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MASS LOSS OF COAL PARTICLES BURNING IN FLUIDIZED BED

UBYTEK MASY ZIAREN WĘGLA SPALANEGO W WARSTWIE FLUIDALNEJ

In this work many conclusions resulting from research carried out on the coal combustion process of the chosen coal type and its accompanying erosion in a two-phase flow of inert material have been presented. The purpose of this flow was to present a model of the conditions of the central and upper zone of the combustion chamber of the fluidized boiler. In the opinion of many authors (Basu, 1999; Chirone et al., 1991), the erosion process results from the contact of a fuel particle with particles of inert material that is responsible for generating fine fuel particles of less than 100 mm. If the particles are in the upper zone of the boiler where there is oxygen deficit, they can increase the loss of incomplete combustion substantially. The results of research do not confirm this common thesis, but rather indicate that the process of comminution that results from erosion under oxidative conditions contributes to the increase of substantial mass loss of a coal particle, however the increased mass loss of particle during combustion is first and foremost due to the whole process of removal of ash from the reactionary surface of a fuel particle. Nevertheless, in the conditions of oxygen deficit the comminution of particles as a result of the erosion process is negligible.

Keywords: coal, combustion, comminution, mechanical coal properties

W pracy przedstawiono szereg wniosków wynikających z przeprowadzonych badań procesu spalania ziaren wybranych typów węgli i towarzyszącej mu erozji w dwufazowym przepływie materiału inertnego. Przepływ ten miał na celu zamodelowanie warunków panujących w środkowej i górnej strefie komory paleniskowej kotła fluidalnego. W opinii wielu autorów (Basu, 1999; Chirone et al., 1991) proces erozji wynikający z kontaktu ziaren paliwa z ziarnami materiału inertnego odpowiedzialny jest za generowanie drobnych ziaren paliwa mniejszych od 100 mm. Jeżeli ziarna te generowane są w górnej strefie kotła, gdzie panuje deficyt tlenowy to w istotny sposób mogą podnosić one stratę niecałkowitego spalania. Zamieszczone w pracy wyniki badań nie potwierdzają tej powszechnej tezy. Wskazują one, iż proces rozdrabniania w wyniku erozji w warunkach utleniających przyczynia się wprawdzie do zwiększonego ubytku masy ziarna węgla jednak za przyspieszony ubytek masy ziarna podczas spalania odpowiada przede wszystkim proces usuwania popiołu z powierzchni reakcyjnej ziarna paliwa. Natomiast w warunkach deficytu tlenowego rozdrabnianie ziarna w wyniku procesu erozji jest pomijalnie małe.

Słowa kluczowe: węgiel, spalanie, rozdrabnianie, mechaniczne własności węgla

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1. Introduction

Coal comminution which takes place in the combustion chamber of a fluidized bed boiler is one of the basic parameters of combustion efficiency and a level of pollution emission. It has been still the subject matter of research (Gajewski & Kosowska, 2004; Gajewski & Kijo-Kleczkowska, 2007; Kijo-Kleczkowska, 2012). This is of particular significance in this type of boiler for the sake of the continual contact of the coal particles with a dispersed bed as well as the high flow of gas velocity across a reactor. Direct mechanisms that reduce the size of a particle and also influence the loss of coal combustion are complicated (complex) and are not entirely known. There are a lot of parameters that may have an effect on the comminution process considering the coal properties and combustion conditions are first of all an increase (gain) of fluidization velocity which intensifies the ratio of generating fine material due to the increased number of collisions at a unit of time and the amount of material removed from a particle during a collision.

In the opinion of Chirone, Massimilla and Salatino (1991), comminution in the combustion chamber of fluidized bed may be considered as a result of four phenomena as follows:

- primary fragmentation,
- secondary fragmentation,
- fragmentation by uniform fragmentation,
- erosion.

These phenomena are run throughout the whole course of combustion from the moment of the coal particles entering into a combustion chamber to its complete burnout or elutriation from the boiler. All these phenomena proceed simultaneously for a greater proportion of time as shown in Fig. 1.

According to Blinichev (1968) erosion is a phenomenon by which fine particles are abraded from the surface of the mother particle by wearing against bed solids and combustor walls and internals.

In the opinion of Basu and Fraser (1991) they are smaller than 100 mm. In contrast to erosion, primary and secondary fragmentations break up coal particles into relatively large pieces with negligible production of fine particles (Fig. 2). The primary fragmentation takes place during devolatilization as a consequence of the increase of gas pressure in the pore network of a coal particle. The second fragmentation results from the weakening and breaking up of bridges connecting the elements of a char particle during its process of burning out. The third form of fragmentation takes place in the further stage of combustion when the process is entirely controlled by the internal surface reaction. Under these conditions, the structural connectedness of particles suddenly collapses due to pore enlargement and coalescence. An important ascertainment is that the erosion generates fine particles of size $<d^*$, which by means of gas velocity typical for circulating fluidized bed are elutriated from the connectedness reactor. In contrast, the particles generated by fragmentation are $>d^*$. Fragmentation by uniform percolation may enhance coal loss only in the case of comparable coal particle densities of $d^{**} > d^*$. Thus, neither primary nor secondary fragmentation directly participates in the generation of elutriable particles. This is a very significant fact that eliminates the contribution of fragmentation to the increase of the loss of incomplete combustion. Hence, the coal loss from the combustor can cause only erosion as a result of the elutriation of unburnt particles $<d^*$, or possibly by uniform percolation. Never-

