Analysis of combustion of pellet fuels in a circulating fluidized-bed

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Abstract

In this paper a combustion process of spherical pellets made of wheat straw, fine brown coal and fine hard coal in a circulating fluidized-bed was analyzed. Pellets were produced with a density of about 300 kg/m³ for wheat straw, 800 kg/m³ for brown coal and 1100 kg/m³ for hard coal from loose solid fuels of bulk density 20 kg/m³, 500 kg/m³ and 650 kg/m³, respectively. Combustion of single pellets was conducted 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 solid fuel pellets, in terms of particle temperature profiles, ignition time, devolatilization time and the total combustion time.

Introduction

Biomass is a potential source of renewable energy. One of the major barriers to its widespread use is that biomass has a lower energy content than traditional fossils fuels, which means that more fuel is required to get the same amount of energy. When combined — low energy content with low density — the volume of biomass handled increases enormously [1].

Most agricultural residues (e.g. wheat straw) have low bulk density, as shown in Figure 1. Bulk density is defined as the weight per unit volume of a material, expressed in kilograms per cubic meter (kg/m^3).

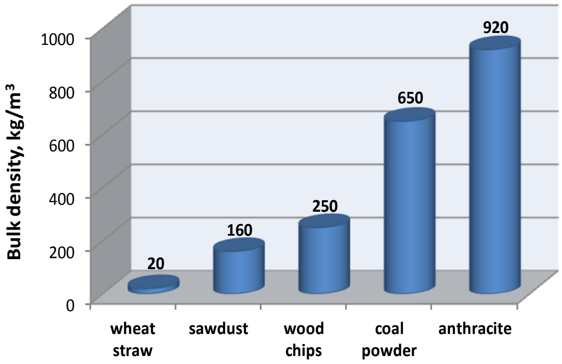

Fig. 1. Bulk densities of unprocessed solid fuels

The low density of biomass fuels poses a challenge for the handling, transportation, storage and combustion processes. These problems may be addressed through densification, a process that produces either liquid or solid fuel with denser and more uniform properties than the raw biomass.

The main advantages of biomass densification for combustion are [1]:

- simplified mechanical handling and feeding,
- uniform combustion in boilers,
- reduced dust production,
- reduced possibility of spontaneous combustion in storage,
- simplified storage and handling infrastructure, lowering capital requirements at the combustion plant,
- reduced cost of transportation due to increased energy density.

The major disadvantage to biomass densification technologies is the high cost associated with some of the densification processes.

Biomass can be densified via two main processes: mechanical densification and torrefaction. Mechanical densification involves applying pressure to densify the material. Torrefaction involves heating the biomass in the absence of oxygen. The method of densification depends on the type of residues and the local situation.

Mechanical densification (pelletization, cubing, baling or briquetting) of particulate matter is achieved by forcing the particles together by applying a mechanical force to create inter-particle bonding, which makes well-defined shapes and sizes such as pellets, cubes, and briquettes. Figure 2 shows biomass products of mechanical densification technologies.

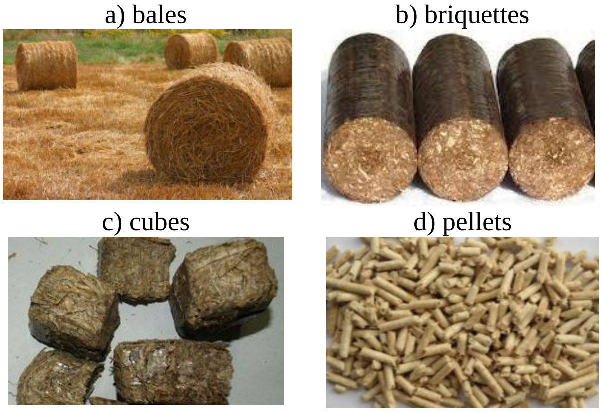
a) bales
b) briquettes
c) cubes
d) pellets

Fig. 2. Biomass products of mechanical densification technologies

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Bales (Fig.2a) are a traditional method of densification commonly used to harvest crops. A bale is formed using farm machinery (called a baler) that compresses the chop. Bales can be square, rectangular or round, depending on the type of baler used. The dimensions of round bales range from 1.2 m x 1.5 m to 1.5 m x 1.5 m. Large rectangular bales typically measure 0.9 m x 0.9 m x 1.8 m in length. Round bales are less expensive to produce, however, large square bales are usually denser and easier to handle and transport [1].

