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COMBUSTION OF COAL-MULE BRIQUETTES

SPALANIE BRYKIETÓW Z MUŁU WĘGLOWEGO

Combustion technologies coal-mule fuels create a number of new possibilities for organising combustion processes so that they fulfil contemporary requirements (e.g., in terms of the environment protection-related issues). The paper describes the problems of coal-mule fuel combustion that have acquired a wider significance as the quality requirements of coal combustion in power plants have been growing. Coal mines that want to fulfill expectations of power industry workers have been forced to develop and modernize plants of coal wet cleaning. It all results in the growing amount of waste arising in the process of coal wet cleaning which contains smaller and smaller coal undersizes. In this situation the concept of direct combustion of the above mentioned waste and their co-combustion with other fuels, coal and biomass, seems to be attractive. Biomass is one from the most promising sources of renewable energy. The main aim of the paper is to identify the mechanism and kinetics of combustion of coal-mule fuels and their co-combustion with coal and biomass in the briquettes form based on extensive experimental research in air.

Keywords: briquettes of fuels; mechanism and kinetics of combustion reaction; co-combustion of fuels; visualization of fuels combustion process

Niekorzystny bilans paliwowy naszego kraju powoduje nadmierne obciążenie środowiska, wywołane emisją CO_2, NO_x, SO_2 i pyłów, a także powiększeniem powierzchni koniecznych na składowanie wciąż narastających stałych odpadów paleniskowych. Górnictwo, od którego energetyka oczekuje coraz lepszego paliwa, musi stosować głębsze wzbogacanie węgla. Powoduje to ciągłą produkcję odpadów w postaci mułów poflotacyjnych. Najlepszą metodą utylizacji tych mułów jest ich spalanie w postaci zawiesin, a także ich współspalanie z innymi paliwami, węglem czy biomasą. Biomasa jest bowiem jednym z najbardziej obiecujących źródeł OZE, a jej współspalanie z paliwami węglowymi znajduje w ostatnich latach coraz szersze zastosowanie zarówno w kraju, jak i na świecie. W tej sytuacji istotne jest prowadzenie badań naukowych, mających na celu identyfikację przebiegu procesu spalania paliw, utworzonych nie tylko z mułów poflotacyjnych, ale również z mieszaniny mułów węglowych oraz pyłów węgla i biomasy. Niniejsza praca podejmuje mechanizm i kinetykę spalania oraz współspalania wspomnianych paliw w postaci brykietów, prowadzonego w strumieniu powietrza.

Słowa kluczowe: brykiety paliwowe; mechanizm i kinetyka reakcji spalania; współspalanie paliw; wizualizacja procesu spalania paliw

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1. Introduction

Coal-mule is the after-flotation fuel, with a moisture content of 20%-40%, fuel value of 8-10 MJ/kg and ash content of 20-35%. The constant phase concentration of fragmented coal, which assures the stability of such 'fuels,' depends on the size of coal particles and the degree of its metamorphism. In specialised literature, we can find some texts concerning coal-water suspensions, as well as in-depth papers dealing with the combustion processes of various fuels, including fuel wastes (Liu & Law, 1986; Dunn-Rankin, 1987; Chan, 1994; Burdukov et al., 2002; Folgueras, 2003; Kijo-Kleczkowska, 2009, 2010a, 2010b, 2011, 2012). The current research is directed towards two main problems: 1) to present a study on the combustion technology of low-concentration coal-water suspensions, which will decrease NO_x emission (the suspensions are made of coal mules, which are formed during the coal cleaning process), and 2) the combustion of low concentration coal-water suspensions, where good stability is preserved, which enables substitution of petrochemical fuel. The latter is mainly carried out in China. The necessity to undertake the research of coal combustion (Pelka et al., in print; Pelka, 2011) and their co-combustion with other fuels in different conditions in Poland results from the fuel structure of the Polish power industry, where 97% of electric energy is produced from coal.

There are several technologies to utilize coal-mules in power. In addition to widespread spraying mule pulp to furnaces, there are also methods of preparation of solid fuels based on coal-mule. The developed methods of technological processes are the processes of agglomeration – compact and produce fuel in the form of granules about the size of 3 to 20 mm or briquette of sizes 30 - 50 mm. The briquetting and pelleting processes are common (Jaworski, 2007; Ściążko, 2004; Wasilewski & Raińczak, 2004). The best properties have mixtures of mule pellets with coal and biomass (Kuczyńska, 2005). The high content of volatile matter in biomass helps to combustion of coal-mule. Biomass enhances the combustion process by lowering the ignition temperature of fuel, but low calorific value of coal-mule and biomass requires the application of basic fuel (coal).

