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RESEARCH ON DESTRUCTION MECHANISM OF DROPS AND EVOLUTION OF COAL-WATER SUSPENSION IN COMBUSTION PROCESS

BADANIE MECHANIZMU DESTRUKCJI KROPEL I EWOLUCJA SUSPENSIJ WĘGLOWO-WODNYCH W PROCESIE SPALANIA

The research undertakes the complex research of the coal-water suspension combustion in air and in the fluidized beds which according to the author best fulfill the difficult conditions that should be completed in order to use the new “fuel” efficiently and ecologically. An important element of the research was the identification of coal-water suspension drops complex morphology and its evolution in the combustion process.

**Keywords:** Destruction mechanism of coal-water suspension, Kinetics of Combustion Reaction, Circulating Fluidized Bed (CFB)

W pracy przedstawiono identyfikację złożonej morfologii suspensji węglowo-wodnej oraz jej ewolucję w procesie spalania. Ciekawym elementem badań była wizualizacja przebiegu procesu spalania paliwa w różnych warunkach procesu, prowadzonego w strumieniu powietrza oraz warstwie fluidalnej.

**Słowa kluczowe:** mechanizm destrukcji suspensji węglowo-wodnej, kinetyka reakcji spalania, warstwa fluidalna

1. Introduction

Combustion technology of coal-water suspension creates a number of new possibilities to organize the combustion process fulfilling contemporary requirements e.g in the environment protection. Therefore an in-depth analysis is necessary to examine the technical application of
coal as energy fuel in the form of suspension. Efficiency improvement of boilers used to burn suspension fuel requires to become acquainted with some processes connected with combustion of coal-water suspension which so far have not been satisfactorily explained in the research. Coal-water suspension is most frequently made of after-flotation mule with moistness content of 20%-40% and fuel value of 8-10 MJ/kg and the ash content of 20-35%. The constant phase concentration of fragmented coal assuring stability of such ‘fuel’ depends on the size of coal particles and the degree of its metamorphism. For coals of high volatile content, suspension shows high stickiness with moistness below 50% and particles whose residue on the screen is R90 = 20-50%. With coal of such fraction content and volatile content of 10-15% the limiting humidity decreases to 40-45% and for anthracite with its small hygroscopic moistness it is even smaller. However, with such moisture content the suspension cannot be treated as the Newton fluid, its stickiness and fluidity at the same time, very much depends on its moistness. The minimal moistness at which the suspension can be transported by pipeline and treated as the disperse system with satisfactory stability for Polish energy coal is 45-50%. Wide interest in coal-water suspension has been forced by the necessity to solve the problem of hydraulic transport of fragmented coal in the 30s. Coal concentration in the slurries reached 40%. It was also characterized by coarse particles which made it difficult to use it directly in the power industry. Another interest rise in the problem appeared in the 70s and was caused by the energy crises at that time. Extensive research was undertaken in order to use the coal-water suspension as the substitute of fuel oil. The current research brought several technologies which have been described in the specialist literature on the preparation and the substitute usage of the liquid fuel. The research was mainly on combustion of spray coal-water suspension in furnaces of dust boilers. Considerable achievements on the process of coal-water suspension combustion were obtained in the former Soviet Union, especially in the utilization of coal slurries transported by pipelines. The necessity to undertake the research in our country results from the fuel structure of the Polish power industry where 97% of electric energy is produced from coal. Such unfavorable fuel balance causes excessive load for our natural environment which is mainly due to NOx, SO2, CO2 emissions and dust production. It also causes big increase of the area necessary for growing permanent furnace waste disposal. For this reason our mining industry is forced to supply still better fuel and has to apply more concentrated coal. It causes constant waste increase in the form of after-flotation mule. The best utilization method of the mule is to burn it in the form of coal-water suspension