VERTICAL SWIRL CHAMBER FOR COAL GASIFICATION AND VITRIFICATION OF FLY ASH

Robert Zarzycki[1*]

[1]*Department of Energy Engineering, Czestochowa University of Technology, Brzeźnicka 60a, 42-201 Częstochowa, Poland*

*Email: zarzycki@is.pcz.czest.pl

Abstract – This study presents a concept of vertical swirl for coal gasification and vitrification of fly ashes. The concept is based on the use of fragmented coal in the process of fly ash melting. The coal dust supplied to the swirl chamber and gasified in the atmosphere of O_2, CO_2 allows for obtaining combustible gases composed of CO and volatile matter (VM), which are burnt with the pneumatically supplied fly ash. The above process allows for obtaining a product in the form of molten slag which does not contain coal grains. The study presents numerical calculations for the process of combustion and coal dust gasification and opportunities for ensuring adequate parameters in the fly ash melting zone. The combustible gases containing over 80% CO obtained during the process of gasification can be supplied to the chamber of a pulverized coal-fired boiler.

INTRODUCTION

Production of electricity and heat in many countries, including Poland, has been based on the processes of fossil fuel combustion, especially hard coal and brown coal. Processes of combustion lead to emissions of CO_2, SO_x, NO_x and dusts in the form of fly ash to the atmosphere. Development of the flue gas treatment allows for a substantial reduction in the emissions of pollutants (including dusts) to the atmosphere. Processes of hard coal and brown coal combustion in pulverized coal-fired boilers and fluidized-bed boilers are incomplete and may result in high content of coal in the separated fly ash. Fly ash is mainly used to fill the excavations in mines and often discharged to landfill sites. Fly ash can be also used in production of building materials (cement, granular materials) which have to meet adequate requirements contained in the building standards concerning carbon content (Zarzycki, 2016; Zarzycki and Bis, 2016).

If fly ash composition is different than the composition required in the building materials industry or the standards concerning storage of combustion by-products, it is necessary to process the fly ash in order to remove (treat) the contaminants present in ash. One of the solutions for this problem is vitrification (Zarzycki, 2016; Zarzycki and Bis, 2016) and the use of the product obtained in order to manufacture building materials. This study presents the concept of a chamber for coal dust gasification and fly ash melting for the purposes of vitrification.

FLY ASH VITRIFICATION

Vitrification is a technological process that consists in controlled heat supply can be found in (Kordylewski and Robak, 2002) for vitrified substances in order to separate gases and combustible substances (e.g. carbon) and then to melt the remaining mineral substance. Using the controlled cooling of the liquid phase, ceramic materials with desirable mechanical properties and structure can be obtained. Process of fly ash vitrification can be compared to glass production in a glass furnace, with high temperatures leading to melting of the mineral substance. Apart from the supply of the sufficiently high temperature, the process of melting of the mineral substance in fly ashes requires supplying the required amount of heat for phase transitions. The heat source is electricity (resistance heating and plasma heating) or heat obtained through combustion of fuel (natural gas, burning oil) in rotary furnaces and cyclone furnaces can be found in (Huczko et al., 2000). The energy of around 2 [MJ/kg] can be found in (Kordylewski and Robak, 2002) is needed for melting the mineral matter in fly ashes. In the case of plasma and arc methods, the energy demand for vitrification was evaluated as ranging from 3.6 to 18 [MJ/kg] can be found in (Huczko et al., 2000). The vitrification processes based on the use of electric power are mainly performed on a smaller scale due to high energy costs. However, the use of chemical energy contained in the fuel for vitrification and, simultaneously, for e.g. supply of hot combustible gases to pulverized-bed furnace improves energy efficiency and ensures a substantial reduction in unit costs of the process. Using fly ashes with higher carbon content for vitrification allows for utilization of the internal chemical energy while reducing the demand for fuel for the vitrification process.

The basic components of fly ashes include silica (SiO_2), aluminum compounds (e.g. Al_2O_3), iron compounds (e.g. Fe_2O_3), calcium compounds (CaO) and magnesium compounds (MgO). The mixtures of these oxides

reach melting temperatures ranging from 1,200 to 1,800ºC. Melting temperature can be reduced through addition of fluxes such as CaO or FeO. In many cases, CaO is present in fly ashes in a natural form. The use of the fluxes helps control vitrification process in order to ensure complete ash melting. Therefore, the temperatures in the melting temperature ranging from 1,500-2,000ºC will allow for melting of fly ashes and obtaining the slag in the molten form.

