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ANALYSIS OF COAL WITH COAL-MULE AND BIOMASS CO-COMBUSTION IN SLURRY FORM

ANALIZA WSPÓŁSPALANIA WĘGLA Z MUŁEM WĘGLOWYM I BIOMASĄ W POSTACI ZAWIESINY

Combustion technology of coal-water fuels 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. The paper undertakes the complex research of the coal with coal-mule and biomass co-combustion. The mathematical model enables the prognosis for change of the surface and the centre temperatures and a mass loss of the fuel during combustion in air and in the fluidized bed.

Keywords: mechanism and kinetics of combustion reaction; co-combustion of coal with coal-mule and biomass; fluidized bed

W pracy omówiono problematykę spalania wysoko zawodnionych paliw, która nabiera coraz większego znaczenia w miarę wzrostu wymagań jakościowych węgli spalanych w elektrowniach. Przeanalizowano spalanie mułów poflotacyjnych, a także zawodnionych paliw, będących mieszaniną pyłu węgla i biomasy oraz wody. Kopalnie węgla kamiennego, chcąc spełnić oczekiwania energetyków, zmuszone zostały do rozbudowy i unowocześnienia zakładów wzbogacania węgla. Powoduje to wzrost ilości odpadów, powstających w procesie mokrego wzbogacania, zawierających coraz mniejsze podziarna. W tej sytuacji koncepcja bezpośredniego spalania wspomnianych odpadów, transportowanych np. hydraulicznie do pobliskich elektrowni, wydaje się atrakcyjna zarówno ze względu na możliwość eliminacji konieczności głębokiego odwadniania i suszenia, jak i likwidacji strat najdrobniejszych frakcji węgla przy zrzucie zamulonych wód z zakładów wzbogacania. Opracowany model matematyczny zawiera równania uwzględniające całokształt zjawisk towarzyszących spalaniu zawiesiny w strumieniu powietrza i w warstwie fluidalnej oraz z dostateczną dokładnością opisuje wspomniane procesy, realizowane podczas badań.

Słowa kluczowe: mechanizm i kinetyka reakcji spalania; współspalanie węgla z mułem węglowym i biomasą; warstwa fluidalna

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Nomenclature

c – specific heat capacity of the coal-water suspension, J/kgK,
d_{ZW} – diameter of a coal-water suspension, m,
d_{inert} – diameter of the particle of inert material, m,
G_s – intensity of inert material stream
m – mass, kg,
Q – heat of reaction, J/kg,
r – radius, m,
S – surface area, m^2,
Sc – Schmidt number,
T – temperature, K,
V – volume, m^3,
w – velocity, m/sec.,
M – content of water in the coal-water suspension, -,
α – heat transfer coefficient, W/m^2K,
λ – thermal conductivity, W/mK,

subscripts

g – gas,
$inert$ – inert material,
ot – ambient of coal-water suspension,

1. Introduction

The combustion technology in the CFB boilers possesses numerous advantages which include: combustion of waste materials and the high combustion efficiency. The circulating flux determining the mechanism of combustion also plays essential role in keeping balanced temperature of 850°C in all zones of combustion chamber, allowing the lowest SOx and NOx emissions. The specificity of combustion in CFB forces the mixing of fuel inside the combustion chamber – the internal circulation and the contour circulation occurring at the combustion chamber, the separator and the downcomer (Fig. 1). Thus, the fuel combustion becomes the cyclic process, comprising a repeated heating, ignition, combustion, extinction and cooling (Grace et al., 1997; Basu, 1999).

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 R_{90} = 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 treatedparibas bank as the Newton fluid, its stickiness and fluidity at the same time,

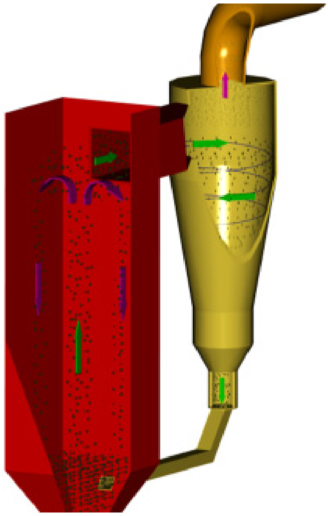


Fig. 1. Fuel movement in the boiler with Circulating Fluidized Bed (combustion chamber, cyclone, downcomer)

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. In relationship to adaptation of requirements European and world, Polish power sector has to reach to sources of renewable energy. Co-combustion of coal and biomass is attractive from the point of view on comparatively low costs of production energy in comparison with other renewables, whether with the alternative sources of energy. Biomass can be used for energy aims in form of solid and can be converted on liquid fuel or gas-fuel (Kowalik, 1994; Limanowski & Agopsowicz, 1996).

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, 2012, 2011a, 2011b, 2010a, 2010b, 2009; Kijo-Kleczkowska et al., 2013).

2. The research stand and measurements methodology

Fig. 2 presents the research stand construction. It allowed to investigate the combustion of fuel in air and in the fluidized bed. The research stand was made of ceramic blocks (1,12) in which the quartz pipes were put. The heating element (12) of the stand comprised three heating coils of 2.0 kW. Each heating coil was placed in six small quartz tubes. These tubes were built into the quartz tube which was thermally insulated by fiber material Al_2O_3 and which was covered with steel sheet. Combustion chamber (1) constituted the quartz pipe, 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 allowed to observe directly,