Briquettes (Fig.2b**)** have a diameter of 25 mm or greater and are formed when biomass is punched, using a piston press, into a die under high pressure. Alternatively, a process referred to as screw extrusion can be used. In screw extrusion, the biomass is extruded by a screw through a heated die. Biomass densified through screw extrusion has higher storability and energy density properties compared to biomass produced by piston press [1].

Cubes (Fig.2c**)** are denser than briquettes and usually square in shape. Cube sizes range from 13–38 mm in cross section, with a length ranging 25–102 mm. The process involves compressing chopped biomass with a heavy press wheel, followed by forcing the biomass through dies to produce cubes [1].

Pellets (Fig.2d**)** are very high in density. They are easier to handle than other densified biomass products, since infrastructure for grain handling is used for pellets. Pellets are formed by an extrusion process, using a piston press, where finely ground biomass material is forced through round or square cross-sectional dies and cut to a desired length. The standard shape of a biomass pellet is a cylinder, having a length smaller than 38 mm and a diameter around 7 mm. Although uniform in shape, pellets are easily broken during handling. Different grades of pellets vary in energy and ash content [1].

Torrefaction of biomass is carried out by heating biofuel in an inert atmosphere at temperatures of 280°C–320ºC for a few minutes. The torrefied fuel shows improved grindability properties. Torrefied biomass has hydrophobic properties (repels water), making it resistant to biological attack and moisture, thereby facilitating its storage. The process requires little energy input since some of the volatile gases liberated during heating are combusted, generating 80% of the heat required for torrefaction. Torrefied biomass is densified into pellets or briquettes, further increasing the density of the material and improving its hydrophobic properties [1,2].

Bulk densities of biomass products for selected densification technologies are shown in Figure 3.

Densification technologies result in higher energy inputs and increased costs. A portion of the cost is recuperated by the lower handling, storage and transportation costs, and better operability of the boiler and combustion process. Some densification technologies mentioned are commercially available, while others are emerging [1].

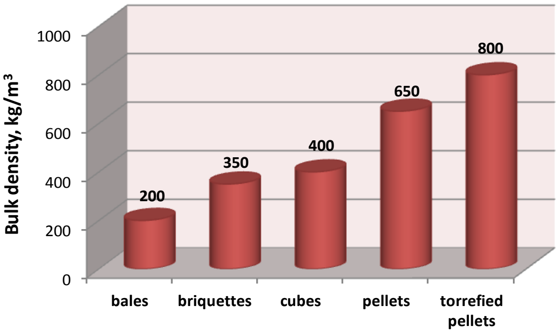

Fig. 3. Bulk densities of biomass for selected densification technologies

On the other hand, large quantities of fine coals are generated during mining and preparation stages and a significant portion of these fines is lost as refuse. Coal fines are generally classified as particles <0.5 mm that are separated from the coal during the beneficiation process [3]. Agglomeration of fine coal offer a solution to the handling problems associated with coal fines. Agglomeration of fine coal can be classified into briquetting and pelletizing, either with or without binders. Pellets (Fig.4a) are normally cylindrical with a diameter ranging from 6 to 12 mm and a length of 4–5 times the diameter but spherical shape is also used (Fig.4b). Briquettes (Fig.4c) can also be cylindrical with a diameter of 80–90 mm, or parallel-piped with average dimensions of 150×70×60 mm [3]. Briquetting with a binder has shown success in Australia (Wallerawang Colliery) where 50 mm diameter briquettes (10–20% moisture content) are produced by a double roller press for the production of fuel for use in a conventional power station using fine coal washery rejects [4].


a) cylindrical pellets b) spherical pellets

c) briquettes

Fig. 4. Hard coal products of densification technologies

Onyemaobi [5] found that pellet strength is directly related to both pelletizing time and feedstock moisture content as well as being influenced by particle size, finer particles producing stronger pellets.

Circulating fluidized bed (CFB) boilers are ideal for efficient power generation. They are capable of firing from broad variety of solid biomass to fossil 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 [6,7].

The objective of this study was to investigate combustion characteristics of the 10 mm spherical pellets made of biomass (wheat straw), fine brown coal and fine hard coal burnt in a laboratory-scale CFB combustor.