THE CONCEPT OF OPERATION OF THE CHAMBER FOR COAL GASIFICATION AND VITRIFICATION OF FLY ASH

The above presented requirements for the vitrification process can be met through combustion of fuel in the form of natural gas, fuel oil or coal dust. The use of natural gas or fuel oil as a fuel makes it easier to control the vitrification process. However, this can involve increased costs due to the high unit energy prices compared to coal. Furthermore, the use of the coal dust in the process of vitrification (Zarzycki, 2016; Zarzycki and Bis, 2016) substantially reduces the unit costs of the process, but it can also lead to the presence of incompletely burnt coal grains in the obtained product (molten slag), which substantially deteriorates the quality of the final product. In order to utilize coal in the vitrification processes it is necessary to gasify coal dust in the strong eddy stream of oxidant and then to control combustion of the part of combustible gases with pneumatically supplied fly ash. This solution allows for the use of cheap fuel such as coal dust (from hard coal or brown coal) in the vitrification process and the fly ash melting process can be performed using combustible gases, which limits the carbon content in the product to the minimum level. The vitrification process has to be performed at temperatures which exceed melting points of the compounds contained in the ash. It is known that NO_x emissions in such temperatures are very high due to the presence of nitrogen contained in the air. However, vitrification in the oxy-fuel atmosphere can substantially reduce NO_x emissions. Using the oxy-fuel atmosphere may also improve the adiabatic combustion temperature, which is essential from the standpoint of the process. However, the opportunities for temperature control due to thermal strength of materials of the vitrification chamber should also be taken into consideration. It can be performed using three methods:

• Combustion process in substoichiometric conditions: coal dust gasification - CO generation;

• Combustion process in substoichiometric conditions with presence of water steam: coal dust gasification - H_2 generation;

• The use of flue gas recirculation.

These methods help control temperature and composition of the combustible gas obtained through gasification of the coal dust. Apart from its basic function, the proposed vitrification chamber can also be used as a system for coal dust gasification and supplying gaseous fuel to a pulverized-bed furnace.

Figure 1 presents the diagram of a chamber for coal dust gasification and fly ash vitrification. It was divided into 5 parts denoted from SC1 to SC5. In side walls, chambers SC1, SC2 and SC3 feature tangentially installed sets of nozzles that supply gas (O_2, CO_2) in order to form the eddy of coal dust and to control the combustion and gasification. The SC1 chamber (Fig. 1d) is equipped in 5 steps (thresholds) used to elongate the time of coal dust presence while reducing the falling rate. The stepped conically-shaped SC2 chamber is located below the SC1 chamber (Fig. 1c). With the decrease in the diameter with the flow, it is possible to increase the centrifugal force and, therefore, to maintain the state of eddy motion of the substantial mass of the coal dust. The cylindrical chamber SC3 (Fig. 1c) performs the role of the last step of combustion, coal dust gasification and combustion of the part of combustible gases generated in the chamber SC1 and SC2. The chamber SC4 below this part performs the role of the fly ash melting chamber. The upper part of the SC4 chamber features the nozzles that allow for the pneumatic transport of the fly ash in the gas stream with controlled oxygen content. Below this part is the SC5 chamber used to separate the melted drops of fly ash from the stream of gases that leave the boiler. This chamber has a centrally installed plunger (Fig. 1b) and tangentially installed outlet of gases which can be transported to the afterburning chamber or the pulverized coal-fired boiler. The lower part of the SC5 chamber predicts the place for collecting of molten slag that flows to the SC4 chamber and its outflow in order to be cooled.
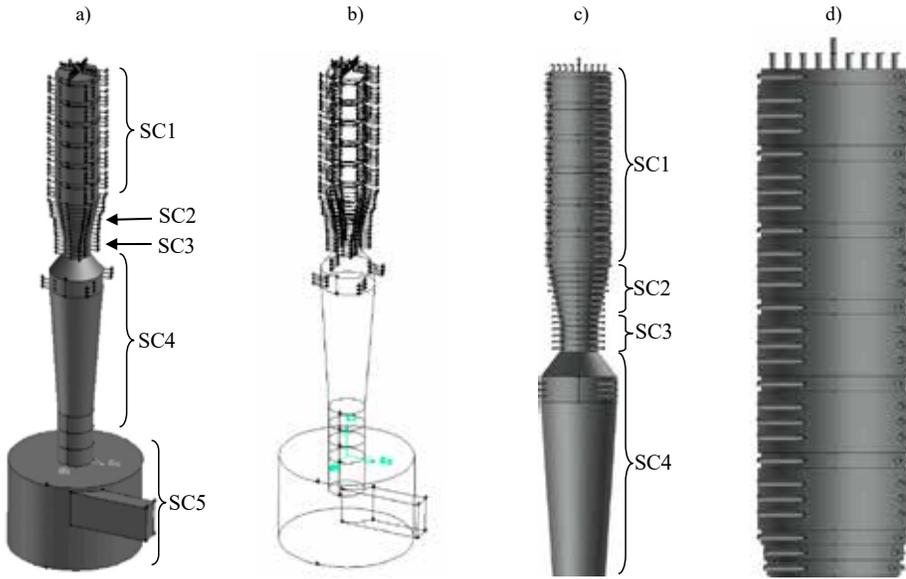
Fig. 1. The design of the chamber for coal dust gasification and fly ash vitrification