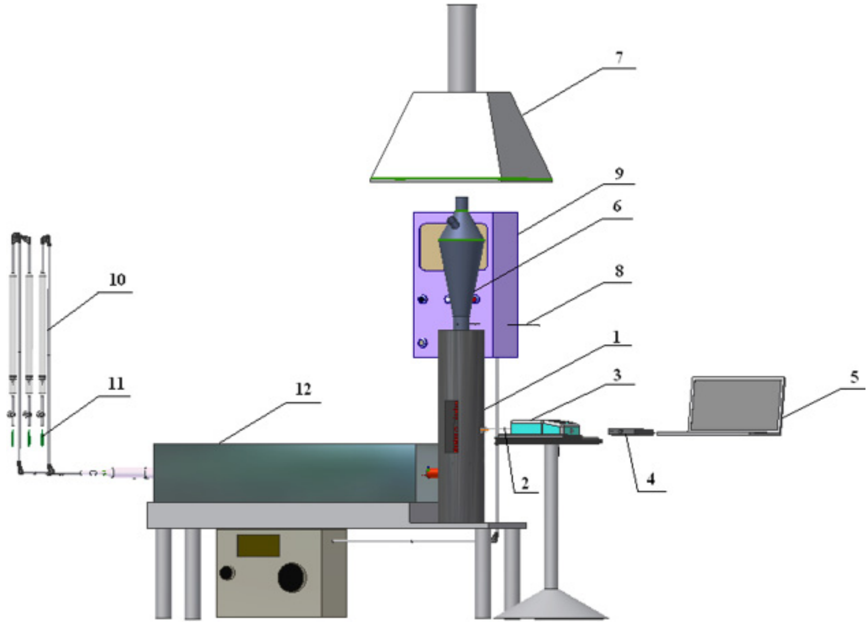


Fig. 2. Research stand scheme; 1 – combustion chamber, 2 – PtRh10-Pt thermocouples, 3 – scale, 4 – measurement card, 5 – computer, 6 – expanding chamber, 7 – furnace gas extractor, 8 – NiCr-Ni thermocouple, 9 – microprocessor thermoregulator, 10 – rotameters, 11 – regulating valves, 12 – block of ceramic material

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 rotameter. 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. 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.

In order to establish the centre and surface temperature of fuel, a special instrument stalk was constructed (Fig. 3). 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 to support the fuel. It also touched the surface of the fuel (2). The thermocouples and the scale were connected to the measurement card and to the computer in order to record the experimental results.

The essential stage of the preliminary work was to make out a suspension fuel, which was a mixture of fuels dust and water. The fuels properties applied in the research are shown in Table 1. In order to produce the coal-water suspension it was necessary to prepare fuels 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 1ml was used.

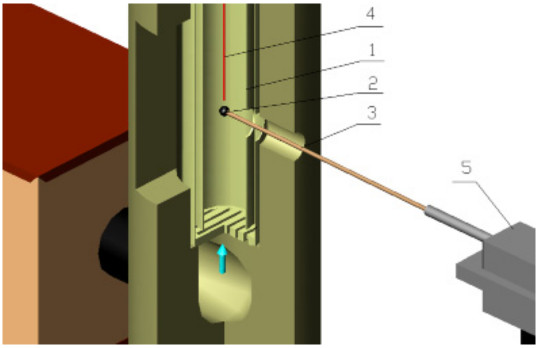


Fig. 3. Measurements Methodology
1 – combustion chamber, 2 – fuel, 3 – PtRh10-Pt thermocouples, 4 – NiCr-Ni thermocouple, 5 – scale

TABLE 1

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

Fuel	Mine	W^a	V^a	A^a	Q_i^a	C_t^a	H_t^a	N^a	O_d^a	S_c^a	S_t^a
		%	%	%	kJ/kg	%	%	%	%	%	%
coal mule	Sobieski	4,51	20,45	39,43	15024	40,12	2,82	0,54	12,11	0,47	0,72
hard coal	Staszic	2,66	30,90	2,36	31198	79,53	4,33	1,27	9,75	0,10	0,31
cereal grain		8,45	70,53	4,55	15825	40,90	6,07	2,73	37,30	–	0,18

3. Experimental research

The research undertakes the complex research of the coal-water suspension combustion. Most attention was paid to the experiments analyzing the coal-water suspension combustion in relationship to the conditions of the process. In-depth experiments enabled to define the accurate physical model of the coal-water suspension drop combustion process. It enabled to work out the set of equations taking into consideration all phenomena accompanying combustion. The appropriate initial and limiting conditions were formulated and the mathematical description of the combustion realities was located.

The combustion analysis of the suspension fuel drop required following of its behavior in the particular process stages. 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. 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. After the char ignition, there was the surface temperature increase. When the temperature reached the maximum value, its decrease was observed. It was caused by the shift of the combustion into the internal part of the fuel and the cooling of the fuel surface. The sample was made of the growing ash layer around the char (Fig. 4, 5).

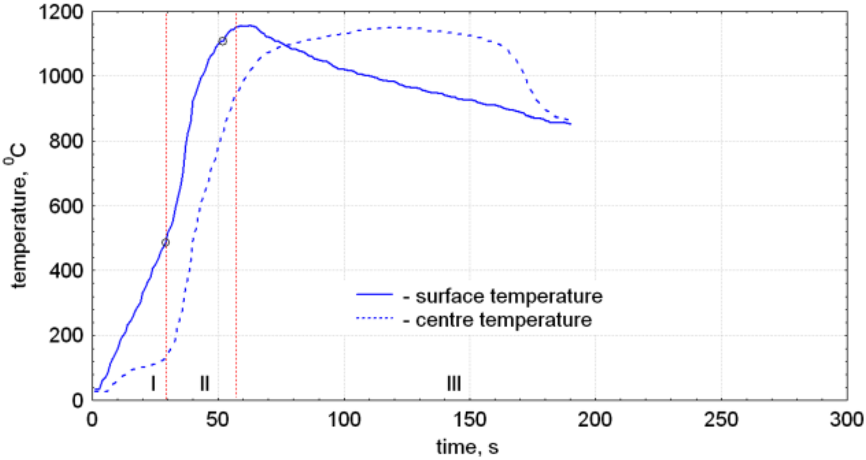


Fig. 4. An example of course of changes of temperature on surface and in centre of fuel during process of combustion in stream of gas oxidizing; t = 850°C
I – stage of heating, vaporization and devolatilization, II – stage further devolatilization and combustions of volatiles, III – stage of char combustion.
First spades means ignition of fuel behind agency volatiles, second spades – char agglomeration ignition