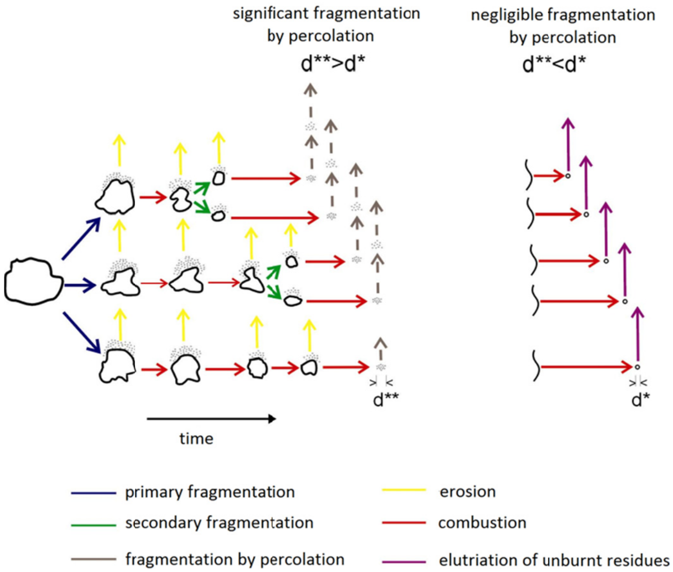

Fig. 1. Phenomena of comminution of an individual coal particle (Chirone et al., 1991)

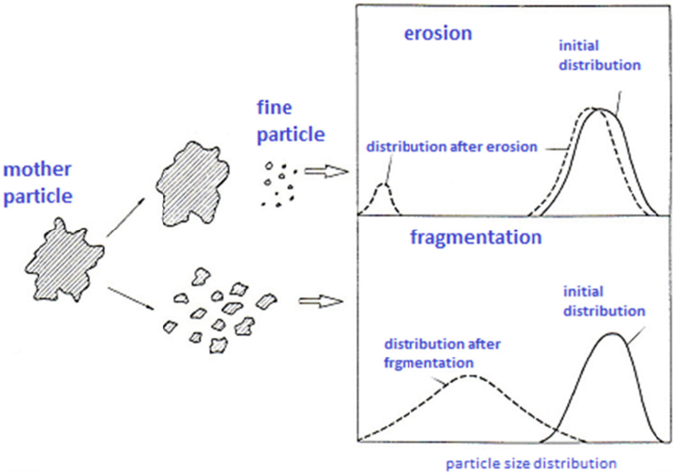

Fig. 2. Fragmentation and erosion mechanism

theless, the authors emphasize that fragmentation indirectly affects the combustion efficiency by changing the size of a coal particle and the surface exposed to erosion. Thus, all the phenomena should be taken into account in the design models of continuous fluidized bed combustors.

Both Ross (1979) and Donsi at al. (1981) during the course of their experiments observed that the number of char particles collected per unit of time at the cyclone of continuously operated combustor was in terms of magnitude larger than the number of coal particles charged into the combustion chamber at the same time. A rather large amount of tests were carried out on a relatively small amount of coal with respect to the layer material. Oxygen concentration in the inlet fluidizing gas was generally below 5%. These conditions together with the rapid decrease of gas temperature downstream of the bed prevented the post-combustion of coal. Thanks to that fact, the rate of carbon fine particles elutriated from the combustor was the difference between the amount of fine particles generated by erosion and the amount of fine particles burned inside the bed per unit time.

The tendency of coal to generate attrited fine particles is commonly expressed by means of semi-empirical erosion rate constant k (Chirone et al., 1991; Basu, 1999):

$$k = \frac{E_e}{\left(U - U_{mf}\right) w_c / d_{av}} \tag{1}$$

where E_c is the mass rate of carbon fines, $(U - U_{mf})$ the excess of gas velocity above the minimum for fluidization and w_c / d_{av} a ratio which is proportional to the carbon surface exposed to attrition in the bed, w_c and d_{av} mass of the coal in the bed and Sauter average coal particle diameter, respectively. By using the dependency of Halder and Basu (1989) they introduced the equation of the overall mass loss of coal particles in a fluidized bed:

$$\frac{dw_c}{dt} = E_r + \frac{kU_g w_c}{d_{av}} \tag{2}$$

where U_g is the gas velocity, and E_r rate of weight loss due to combustion. In bubbling beds $U_g = U - U_{mf}$, as the erosion rate is proportional to the excess velocity over minimum fluidization. In turbulent beds, $U_g = U$, as the erosion is proportional to the superficial gas velocity. The equation (2) indicates that the basic problem in order to determine the overall mass loss of particles burn in a fluidized bed is to correctly estimate the value of erosion rate constant k. Basu (1999) that presented the range of the rate constant for mechanical erosion at $0.5\text{-}5.0 \times 10^{-7}$, which was found independent of the fluidization regime. The rate constant in combustion assisted erosion in fast bed is in the range of $0.05\text{-}0.31 \times 10^{-7}$. In both cases, the range is large, which in turn leads to substantial discrepancies in calculations for even two orders of magnitude. All attempts to determine the erosion rate constant for the chosen hydrodynamic conditions, as well as the coal type experimental methods are burdened with mistakes resulting from both the difficulty to obtain real conditions during an experiment and the different types and properties of coals burnt in a fluidized bed. In this paper, the test results have been presented that enable the determination of the mass loss of different types of Polish coal during combustion in a fluidized bed, as well as the new proposition for the mathematical model of erosion mass loss based on the two chosen mechanical properties of coal: Vickers hardness and fracture toughness.