The energy-use of low-carbon fuels has two aspects:

- cost, associated with the need to reduce the cost of fuel,
- ecological, consisting of rational management of mineral resources and coal waste products deposited in the mine's settlers (Lorenz & Ozga-Blaschke, 2005).

2. The research stand and measurements methodology

The experimental nature of the research required the preparation of a research stand (Fig. 1) (Kijo-Kleczkowska, 2010c), as well as working out of the methodology of measurements. In order to establish the centre and surface temperature of the fuel, a special instrument stalk was constructed (Fig. 2). It had two thermocouples, PtRh10-Pt (3), and a built in scale pan of a scale (5). One of the thermocouples was located inside the fuel while the other served as a basket, which was used to support the fuel. It also touched the surface of the fuel. The thermocouples and scale were connected to the measurement card and computer in order to record the experimental results. The combustion chamber consisted of a quartz pipe (1 – Fig. 1), which was additionally thermally insulated, to maintain the necessary temperature of the entering gas and reduce heat loss. The application of the quartz pipe and sight-glass in a metal shield allowed for direct observation, to film and photograph the combustion process of fuel. The essential stage of the preliminary work

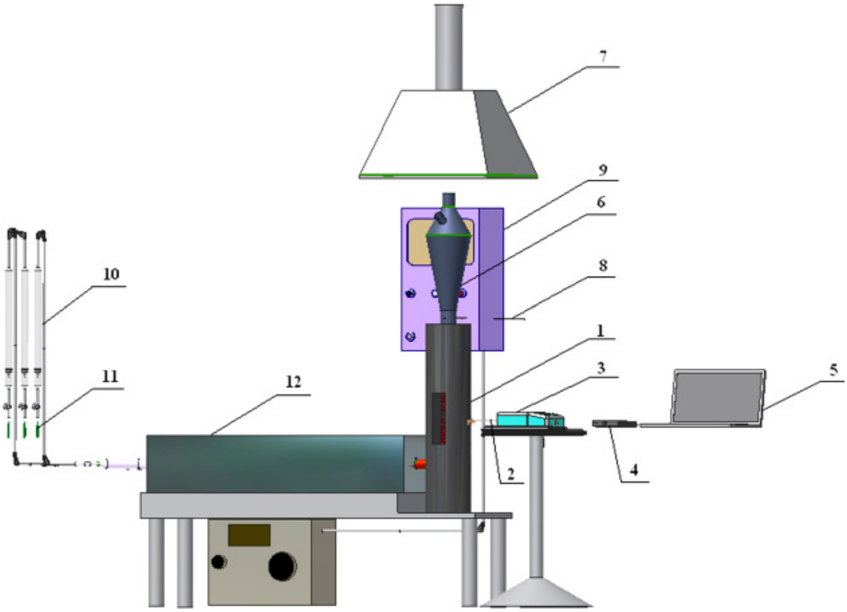


Fig. 1. Research Stand Scheme; 1 – combustion chamber, 2 – Pt-PtRh10 thermocouples, 3 – scale, 4 – measurement card, 5 – computer, 6 – expansion chamber, 7 – exhaust, 8 – NiCr-Ni thermocouple, 9 – microprocessor thermoregulators, 10 – rotameter, 11 – control valves, 12 – ceramic block

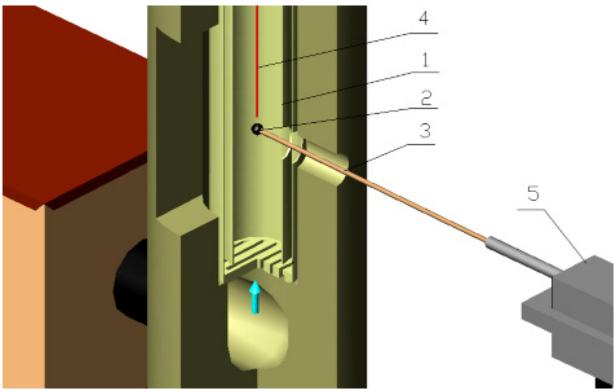


Fig. 2. Measurements Methodology; 1 – combustion chamber, 2 – particle of fuel, 3 – thermocouples PtRh-Pt, 4 – thermocouple Ni-NiCr, 5 – scale