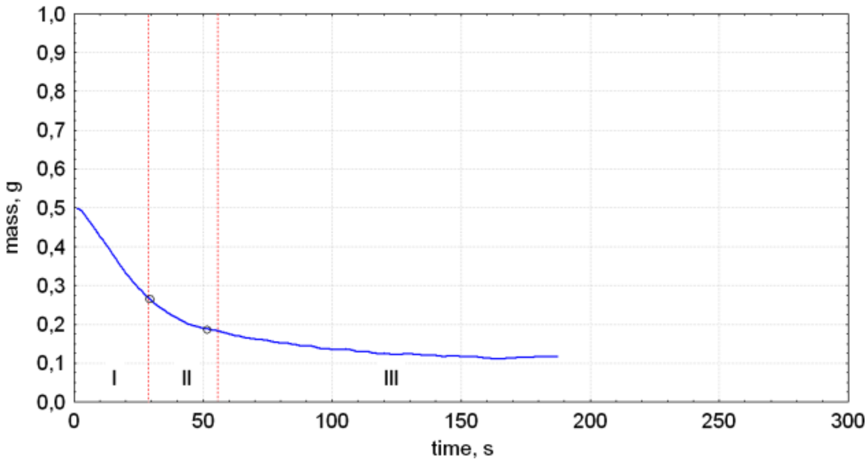
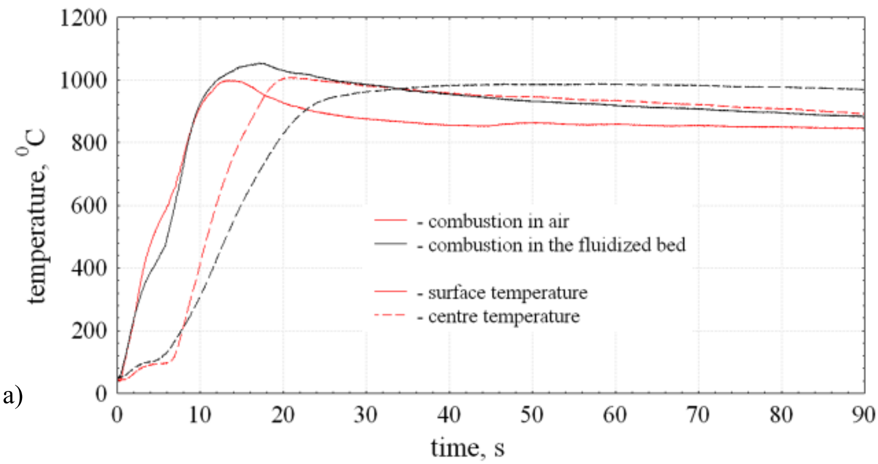


Fig. 5. An example of course of changes of mass of fuel during process of combustion in stream of gas oxidizing; t = 850°C

Another element of the research was to determine the combustion course of the coal-water suspension in the air stream and in the fluidized bed condition (Fig. 6, Table 2,3). During the combustion in a fluidized bed all coal-water suspensions are characterized by longer combustion time in comparison to the combustion in the air stream. The longest combustion time was recorded during the examination of suspension made of anthracite dust, and the shortest one for



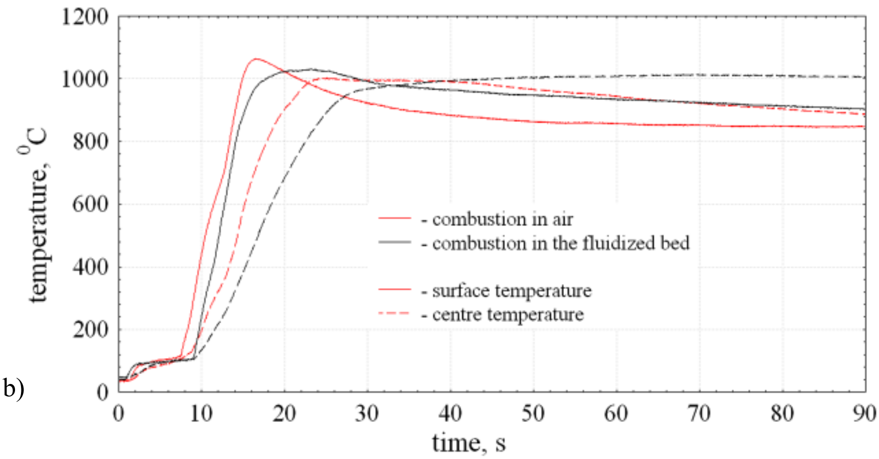


Fig. 6. An example of course of changes of surface and centre temperature and mass of fuel (hard coal dust and water) during process of combustion in air and fluidized bed; t = 850°C; a) M = 20%, b) M = 50%, G_s = 13 kg/m^{2}s

the suspension made with brown dust. The circulating inert material during the combustion in a fluidized bed takes away the heat from the suspension. The heat taking causes the temperature lowering of the fuel combustion which results in the total time of the process. During the suspension combustion in a fluidized bed the covering of the surface by the circulating sand is getting stronger and stronger which lengthens the combustion time. During the combustion of carbonization product one can observe the increase of the suspension porosity. The pores are usually filled up on the surface with the sticking in the inert material particles. Therefore, the coal-water suspension burns more intensively in the air stream. In these conditions the combustion temperature is higher which in consequence influences the combustion time shortening.

TABLE 2

Combustion of fuel formed from water and hard coal dust in the fluidized bed t = 850°C

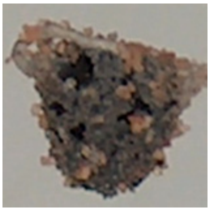
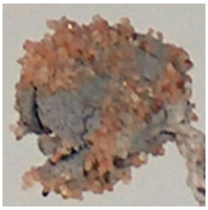
***M* = 50%**	
before combustion	after 30 s of process
	
***M* = 35%**	
before combustion	after 30 s of process
	

TABLE 3

The slurries after 30s of combustion in air and in fluidized bed; M = 35%, t = 850°C

fuel formed from dust of:	**before combustion**	**after 30 s combustion in air**	**after 30 s combustion in the fluidized bed**
cereal grain			
hard coal and coal-mule			
hard coal and coal-mule and cereal grain			

4. Working out of a mathematical model of coal-water suspension combustion

Apart from the research experiments, it is important to thoroughly analyze the physical and chemical phenomena, occurring during the coal-water suspension combustion as well as to competently describe the mathematical relationships between them. In the so far worked out mathematical models, there have been attempts to find the equations on the basis of which from the well known initial conditions one could forecast the phenomenon course i.e. to determine the coal-water suspension combustion velocity, the flowing exhaust content or the local concentration of their components. It was interesting to determine the mass of fuel and the temperature of the suspension surface and the center fuel, considering its combustion according to the model of contracting core (Kijo-Kleczkowska, 2008-2010, 2011b).