Experimental

CFB combustor

Pellet fuels combustion tests were conducted in a 12-kW laboratory-scale CFB combustor shown schematically in Figure 5.

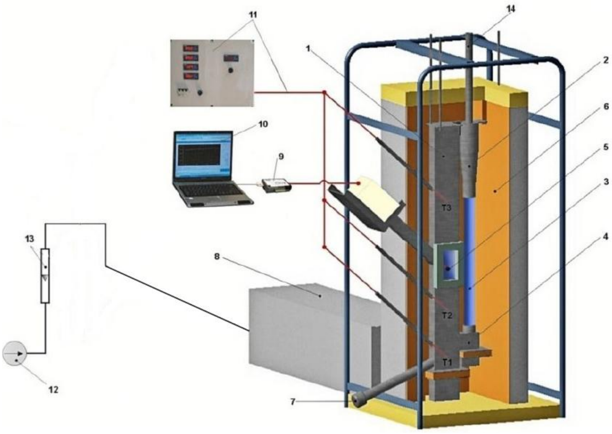

Fig. 5. Schematic diagram of the experimental apparatus for CFB combustion

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 - air compressor, 13 - rotameter, 14 - ventilation duct, T1–T3 S-type thermocouples

The facility consists of a riser (1), a cyclone (2), a downcomer (3) and a loop seal (4). 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 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 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.

Laboratory method of solid fuels pellets production

Figure 6 shows a flow diagram of pellets production. First stage was preliminary size reduction which consisted in cutting biomass into small pieces or crushing coal. Next fuel was milled in a laboratory mill. Then milled fuel was sifted by a series of standard sieves by up to 0.1 mm fraction. Sifted fuel 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.

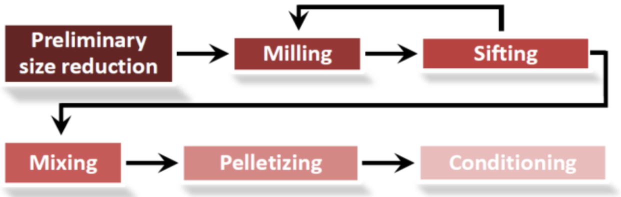

Fig. 6. Flow diagram of pellets production [8]

Solid fuels tested

10-mm spherical solid fuels pellets made of wheat straw (Fig.7a), fine brown coal (Fig.7b) and fine hard coal (Fig.7c) were used in this study.

a) wheat straw b) brown coal c) hard coal

Fig. 7. Spherical pellets (d = 10 mm) made from various solid fuels

Pellets were produced with a density of about 300 kg/m³ for wheat straw, 800 kg/m³ for brown coal and 1100 kg/m³ for hard coal from loose solid fuels of bulk density 20 kg/m³, 500 kg/m³ and 650 kg/m³, respectively.

The proximate and ultimate analyses of solid fuels tested are presented in Table 1. Biomass contains more volatiles and low carbon content as compared to coals, which makes biomass a highly reactive fuel. Wheat straw contains minimal amount of sulfur.

Tab. 1. Proximate and ultimate analyses for solid fuels

Parameter	**wheat straw**	**brown coal**	**hard coal**
Proximate analysis *(air-dryed basis)*			
Moisture (M), %	8.4	13.3	8.7
Ash (A), %	6.1	22.4	18.9
Volatile matter (VM),%	68.3	39.1	26.8
Fixed carbon (FC), %	17.2	25.2	45.6
Calorific value (LHV), MJ/kg	15.57	17.33	21.69
Ultimate analysis *(dry, ash-free basis)*			
Carbon (C), %	50.2	64.4	73.3
Sulphur (S), %	0.08	1.5	2.3
Hydrogen (H), %	5.8	4.6	4.3
Nitrogen (N), %	0.8	0.9	1.1
Oxygen (O), %	43.12	28.6	19.0

Results and discussion

A fuel particle dropped into the combustion chamber may undergo the following sequence of events [9]:

1. Thermal shock fragmentation (for some types of fuel).
2. Heating and drying.
3. Ignition of volatiles.
4. Devolatilization and volatiles combustion.
5. Primary fragmentation (for some types of coal).
6. Char combustion.
7. Secondary fragmentation (for some types of coal).