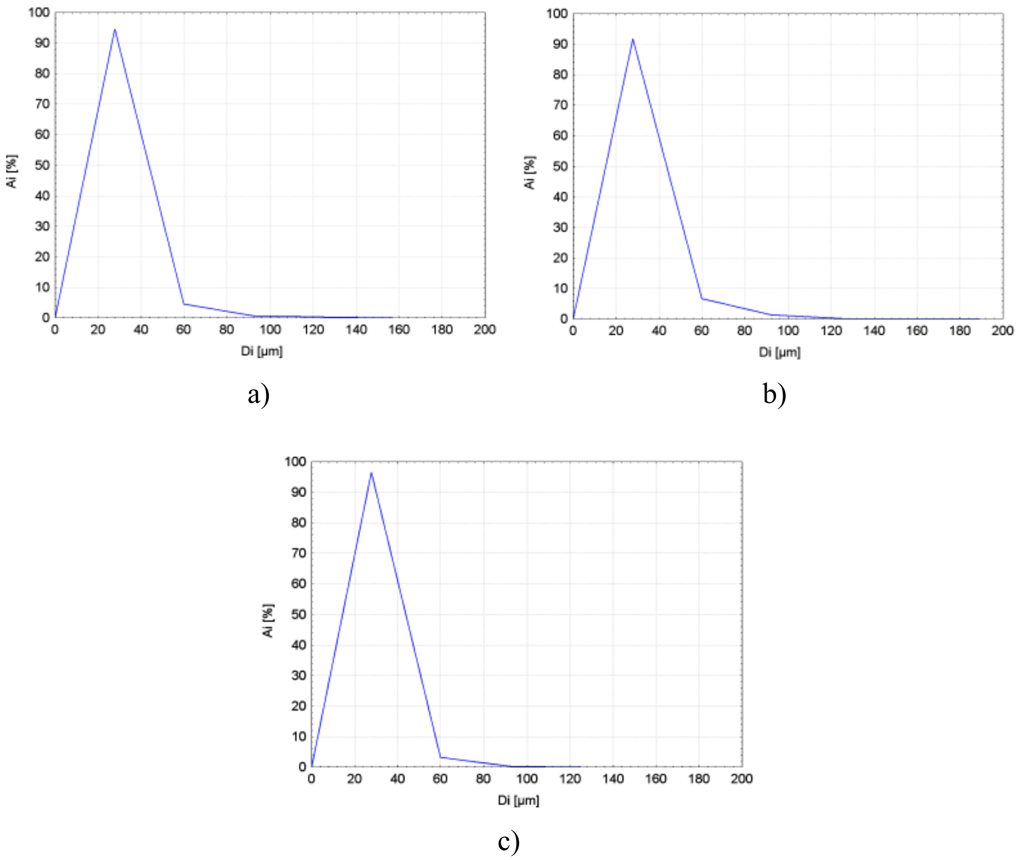
was to make the briquettes, which were a mixture of coal, coal-mule and biomass dust, in different proportions. In order to produce the fuels, it was necessary to prepare coal dust after grinding and sifting. Particle size distribution of fuels was carried out by means of Infrared Particle Sizer (IPS) (Kijo-Kleczkowska, 2010c). Figure 3 illustrates an example of the size distribution of coal, biomass and coal-mule dust. The fuels properties applied in the research are shown in Table 1.

TABLE 1

Analysis of the fuel used in the research (air-dry state)

		Moisture	Volatiles	Ash	Calorific Value	C^a	H^a	N^a	O^a	S^a
		W^a	V^a	A^a	Q_i^a	C_t^a	H_t^a	N^a	O_d^a	S_t^a
		%	%	%	kJ/kg	%	%	%	%	%
Coal-mule	Sobieski	4,51	20,45	39,43	15024	40,12	2,82	0,54	12,11	0,72
Hard coal	Staszic	2,66	30,90	2,36	31198	79,53	4,33	1,27	9,75	0,31
ground grain		8,45	70,53	4,55	15825	40,90	6,07	2,73	37,30	0,18