General model assumptions

During the model realization were assumed the basic data characteristic for the process of the coal-water suspension combustion i.e. the mass change, and the coal-water suspension temperature. The model formulation required to accept the following assumptions:

- coal-water suspension possesses a homogeneous structure and does not undergo fragmentation during the combustion process,
- has a spherical shape of a known radius R which does not change during the process,
- combustion of coal-water suspension is held according to the model of "contracting core" which leads to the isolation of suspension center through the growing ash layer,
- suspension density does not depend on temperature,
- the process is held since the fuel is introduced to the combustion chamber to the moment it is burnt down,

in the case of combustion in the fluidized bed

- after the coal-water suspension introduction to the combustion chamber it is covered with the particles of inert material and additionally the fuel surface erosion takes place. This is due to the collision with the layer material particles.

The course of ignition and combustion of coal-water suspension are determined by water evaporation process and coal combustion. The coal-water suspension, after entering the high temperature combustion chamber, gets dry fast from the surface and as a result, the characteristic zones inside the drop are formed (Fig. 7). In the zone of entrance fuel (1) the temperature is equal or slightly lower than the water boiling temperature. The width of the water evaporation zone (2) is determined by the isothermal surfaces of the beginning and end of water boiling.

On the border of zone 1 and 2 is held the initial mutual interaction of coal and water with the generated gas products of the reaction. We assume that the coal-water suspension drop during the combustion in not destructed, due to the action of the aerodynamic strength. During combustion the oxygen does not diffuse to the drop inside and the total reaction of coal-water suspension with oxygen proceeds, according to the first order reaction. We assume that the oxygen diffusion to the drop surface is at the expense of turbulent diffusion resulting from drop movement in the stream of air.

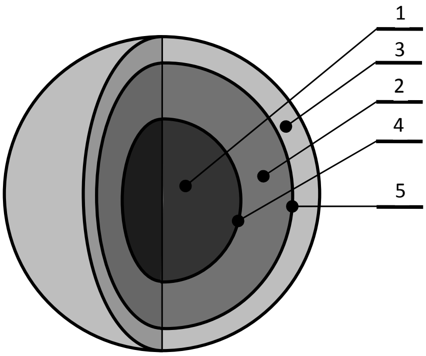


Fig. 7. Combustion model of coal-water suspension
1 – zone of exit fuel, 2 – zone of dry fuel, 3 – zone of volume after burning of transitory reaction products, 4 – water evaporation surface, 5 – dry coal combustion phase

In order to calculate the temperature changes of coal-water suspension was used the equation of Fourier-Kichhoff:

$$c\,\rho \frac{\partial T}{\partial \tau} = \mathrm{div}\left(\lambda\, \mathrm{grad}\, T\right) + q_V \tag{1}$$

which in the spherical coordinates (Adesanya & Pham, 1995):

$$c\,\rho \frac{\partial T(r,\tau)}{\partial \tau} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\,\lambda \frac{\partial T(r,\tau)}{\partial r}\right) + q_V(r,\tau) \tag{2}$$

The following boundary conditions were accepted (Adesanya & Pham, 1995; Saxena, 1990):

– for n (outer) cell- the boundary condition of the third type:

$$\dot{q} = -\lambda \left.\frac{\partial T(r,\tau)}{\partial r}\right|_{r=R} = \alpha\left(T(R,\tau) - T_{ot}(\tau)\right) \tag{3}$$

– for 0 (inner) cell- the boundary condition of the second type:

$$\left.\frac{\partial T(r,\tau)}{\partial r}\right|_{r=0} = 0 \tag{4}$$

The calculations were carried out by means of the control volume method.

<u>Discretisation of time</u>

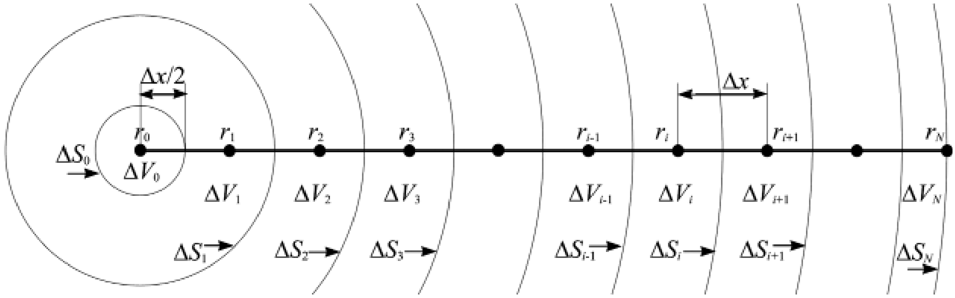
The following time net was accepted:

$$0 = \tau^0 < \tau^1 < \tau^2 < \ldots < \tau^f < \tau^{f+1} < \ldots < \tau^F = F \tag{5}$$

where:

$$\Delta\tau = \tau^{f+1} - \tau^f, \quad \tau^{f+1} = f\Delta\tau \tag{6}$$

Discretisation of geometry



$$\Delta V_i = \frac{4}{3}\pi\left(\left(i\,\Delta r + \frac{\Delta r}{2}\right)^3 - \left(i\,\Delta r - \frac{\Delta r}{2}\right)^3\right) = \frac{4}{3}\pi(\Delta r)^3\left(\left(i+\frac{1}{2}\right)^3 - \left(i-\frac{1}{2}\right)^3\right),\ i = 1,\dots,N-1 \tag{7}$$

$$\Delta V_0 = \frac{4}{3}\pi\left(\frac{\Delta r}{2}\right)^3 \tag{8}$$

$$\Delta V_N = \frac{4}{3}\pi\left((N\Delta r)^3 - \left(N\Delta x - \frac{\Delta r}{2}\right)^3\right) = \frac{4}{3}\pi(\Delta r)^3\left(N^3 - \left(N-\frac{1}{2}\right)^3\right) \tag{9}$$

