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Experimental investigation into coal-biomass-water fuels combustion in a circulating fluidized bed

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Abstract

Coal upgrading processes (screening, washing etc.) generate large quantities of fine and ultra-fine coal particles usually in the form of coal-water slurries. Utilization of these waste-coals is a preferable option to their disposal and offers opportunities for adding value. Direct combustion of coal slurries can eliminate troublesome dewatering and drying processes. Combustion or co-combustion of coal slurries with other fuels (higher quality coal, biomass) in circulating fluidized-bed (CFB) boilers is the best option for their utilization. High combustion efficiencies can be achieved provided that the combustion process is properly designed to take into account the unique properties of the fuel. Because biomass is considered as a carbon-neutral fuel, co-combustion of coal slurries with biomass can lower the CO_2 footprint and decrease the cost of electricity. This paper describes the results of experiments carried out in a laboratory-scale CFB combustor with coal-biomass-water fuels. It has been found that the combustion time and ignition temperature decrease with an increase in the biomass content in the fuel and the superficial gas velocity.

Keywords: coal-biomass-water fuels, fuels combustion, circulating fluidized bed

Streszczenie

Badania eksperymentalne spalania paliw węglowo-biomasowo-wodnych w cyrkulacyjnej warstwie fluidalnej

Niekorzystny bilans paliwowy naszego kraju powoduje nadmierne obciążenie środowiska, wywołane emisją NO_x, SO_2, CO_2 i pyłów, a także powiększeniem powierzchni koniecznych na składowanie narastających stałych odpadów paleniskowych. Górnictwo, zmuszane dostarczać energetyce coraz lepsze paliwo, musi stosować głębsze wzbogacanie węgla. Powoduje to ciągły wzrost odpadów w postaci mułów poflotacyjnych. Najlepszą metodą utylizacji tych mułów jest ich spalanie w postaci zawiesin oraz współspalanie z innymi paliwami, prowadzone przede wszystkim w kotłach fluidyzacyjnych. Z drugiej strony, rozwój technologii wykorzystania biomasy na cele energetyczne daje szereg przyszłościowych korzyści. Biomasa jest jednym z najbardziej obiecujących źródeł energii odnawialnej w Polsce, a jej współspalanie z węglem znajduje w ostatnich latach coraz szersze zastosowanie, zarówno w Polsce, jak i na świecie. Praca podejmuje wyniki badań eksperymentalnych współspalania węgla z biomasą w postaci zawiesin w warunkach cyrkulacyjnej warstwy fluidalnej. Stwierdzono m.in. skrócenie czasu spalania paliwa oraz obniżenie temperatury jego zapłonu za pośrednictwem części lotnych, w miarę wzrostu zawartości biomasy w zawiesinie.

Słowa kluczowe: paliwa węglowo-biomasowo-wodne, spalanie paliw, cyrkulacyjna warstwa fluidalna

1. Introduction

Important factors determining the state of a fluidized bed are the superficial gas velocity, physical properties of gas and bed material and the mass of inert material in the system [1, 2, 3, 4, 5]. Coal particles fed to the bed undergo the fragmentation process caused by thermal shock, release of volatile matter (primary fragmentation), combustion of bridges connecting fragments of fuel particles (secondary fragmentation) and collisions of fuel and inert material particles [6, 7]. Due to intensive mixing and associated particle interactions, the ash layer formed on the external surface is continuously stripped of the burning char particles. This improves oxygen diffusion and speeds up the combustion process.