Figure 8 shows pictures of spherical pellets burning in a circulating fluidized-bed.

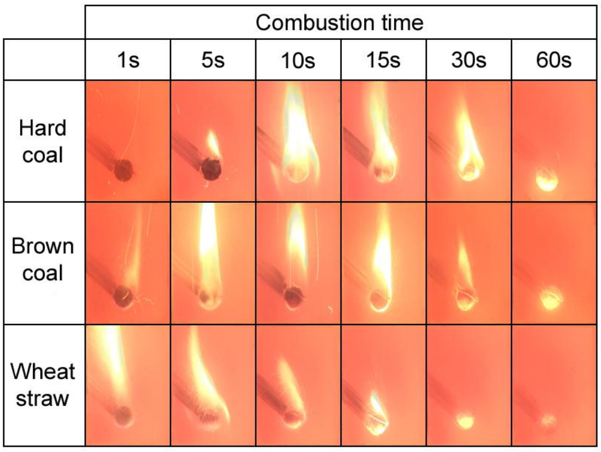

Fig. 8. Combustion of pellet fuels burning in CFB at 850°C

After fast heating and drying, the ignition of volatiles follows. Burning volatiles form a distinctive long flame. Differences in ignition and volatiles combustion times that are related to the composition of fuels can be noticed. Pellet fuels didn't undergo any fragmentation processes.

Ignition time was characterized by the time required to achieve a visible flame [10]. Figure 9 shows the average ignition time for solid fuel pellets. The ignition time of pellet fuels decreases with an increase in volatiles content.

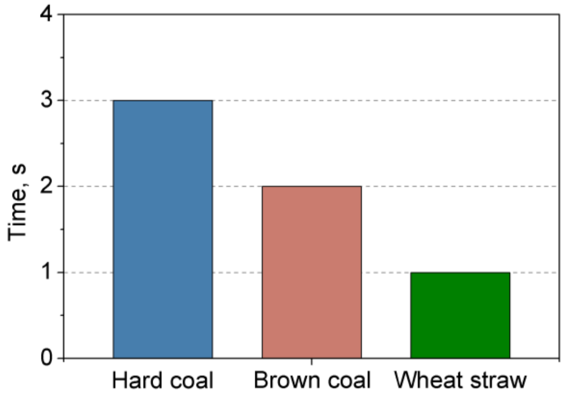

Fig. 9. Average ignition times for pellet fuels burning in CFB at 850°C

Volatiles combustion time was the duration of the visible flame (from ignition of volatile matter to the end of combustion of volatile matter) [10]. Figure 10 shows volatiles combustion times for pellets. The volatiles combustion times of pellet fuels were in the range of 18 s to 48 s. They depend on volatiles matter content in the fuel and density of pellets. Although wheat straw pellets content the highest volatiles matter content the volatiles combustion times were the shortest.

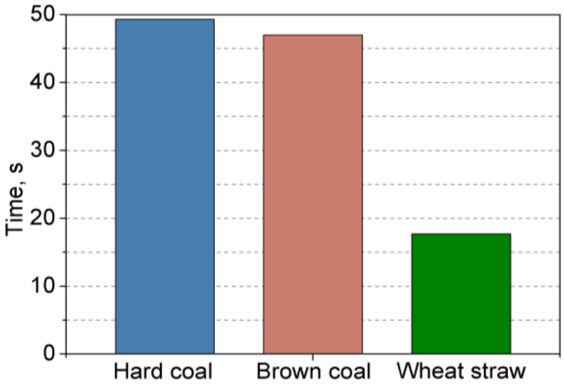

Fig. 10. Average volatiles combustion times for pellet fuels burning in CFB at 850°C

Average char combustion times for pellet fuels are shown in Figure 11. The char combustion time varied from 60 s for wheat straw pellets to 510 s for hard coal pellets. The char combustion time strongly depends on carbon content of the fuel and density of pellets.