in a CFB. Improvement of the process required to urgently undertake the research explaining this type of combustion technology. In the specialist 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. The current research is directed into two main problems: 1) to present a study on the combustion technology of low-concentration coal-water suspension which will decrease NOx emission. The suspensions are made of coal mules which are formed during the coal cleaning process, 2) the combustion of low concentration coal-water suspension, where good stability is preserved which enables to substitute the petrochemical fuel, this research is mainly carried out in China. Water which is a part of coal-water suspension moistens the coal particles (small value of moisture radius) and penetrates them (value of dihedral angle is almost zero). The result of the process is reorganization. In the systems with fluid, concentration fluctuations create the possibility of movement for all particles under the influence of capillary strength. The reorganization process takes place much faster when the fluid which functions as “lubricant” is present. This is because the lubricant enables the particles to skid mutually as the stickiness of
the fluid layers is smaller than the effective stickiness of intergranular limits. Capillary strength strives to decrease the size of pores to the surface of which some particles are “attached” in a way. Thus, the particles move into the inside of the pores, filling them at the same time. This situation can be described as the substitute action, where the outer hydrostatic pressure causes the volume contraction of the system. As the process continues, the pore size decreases which results in the increase of the above mentioned pressure and the velocity increase of the process. Uneven distribution of the liquid phase can be caused either by mistakes of the homogenization technique (e.g. the time of grinding is too short) or by too big size of the particles. In the system there are some areas which are rich in fluid, some other areas containing less fluid, and the areas totally deprived of it. Then, the surface tension strength which is active on the particle dewatering circuits of the constant phase, is situated on the boundary of the above mentioned areas. The strength causes “pulling in” of the coal particles into the fluid. As a result, near the areas rich in fluid appear big pores. They close but the process is difficult even after the fluid has spilled in the system because the big radius of the curve (small value of capillary strength). Application of slurry and coal-water suspension to supply the furnace is dictated by many reasons. In the case we have mules of high calorific value, usually of high water content, it is appropriate to burn them directly. The solution has been applied in the French power station “Emile Hucliet” where the furnace with CFB is supplied with the pulp containing 33% of water from the mine situated 16 km from the power station. Also, in one of Polish power stations the suspension is made of mule and waste coming from the coal cleaning installation. Although the high content of mineral parts in such waste results in low calorific value of the water suspension, there are some possibilities of their stable combustion. Appropriate organization of the combustion process is provided in this case, by providing the adequate heat amount to the ignition area. It can be carried out in many ways e.g. by using auxiliary fuel. In this power station, the suspension made of mule is burnt in a fluidized bed. The mule coming from after-floating coal cleaning constitutes the supplementary fuel. It is brought to the station by the road transport, and unloaded at the preparatory stations or at the substitute stock pile. The amount of the burnt mule depends on the furnace load and the amount of basic fuel. Increase of the mule stream causes the proportional decrease of the amount of the used coal. The limiting ratio of both fuels is 50/50% and is measured according to the chemical energy introduced into the furnace. In terms of weight the relationship is at the most 70/30% in favor of mule. The coal and mule combustion technology possesses a number of advantages: the more stable action of the combustion chamber, the smaller amount of bottom ash, the smaller the coal demand, the bigger the decrease of the production cost of electric energy and heat.