MODELLING OF COAL DUST GASIFICATION PROCESS

The Reynolds Stress turbulence model was used due to strong gas eddy and fuel eddy in the swirl chamber. Modelling of flow of coal grains was based on the Discrete Phase Model, whereas coal dust combustion was performed using Species Transport model, which allows for modelling chemical reactions both in the solid phase and gaseous phase can be found in (Toporov et al., 2008; Vascellari and Cau, 2009; Chen et al., 2010; Warzecha and Bogusławski, 2012). Calculations were based on the radiation model termed Discrete Ordinate.

Calculations of the combustion process and gasification of coal dust with replacement diameter of 500 [µm] were carried out for the fuel with physicochemical parameters presented in Table 1. For simplification purposes, it was adopted that the fuel does not contain sulphur. Reaction rate constants can be found in (Toporov et al., 2008; Vascellari and Cau, 2009). Table 1 presents the parameters of the fuel used in the study.

Table.1: Results of technical and elemental analysis of the fuel used for simulations (dry state)

Technical analysis	[-]	Elemental analysis	[-]
VM (volatile matter)	0.45	C	0.85
FC (fixed carbon)	0.45	H	0.1
A (ash)	0.05	O	0.04
M (moisture)	0.05	N	0.01

Calculations for combustion and gasification of coal dust were described with seven reactions:

- Reaction of volatile matter combustion

$$x_1 \cdot VM + x_2 \cdot O_2 = y_1 \cdot CO + y_2 \cdot H_2O + y_3 \cdot N_2$$

(1)

where x_1, x_2, y_1, y_2, y_3 are stoichiometric coefficients

- Reaction of oxidation of carbon oxide

$$CO + 0.5O_2 = CO_2$$

(2)

- Reaction of oxidation of fixed carbon (FC)

$$C_{(s)} + 0.5O_2 = CO$$

(3)

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- Boudouard's reaction

$$C_{(s)} + CO_2 = 2CO \qquad (4)$$

- Synthesis of water gas

$$C_{(s)} + H_2O = CO + H_2 \qquad (5)$$

- Hydrogen oxidation reaction

$$H_2 + 0.5O_2 = H_2O \qquad (6)$$

- Methane oxidation reaction

$$CH_4 + 1.5O_2 = CO + 2H_2O \qquad (7)$$
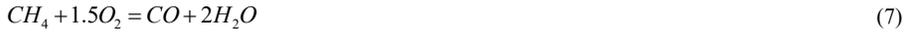
Heat loss was also taken into consideration during numerical calculations of the combustion and coal dust gasification processes. It was assumed that the thickness of walls made of high-temperature and thermal insulation concrete is 0.4 [m], whereas mean heat transfer coefficient for the wall is 0.3 [W/(m·K)]. It was assumed that a metal jacket is installed on the external part, allowing for the initial heating of feeding gases of up to 600 [K]. This allows for heat recuperation that allows for improving the mean process temperature inside the gasification reactor.

ANALYSIS OF THE RESULTS OF CALCULATIONS FOR THE COAL DUST COMBUSTION AND GASIFICATION PROCESSES

The results of calculations for combustion and coal dust gasification presented in this chapter were obtained for the fuel stream of 70 [g/s] supplied with the nozzles installed in the upper part of the SC1 chamber near the methane burner. The mixtures of O_2/CO_2 were supplied to the SC1, SC2 and SC3 chambers with the speed of 10 [m/s] and the temperature of 800 [K] using the nozzles and diameter of 20 [mm]. Furthermore, the mixture of O_2/CO_2 60/40% was supplied to the SC1 chamber, whereas the mixture of O_2/CO_2 70/30% - to the SC2 and SC3 chambers. Oxygen was supplied to the SC4 chamber with the rate of 20 [m/s] and temperature of 800 [K]. The nozzle installed in the roof of the chamber SC1 was used to supply the mixture of O_2/CH_4 with composition of 80/20% at the speed of 5 [m/s] in order to initiate the coal gasification and stabilization processes.