More than 90% of electricity generated in Poland comes from coal-fired power plants. Such an extensive use of coal has a negative impact on the environment (CO_2, NO_x, SO_2 and dust emissions, increasing demand for land to store coal combustion products). The coal mining industry is under pressure to deliver higher quality fuels. This is achieved via coal beneficiation processes such as screening, washing and flotation. However, the wide use of these processes generates large quantities of waste in the form of coal-water slurries containing fine and ultra-fine (smaller than 100 μm) coal particles. The best method of utilization of these waste-coals is their co-combustion with higher quality coals and biomass [8, 9] in CFB boilers. Several papers dealing with various aspects of coal-water slurry and wastes combustion can be found in the literature for example [10, 11, 12, 13, 14, 15]. Some experimental data suggest that combustion of coal-water fuels can result in lower NO_x emissions from fluidized-bed boilers. It was demonstrated that coal-water fuels can be processed in fluidized-bed combustors with high combustion efficiencies [16].

The particle size distribution and coal concentration in the coal-water fuel determine its rheological properties. Water in the fuel combines fine coal particles into bigger agglomerates. After water evaporation and devolatilization, a char with spongy structure is formed. Combustion of coal-water fuels is violent because of rapid release of volatiles and their ignition at the surface of the agglomerate surface.

Biomass of forest and agriculture origin is one of the most promising sources of renewable energy in Poland. Co-combustion of biomass with coal is carried out in a number of Polish power plants. The main objective of this study is to investigate the mechanism and kinetics of combustion for mixtures of coal fines (from a coal washing plant), coal and biomass (crushed cereal grains) with water contents in the range from 20 to 50%.

2. Experimental apparatus and methodology

Experiments were carried out in a laboratory-scale, electrically heated CFB combustor at 850°C (Fig.2.1, 2.2). The experimental apparatus consists of a rectangular riser (780×75×35 mm), a cyclone, a solids return system and an air heater. Silica sand particles (smaller than 160 μm) were used as a bed material. A quartz window at the front wall of the riser enables visual observation of the combustion process. Gas flow to the combustor has been controlled by means of rotameters installed next to the research stand. K-type thermocouples and microprocessor controllers were used to measure and to control temperature inside the combustion chamber (riser) and air heater. Fuel samples were fed to the riser through a stainless steel feeder installed at the angle of 40° to prevent the blowing out of hot bed particles. Two Pt-PtRh thermocouples were used to measure the surface temperature and the centre temperature of burning fuel samples.

The main objective of the test work was to identify the impact of different parameters (moisture content, coal, waste-coal and biomass content and superficial gas velocity) on the combustion time. The mass flux of the inert material varied from 0.8 to 5.2 $kg/m^2 \cdot s$, depending on the superficial gas velocity. The fuel was a mixture of coal, waste-coal, biomass fines (particles smaller than 100 μm) and water in different proportions. Properties of the coal, waste-coal and biomass used in the experimental program are shown in Table 2.1. The concentration of vitrinite in the hard coal is higher than that in the coal fines which makes it more hydrophobic.

Table 2.1. Properties of coal, coal fines and biomass

Fuel	Moisture	Volatiles	Ash	LHV	Carbon	Vitrinite	Egzinite	Inertinite	Mineral matter
	%	%	%	kJ/kg	%	$\%_{vol.}$	$\%_{vol.}$	$\%_{vol.}$	$\%_{vol.}$
waste-coal	4.51	20.45	39.43	15024	40.12	65	0	35	10
hard coal	4.30	30.90	8.20	27663	72.60	88	2	6	4
cereal grains	8.45	70.53	4.55	15825	40.90	–	–	–	–

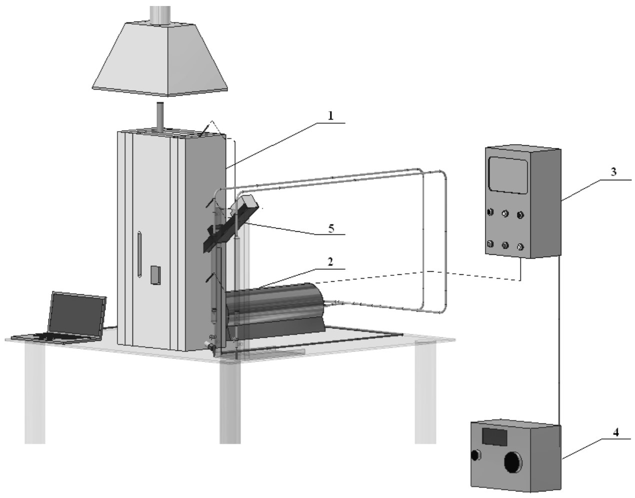

Fig.2.1. The experimental apparatus (1-CFB combustor, 2-gas heater, 3-temperature controller, 4-power supply system, 5-fuel introduction system)

