surface temperature reaches its maximum value. This maximum value was ~1090°C for both biomass samples. In the next stage, i.e. char combustion, the centre temperature

was higher than the surface temperature. The maximum centre temperature was 1017°C for Scots pine and 987°C for wheat straw. When the char combustion process is completed, the surface temperature and the centre temperature drop to value corresponding to temperature in the combustion chamber.

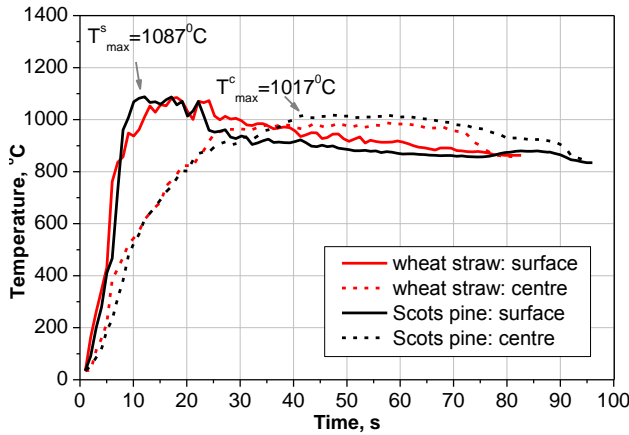


Fig. 8. Temperature profiles for biomass pellets burned at 850°C in air

Figure 9 shows temperatures profiles for biomass briquettes burned at 850°C in the mixture of 21oxy. Combustion of Scots pine pellets in a O_2/CO_2 mixture at 21% O_2 resulted in the centre temperature being ~40°C lower than that for combustion in air. Higher specific heat capacity of CO_2 lowers the heating rate of the biomass particle. The diffusion coefficient of O_2 in CO_2 is smaller than that in N_2 . These two factors influence negatively the kinetics of the combustion process and are responsible for observed decrease in the centre temperature. The char- CO_2 gasification reaction in the 79% CO_2 atmosphere is highly endothermic and may lower the particle temperature. Combustion of wheat straw in air was slightly shorter in time compared to combustion in O_2/CO_2 mixture with 21% vol. O_2 .

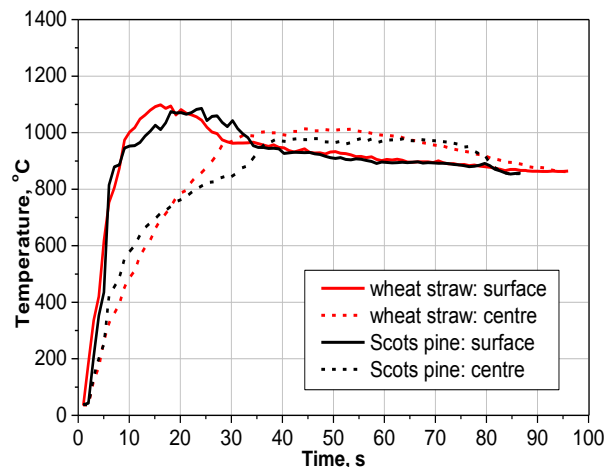


Fig. 9. Temperature profiles for biomass pellets burned at 850°C in 21% O_2 +79% CO_2

Figure 10 shows temperature measured at the surface and in the centre of biomass briquettes burned at

850°C in the 30oxy atmosphere. The maximum value of surface temperature was ~1140°C for wheat straw and ~1220°C for Scots pine. The maximum centre temperature was higher ~70°C for wheat straw and ~80°C for Scots pine during combustion in the 30oxy than during combustion in air.

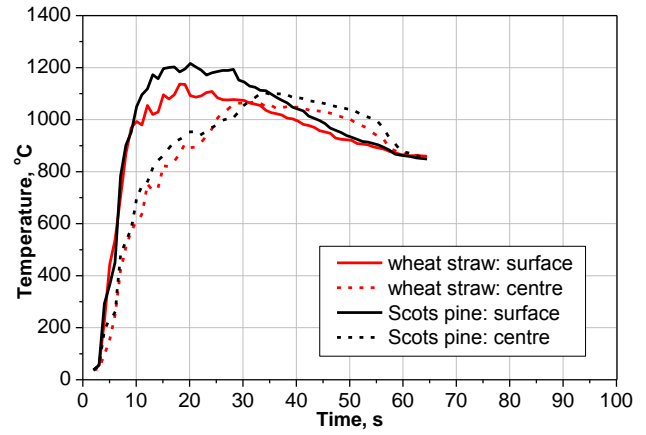


Fig. 10. Temperature profiles for biomass pellets burned at 850°C in 30% O_2 +70% CO_2

Figure 11 shows temperatures profiles for biomass pellets burned at 850°C in the mixture of 40oxy. The maximum surface temperature value varies from ~1090°C, for combustion in air, to ~1270°C for combustion in the mixture of 40% O_2 +60% CO_2 . The maximum centre temperature was higher ~80°C for wheat straw and ~120°C for Scots pine during combustion in the 40oxy than during combustion in air.