$$\Delta S_i = 4\pi\left(i\,\Delta r + \frac{\Delta r}{2}\right)^2 = 4\pi(\Delta r)^2\left(i+\frac{1}{2}\right)^2,\quad i = 1,\dots,N-1 \tag{10}$$

$$\Delta S_0 = 4\pi\left(\frac{\Delta r}{2}\right)^2 \tag{11}$$

$$\Delta S_N = 4\pi(N\Delta r)^2 = 4\pi(\Delta r)^2 N^2 \tag{12}$$

The balances of energy qualifying heat flow among volumes result from integrating Fourier-Kirchhoff equalization after time and the geometrical coordinates,

$$\int_{\tau^f}^{\tau^{f+1}}\int_{CV_i} c\rho\frac{\partial T}{\partial \tau}dV_i\,d\tau = \int_{\tau^f}^{\tau^{f+1}}\int_{CV_i}\mathrm{div}(\lambda\,\mathrm{grad}\,T)dV_i\,d\tau + \int_{\tau^f}^{\tau^{f+1}}\int_{CV_i} q_V\,dV_i\,d\tau \tag{13}$$

One received the following dependences:

- for $i = 1, ..., N - 1$:

$$c_i^f \rho_i^f \left(T_i^{f+1} - T_i^f\right)\Delta V_i = \lambda_{i,i+1}^f \frac{T_{i+1}^f - T_i^f}{\Delta r}\Delta S_i \,\Delta\tau + \lambda_{i,i-1}^f \frac{T_{i-1}^f - T_i^f}{\Delta r}\Delta S_{i-1}\,\Delta\tau + q_{Vi}^f \,\Delta V_i \,\Delta\tau \tag{14}$$

$$T_i^{f+1} = T_i^f + \frac{\Delta\tau}{c_i^f \rho_i^f}\left(\lambda_{i,i+1}^f \frac{\Delta S_i}{\Delta V_i \,\Delta r}\left(T_{i+1}^f - T_i^f\right) + \lambda_{i,i-1}^f \frac{\Delta S_{i-1}}{\Delta V_i\,\Delta r}\left(T_{i-1}^f - T_i^f\right) + q_{Vi}^f\right) \tag{15}$$

- for $i = N$:

$$c_N^f \rho_N^f \left(T_N^{f+1} - T_N^f\right)\Delta V_N = \alpha\left(T_{ot}{}^f - T_N^f\right)\Delta S_N\,\Delta\tau + \lambda_{N,N-1}^f \frac{T_{N-1}^f - T_N^f}{\Delta r}\Delta S_{N-1}\,\Delta\tau + q_{V_N}^f\,\Delta V_N \Delta\tau \tag{16}$$

$$T_N^{f+1} = T_N^f + \frac{\Delta t}{c_N^f \rho_N^f}\left(\alpha\frac{\Delta S_N}{\Delta V_N}\left(T_{ot}{}^f - T_N^f\right) + \lambda_{N,N-1}^f \frac{\Delta S_{N-1}}{\Delta V_N \Delta r}\left(T_{N-1}^f - T_N^f\right) + q_{V_N}^f\right) \tag{17}$$

- for $i = 0$:

$$c_0^f \rho_0^f \left(T_0^{f+1} - T_0^f\right)\Delta V_0 = \lambda_{0,1}^f \frac{T_1^f - T_0^f}{\Delta r}\Delta S_0\,\Delta\tau + q_{V_0}^f \Delta V_0\,\Delta\tau \tag{18}$$

$$T_0^{f+1} = T_0^f + \frac{\Delta\tau}{c_0^f \rho_0^f}\left(\lambda_{0,1}^f \frac{\Delta S_0}{\Delta V_0\,\Delta r}\left(T_1^f - T_0^f\right) + q_{V_0}^f\right) \tag{19}$$

The voluminal source of heat was expressed with following dependence:

$$q_V = q_V(r,\tau) = \frac{dQ_{\text{evaporation}}(r,\tau)}{dV\,d\tau} + \frac{dQ_{\text{devolatilization}}(r,\tau)}{dV\,d\tau} + \frac{dQ_{\text{volatiles combustion}}(r,\tau)}{dV\,d\tau} + \frac{dQ_{\text{char combustion}}(r,\tau)}{dV\,d\tau} \tag{20}$$

where Q_k is heat of reaction (index k means stages of combustion process, that is to say: vaporization, devolatilisation, combustion of volatiles, char combustion.

Stream of heat of *k*-reaction one defined as:

$$\frac{dQ_k(r,\tau)}{d\tau} = H_k \frac{dm_k(r,\tau)}{d\tau} \tag{21}$$

where:

H_k — enthalpy of *k*-reaction, J/kg,
m_k — mass *k*-component of reaction, kg.

The change of mass m_k during time *t*:

$$\frac{dm_k(r,\tau)}{d\tau} = f(m_k, r, \tau) \tag{22}$$

where $f(m_k, r, \tau)$ is general form of function and in the concretely phases of process described with dependences for the talked stage of combustion.

Assumptions about the model of the fuel combustion of coal-water suspension in the fluidized bed are the same as above, considering the interaction of particle combustion of the layer material (the quartz sand). According to the experiment observation, it was accepted that immediately after the suspension introduction to the fluidized bed, the quartz sand particles stick to the surface which leads to the initial increase of the fuel mass by the inertia mass. It, of course, does not take part in the process of burning out of suspension (the phenomenon of sticking to the surface depends on the type of coal, humidity and air flow velocity). The phenomenon of "sticking to the surface" mainly takes place during fuel evaporation. The flowing material of bed strike the surface of agglomerate and tear out from it the suspensions and the coal particles stuck to the inert material. This phenomenon was observed mainly at the stage of burning of char-agglomerate on account of weakening of the agglomerate structure, which was preceded by the earlier fluidization and high fuel stickiness.

In the combustion model of coal-water suspension in a fluidized bed were applied, in addition, the following relationships (Basu & Fraser, 1991; Gajewski, 1996-1998; Grace et al., 1997; Saxena, 1990; Tomeczek, 1992):

$$Nu = 0,33\,\mathrm{Re}^{0,62}\left(\frac{d_{Zw}}{d_{inert}}\right)^{0,1} + \frac{d_{Zw}\,\xi\sigma}{\lambda_g}\left(\frac{T_{ot}^4 - T_Z^4}{T_{ot} - T_Z}\right) \tag{23}$$

Sherwood's number is accepted depending on the character of the suspension flow by the fluidizing bed material (Fig. 8).