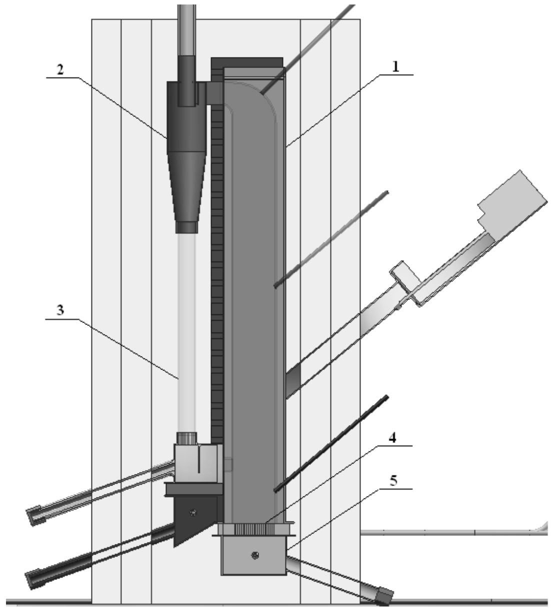

Fig.2.2. Schematic of the experimental apparatus (1- riser, 2-cyclone, 3-solids return system, 4-distributor plate, 5-wind box)

3. Experimental results

The test work was conducted according to the rotary and uniform experiment design [17] that enabled to identify interactions between process parameters:

x_1 - waste-coal content of coal-fuel*, (0–100%),

x_2 - biomass content of fuel**, (0–100%),

x_3 - moisture content, (20–50%),

x_4 - air velocity, (1.4–2.2 m/s).

* mixture of hard coal and waste-coal
** mixture of biomass dust and coal-fuel

Results of the research have been approximated with a polynomial function of the second degree with interactions of the first line. After introduction of the calculated coefficients of approximated polynomial the following results have been received:

$$\breve{z} = 239 - 24{,}8\hat{x}_1 - 24{,}1\hat{x}_2 - 8{,}2\hat{x}_3 - 7{,}6\hat{x}_4 + 1{,}3\hat{x}_1^{\,2} + 8{,}3\hat{x}_2^{\,2} - 13{,}3\hat{x}_3^{\,2} - 5{,}3\hat{x}_4^{\,2}$$
$$+ 11{,}8\hat{x}_1\hat{x}_2 + 3{,}5\hat{x}_1\hat{x}_3 + 13{,}9\hat{x}_1\hat{x}_4 + 9{,}9\hat{x}_2\hat{x}_3 + 8{,}8\hat{x}_2\hat{x}_4 + 0{,}25\hat{x}_3\hat{x}_4 \quad (3.1)$$

$\breve{z}$ - approximated value of exit-magnitude (combustion time) calculated from the function of the research object for u - measurement,

$$\hat{x}_k = \frac{2\alpha_{rot}\left(x_k - \bar{x}_k\right)}{x_{kmax} - x_{kmin}} \quad (3.2)$$

$\alpha_{rot} = 2$, $\bar{x}_1 = 50$ $\bar{x}_2 = 50$ $\bar{x}_3 = 35$ $\bar{x}_4 = 1.8$

Figures 3.1–3.6 show the influence fuel composition and superficial gas velocity on the combustion time of coal-biomass-water fuels.