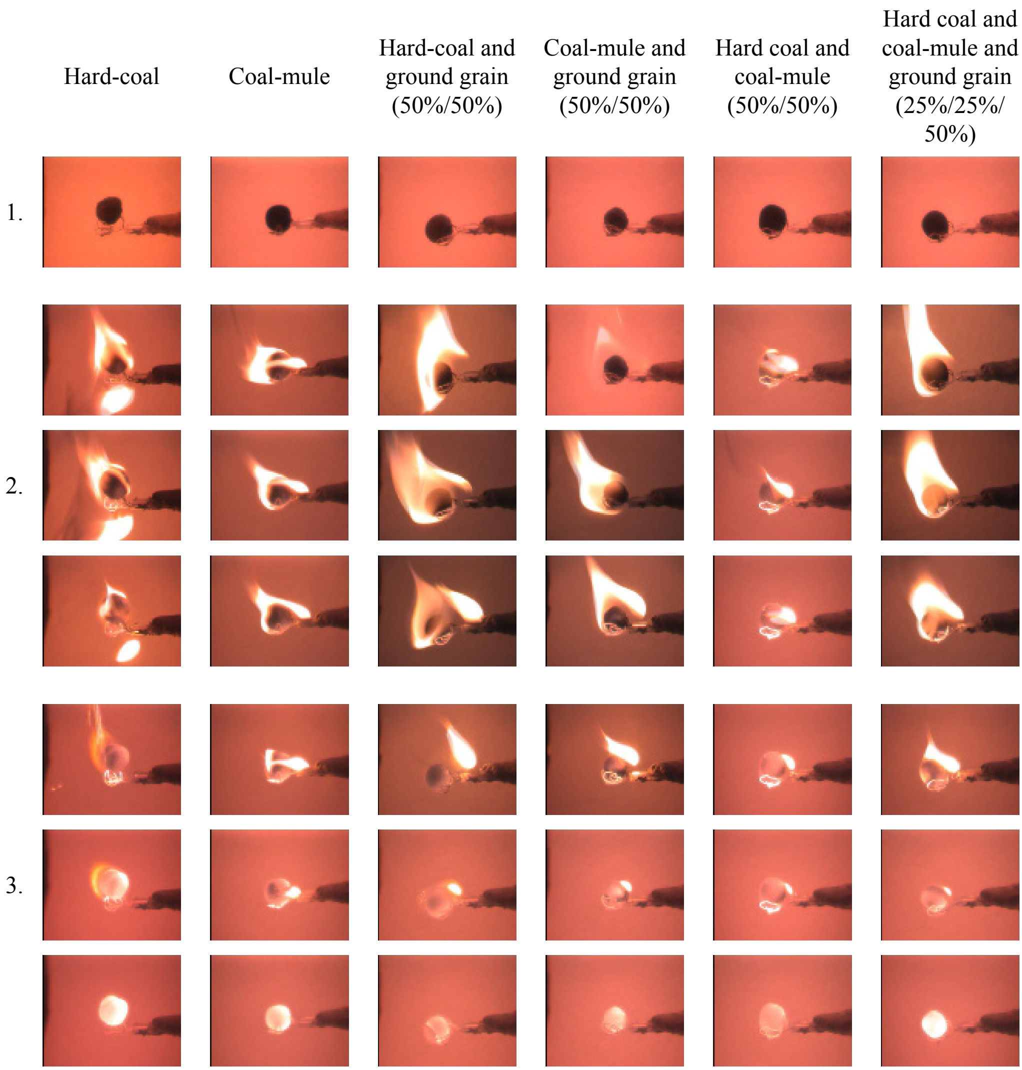
The research included the determination of temperature changes of fuels during combustion, determination of the combustion mechanism and kinetics of the fuels in air stream.



Rys. 3. Differential distribution – the share quantity for dust of:
a) coal-mule; *Da* = 46,0 mm; b) hard coal; *Da* = 53,7 mm; c) ground grain; *Da* = 36,6 mm

3. Experimental research

The combustion analysis of the fuel required following its behaviour in the particular process stages. Fig. 4 shows the course of combustion of the fuel-briquettes, made from coal, coal-mule and biomass dust. In the first combustion stage of the fuel, evaporation of moisture occurs. It was noticed that after the evaporation, the size of the agglomerate remained the same. After the evaporation stage there is heating and carbonisation of the coal particle agglomerate, which



Rys. 4. Combustion of fuel-briquettes.
1 – heating and evaporation of moisture; 2 – devolatilization, ignition and volatiles combustion; 3 – char combustion

leads to thermal decomposition. The final stage is the non-homogeneous combustion of the agglomerate, which is characterised by the absence of flame occurring during volatile combustion. The completion of the process is signalled by the sudden fall of the char product temperature. The char-agglomerate combustion period is definitely longer than the ignition time and volatile combustion. It was observed that during intensive volatile combustion, a sudden temperature rise of fuel occurs. The fuel, which constitutes the coal mule, burns violently because of volatiles situated at the fuel surface.

The basic aim of the research was to identify the participation of coal-mule in the fuel (0-100%), the participation of biomass in the fuel (0-100%), temperature in the combustion chamber (800-900°C), gas velocity (3-6 m/s) on the time of combustion of the fuel in air. In this research, fuel was made of hard coal (Staszic mine), biomass (ground grain) and mule coal (Sobieski mine). To conduct the research, a rotating and uniform research schedule PS/DS-Pl(l) (Polanski, 1984) was used which, due to the parallel change of all process parameters, enabled us to catch the interactions between the decisive parameters for combustion, eliminating at the same time the need to acquire x a large number of measurements (Table 2).