When coal-water suspension stays in the rarefaction phase (subdomain 1):

$$Sh = 2\varepsilon + 0,69\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{0,5} Sc^{0,33} \tag{24}$$

where:

$$\varepsilon = \frac{w - w_{inert}}{w_{tr}} \tag{25}$$

$$w_{tr} = 1,45\,\frac{\eta_g\, Ar_{inert}^{\;0,484}}{d_{inert}\,\rho_g} \tag{26}$$

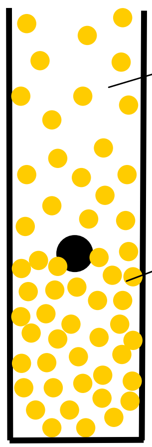


Fig. 8. Subregions in the fluidized bed

When coal-water suspension stays in the dense phase (subdomain II):

$$\frac{Sh}{\varepsilon_{mf}} = \left[4 + 0,576 \left(\frac{w_{mf}\, d_{Zw}}{D_m^{'}\, \varepsilon_{mf}} \right)^{0,78} + 1,28 \left(\frac{w_{mf}\, d_{Zw}}{D_m^{'}\, \varepsilon_{mf}} \right) + 0,141 \left(\frac{w_{mf}\, d_{Zw}}{D_m^{'}\, \varepsilon_{mf}} \right)^{2} \left(\frac{d_{inert}}{d_{Zw}} \right) \right]^{0,5} \tag{27}$$

where:

$$D_m^{'} = \frac{D_g}{\sqrt{2}} \tag{28}$$

$$\varepsilon_{mf} = \frac{\rho_{inert} - \rho_n}{\rho_{inert} - \rho_g} \tag{29}$$

$$w_{mf} = \frac{\eta_g \, \mathrm{Re}_{mf}}{d_{inert}\, \rho_g} \tag{30}$$

$$\mathrm{Re}_{mf} = \left(C_1^2 + C_2\, Ar_{inert} \right)^{0,5} - C_1 \tag{31}$$

where: $C_1 = 27{,}2$; $C_2 = 0{,}0408$.

Evaporation, devolatization and volatile combustion were modeled in the same way, as in the case of coal-water suspension combustion in the stream of air at the assumption of sticking to the fuel by the inert material and erosion of fuel, thus:

$$\frac{dm_{Zwcał.}}{d\tau} = -\frac{dm_{Zw}}{d\tau}(\text{combustion}) + \frac{dm_{inert}}{d\tau}(\text{sticking}) - \frac{dm_{Zw}}{d\tau}(\text{erosion}) \quad (32)$$

Below are shown the digitally calculated temperature changes of the surface and center and the mass loss of coal-water suspension examined in the combustion conditions (Fig. 9-18). On the basis of the shown analysis one can state that the curves calculated from the model with satisfactory precision, describe the combustion process carried out during the research experiments.

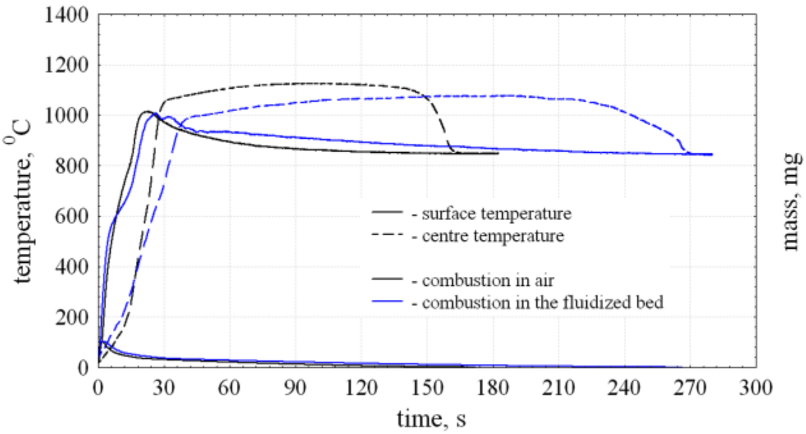


Fig. 9. An example of course of changes of surface and centre temperature and mass of fuel formed from water and dust of hard coal (Staszic mine) during combustion in air and in the fluidized bed; $t = 850°C$, $M = 50\%$, $m = 100$ mg (experiment)

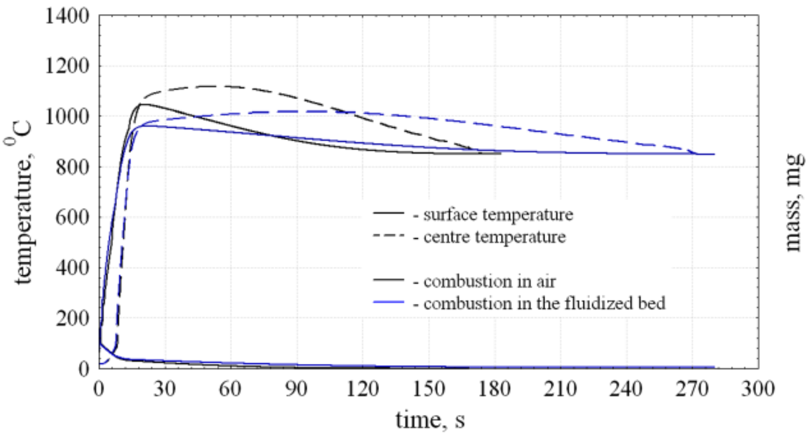


Fig. 10. Numerically calculated course of changes of surface and centre temperature and mass of fuel formed from water and dust of hard coal (Staszic mine) during combustion in air and in the fluidized bed; $t = 850°C$, $M = 50\%$, $m = 100$ mg