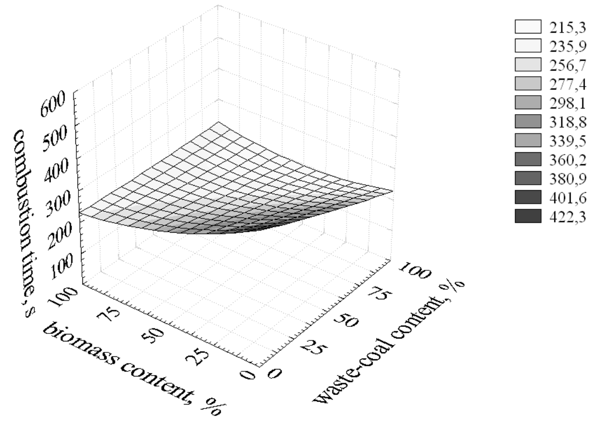

Fig.3.1. Influence of biomass content and waste-coal content on combustion time

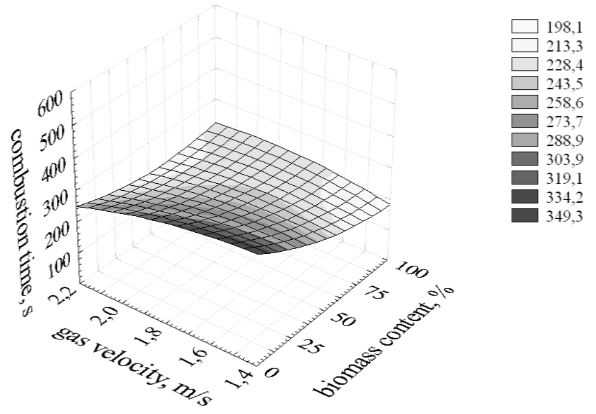

Fig.3.2. Influence of superficial gas velocity and biomass content on combustion time

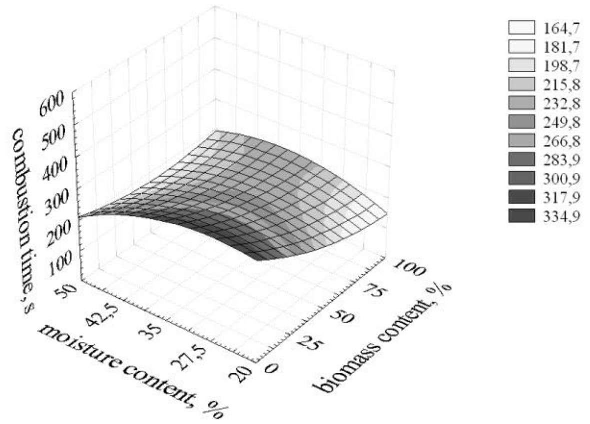

Fig.3.3. Influence of moisture content and biomass content on combustion time

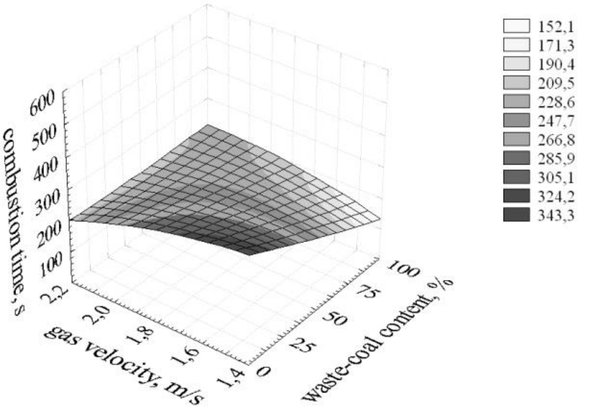

Fig.3.4. Influence of superficial gas velocity and waste-coal content on combustion time