2. Experiment

2.1. Test stand

The mechanism of the combustion of a coal particle in the flow of inert material taking place in a fluidized bed patently differs from the combustion mechanism in the air. Becoming acquainted with this mechanism required a test stand which facilitates the model of the real conditions in the central and upper fluidized combustor, as well as the recording of the mass loss of burning coal. The tests on the erosion process of a coal particle during combustion were carried out using a test stand as shown in Fig. 3

The main elements of this test stand are as follows: a ceramic combustion chamber of the size of 80×100×120 mm (9) and an acceleration pipe with a vessel of inert material (1). The total power of the test stand was 20 kW. The front wall of chamber was made of quartz glass in order to

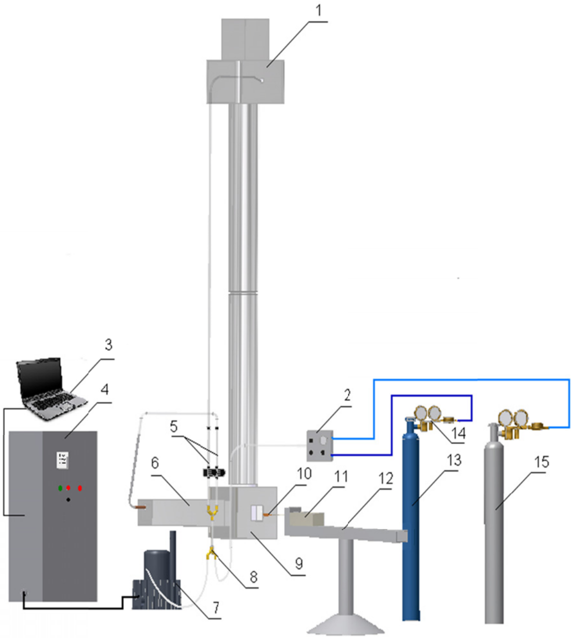

Fig. 3. The scheme of test apparatus. (1) vessel of inert material, (2) gas mixer, (3) PC-computer, (4) control panel, (5) rotametres, (6) gas heater, (7) ventilator, (8) T-connector, (9) combustion chamber, (10) coal particle, (11) tensometric branch scale, (12) support, (13,15) technical gases, (14)-reducer

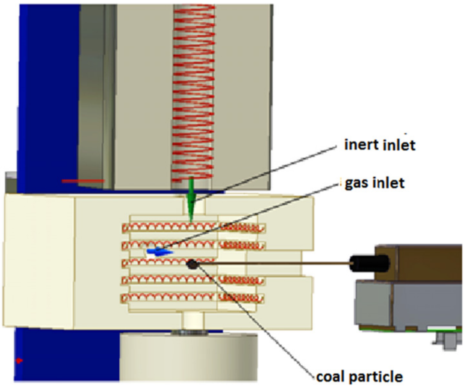

Fig. 4. Layout of combustion chamber with ways of feeding inert material, gas and coal particles

observe the process conducted. During the test inert material and heated gases were supplied to the combustion chamber (Fig. 4). The adequate volume rate flow of gas or mixture of gasses was regulated by means of a gas mixer (2), as well as a set of rotametres and regulatory valves (5). The gas provided was heated in the section of a gas heater (6). A single spherical coal particle (Fig. 4) was placed on the handle (10) of the tensometric branch scale (11). The precision of the applied branch scale was 0.001 g. The system particle – thermocouple-branch scale was moved into position by a special support system (12). Inert material formed from quartz sand used in commercial CFB boilers was heated to the measurement temperature – 850°C in the vessel (1), which during the test was fed to the acceleration pipe whose length and diameter were 2,000 and 30 mm, respectively. The rate of flow by means of a siphon valve placed under the vessel of inert material was regulated. The inert material used during the experiment was collected under the combustion chamber in order to determine the average value of the flow rate. The actual course of the real mass loss of the particle was isolated from the recorded signal by subtracting the mechanical interaction of the inert material. The interaction was estimated on the basis of the assumption its proportionality to mass of the char particles. The maximum of mechanical interaction at the beginning of experiment was recorded.

2.2. Results of experiment

The research described in this paper related to the erosion process of coal particles in central and first and foremost in the upper zone, thus, for the most part the values of the mass flow rate of inert material typical for this zone were taken i.e. $Gs \leq 10$ kg/m^{2}s (Sekret, 2005). The tests for the chosen coal type of the features shown in Table 1 were performed. The initial diameter of the spherical coal particle prepared for research was 10 mm.

TABLE 1

The results of proximate analysis of tested coal types

Coal type	**Mine**	**Proximate analyses**				
		Volatile matter V^a, [%]	**Moisture W^a, [%]**	**Ash A^a, [%]**	**Fixed coal FC, [%]**	**Lower heating value Q^a, [kJ/kg]**
Lignite	Bełchatow	42,5	14,5	18,5	24,5	18460
Hard	Julian	37,5	7,6	5,9	49,0	29026
Hard	Ziemowit	26,9	7,6	20,7	44,8	21179
Hard	Sobieski	27,9	12,4	16,7	43,0	21558
Hard	Czeczot	29,3	9,5	14,6	46,6	20300
Hard	Miechowice	30,2	6,7	12,0	51,1	23000
Hard	Bogdanka	27,8	2,9	25,4	43,9	22542
Hard	Pokoj	31,5	1,9	2,7	63,9	31500

Fig. 5 shows the registered mass loss coal particles initially combusted without the flow of inert material $Gs = 0$, as well as by the rate flow of inert material $Gs = 2{,}5$ and $Gs = 5.0$ kg/m^{2}s respectively. In the conditions of the flow of inert material $Gs = 2{,}5$ (Fig. 5b) the time of overall mass loss in comparison to the loss registered during combustion in the air $Gs = 0$ (Fig. 5a) un-