There are also some unfavorable aspects of the process: the increase of the fume temperature from 130°C to 140-145°C, the furnace performance fall from 93% to 91% in comparison to the only coal combustion. Good performance experience connected with the mule usage in the above mentioned power station proved that the technology with CFB furnaces provides economic and effective usage of coal and coal waste of poor quality.

Application of coal slurry as fuel in the facility adapted to burn fuel oil require to lower its energy power, on average by 10%. The change is dictated by different ignition and combustion characteristics and the heat transmission conditions when coal-water suspension is applied, in comparison to combustion of fuel oil. Big disproportions occur mainly in modern units designed to burn fuel oil. The necessity to reduce the load with coal-water slurry application does not occur when in the furnaces the coal dust is used. The experiments carried out proved that sus-
pension containing 65% of coal is burnt comparably with respect to the coal dust despite the bigger ignition delay. Combustion of suspension fuel in a furnace which is not adapted to this purpose results in slug and ash occurrence. This problem can be partly eliminated by introducing the combustion process in the dust furnaces where the remaining ash and slug are characterized by far more favorable properties. Favorable dust properties arise as the result of inflation and agglomeration of ash particles. The formed granulated products contain negligible residue of under-burnt coal of which major part is kept in the system of introductory fume purification.

Other technologies that can be used for burning of coal-water suspension are the combustion processes in a fluidized layer and the coal gasification. In the above mentioned technologies it is easier to prepare the material and the process itself is much safer. Efficient regulation, control of the process and stable fuel supply in the case of CFB combustion can be reached by lowering of its energy power by 0.8%. The gasification process efficiency is approximately 80%. The added water and the suspension constitute the reagent. Also, the application of coal-water suspension as auxiliary fuel in a blast furnace results in the lower coke consumption. According to some experts’ opinion, the production of coal suspension will increase the cost of energy it possesses by approximately 24% and according to some other sources by 40% in comparison to coal. Water addition to coal suspension causes deterioration of its energy properties and depends on the coal and water proportion. From the available specialist literature we know that with the suspension containing 60% of coal and its fuel value 33.75 MJ/kg the loss caused by moisture evaporation is only 4.2%. Most troublesome and not very precise are evaluations of combustion efficiency and energy transportation. The reason for this situation are the differences resulting from the combustion characteristics of water-coal slurry as well as from the construction differences of the furnace, where the experiments were carried out. After the data analysis we can state that after we have calculated the decrease of the boiler power, the cost of energy production with the use of coal-water suspension would be higher by 30% in comparison to the cost of energy we get from the coal combustion. In the face of competition, the coal combustion in the form of dust-air mixture seems to be more profitable when we use the coal-water suspension in the so called special solutions. The priority is to utilize combustible waste which is the result of the coal cleaning process. The waste is not used despite having the substantial amount of coal as there are problems with its effective adaptation. Despite high mineral content (ash) in the waste and the low fuel value of the coal-water suspension produced from the waste, there are possibilities of its stable combustion. Appropriate combustion process of suspension made from mule is provided when we supply the adequate amount of heat to the combustion zone. Sufficient amount of heat is provided by application of auxiliary fuel. On example of the grate furnace we can describe a simple and efficient way of burning with application of the auxiliary fuel. This concept allows not only to adapt the coal waste containing from 15 to 55% of mineral parts but also improves the functioning parameters of the original grate furnace. The applied coal suspension contained from 43.7 to 50.6% of water and its fuel value was from 6000 to 15900 kJ/kg.

It was introduced to the bed by the side burners, under the coal layer. As a result of the coal suspension addition, it was found that the coal particles taken from the layer were better burnt. Apart from that, there was an under-burn decrease by 10-15% in comparison to the designed furnace parameters. The experiment resulted in lowering of the excessive air coefficient and the general system efficiency rose by 10%. During the experiment, the boiler produced from 17 to 23 t steam/h at its planned capacity of 10 t steam/h. Similar to these solutions can enable the
efficient adaptation of other permanent industrial waste. The applications of suspension coal fuels prove legitimacy of the research, especially into application of the technology based on the material with non-optimal particle distribution. Omitting the material introductory preparation, when we apply the fuel modification or appropriate means which stabilize and introduce dispersion can lower significantly the total cost of the technology. The above described ecological and economical advantages which come from application of coal-water suspension, form the basis for further search of new solutions and the optimization of the existing ones. The main development directions are the following: the fuel substitutes of petrochemical origin, the preparation of suspension fuel based on the brown coal, the modification of suspension coal fuel by application of the supplements increasing fractions with smaller diameters, which improve the combustion emission parameters of high-concentration suspension coal fuel, the combustion of low-concentration coal suspension with low stability, without stabilizing supplements, directly after the production, the usage of new means which stabilize, introduce dispersion and enable getting very stable suspension in over two weeks, which are characterized by appropriate theological properties in the case of transport, pressure and spraying, the search of technologies whose products can be used as the material in the coal fuel preparation, it concerns the above described technology of coal cleaning as well as waste (mule), application of solutions enabling to stabilize suspension e.g. ultrasounds (Liu & Law, 1986; Dunn-Rankin, 1987; Gajewski, 1996; Limanowski & Agopsowicz, 1996; Atesok et al., 2002).

2. The research stand and measurements methodology

   Experimental character of the research required the research stand preparation, as well as working out of the measurements methodology. Fig. 1 presents the stand construction. The research stand was made of ceramic blocks (1,2) in which the quartz pipes were put (3,7). The heating element of the stand comprised three heating coils of 2.0 kW. Each heating coil (4) was placed in six small quartz tubes (5). These tubes were built into the quartz tube which was thermally insulated by fiber material Al₂O₃ and which was covered with steel sheet (6). Combustion chamber constituted the quartz pipe (7,8), which was additionally insulated thermally, to keep the necessary temperature of the entering gas and to reduce the heat loss. The application of the quartz pipe and the sight-glass in a metal shield (14) allowed to observe directly, to film and to photograph the combustion process of fuel. The compressed air was transported to the quartz tube through the electro-valves, the control valves, and the rotameters. The fumes were removed outside by means of a fan fume cupboard. To regulate the temperature inside the combustion chamber, the Lumel microprocessor thermoregulator was applied (8-Fig. 2). The regulator controlled the work of tri-phase Lumel power controller supplying the main heating elements (gas heater) allowing to measure the actual temperature with accuracy of measurements to 2°C.