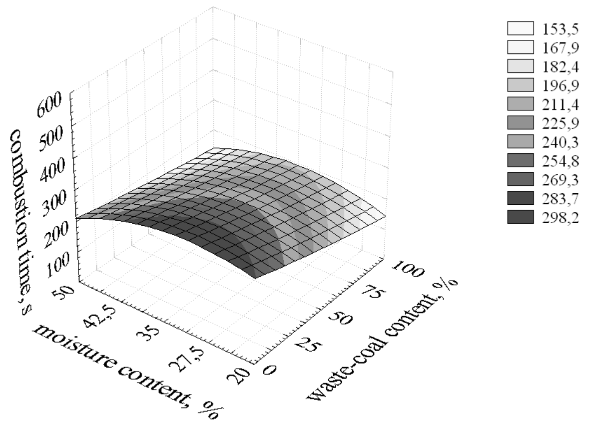

Fig.3.5. Influence of moisture content and waste-coal content on combustion time

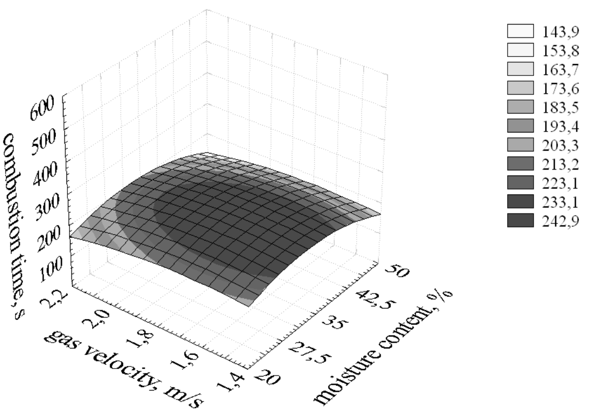

Fig.3.6. Influence of moisture content and superficial gas velocity on combustion time

It has been found that:

- the combustion time decreases significantly with an increase in biomass content at small waste-coal content in the fuel (Fig.3.1),

- the influence of the superficial gas velocity on the combustion time is significant in the case of fuel that contains smaller amount of biomass (Fig.3.2),

- the combustion time decreases with an increase in fuel moisture in the case of fuels containing smaller amount of biomass (Fig.3.3),

- the influence of superficial gas velocity on the combustion time is significant for fuels at small waste-coal content (Fig.3.4),

- the combustion time decreases significantly for fuels with small waste-coal content and with higher moisture contents (Fig.3.5),

- the combustion time decreases with an increase in the waste-coal content, at smaller moisture and biomass contents (Fig.3.1, 3.5),

- the combustion time decreases significantly with an increase in the superficial gas velocity at smaller contents of moisture in the fuel (Fig.3.6).

It should be stressed that a clear tendency to decrease the combustion time with increasing superficial gas velocity is caused by a more pronounced attrition of the coal-water fuel. The attrition process reduces the size of coal-water fuel agglomerates, accelerates their heating and ignition of volatiles. Characteristics of coal-water fuels influence mechanism and kinetics of the combustion process. The process of coal-water fuel combustion takes place in the transition region, with the diffusion-control regime prevailing in the case of fuels with lower moisture contents and at higher superficial gas velocities.

In the transition region, the chemical reaction rate and the rate of diffusion into the pores are comparable with each other. The penetration of oxygen through pores into char particles is limited; the majority of oxygen is consumed at the surface. In the case of the diffusion-controlled combustion, the rapid chemical reactions lead to a decrease in oxygen concentration on the fuel particle surface, and as a result, the oxygen influx from ambient is limited. An increase in the superficial gas velocity improves the oxygen diffusion process and, therefore, reduces the combustion time.