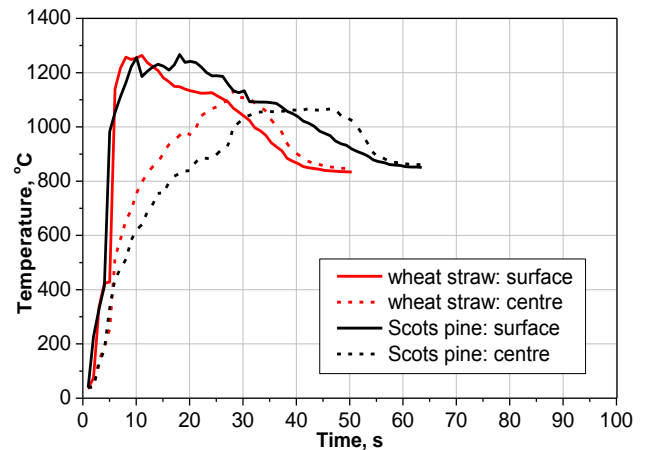


Fig. 11. Temperature profiles for biomass pellets burned at 850°C in 40% O_2 +60% CO_2

Graphs shown in Figures 8-11 can be used to determine, with good accuracy, the total time of combustion.

Table 2 shows the average values of maximum temperature of surface and centre during biomass pellets combustion in various atmospheres.

Tab. 2. Average maximum temperature of surface (T_{\max}^s) and centre (T_{\max}^c) during biomass pellets combustion in various atmospheres

Atmosphere	Wheat straw		Scots pine	
	T_{\max}^s	T_{\max}^c	T_{\max}^s	T_{\max}^c
air	1090	1000	1095	1020
21% O ₂ + 79% CO ₂	1080	990	1085	980
30% O ₂ + 70% CO ₂	1140	1070	1220	1100
40% O ₂ + 60% CO ₂	1260	1080	1270	1140

Burning biomass in CFB boilers is known to cause slagging and fouling problems due to low ash fusion temperature. Such high values of particle temperature in the 40oxy can cause slagging and fouling problems in CFB boilers. Gulyurtlu et al. [14] found that wood biomass can successfully be used as biofuel without slagging and fouling problems. However, agglomerated particles of agro biomass contained high quantities of Si, Ca and K, which in function of the different proportions of K₂O-CaO-SiO₂ could melt or soften at low temperatures, forming ash particles with a wide range of compositions, shapes and sizes.

Conclusions

Spherical biomass pellets were burned in a laboratory-scale CFB combustor at 850°C in air and in different oxy-fuel atmospheres, simulated by dry O₂/CO₂ mixtures. The results of experimental research show that the composition of the oxidizing atmosphere strongly influences the combustion process of biomass fuels. The weakest biomass pellets combustion intensities were obtained in the 21%O₂+79%CO₂ atmosphere due to the lower particle temperatures, which resulted from the lower diffusivity of oxygen in CO₂ than in N₂ and the higher volumetric heat capacity of CO₂ (than N₂). The combustion process in O₂/CO₂ mixtures at 30% and 40% O₂ is faster and shorter than that at lower O₂ concentrations. Ignition times for both biomass pellets were below 1 s in all atmospheres tested. The volatiles combustion time decreases with increasing O₂ concentration for both biomass samples tested. The average volatiles combustion time varied from 27 s in air to 19 s in 40oxy for Scots pine and for wheat straw from 17 s to 14 s, respectively. Volatiles combustion times of Scots pine pellets were longer because of higher volatiles matter content compared to wheat straw. The total combustion time for both biomass pellets decreases significantly with an increase in oxygen concentration. The total combustion time in the 40%O₂+60%CO₂ mixture was approximately 42% shorter than that for combustion in air. Scots pine pellets combusted longer because of higher density and calorific value compared to wheat straw. The maximum surface temperature value varies from ~1090°C, for combustion in air, to ~1270°C for combustion in the mixture of 40% O₂+60% CO₂. Such high values of particle temperature, especially in the 40oxy atmosphere, can cause slagging and fouling problems in CFB boilers.

Acknowledgements

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