Adoption of the above compositions of the gaseous mixtures resulted from the assumptions concerning coal dust gasification in the chamber SC1. It was assumed that complete fuel conversion occurs in the SC2 stepped chamber through its gasification to CO. The SC3 chamber is used to ensure afterburning of the finest fuel grains and combustion of the part of gases generated in the SC1 and SC2 in order to increase temperature. The task of the SC4 is to further elevate temperature and ensure the conditions that allow for the process of fly ash vitrification, which can be supplied pneumatically with the oxygen to the SC4 chamber. Part of gases generated in the SC1 and SC2 chambers are expected to be burnt in the SC4 chamber in order to achieve adequate temperature that allows for fly ash melting.

The results of numerical computations for gas and fuel flow and the process of its gasification are presented in Figures 2, 3, 4 and 5. Supplying the gas with tangentially installed nozzles allows for generation of the swirling motion of the gas (see Fig. 2a) and the coal dust inside the chamber. With the strong eddy motion, apart from the peripheral component, the vertical gas flow is also observed in the axis of the SC1, SC2 and SC3 chambers (see Fig. 2b). With the effect of the centrifugal force, the rotating coal dust is collected mainly near the walls of the chambers SC1 and SC2 (see Figs. 2c and 2d). The stepped design of the SC1 (Fig. 1d) substantially extends the time of remaining the fuel in this zone thus limiting the rate of its transport to the SC2 chamber. The reducing diameter of the SC2 chamber (see Fig. 1c) allows for the increase in the value of the centrifugal force that affects the fuel grains, which results in elongation of the time of coal dust presence in the SC2 chamber to substantially limit the fuel flow to other parts of the swirl chamber.

With the O_2/CO_2 mixture supplied to SC1, SC2 and SC3 chambers, it is possible to reach adequate temperature (Fig. 3a, 3b) that allows for the combustion process and coal dust gasification. Figure 2e presents distribution of the parameter that presents the speed of fuel burning. The highest values of the parameter are located near the internal walls close to the locations of oxidant supply. Values of this parameter largely depend on the fuel and oxidant contents and temperature. The temperatures in the SC1 and SC2 chambers near the walls range from 1000 to 1300 [K] and should not exceed the softening point of the ash contained in the fuel. In the upper part of the SC4 chamber and the location of oxygen supply, the temperature exceeds the level of 2300 [K]. Due to the substoichiometric oxygen volume supplied to the SC1, SC2 and SC3 chambers, local temperature increases are observed directly following the gas outlet from the nozzle (see Fig. 3b) which, on the one hand ensures the adequate amount of heat to ensure the gasification

process and, on the other hand, limits the danger of melting the ash contained in the fuel in this part of the swirl chamber. The highest rate of burning of the tiniest fuel grains is observed in the upper part of the SC4 chamber which, despite the strong eddy motion in the SC2 and SC3 chamber, flow at the insignificant amount to the SC4 chamber. Figure 5 illustrates distributions of selected reaction rates denoted according to the number ordering adopted in the previous chapter. It is observed that the highest rates of conversion of the devolatilized fuel occur near the walls of SC1, SC2 and SC3 (see Figs. 5c, 5d, 5e).