   The temperature measurements in the combustion chamber were carried out by means of the thermocouple NiCr-NiAl (10-Fig. 2). In order to establish the centre and surface temperature of the fuel, a special instrument stalk was constructed. It had two thermocouples PtRh10-Pt. One of the thermocouples was located inside the fuel, while the other served as a basket which was to support the fuel. It also touched the surface of the fuel (Fig. 3). The thermocouples were
Fig. 1. Research Stand Section
1,2 – blocks of ceramic material, 3 – quartz pipe, 4 – heating elements, 5 – quartz pipes, 6 – steel sheet, 7,8 – combustion chamber, 9 – warmer, 10 – ceramic sieve, 11 – block of ceramic material, 12 – handles, 13 – furnace gas extractor, 14 – sight-hole for visualization of the process, 15 – screws

Fig. 2. Research Stand Scheme
1 – research stand, 2 – electric valves, 3 – control valves, 4,5 – rotameters, 6 – time transmitters, 7 – relay switch, 8 – microprocessor thermoregulator, 9 – three-phase power controller, 10 – NiCr-Ni thermocouple, 11 – measurement card, 12 – computer
connected to the measurement card (11-Fig. 2) and to the computer (12-Fig. 2) in order to record the experimental results.

The essential stage of the preliminary work was to make out a suspension fuel drop, which was a mixture of coal dust (with appropriate particles) and water, in different proportions. The coal properties applied in the research are shown in Table 1. In order to produce the coal-water suspension it was necessary to prepare coal dust after grinding it and sifting. The particle fractions prepared in this way were weighed on a laboratory scale. To prepare the suspension a laboratory pipette of accuracy 1 µl was used.

### TABLE 1

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Moisture [%]</th>
<th>ASH [%]</th>
<th>Volatiles [%]</th>
<th>Calorific value [kJ/kg]</th>
<th>Total sulphur [%]</th>
<th>C [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown coal</td>
<td>14,5</td>
<td>18,5</td>
<td>42,5</td>
<td>18460</td>
<td>1,1</td>
<td>46,0</td>
</tr>
<tr>
<td>Hard coal (mine Sobieski)</td>
<td>12,4</td>
<td>16,7</td>
<td>27,9</td>
<td>21558</td>
<td>1,4</td>
<td>55,8</td>
</tr>
<tr>
<td>Hard coal (mine Staszic)</td>
<td>2,7</td>
<td>2,4</td>
<td>28,6</td>
<td>24634</td>
<td>0,9</td>
<td>62,8</td>
</tr>
<tr>
<td>Hard coal (mine Piast)</td>
<td>10,2</td>
<td>16,9</td>
<td>31</td>
<td>23165</td>
<td>1,1</td>
<td>-</td>
</tr>
<tr>
<td>Antracite</td>
<td>1,5</td>
<td>2,5</td>
<td>3,0</td>
<td>39350</td>
<td>-</td>
<td>97,0</td>
</tr>
<tr>
<td>Coal mule</td>
<td>3,7</td>
<td>41,5</td>
<td>19,5</td>
<td>15394</td>
<td>1,1</td>
<td>43,3</td>
</tr>
<tr>
<td>Biomass</td>
<td>8,45</td>
<td>4,55</td>
<td>70,53</td>
<td>15825</td>
<td>0,18</td>
<td>40,90</td>
</tr>
</tbody>
</table>
The research included:

– the determination of temperature changes inside the drops during combustion, the determination of combustion mechanism and kinetics of coal-water suspension in a air stream and in the fluidized bed conditions (continuous combustion),
– the determination of mechanism and kinetics of cyclic combustion of coal water suspension, (by alternate air and nitrogen flux on the coal-water suspension).

The cyclic nature of fuel combustion results from the movement of loose material in the flow contour of the circulating fluidized bed (CFB): the combustion chamber, the cyclone, the downcomer. The experimental results proved that the cyclic change of the oxygen concentration around fuel, led to the vital change of both mechanism and combustion kinetics.

3. Experimental research

The subject of the research was to determine the suspension fuel properties in relation to the moisture content (20-90%) and the degree of coal fragmentation (particles below 1 mm). It was found that both the particles distribution and the coal concentration in suspension determine the stickiness and rheological coal-water suspension. Small affinity of coal to water enables to get the high concentration long-lasting suspension fuels. Optimal graining distribution should guarantee the best coal particles packing in the suspension.