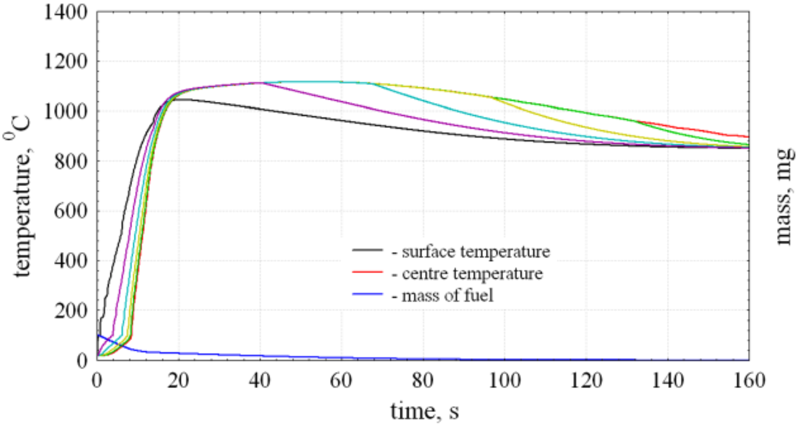


Fig. 11. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and dust of hard coal (Staszic mine) during combustion in air; $t = 850°C$, $M = 50\%$, $m = 100$ mg

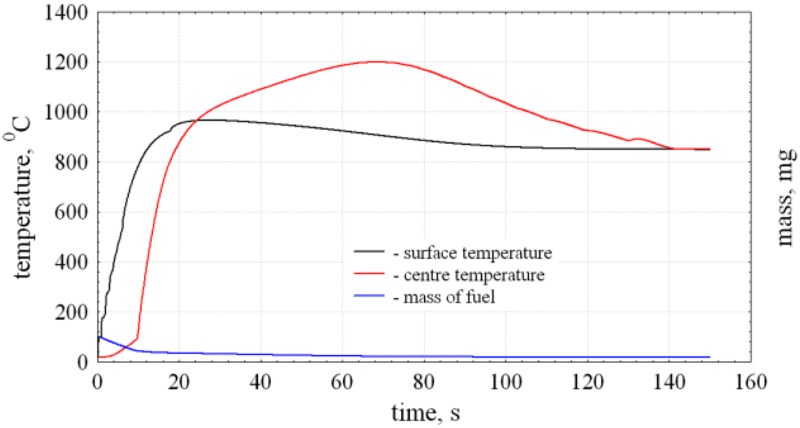


Fig. 12. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and dust of coal-mule (Sobieski mine) during combustion in air; $t = 850°C$, $M = 50\%$, $m = 100$ mg

The height contents of moisture in fuel drives to extensions of time of vaporization of fuel and of the lowering of its ignition temperatures. After introduction of fuel to combustion chamber, fuel surrenders to heating to temperatures of ignition. In this moment follows height of speed of heating of fuel to obtainments maximum temperature by surface of fuel. Then takes place gradual fall of temperature of surface of fuel, connected with char combustion, with the growth of ash layer on surface of fuel and pushing of combustion front to fuel interiors. The fuel formed from dust of coal-mule is characterized by lower temperature of combustion on its surface. Height of biomass addition to fuels causes shortening time of combustion process of fuel and drives to lowering of average temperature of fuel surface, in comparison to suspensions formed exclusively from coal-dust.

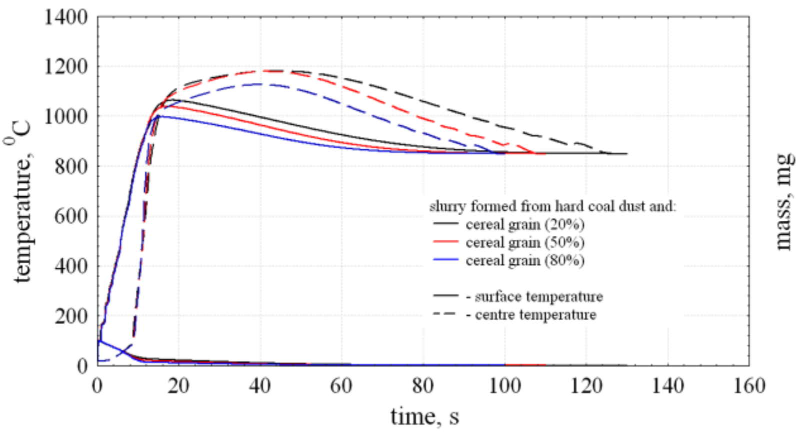


Fig. 13. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and mixture of dust of hard coal (Staszic mine) and:
– cereal grain (20%); – cereal grain (50%); – cereal grain (80%);
during combustion in air; t = 850°C, M = 50%, m = 100 mg

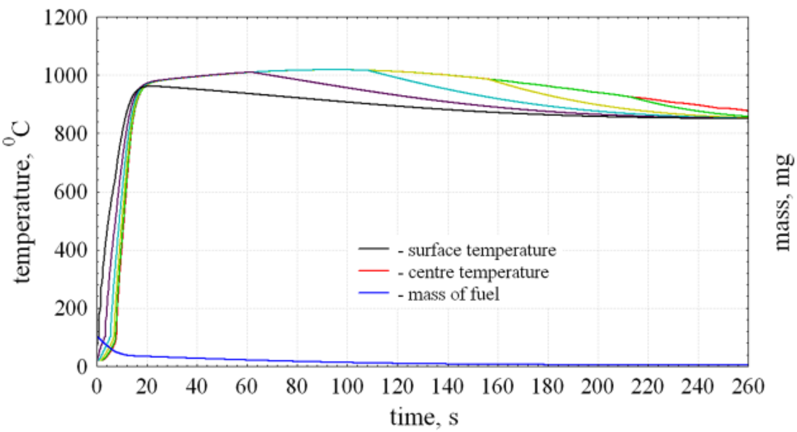


Fig. 14. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and dust of hard coal (Staszic mine) during combustion in the fluidized bed; t = 850°C, M = 50%, m = 100 mg

Specificity of the coal-water suspension combustion in a fluidized bed changes the character of mass and heat exchange between the fuel and the environment. In the conditions of a fluidized bed, at the initial combustion stage, the fuel heats faster (due to its strike with the heated material of bed) but further intensive heat exchange between the fuel and the material of bed leads to the lowering of he medium coal-water suspension (due to the fact that the flowing inert material took the heat from the suspension surface). The erosion process leads to intensive suspension mass loss to the final value which is below the initial ash mass.