TABLE 2

Research schedule

u	$\hat{x}_k$				x_k			
	$\hat{x}_1$	$\hat{x}_2$	$\hat{x}_3$	$\hat{x}_4$	x_1	x_2	x_3	x_4
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	–1	–1	–1	–1	25	25	825	3,75
2	1	–1	–1	–1	75	25	825	3,75
3	–1	1	–1	–1	25	75	825	3,75
4	1	1	–1	–1	75	75	825	3,75
5	–1	–1	1	–1	25	25	875	3,75
6	1	–1	1	–1	75	25	875	3,75
7	–1	1	1	–1	25	75	875	3,75
8	1	1	1	–1	75	75	875	3,75
9	–1	–1	1	1	25	25	825	5,25
10	1	–1	–1	1	75	25	825	5,25
11	–1	1	–1	1	25	75	825	5,25
12	1	1	–1	1	75	75	825	5,25
13	–1	–1	1	1	25	25	875	5,25
14	1	–1	1	1	75	25	875	5,25
15	–1	1	1	1	25	75	875	5,25
16	1	1	1	1	75	75	875	5,25
17	–2	0	0	0	0	50	850	4,5
18	2	0	0	0	100	50	850	4,5
19	0	–2	0	0	50	0	850	4,5
20	0	2	0	0	50	100	850	4,5
21	0	0	–2	0	50	50	800	4,5
22	0	0	2	0	50	50	900	4,5
23	0	0	0	–2	50	50	850	3
24	0	0	0	2	50	50	850	6

TABLE 2. Continued

1	2	3	4	5	6	7	8	9
25	0	0	0	0	50	50	850	4,5
26	0	0	0	0	50	50	850	4,5
27	0	0	0	0	50	50	850	4,5
28	0	0	0	0	50	50	850	4,5
29	0	0	0	0	50	50	850	4,5
30	0	0	0	0	50	50	850	4,5
31	0	0	0	0	50	50	850	4,5

The conducted research gives the vast material that included experimental results of the fuel combustion in various conditions that were anticipated by the research program. Each unit of measurement was repeated three times. The most representative function approximating the measurement results was the quadratic multinomial:

$$\begin{aligned}\tau = {} & b_{00} + b_{01}\cdot\hat{x}_1 + b_{02}\cdot\hat{x}_2 + b_{03}\cdot\hat{x}_3 + b_{04}\cdot\hat{x}_4 + b_{11}\cdot\hat{x}_1^{\,2} + b_{22}\cdot\hat{x}_2^{\,2} + b_{33}\cdot\hat{x}_3^{\,2} \\ & + b_{44}\cdot\hat{x}_4^{\,2} + b_{12}\cdot\hat{x}_1\cdot\hat{x}_2 + b_{13}\cdot\hat{x}_1\cdot\hat{x}_3 + b_{14}\cdot\hat{x}_1\cdot\hat{x}_4 + b_{23}\cdot\hat{x}_2\cdot\hat{x}_3 \\ & + b_{24}\cdot\hat{x}_2\cdot\hat{x}_4 + b_{34}\cdot\hat{x}_3\cdot\hat{x}_4\end{aligned} \tag{1}$$

The following standardisation relations were used:

$$\hat{x}_k = \frac{2\cdot\alpha\cdot\left(x_k - \overline{x}_k\right)}{x_{k\,\max} - x_{k\,\min}} \tag{2}$$

where:

- τ — combustion time of fuel, s,
- b — regression factors (Table 3)
- x_k — established decision-making parameters, defined as initial quantities, respectively:
- x_1 — participation of coal-mule in the fuel, %,
- x_2 — participation of biomass in the fuel, %,
- x_3 — temperature in the combustion chamber, °C,
- x_4 — gas velocity, m/s.

TABLE 3

Regression coefficients

Coefficients	Values of regression coefficients	Coefficients	Values of regression coefficients
b_{00}	380,09	b_{14}	–0,81
b_{01}	–32,21	b_{22}	20,03
b_{02}	–11,95	b_{23}	2,93
b_{03}	0,375	b_{24}	9,43
b_{04}	–14,04	b_{33}	–7,34
b_{11}	–24,72	b_{34}	–11,81
b_{12}	15,18	b_{35}	–17,47
b_{13}	–4,56	b_{44}	–17,47

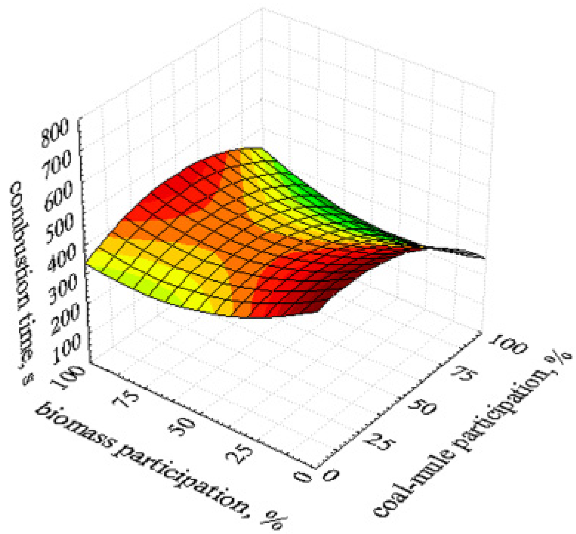
Regression equation (1) allowed us to determine the time of fuel combustion at various conditions of the process (Fig. 5-11).