3.1. Properties of coal-water suspension

Macro and microscopic examination of coal-water suspension morphology were carried out by means of a scanning electron microscope and a stereoscopic microscope with a digital camera of definition 8 Mpixel. It was observed that the coal particles in a coal-water suspension drop were arranged irregularly and the fluid in suspension joins the isolated coal particles in agglomerations. The size reduction of coal particles in the suspension determines the increase of coal total surface in relation to the suspension fuel volume. In the case of suspension largely made of very fine particles their big packing was observed in the suspension among the coarse particles. This kind of suspension is characterized by significant stickiness. It was observed that the size reduction of coal particles in the suspension leads to lowering of the particle diameter which is the result of suspension stickiness increase. As we know, coal has absorptive abilities compared to water when it is water soaked. Well known is also a big influence of the porous structure and oxygen content in coal on the above mentioned water absorption. If we assume that coal oxygen is arranged identically then the number of hydrophilic sites is proportional to the oxygen content and the porous surface. According to the specialist literature water absorption by coal is determined in three stages: one-layer sorption, multi-layer condensation and the capillary condensation. Water sorption on coal depends on polar groups on the absorbing surface. One-layer sorption correlates well with the number of function hydrophilic groups and not with the proper surface and water in the mono-layer is fixed with coal by means of a hydrogen bond. Water sorption is considered by concentration around hydrophilic sites on the top of the mono-layer which leads to water condensation in the capillary structure. It is considered that determination of water capacity fixed with coal, crucial role is played by the hydrophilic sites on the coal surface. Function groups
containing oxygen constitute majority of hydrophilic sites. Water is sorbed at hydrophilic sites, forming probably the clusters or joining together. It was found that in order to get the coal-water suspension of the same stickiness from coals of different types it is required the lower content of long-lasting parts in the case of lower type coal. It is connected with the fact, that adding water to coal causes filling its pores, which leads to the decrease of water among particles in the case of highly porous coal. The stickiness increase is caused by the delay of particle movement inside the suspension. The moisture on the coal surface can lead to its loading, and as a consequence, to the suspension stickiness decrease. As we know, fusain which is a component of exinite increases the coal-water suspension stickiness because of its porous structure and larger specific surface. Therefore, the suspensions made from the lower coal type reveal bigger stickiness. The lower moisture content is a result of its lower porosity. Dull maceral in the coal structure (fusain and semi-fusain) possess cell walls which provide the space for water. Vitrinite, a component of anthracite does not have such an open structure and shows a tendency to micro pores. Also, it has been observed that the suspension whose size particle distribution is regular has better rheological properties. In the suspension rheology the concentration of long-lasting particles is treated as a volume fraction and as a parameter which depends on the size distribution and the particles shape. Therefore, suspension made of fine coal particles is characterized by high stickiness and low volume fraction. As it was above mentioned the suspension stickiness lowers from lower to higher coal type. Together with the increase of suspension density, its stickiness increases for various particle distributions. The wide particle distribution causes the coal particles to fill pores among coarse particles and that leads to getting the higher volume fractions. In order to obtain as big coal concentration as possible the coal particles should have various size so that they could fill the intergranular space. To get the suspension of identical coal concentration from materials of various C/O relationships we should, in the case of higher value of this relationship, apply bigger particle diameters. The coal size, indeed, influences the coal-water suspension stickiness.

When fuel contains the same amount of coal the suspension which has the finest coal particles has the biggest stickiness. It was also found, that the addition of coarse coal fractions to the suspension made of fine particles can lower the suspension stickiness. Addition of bigger amount of coarse particles can lead to the suspension destabilization, but it does not significantly influence the suspension rheology. Suspension rheology is closely connected with the coal content. With lower concentrations the suspension is the Newton one. With higher concentrations it is getting pseudo plastic or rare with decreasing stickiness. In the case of suspension made of fine particles their stability was found. In the case of adding the coarse particles to suspension was observed an irregular particle distribution and empty space filled by fine particles which were among the coarse ones. This particle movement drives to the lowering of the suspension stickiness. During the process of suspension vaporization, at room temperature, moisture distribution, inside the drop depends on the particles porosity and the relationship between particles size and its water content, after a dry outer coat has been formed. Dry suspension fuel possesses particle agglomerations of bigger size in comparison to the output particle of coal dust, out of which the coal-water suspension was made. According to the specialist literature, the mono-molecular water layer is hydrogen bounded with hydrophilic sites in coal. Gathering of water around the sites leads to the capillary structure condensation. The mono-molecular water layers can be treated as glue in coal-water agglomerations. As on the coal surface most hydrophilic sites make function groups containing oxygen, in the case of lower type coals the suspension evaporation leads to lowering of hydrophilic sites, which results in forming smaller agglomerates. Despite water vaporization
the agglomerates remain untouched. It was found that the slurry agglomerates do not disintegrate even when water, initially integrating the drops, evaporates. After water evaporation, the coal particles situated outside the agglomerate join together, forming one unity (Fig. 4-5).