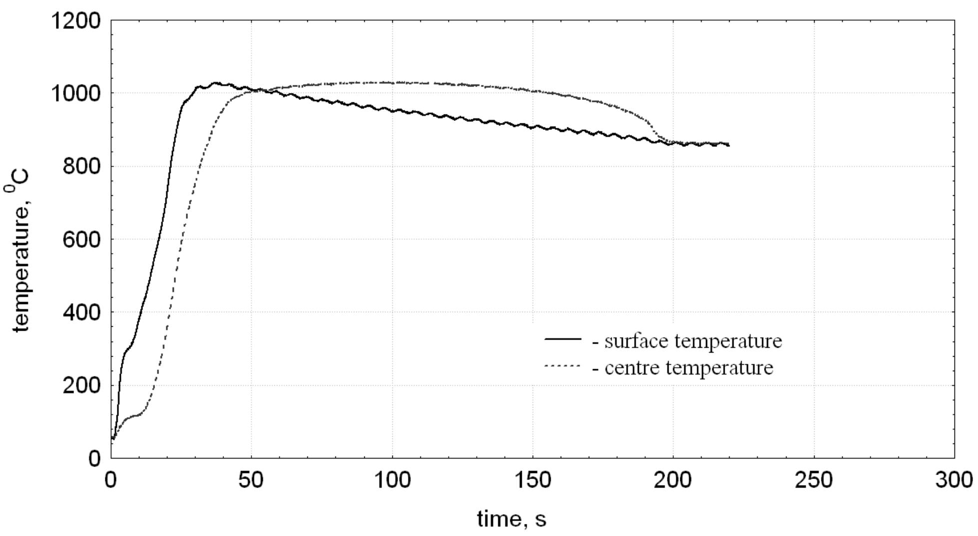

Fig.3.7. Surface and centre temperature as a function of time

Typical temperature profiles at the surface and in the centre of burning coal-water fuel sample are shown in Fig. 3.7. Large temperature gradients within the sample are clearly visible especially at the early stage of devolatilization. The volatile ignition temperature decreases with an increase in moisture content. After the ignition, the temperature of the surface increases and reaches its maximum value after flame extinction. This moment is preceded by the char ignition. Then the recorded surface temperature falls, indicating that the surface of fuel sample cools down. The char agglomerate combustion time is definitely longer than the ignition and volatiles combustion time. The completion of the process is signalled by the sudden fall of the char temperature. Recording of the combustion process and its subsequent visual observation allowed to confirm that high concentrations of volatiles in the fuel (high contents of biomass) lead to the intensification of combustion process, lowering of fuel ignition temperature and reduction in the combustion time.

Concentration of inert particles in the riser increases with an increase in solids circulation rate (or solid flux) G_s. At higher G_s, the frequency of collisions between inert particles and coal-water fuel agglomerates is also higher. However, when G_s exceeds certain value the particles of inert material stop bouncing back and instead stick to the surface of fuel agglomerates. At high values of G_s, the entire surface of fuel agglomerates can be covered by particles of inert material. High value G_s of the stream intensity of bed material can cause a situation, in which the concentration of grains of bed material surrounding the fuel practically covers their surface, leading even to disappearance of marks showing that fuel has been covered. When fuel agglomerates are covered by particles of bed material, the particles of inert material and fuel agglomerates exchange heat in two ways: by direct contact of the fuel surface with small particles and by a thermal contact that occurs when the particles stay in the fluidized bed surrounding fuel [18]. In case of intensive erosion of fuel suspension which is a result of collisions with the fluidized bed material there occurs a visible tearing out of particles from the surface of suspension and also the breakdown of fuel into smaller fragments.

4. Conclusions

The following conclusions can be drawn from the experimental data presented in this paper:

1. After water evaporation, fuel particles stick to each other and form agglomerates.

2. Water in the coal–water fuel intensifies process by lowering the ignition temperature of fuel.

3. The characteristics of coal-biomass-water fuels influence the mechanism and kinetics of their combustion process.

4. Addition of biomass (fuel with high volatiles content) intensifies the combustion process and lowers the ignition temperature.

5. A significant reduction in the combustion time is observed with an increase in the superficial gas velocity at smaller waste-coal contents and moisture contents as well as at higher biomass contents in the fuel.

6. At higher concentration of moisture in coal-biomass-water fuel, an intensification in covering of the fuel surface by the particles of inert material is observed which is more pronounced at lower superficial fluidization velocities.

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