Research have shown that:

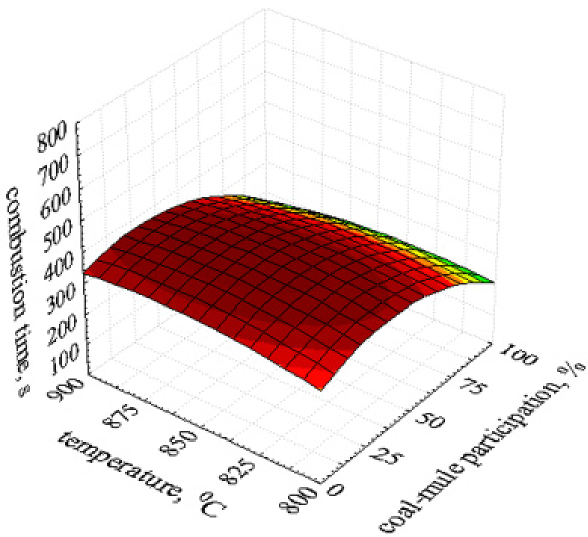
– increase of participation of mule-coal in the fuel leads to reduction in process time for smaller participation of biomass in the fuel (Fig. 5),
– growth of biomass participation in the fuel reduces the process time for low coal-mule content in the fuel (Fig. 5),
– temperature in the combustion chamber does not significantly affect the process (Fig. 6),
– combustion of fuel at higher velocity of the air flow leads to reduction in process time (Fig. 7),
– increase of coal-mule participation in the fuel reduces the process time in the entire range of air flow velocity (Fig. 7) and temperature in the combustion chamber (Fig. 6),
– growth of biomass participation in the fuel reduces the process time in the entire range of air flow velocity (Fig. 9) and temperature in the combustion chamber (Fig. 8),
– temperature affects the process at the higher air flow velocity (Fig. 10),
– air velocity has an effect on the process time at high temperatures in the combustion chamber (Fig. 10).

The observed lack of influence of temperature on the combustion rate, indicated a slight shift of the process into the area where diffusion processes dominated.

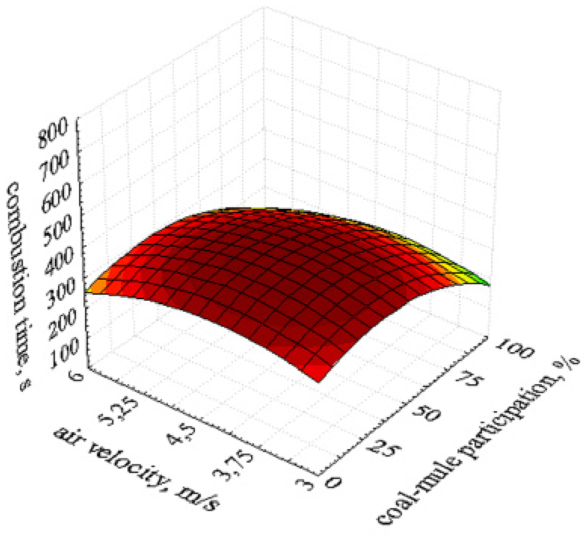
The research of combustion process kinetics was based on measurements of the surface and centre temperature changes during the combustion in air. After introduction of the fuel to the combustion chamber in 850°C incoming air, the ignition of volatile substances coming from the fuel was observed (Fig. 11).



Rys. 5. The relation between coal-mule participation and biomass participation and combustion time of fuel briquettes during process in air; t = 850°C

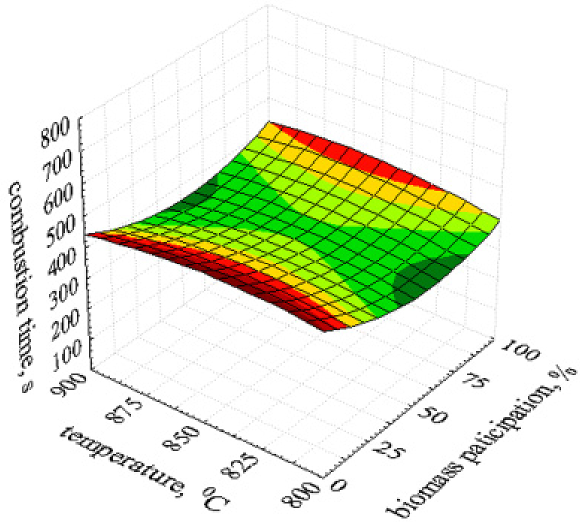


Rys. 6. The relation between coal-mule participation and temperature in combustion chamber and combustion time of fuel briquettes during process in air; t = 850°C