Pneumatically supplied fuel is heated, dried and devolatilized in the upper part of the SC1 chamber with the area of the elevated temperatures in the chamber axis (see Fig. 3a). Fig 3c shows the distribution of fuel devolatilization rate. It is remarkable that fuel devolatilization ends in half height of the SC1 chamber. Fig. 3d presents the distribution of concentration of volatile matter in the vertical cross-section of the swirl chamber. The highest values of volatile matter concentration (Fig. 3d) are coincident with the area of the highest fuel devolatilization rates (Fig. 3c). A noticeably lower level of volatile matter concentration is observed in the axis of the SC1 chamber. This is connected with the O_2/CH_4 burner centrally installed in the roof, which operates in superstoichiometric conditions and ensures the supply of oxygen (Fig. 3e) for combustion of a specific amount of volatile matter, which is reflected by the increase in the rate of combustion of volatile matter (Fig. 5a) and temperature increase (Fig. 3a). Despite oxygen supply with the nozzles installed in side walls of the SC1, SC2 and SC3 chambers, the substoichiometric conditions are observed in these chambers, allowing for fuel gasification, and, consequently, temperature control. This is also confirmed by the distribution of CO concentration presented in Fig. 4a. It is noticeable that the highest CO concentrations occur in the bottom part of the SC1 chamber near the walls and the devolatilized fuel present in this area. More insights into the location and rate of CO generation can be provided based on the analysis of the distribution of the reaction rates (3), (4) and (5) presented in Figs. 5c, 5d and 5e, respectively. The stream obtained through combustion of fuel and volatile matter of CO_2 observed in the axis of the SC1 chamber (Fig. 4b) is diluted in the stream of CO and takes part in the reaction of fuel gasification according to the reaction (5). Furthermore, a local increase in the CO_2 content is observed in the upper part of the SC4 chamber. It results from afterburning of the tiniest fuel grains (see Fig. 5c), combustion of a specific amount of volatile parts (Fig. 5a) and combustion of the CO (Fig. 5b) and H_2 (Fig. 4e, 5f). The control of oxygen stream supplied to the nozzles installed in the SC4 ensures the control of the temperature and the amount of heat needed for vitrification of the fly ash supplied with these nozzles.

Figure 4c presents distributions of CH_4 content. Due to the excess oxygen supplied with the methane, it is quickly burnt and increases local temperature (see Fig. 3a) while stabilizing the process of combustion of volatile matter (see Fig. 3d, 5a). Consequently, elevated concentration of H_2O is observed in the axis of the SC1 chamber (see Fig. 4d). Strong mixing processes reduce the efficiency of H_2O transport near the walls, where hydrogen is generated (Fig. 4e) according to the reaction (6) (Fig. 5e).
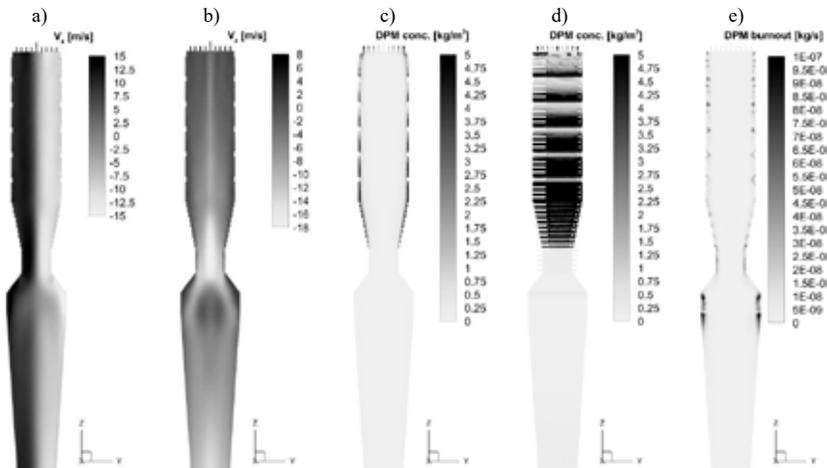