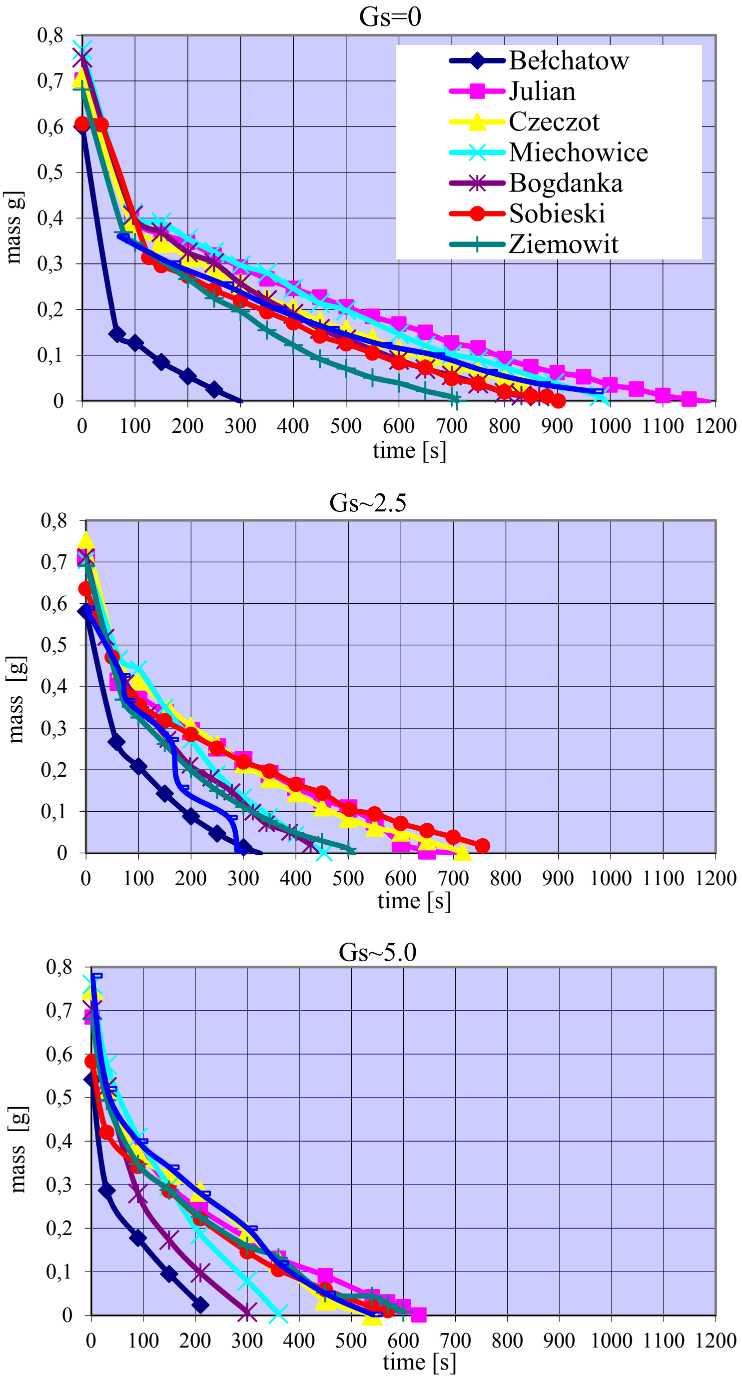

Fig. 5. Mass loss of tested coal type during combustion in the air and in the flow of inert material for *Gs* = 2,5 and 5,0

derwent shortening from 16% to 48%, which in turn indicates that the particle mass loss in the flow of inert material characterizes significantly more intensity. Precise analyses of the chosen coal types for the tests presented in Pelka (2009), Pelka (2013) show that the strongest parameter which accelerates coal type particle mass loss was the amount of ash in the coal. The curve of coal mass loss of type 34.2 from Pokoj mine had a few points of inflexion during the registered process. This saccadic mass loss is due to the process of secondary fragmentation (Gajewski & Kosowska, 2007; Kosowska et al., 2012). The clear shortening of the overall time mass loss of the other coal particles is merely the effect of the influence of the flow of inert material coming into contact with the combusted particle.

Further increases in the mass rate flow of inert material to *Gs* = 5 kg/m^{2}s (Fig. 5c) intensifies the mass loss by a further 20% in the case of all the hard coal types and 30% for lignite coal. Thus, increasing the mass rate flow of inert material shortens the overall time of mass loss both