![Fig. 4. Antracite – water suspension](image1)

- a) particles-below 80 µm
- b) particles-315÷400 µm
- c) particles-50%: below 80 µm and 50%: 315÷400 µm; moistness: 50%

![Fig. 5. Evaporation of anthracite-water; size of coal particles: below 80 µm; T = 293K](image2)

3.2. Combustion of coal-water suspension

A drop of suspension fuel after introduction to a high temperature medium, changes its size at the initial combustion stages, as a result of the volatile release and the solid substance burn (Fig. 6-8). The degree of initial expanding and then shrinking of a drop, during the process, depends on the type of coal dust and its structure. It was observed that during the intensive volatile combustion, occurs a sudden temperature rise of a coal-water suspension drop. After ignition of vaporized, carbonized, suspension tar fuel, was found an intensive suspension temperature increase to its maximum value. The increase of moisture content in the suspension leads to the time extension and to the lowering of fuel ignition temperature. After the evaporation stage there is heating and carbonization of the coal particle agglomerate which leads to thermal decomposition and expansion. The final stage is the non-homogeneous combustion of the agglomerate that
Fig. 6. The relation between moistness of slurry (20%, 35%, 50%) and temperature of coal-water slurry during continuous combustion.

Fig. 7. The relation between moistness of slurry (20%, 35%, 50%) and temperature of coal-water slurry during cyclic combustion 10sec.A/10sec.N sec.A/sec.N – time combustion in air/time resident in nitrogen.
is characterized by the absence of flame occurring during volatile combustion. The completion of the process is signaled by the sudden fall of the carbonization product temperature. The tar combustion period is definitely longer than the ignition time and volatile combustion. After evaporation, the coal particles of the agglomeration which are situated outside, reach the melting temperature and combine in one unity. The result of this process is the barrier to devolatilization and the resistance for the fragmentation which causes the lengthened induction period, and a long, relatively unstable flame. It was found, that during devolatilization the coal particles of the suspension go through the softening stage, showing some plastic properties. At the end of the process, the coal particles got solidificated again. The evidence confirming this process are the numerous craters set in the solidifying material. Special attention should be paid to the spongy structure of the suspension, resulting from the hardening of the liquid bubble mass of volatiles that did not manage to get outside the fuel. The combustion process leads to the pore volume increase in the suspension and their coalescence. On the basis of the visual observation it was found, that the coal water suspension burns with longer and more intensive flame. This is caused by the large moisture content of the flurry. It was found, that during devolatilization of the char-agglomerate the ash makes a significant part of the small particle mass and the arrangement of the large particles and agglomerations depend very much on the type of coal. One could observe the swelling of suspension during devolatilization and volatile combustion, the result of which was the increase of the large size particles. Apart from that, there was not any big difference between the brown coal and the fuels made of high rank coals at this stage of the process. During the burning of carbonization product in the suspense, one could observe the significant decrease of large particles in relation to the stage of fuel devolatilization. The mineral substance forms

Fig. 8. An example of the temperatures changes of hard coal (Staszic mine) – water suspension during its continuous combustion in air and in the fluidized bed.
ash which is released during the coal combustion and oxidation. The ash becomes a part of the small particle distribution of the burnt suspension. It should be stressed that the low type coal has a bigger porosity and a large reactivity, and as a consequence, it burns more violently. It means that the evolution of particle distribution appears sooner in the case of this coal. Secondly, the low type coal contains more non-flammable mineral substance. Thirdly, the high rank coals usually expand significantly which results in the fact, that the distribution concerns the particles of larger size. As we know, coal is a highly porous substance. The structure of pores is identified by their inner volume, the inner surface and their distribution according to their size. The distribution of inner volume and surface according to the pore size determines the inner surface availability for the gaseous reagents. A large number of pore canals causes that its inner surface in comparison to its volume is big, which affects the mechanical, physical and chemical coal properties. The size of the inner coal surface depends on the kind of coal, its petrography content and the degree of coalification. One of the research methods of porosity is mercury porosimetry. This method was used to analyze the chosen coals. It consisted of squeezing mercury into the fuel pores by means of high pressure (to 399 MPa) and enabled to determine the coal porosity, its real and apparent density as well as the coal pores distribution. In the case of the initial coals, the significant part of the inner surface is situated in the micro and meso-pores. It was found that as the degree of the fuel coalification increased, the size of pores and the total pore porosity substantially decreased. Addition of biomass dust to coal-water fuel leads to increasing of sticky of suspension (Fig. 29) and average pore radius in fuel during combustion process (Fig. 30).