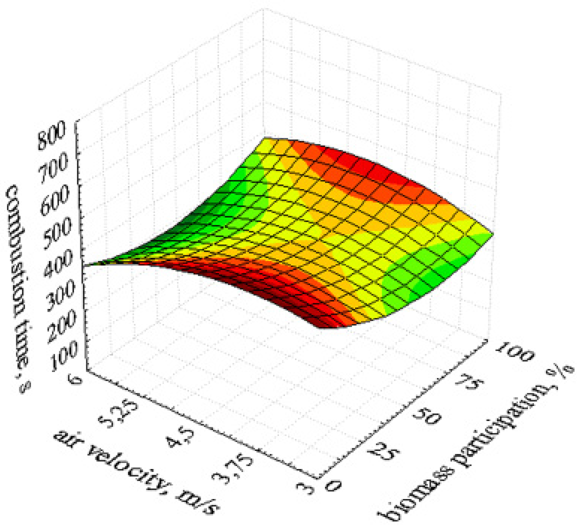


Rys. 7. The relation between coal-mule participation and air velocity and combustion time of fuel briquettes during process in air; t = 850°C

The ignition time and temperature of the fuel surface was increasing, reaching its maximum value after some time. After volatile ignition, a tendency to increase the temperature of the particle centre was observed. The visual display of the process enables stating that when the surface

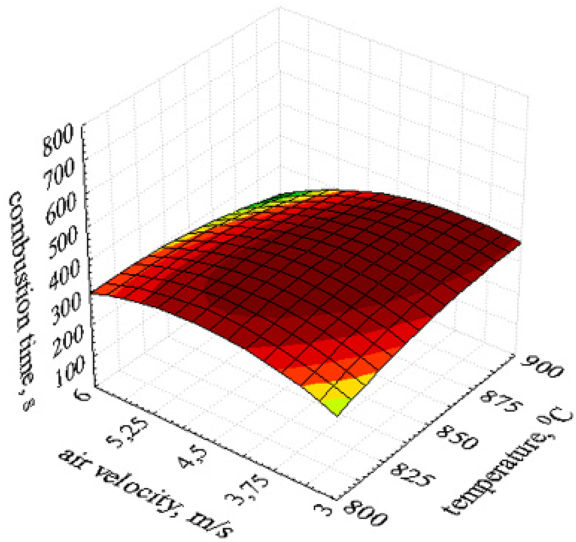


Rys. 8. The relation between biomass participation and temperature in combustion chamber and combustion time of fuel briquettes during process in air; t = 850°C



Rys. 9. The relation between biomass participation and air velocity and combustion time of fuel briquettes during process in air; t = 850°C

particle reaches the maximum temperature, the volatiles are completely consumed. This moment is preceded by ignition of the char product. The surface temperature then falls, indicating that the combustion front is moving inside the combustion, and that the fuel surface is cooling. At the same time, the ash layer surrounding the core of the char product is growing. The speed of



Rys. 10. The relation between temperature in combustion chamber and air velocity and combustion time of fuel briquettes during process in air; $t = 850°C$

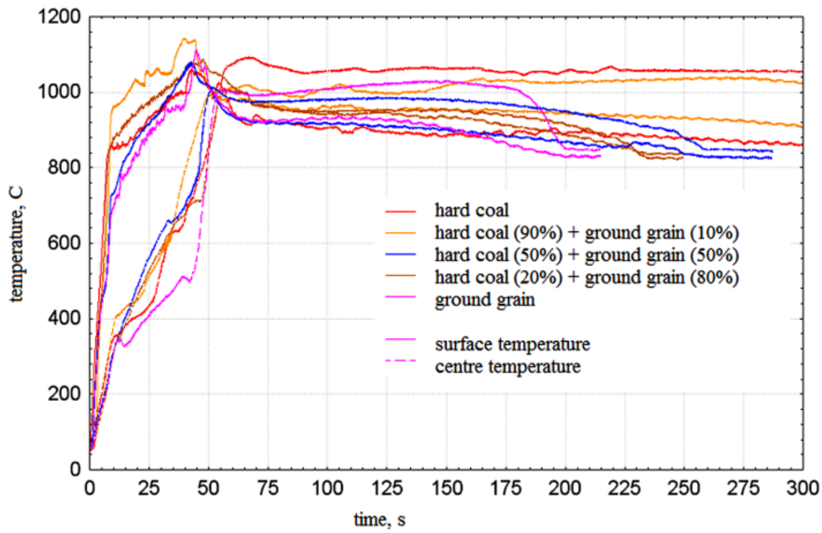


Fig. 11. Course of changes of surface and centre temperature of fuel briquettes from hard coal and ground grain dust during combustion in air; $t = 850°C$

the surface temperature increase, and the temperature profile in the fuel (especially at the initial combustion stages), are highly dependent on the kind of fuel, as well as on the humidity and volatile content in the fuel.