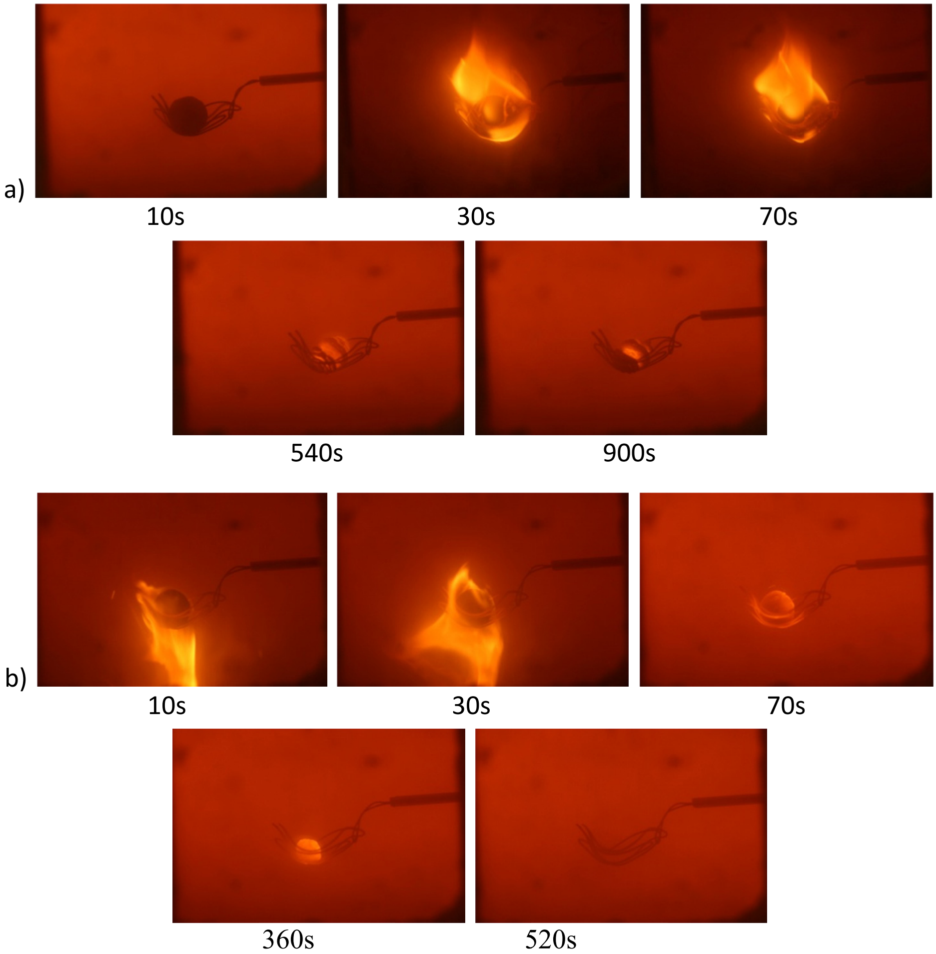

Fig. 6. Individual combustion phase of a coal particle from Sobieski mine (a) in the air (b) in the flow of inert material

in the range of char combustion and volatile matter. In order to carry out a detailed analysis of the causes of the accelerated mass loss of combusted coal particles in the flow of inert material in both tested conditions a number of pictures of combustion process of particle were taken through the peephole of the combustion chamber. In the pictures (Fig. 6), the combusted coal particle from Sobieski mine is shown from the firing stage to its overall burning out with the time period of the particle remaining in the combustion chamber (at the bottom). During the observation of the next phases of combustion, we can see substantial differences in the case of combustion in a two-phase flow (Fig. 6b) in relation to combustion in the air (Fig. 6a). After putting a particle into the combustion chamber in the presence of inert material it is heated faster as a result of contact with solid material that is heated to the temperature of the combustion chamber, which is also faster as within 10s the process of the ignition of the volatile matter is observed. After 70s the process of the combustion of volatile matter is completed, although in the atmosphere of air this runs completely. Likewise, the shape of the flame is also different, which together with the two-phase flow is directed down the combustion chamber.

The following difference observed in relation to combustion in the air is the lack of ash on the surface of a burning coal particle during the phase of char combustion, which indicates that the stream of inert material removes the incombustible part of coal from the particle surface that is revealed during combustion. The lack of ash on the reactionary surface simplifies the combustion process, by accelerating the registered mass loss and making contact with the surface of the char solid particle removing the fine coal particles, which is illustrated in Fig. 7a. Moreover, a frequently observed regularity was that of the break-up of a particle as a result of the mechanical influence of the bed particles in the final stage of the process. It indicates the role of inert material in increasing the probability of secondary fragmentation of a coal particle (Fig. 7b).

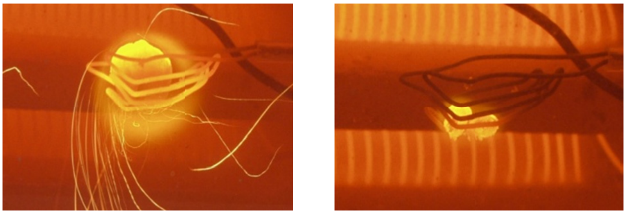

Fig. 7. Images of erosion and fragmentation processes of coal from Czeczot mine

The results obtained during the experiment indicated that the mass rate flow of *Gs* is an important parameter of the determined mass loss of combusted coal particle. However, some limiting value of mass rate flow was noticed, which after exceeding this value the rate of the mass loss stabilized at an approximate level. This value was close to Gs=4 kg/m^{2}s. The time of the overall mass loss of the tested coal particle in terms of the function of mass rate flow in the analysed sphere is presented in Fig. 8.

The measured mass loss of particle burning in the atmosphere of air and then in the flow of inert material enabled the stipulation of the average, or sum value resulting from both the combustion and mechanical effect combined, while subsequently combustion and erosion separately for the different values of *Gs* (Pelka, 2009). The results proved the previous observations that the greatest intensity of mass loss occurs in the range $0 < Gs > 4$ kg/m^{2}s. Further increases in *Gs* accelerates the mass loss less and less. The approximate values of the mass loss rate, 6-14×10^{-7}

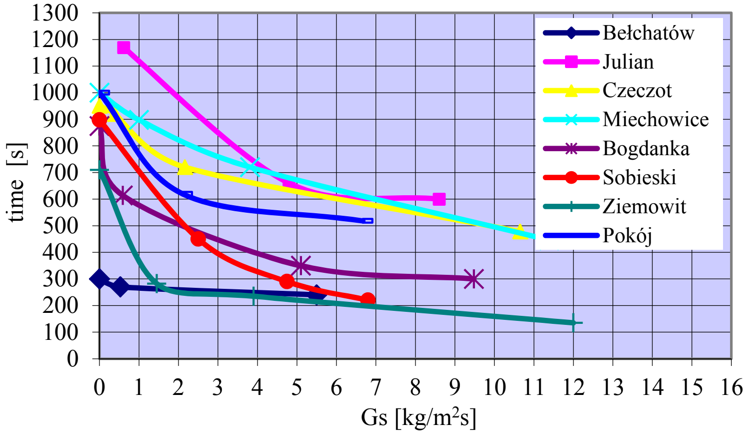

Fig. 8. Time of combustion of tested coal in the function of mass rate flow of inert material

kg/s are close to the values obtained by Basu and Halder (1989) who calculated the burning rate for fast fluidization for 8.5 mm coal particles 5×10^{-7} kg/s. Moreover, based on equation (2) the value of erosion rate constant was estimated, which as exemplified by coal from Miechowice mine was valued at $k = 1.1\text{-}6.0\times10^{-6}$. The range of its value obtained is higher than the results of Basu and Halder which probably points to the underestimation of mass loss resulting from combustion.