It was also found the big impact of fluidized layer on the change of the fuel inner structure, size and volume. It was stated, that the alternate lighting up and extinguishing leads to the increase of the total pore volume. With low pressure (to 20 MPa) of mercury pressing, the pore volume increases abruptly. The coal combustion carried out in the conditions of total fuel extinguishing causes the share increase of bigger size pores. It was observed that in the case of coals that go out, a significant part of the inner surface is situated in micro and meso-pores. The combustion process leads to the increase of pore volume in coal due to their coalescence. This is particularly visible in a cyclic combustion consisting of the alternate coal lighting and extinguishing, at short intervals. Negligible increase of the pore volume in a particle during the combustion 10sec.A/30sec.N concerns the fuels of big volatile share and proves that after the defined time the coal has not been devolatilized completely. This is the result of a long extinguishing process. One can state that the cyclic combustion of a coal particle leads to the increase of the average pore size and their total volume except for the process 10sec.A/30sec.N which is on account of a long time of fuel extinguishing. It was observed that when the degree of coalification increases the total coal porosity decreases. This is the result of the intensive devolatilization of low type coal particles, that contain a lot of volatiles. The coal combustion causes lowering of its real density and at the same time increasing of its apparent density. Real coal density is the relationship of coal mass to its volume omitting the pores. It refers to the coal substance without pores. The apparent density is the relationship of coal mass to its volume with pores (Fig. 9).

3.3. Visual display of combustion of coal-water suspension

Figures 10-28 present visual display of combustion of coal-water suspension. Observing the combustion of the suspension fuel one could find that the first stage of the process is the moisture vaporization. The high level of water participation in the suspension is the reason for the ignition
delay of the suspension fuel. After introduction of suspension to the suspension chamber, the drop consists mainly of water and its evaporation velocity is controlled mainly by the resistance of the gas phase. During the second stage of drying, the process is determined by the environment conditions (temperature of the environment, pressure). Small fragmentation occurs when the partial steam pressure of the wet surface equals the temperature of the environment. The coal-
water suspension drop is surrounded by a stiff ring during the second drying stage, the amount of water keeps falling down, appropriately to the gasification caused by the continuous expansion of bubbles filled with the steam inside the wet core. The boiling inside the wet core is the reason for the porous shell cracking and the pressure rise inside the drop, causes the suspension expansion. Fragmentation of the porous ring is the result of the thermal shock and high internal pressure. During evaporation the shape and size of the agglomerate drop practically do not change. After vaporization, another process stage is the devolatilization of a coal particle agglomerate leading to its thermal distribution and expansion to the size 10-15% bigger than the initial drop. After vaporization, the agglomeration coal particles that are situated outside, reach the melting temperature, combine with each other forming a shell. It was found that during the devolatilization, the coal particles in the suspension go through the softening phase, showing some plastic properties, and at the end of the process the suspension coal properties consolidate again. The evidence are the numerous craters after the gas bubbles set in the consolidating mass. The combustion process leads to the increase of pores volume in the suspension and their coalescence. After evaporation and devolatilization the char-agglomerate was formed, surrounded by the set mass of earlier emitting liquid hydrocarbons, showing the spongy structure and negligible surface cracks. It especially concerns the drops possessing a large number of volatiles. Combustion of the left part of the carbonization product is accompanied by a slight reduction of agglomerate size and the sudden fuel darkening signifies the completion of the process. The suspension agglomerates of higher humidity practically do not undergo fragmentation, even after the water which initially combines the drop particle evaporates. Expansion of the suspension during the devolatilization and volatile combustion leads to the increase of the bigger size particles. As the suspension evaporates, the drop density increases and after the moisture release, reaches the value which is almost equal to the coal particle density. High humidity content in the suspension, results in the fact, that the coal-water suspension burns with longer and more intensive flame. Devolatilization can lead to the disintegration of function groups containing oxygen and to the reduction of hydrophilic coal properties causing the lower volume of the water bonded with coal. According to the specialist literature, the lowering of fuel specific surface, can result from the slight volatile devolatilization at the temperature of 400°C in the small pores. Pyrolysis reduces the volume of water bonded with coal by lowering the number of hydrophilic sites, both by the decomposition of groups containing oxygen and by closing small pores. On the account of the coal-water suspension the intensive erosion in the conditions of the developed fluidized bed, the flow conditions were so selected as to determine the mechanism of the suspension fuel combustion, in the conditions of fluidized bed (the chapter concerning the research on mechanism and kinetics of the suspension combustion in the fluidized bed conditions). Below are shown examples of the coal-water suspension combustion, in the changeable fluidized conditions from the bubble to circulating layer, depending on the gas flow velocity. It was observed that as the suspension humidity and the particle size distribution increase, the covering of the fuel surface by the sticking material is bigger. The process is developing as the velocity of fluidization lowers and the amount of the inert material circulating in fluidized chamber, increases.
Fig. 10. Hard coal-water suspension after 10 sec. combustion in air