4. Conclusions

1. Fuel-briquette made of hard coal dust has the highest average combustion temperature and its combustion time is the longest.

2. Combustion of the fuel-briquettes in air, occurring in the temperature range of 800°C-900°C, takes place in the area, with the majority of diffusive factors, in the range of small participation of biomass and higher temperature in the combustion chamber.

3. Biomass has a low average temperature of combustion and the shortest total combustion time.

4. After the ignition of evaporated and devolatilized fuel, one can observe the intensive increase of fuel temperature to the maximum value.

5. The volatiles emitted from the fuels rich in coal-mule burn near the fuel surface.

References

Burdukov A.P., Popov V.I., Tomilov V.G.. 2002. *The rheodynamics and combustion of coal-water mixtures*. Fuel 81, p. 927-933.

Chan K.K., 1994. *Pilot-scale combustion tests on coal-water mixtures with reference to particle agglomeration*, Fuel 73, p. 1632-1637.

Dunn-Rankin D., 1987. *Combustion of coal-water Slurries. Evolution of particle size distribution for coals of different rank*. Fuel 66, p. 1139-1145.

Folgueras B., 2003. *Thermogravimetric analysis of the co-combustion of coal and sewage sludge*. Fuel 82, p. 2051-2055.

Jaworski T.J., 2007. *Modelowanie procesu spalania pojedynczego ziarna paliwa formowanego na bazie odpadów stałych. Systemy i technologie termicznej utylizacji odpadów*. Paliwa z odpadów, tom VI (praca pod red. J. Wandrasza), Helion, Gliwice 2007, s. 91-97 (in polish).

Kijo-Kleczkowska A., 2009. *Analysis combustion process of coal-water fuel*. Arch. Min. Sci., Vol. 54, No. 1, p. 119-133.

Kijo-Kleczkowska A., 2010a. *Research on destruction mechanism of drops and evolution of coal-water suspension in combustion process*. Arch. Min. Sci., Vol. 55, No. 4, p. 923-946.

Kijo-Kleczkowska A., 2010b. *Analysis of the co-combustion process of coal-water slurries and biomass*. Arch. Min. Sci., Vol. 55, No. 3, p.487-500.

Kijo-Kleczkowska A., 2010c. *Mechanizm współspalania zawiesinowych paliw węglowo-wodnych z biomasą*. Raport projektu badawczego Nr N N513 309935, 2008-2010 (in polish).

Kijo-Kleczkowska A., 2011. *Combustion of coal-water suspensions*. Fuel, Vol. 90, p. 865-877.

Kijo-Kleczkowska A., 2012. *Research on coal-water fuel combustion in a circulating fluidized bed*. Arch. Min. Sci., Vol. 57, No. 1, p. 79-92.

Kuczyńska I., 2005. *Badania mułów węglowych i odpadów niemineralnych w zakresie możliwości otrzymania paliw*. Górnictwo i Geoinżynieria, z. 4, s. 83-92 (in polish).

Liu G.E., Law C.K., 1986. *Combustion of coal-water droplets*. Fuel 65, p. 171-176.

Lorenz U., Ozga-Blaschke U., 2005. *Muły węgla kamiennego – produkt energetyczny czy odpad*. VII Ogólnopolska Konferencja Naukowa Kompleksowe i szczegółowe problem inżynierii środowiska. Koszalin-Ustronie Morskie 2005, s. 681-692 (in polish).

Pełka P., 2011. *Modeling of mass loss of char particle during combustion on flow of inert material*. Fuel 90, p. 904-932.

Pełka P., Golański G., Wieczorek P., 2013. *Evolution of the structure and mechanical strength of a coal particle during combustion in the atmosphere of air in the mixture of oxygen and carbon dioxide*, Arch. Min. Sci., (in print).

Polański R., 1984. *Planowanie doświadczeń w technice*. PWN, Warszawa, (in polish).

Ściążko M., 2004. *Z węglem kamiennym - ekologicznie i oszczędnie*. Trybuna Górnicza – 26.02.2004, nr 9 (490) (in polish).

Wasilewski R., Raińczak J., 2004. *Formowane paliwo stałe na bazie mułu węglowego*. Inżynieria Chemiczna i Procesowa 25, s. 2385-2391 (in polish).

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