3. Mass loss model

The tests carried out indicated that the contact of inert material with the burning coal particle looms large during all the phases of combustion process. The first three phases proceed over a short time of approximately 10% of overall time combustion when the highest mass loss is observed relating to drying, devolatilization and volatile combustion. In this time, the mass loss related to erosion is small and difficult to separate from the overall mass loss of burning particle. Moreover, we may assume that in real conditions, the particles that reached the upper zone of the boiler completed the process of volatile combustion. Therefore, in the model, only mass loss during the combustion of char was taken into account and the following equation of mass loss of char was proposed:

$$\frac{dw_k}{dt} = -w - \rho_k \frac{H_V}{K_c^2} \cdot w_k \left[\sum_{i=1}^{n} cv_i u_i^3 \right] \tag{3}$$

where:

ρ_k — char density [kg/m^3],
H_V — Vickers hardness [N/m^2],
K_c — fracture toughness [N m$^{-3/2}$],
w_k — char mass [kg],
w — rate of mass loss due to combustion [kg/s]
cv — concentration of inert material [m^3/m^3],
u — velocity of inert material [m/s].

The detailed assumptions of the model were described in (Pelka, 2011). The first element of equation (3) on the left hand is described in a similar way as in the equation, (2) while the mass loss as a result of the chemical combustion reaction and the latter represents the process of erosion as a result of the collision of the particles. Indications of mass loss that is the consequence of the collision between particles of known hardness that is measured by the Vickers method H_V and fracture toughness K_c were proposed and verified in experiments by Zhang and Ghadiri (2002a, 2002b). Availing of this dependency in the equation (3) facilitates the direct determination of the erosion mass loss on the basis of individual properties of coal in the precisely defined flow of inert material without the necessity of experimental measurement of the erosion rate constant.

4. Model verification

The proposed numerical model was verified by way of experiment during the combustion of the char particle of coal from Sobieski mine in a diversified range of combustion atmosphere formed from a mixture of carbon dioxide and oxygen. This coal is commonly used in CFB technology in Poland as it does not fragmentate and maintains a spherical shape during the whole combustion process, which is the basic assumptions of the model.

Initially, the model was verified in the case of $Gs = 0$ i.e. during combustion of particle without the impact of inert material, while subsequently in the case of $Gs = 2.5$ and 5.0 with the flow of inert material. Thus, the verification of both terms of equation (3) was possible. The first generates the mass loss only as a result of a chemical reaction and the second only as a result of erosion. During the verification, the mechanical coal parameters indicated during the course of an additional experiment were utilized, i.e. Vickers hardness and the fracture toughness. The research methodology of our courses and results were presented in (Pelka, 2013). The fracture toughness ratio was measured using the procedure described by Klepaczko (1984).

In Fig. 9, the results of model verification obtained in the atmosphere of a mixture of oxygen and carbon dioxide for the volume contribution of oxygen in the mixture were presented as follows: 21%, 30% and 40% respectively. During the verification in the case without the flow of inert material ($Gs = 0$) the second element of the equation was inactive. The obtained results indicate that the numerical model in the range of char combustion based on the shrinking unreacted core model (Tomeczek, 1992; Bsau & Fraser, 1991) correctly reproduces the process of the mass loss of a single particle by variable oxygen concentrations. During the modelling process in the flow of inert material, the calculation was performed using real values $H_V = 0.05\times10^9$ and $K_C = 0.5\times10^5$ N/m$^{-3/2}$. As we may see ($Gs \neq 0$), the results obtained on the basis of the model results did not match those acquired during the experiment.

The combustion time obtained from the model was almost 100s longer than the time measured in tests. The fundamental question which requires answering is the following: Which of the elements generates bad results? The element proposed in the paper is responsible for the mechanical erosion or the first equation does not take account of the significant changes in combustion conditions. Detailed analysis of the results of the experiment as well as microscopic pictures of the surface of burning particles (Pelka, 2014) indicated that the assumption of the superposition processes of combustion and erosion in the model was wrong. In order to confirm this observation, an additional test was executed that involved the definition of only the mechanical influence of inert material at the combustion temperature. After devolatilization and volatile combustion to the combustion chamber instead of nitrogen heated to 850°C, air was supplied.