Fig. 11. Brown coal-water suspension after 10 sec. combustion in air

Fig. 12. Anthracite-water suspension after 10 sec. combustion in air

Fig. 13. Mule coal-water suspension before combustion process
Fig. 14. Mule coal-water suspension after 10 sec. combustion in air; blow-up 350×

Fig. 15. Mule coal-water suspension after 15 sec. combustion in air; blow-up 350×

Fig. 16. Mule coal-water suspension after 30 sec. combustion in air; blow-up 350×

Fig. 17. Mule coal-water suspension after 70 sec. combustion in air; blow-up 350×

Fig. 18. The surface of coal-water suspension (hard coal) after 30 sec. combustion in air
Fig. 19. The surface of coal-water suspension (hard coal) after 30 sec. combustion in the fluidized bed

Fig. 20. The surface of coal-water suspension (hard coal) after 30 sec. cyclic combustion in air

Fig. 21. The surface of coal-water suspension (coal mule) after 30 sec. combustion in air
Fig. 22 The surface of coal-water suspension (coal mule) after 30 sec. combustion in the fluidized bed

Fig. 23. The surface of coal-water suspension (coal mule+hard coal) after 30 sec. combustion in air

Fig. 24. The surface of coal-water suspension (coal mule+hard coal) after 30 sec. combustion in the fluidized bed
Before combustion

After 5 sec. of process

Before combustion

After 10 sec. of process

Before combustion

After 20 sec. of process

Before combustion

After 30 sec. of process

Fig. 25. Combustion coal-mule-water suspension in air
Fig. 26. Combustion coal-mule-water suspension in the fluidized bed
Fig. 27. Combustion coal-water suspension in air

Fig. 28. Combustion coal-water suspension in the fluidized bed
4. Conclusions

The paper contains the analysis of the complex morphology of the coal-water suspension drops during the combustion of coal suspension fuels in various conditions. The analysis enables to formulate the following conclusions.

1. The particle size distribution and the coal substance concentration in the coal-water suspension decide about the stickiness and the rheological properties of suspension fuel. The coal particles of coal-water suspension drops are located irregularly.

2. When the suspension is largely made of very fine particles one can observe their big packing in the suspension, among the coarse particles.
3. The increase of both suspension stickiness and the total surface of fine coal particles causes the growing resistance, which makes it impossible for the particles to move in water.

4. The bigger coalescence of highly packed coal-water suspension generate, during the spray, the suspension drops of large size. The bigger particles packing and the larger total particle surface, when the suspension contains coal particles, leads to intensive interaction among particles and among particles and water.

5. In the case of the coal-water suspension spray which is made of smaller coal particles one can observe formation of drops, containing only water and the constant parts.

6. After water evaporation, the located outside the agglomerate, coal particles reach the melting temperature and stick with each other, forming a shell.

7. After the ignition of evaporated and devolatized agglomeration of suspension fuel, one can observe the intensive increase of coal-water suspension temperature to the maximum value.

8. The cyclic change of oxygen concentration around the burning suspension fuel leads to the lowering of the fuel medium temperature and to the changes of combustion mechanism, moving it slightly in the kinetic direction.

9. The specificity of coal-water suspension combustion in the conditions of fluidized bed, changes the mechanism and kinetics of the process. The humidity increase of coal-water suspension and the size of coal particles cause the bigger sticking of the layer material to the suspension fuel surface. The sticking is growing along with the lowering of the fluidization velocity and the increase of the inert material amount, circulating in the fluidized chamber. During combustion in the conditions of fluidized bed, one can observe the intensive fuel heating in the initial stage of the process and then the heat taking off from the coal-water suspension by the striking inert material which leads to the lowering of the medium fuel temperature and to the slight lengthening of its combustion time.

10. Addition of biomass dust to coal-water fuel leads to increasing of suspension sticky and average pore radius in fuel during combustion process.

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References


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