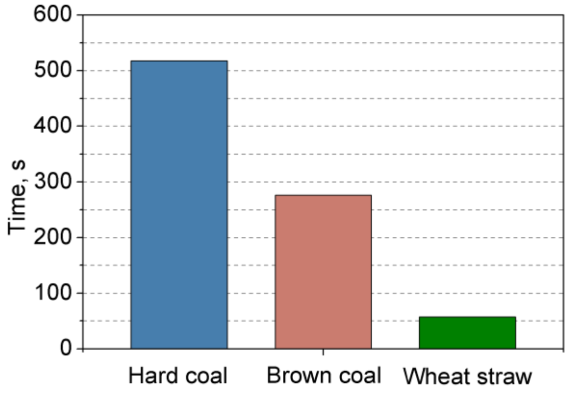

Fig. 11. Average char combustion times for pellet fuels burning in CFB at 850°C

Figure 12 shows the effect of pellet composition on the total combustion time. Hard coal pellets combusted the longest because of higher density and calorific value compared to brown coal and wheat straw pellets. The total combustion time for wheat straw pellets was approximately seven times shorter than that for hard coal pellets and four times shorter compared to brown coal pellet.

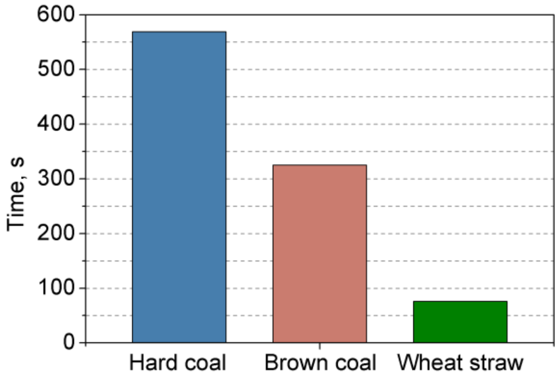

Fig. 12. Average total combustion times for pellet fuels burning in CFB at 850°C

Figure 13 shows temperatures measured at the surface and in the centre of hard coal pellet burned at 850˚C.

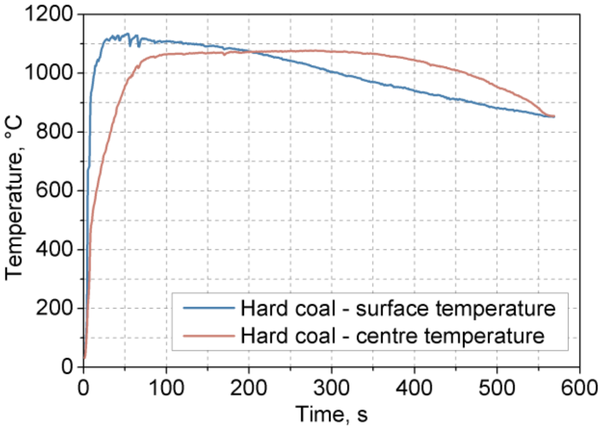

Fig. 13. Temperature profiles for hard coal pellet burned in CFB at 850°C

After an initial delay, the centre temperature exceeds the surface temperature and is 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 ~1130°C. In the next stage, i.e. char combustion, the centre temperature was approximately 100°C higher than the surface temperature. The maximum centre temperature was 1080°C. When the char combustion process is completed, the surface temperature and the centre temperature drop to value corresponding to temperature in the combustion chamber.

Temperature profiles for brown coal pellet burned at 850˚C are shown in Figure 14. The maximum temperature of surface was 1130°C and was noticed during volatiles combustion. However the maximum centre temperature (1040°C) was measured during char combustion.

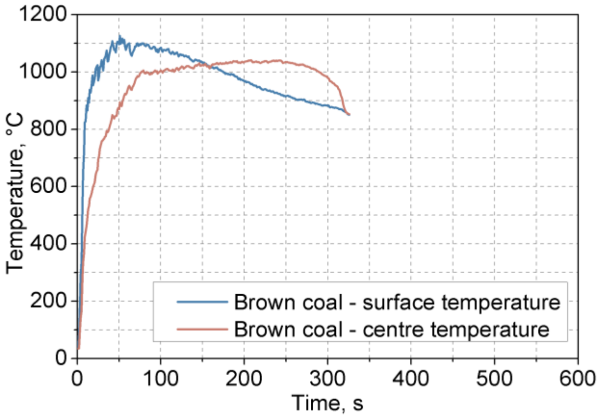

Fig. 14. Temperature profiles for brown coal pellet burned in CFB at 850°C

Figure 15 shows temperature measured at the surface and in the centre of wheat straw pellet burned at 850˚C. The maximum value of surface temperature was about 1150˚C and the maximum centre temperature was ~1030˚C.