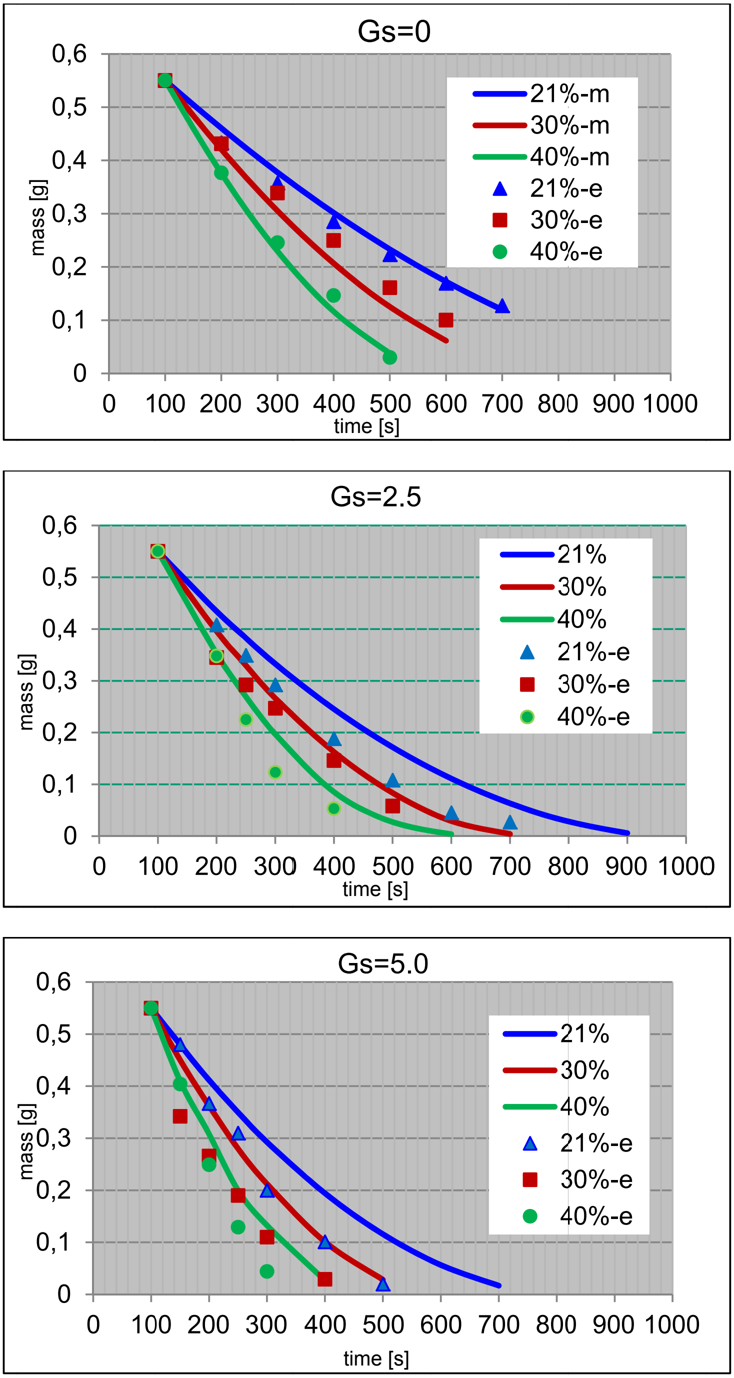

Fig. 9. Mass loss of coal particle measured during the experiment (-e) and from the numerical model (-m) by volume oxygen contribution at 21%, 30% and 40% respectively

The changed atmosphere around the coal particle stopped the process of combustion. From this moment onwards, the mass loss was registered as one minute in nitrogen atmosphere and one minute in air atmosphere.

A test on the average mass rate flow of material $Gs = 3{,}6$ kg/m^{2}s was conducted, the results of which have been presented in Fig. 10.

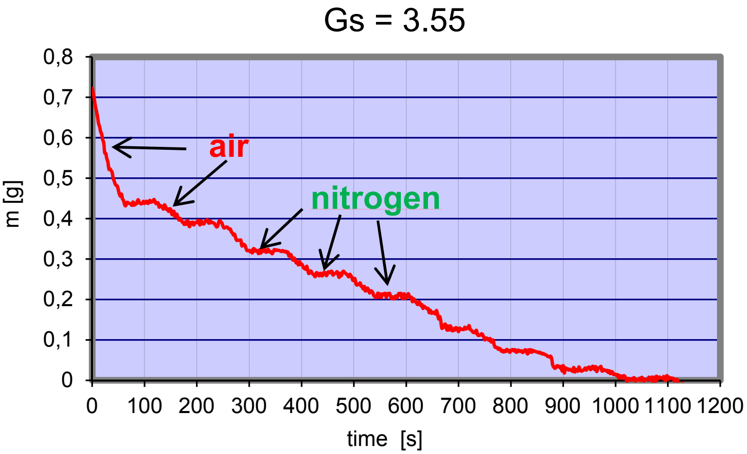

Fig. 10. Mass loss of hard coal particle from Miechowice mine combusted in the flow of inert material in atmosphere of air and nitrogen

They indicate unequivocally that the intensity of the erosion process is strictly related to the ongoing combustion process. At the moment of terminating the burning as a result of a change of atmosphere, the registered mass loss is much less than recorded in the air atmosphere. It should be stated that the combustion process is the key process in determining the process of erosion observed in the fluidized bed. As a consequence of this, the process of peripheral percolation develops which weakens the surface structure of coal, making it susceptible to the erosion process. As a result of its particle of inert material making contact with the burning coal surface it removes the ash forming on the surface and removes the fine coal particles. By contrast, the erosion process simplifies gas diffusion to and from the surface of the chemical reaction and the enlarged combustion surface. In order to consider the aforesaid observations in the proposed model, changes were essential that lead to increasing the contribution of the first element of the equation in the sum mass loss of a char particle. The first element of the model of burning rate as a result of chemical reaction may be presented as (4) (Basu, 2006):

$$w = \frac{AC_g}{1/h_m + 1/k_c} \tag{4}$$

where: A – burning surface, C_g – oxygen concentration, h_m – mass transfer coefficient, k_c – apparent reaction rate based on external surface.

Thus, in order to consider improvement in the diffusion conditions related to a two-phase flow around the particle, the value of the mass transfer coefficient by the assumed constant oxygen concentration should increase. This coefficient is calculated from the following relation (5):

$$h_m = \frac{12\varphi Sh D_g}{d_c R T_m} \tag{5}$$

where: φ – mechanism factor, Sh – Sherwood number, D_g – molecular diffusity of oxygen, d_c – diameter of coal particle, R – universal gas constant, T_m – mean temperature of the diffusion layer.