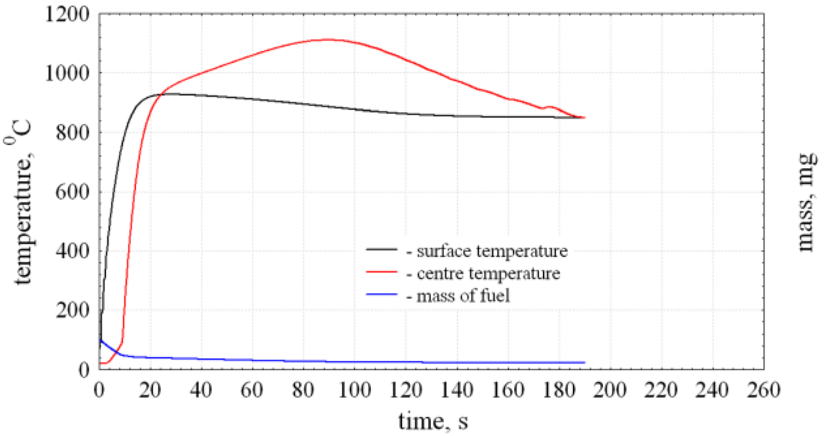


Fig. 15. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and dust of coal-mule during combustion in the fluidized bed; t = 850°C, M = 50%, m = 100 mg

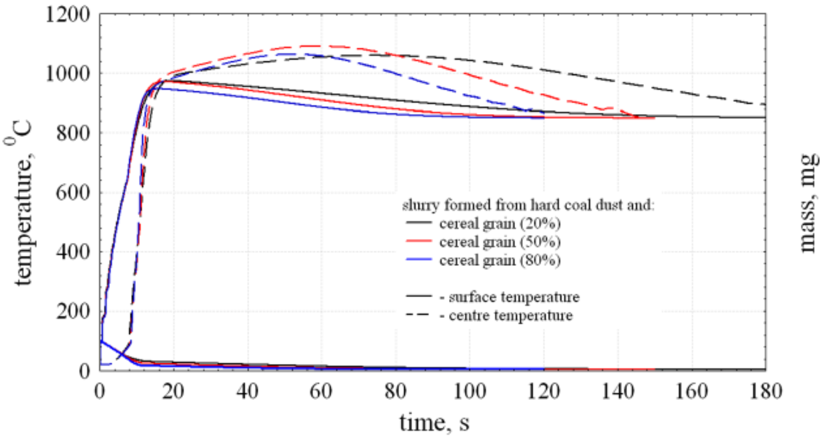


Fig. 16. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and mixture of dust of hard coal (Staszic mine) and:
– cereal grain (20%); – cereal grain (50%); – cereal grain (80%)
during combustion in the fluidized bed; t = 850°C, M = 50%, m = 100 mg

5. Conclusions

The research results presented in the paper and the theoretical analyses considering the combustion of coal-water suspension, allowed to formulate the following conclusions:

Different moisture share in the suspension leads to the change in both the mechanism and kinetics of combustion. Water from the coal-water suspension clearly intensifies the combustion process, causing among others, the lowering of ignition temperature.

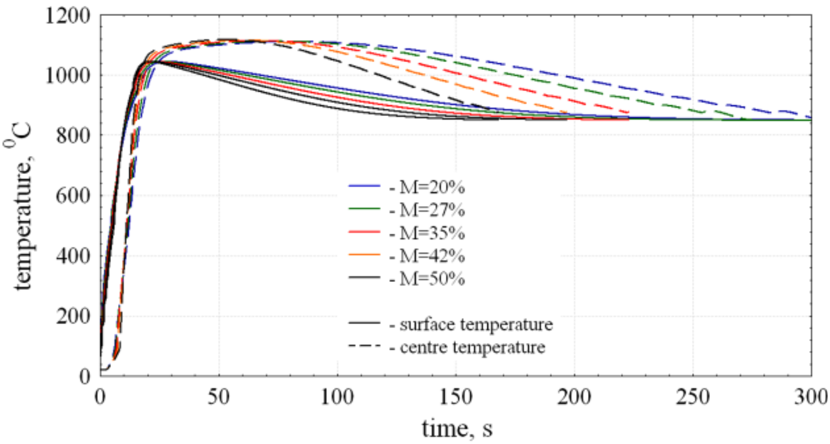


Fig. 17. Numerically calculated course of changes of surface and centre temperature of fuel formed from water and dust of hard coal (Staszic mine) during combustion in air; t = 850°C, m = 100 mg

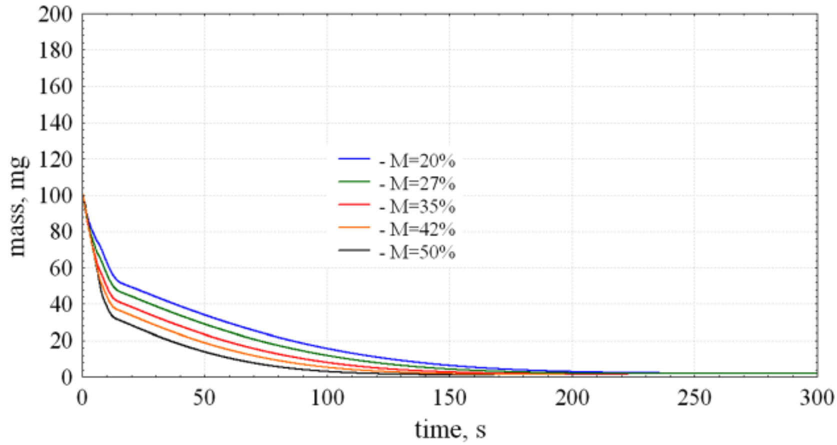


Fig. 18. Numerically calculated course of changes of mass of fuel formed from water and dust of hard coal (Staszic mine) during combustion in air; t = 850°C, m = 100 mg

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

The increase of humidity content in the suspension leads to lengthening of fuel ignition time.

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.

The worked out mathematical model contains the equations considering all phenomena accompanying the suspension fuel combustion in various conditions: in the air stream and in the conditions of fluidized bed. The suggested model describes with the sufficient precision, the above mentioned processes, that take place during the research experiments.

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