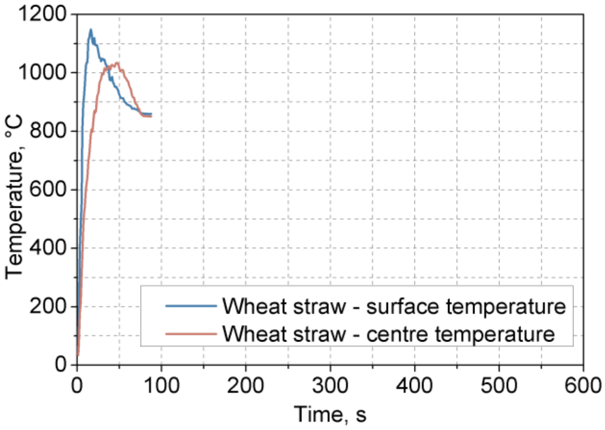

Fig. 15. Temperature profiles for wheat straw pellet burned in CFB at 850°C

Figure 16 shows the comparison of measured temperatures for all solid fuels pellets tested. Temperatures profiles of pellet fuels burned in a circulating fluidized bed were very similar. They differed in the length of the combustion process. The maximum surface temperature value varied from ~1130°C, for hard coal pellets, to ~1150°C for wheat straw pellets. The maximum centre temperature was higher ~50°C for hard coal pellet than for wheat straw pellets. Graphs shown in Figure 16 can be used to determine, with good accuracy, the total time of combustion.

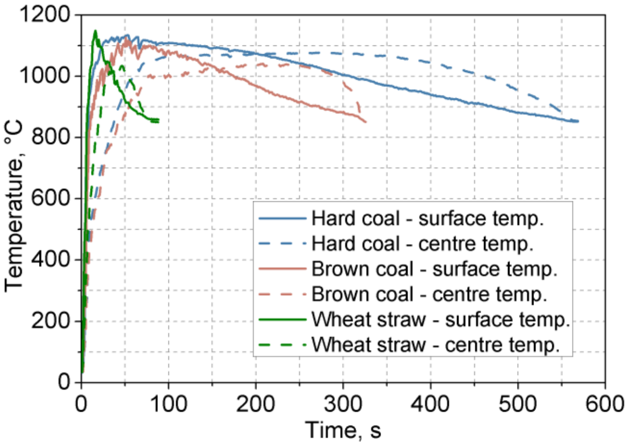

Fig. 16. The comparison of temperature profiles for all pellet fuels tested burned in CFB at 850°C

Conclusions

Spherical pellets made of wheat straw, fine brown coal and fine hard coal were burned in a laboratory-scale CFB combustor at 850°C. The results of experimental research show that the composition of the fuel strongly influences the combustion process of pellets. Pellets were produced with a density of about 300 kg/m³ for wheat straw, 800 kg/m³ for brown coal and 1100 kg/m³ for hard coal from loose solid fuels of bulk density 20 kg/m³, 500 kg/m³ and 650 kg/m³, respectively. The ignition time depend on volatiles content in fuel and varied from 1 s, for wheat straw pellets, to 3 s for hard coal pellets. The volatiles combustion times of pellet fuels were in the range of 18 s to 48 s and they depend on volatiles matter content in the fuel and density of pellets. The char combustion time varied from 60 s, for wheat straw pellets, to 510 s for hard coal pellets. The char combustion time strongly depends on carbon content of the fuel and density of pellets. The total combustion times of pellet fuels were in the range of 80 s to 560 s Hard coal pellets combusted the longest because of higher density and calorific value compared to brown coal and wheat straw pellets. The total combustion time for wheat straw pellets was approximately seven times shorter than that for hard coal pellets and four times shorter compared to brown coal pellet. Temperatures profiles of pellet fuels burned in a circulating fluidized bed were very similar. They differed in the length of the combustion process and maximum values of temperature on the surface and in the centre. The maximum surface temperature value varied from ~1130°C, for hard coal pellets, to ~1150°C for wheat straw pellets. The maximum centre temperature was higher was higher ~50°C for hard coal pellet than for wheat straw pellets.

Acknowledgements

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