Analysis of relationship (5) points out that only one of the parameters depending on flow conditions is the Sherwood number (6) that characterizes the diffusion rate. Undoubtedly, the flow of inert material in the analysed case must increase the value of Sh.

$$Sh = 2 + 0.6(\mathrm{Re}_T)^{0.5} Sc^{0.33} \tag{6}$$

where Re_T is the Reynolds number based on terminal velocity of the char particle and Sc is the Schmidt number.For fast fluidized beds the Sherwood number depends on gas-solid slip velocity rather than on the fluidizing velocity such as in bubbling beds. In the case of thick coal particle >8.5 mm, the Sherwood number is empirically provided as (7) where ε is the voidage of the bed and γ_g the kinematic viscosity of gas. In this case, its value is also dependent on the voidage of the bed in the area of particle.

$$Sh = 2\varepsilon + 0.69\left[\frac{\left(U_g - U_p\right)d_c}{\varepsilon\gamma_g}\right]^{0.5} Sc^{0.33} \tag{7}$$

In the conditions of the experiment executed, the coal particle was motionless, thus $U_p = 0$, and the gas flow around the particle was enhanced by the flow of free falling particles of solid material, as opposed to the real process. Thus, it is difficult to determine the changing mass rate flow Gs together with the relative velocity accurately. Likewise, it is also necessary to pay attention to the change of value of the bed voidage proportionally to Gs in the area of the burnt particle.

The results of the modelling presented in Fig. 11 were obtained using the relation (7), in which real voidage of inert material around the particle was applied, but slip velocity was stated from the model after acquiring the convergence with the experiment. The convergence was obtained by the mass flow rate which equals $Gs = 2.5$ for slip velocity $U_g - U_p = U_g = 0.5$ m/s and by $Gs = 5.0$, $U_g = 1.0$ m/s that caused increases of 30% and 67% in terms of the Sherwood number and consequently the analogous increase of mass transfer coefficient. It should be noticed that the primary calculations were performed for gas velocity around the coal particle $U_g = 0.2$ m/s. On the basis of the previously calculated (Pelka, 2011) velocities of solid particles at the moment of their contact with the burning char particles in the case of the diameters of the particles ranging from 50 to 400 μm, which determined their velocity at a range of 0.7-2.5 m/s., thus, it can be stated that the slip velocities obtained during the numerical test gas around the char particle are very close to their real values. This fact confirms the previously set thesis that the observed accelerated mass loss of char particle in the flow of inert material first and foremost result from a correction of the combustion conditions thanks to the improvement of gas diffusion in the area of the burning char. Hence, the erosion role depending on the mechanical generation of the loss of char mass is small and only depends to a small degree on the increase of the mass rate flow of inert material.

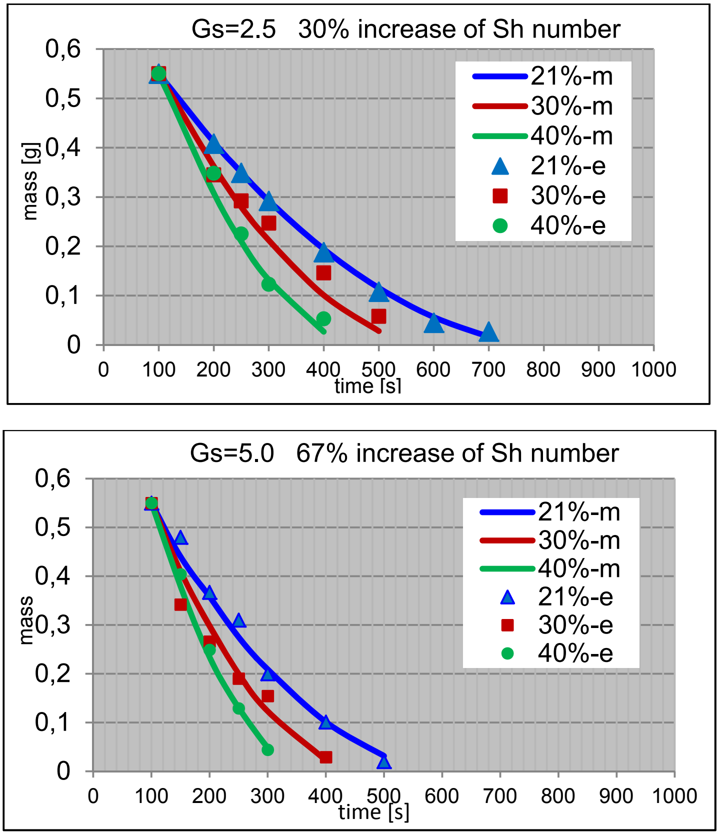

Fig. 11. Obtained from the experiment (-e) and corrected numerical (-m) mass loss of coal particle in flow of inert material increased by 30% and 67% of Sherwood number

5. Conclusions

The results presented in the paper obtained on the basis of large-scale experiment confirmed the previously known opinion that the combustion of coal in a fluidized bed is characterized by a greater intensity of combustion in relation to combustion in the air atmosphere. This greater intensity was observed for all the tested hard and lignite coals. The difference is first and foremost related to the amount of ash in raw coal. Coal with a higher amount of ash possesses larger susceptibility for accelerated mass loss. Contact of the char particle with the particle of inert material simplifies and intensifies the process of coal combustion mainly as a result of removing the ash of the particle forming on the char particle surface which is important information that indicates the possibility of burning very low quality solid fuel in the fluidized bed, thus guaranteeing the complete burnout of the particle. The results of experiments did not confirm the meaningful role of erosion in the intensification of mass loss of burning particle depending on the generation of fine coal particles from the mother surface particle as described in literature. This does not mean that this process does not occur. However, its role in the mass loss is small and strongly related to the combustion process. Taking account of the time period of the fuel particle remaining in the upper zone of the combustion chamber in conditions of oxygen deficit, the process of combustion slows down the amount of the generated mass, as a result of which the erosion will be negligible. The biggest share in the acceleration of the mass loss of coal particle has a characteristic flow gas in terms of a fluidized bed intensifying the diffusion process in the reaction area. The model proposed in the tests based on the mechanical properties of combusted coal particle facilitates the correct estimation of the real mass loss in conditions modelling the central and upper combustion chamber of a fluidized bed. In order to estimate the mass loss of a char particle, it is necessary to determine the gas-particle slip velocity correctly. In real conditions, this velocity decides on the burning rate and the overall mass loss rate of coal particles.

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