Fig. 2.Distributions of the selected process values: a) peripheral velocity component, b) vertical velocity component, c) fuel concentration, d) fuel concentration near walls, e) rate of fuel combustion.
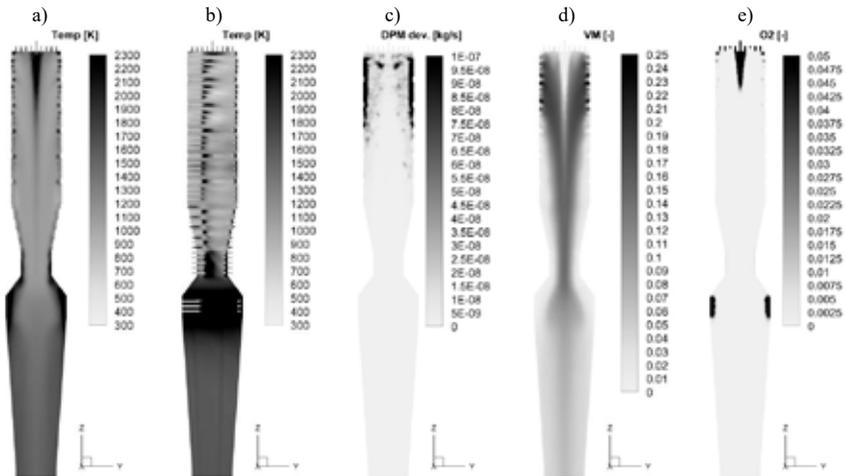
Fig. 3.Distributions of the selected process values: a) temperature, b) temperature near walls, c) fuel devolatilization rate, d) volatile matter concentration, e) O_2 concentration.
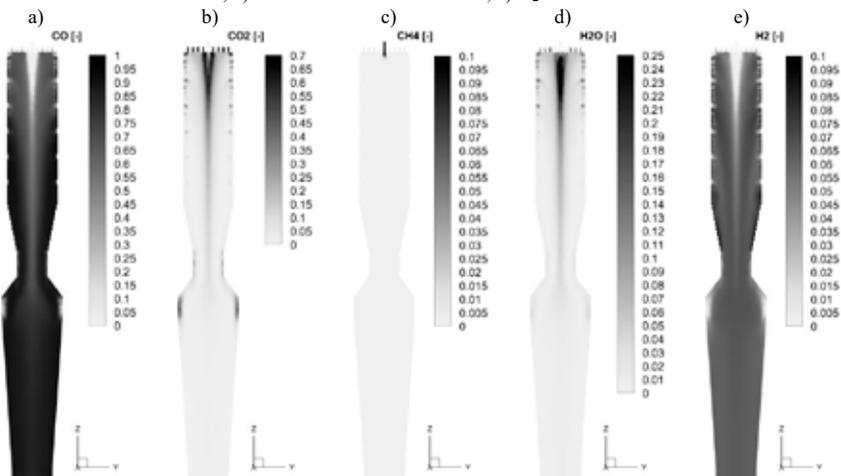

Fig. 4.Distributions of the selected process values: a) CO concentration, b) CO_2 concentration, c) CH_4 concentration, d) H_2O concentration, e) H_2 concentration.
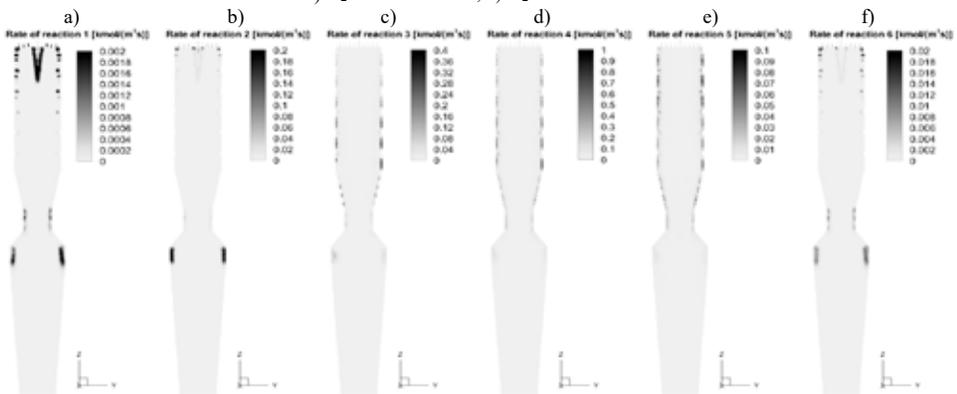

Fig. 5.Distributions of reaction rate: a) reaction (1), b) reaction (2), c) reaction (3), d) reaction (4), e) reaction (5), f) reaction (6).

Table 2 presents selected mean process parameters in the planes located at the outlet from the SC1, SC2, SC3 and SC4 chambers. Analysis of the data compared in Table 2 shows that it is possible to obtain the CO concentration at the outlet from the SC1 chamber at the level of over 86%, which insignificantly reduces to the level of 80% at the outlet from the SC4 chamber with the flow. This decline is connected with the use of the CO obtained in the process of gasification as a fuel that allows for the temperature increase. Mean temperature of gases that leave the SC4 chamber exceeds 1600 [K], which should facilitate the discharge of the molten volatile ash in the liquid form. The CO combustion results in an insignificant increase in CO_2 content. The insignificant decline in VM and H_2 concentrations is observed. Mean oxygen content at the outlet from each chamber is close to zero. The increase in mean vertical component of velocity is observed with the flow, which results, on the one hand, from generation of the gaseous components in the process of fuel gasification and, on the other hand, from the increase in mean gas temperature.

Table.2: Mean process parameters in the planes located at the outlet from the SC1, SC2, SC3 and SC4 chambers.

	CO [-]	CO_2 [-]	VM [-]	H_2 [-]	O_2 [-]	H_2O [-]	CH_4 [-]	V_z [m/s]	Temp [K]
SC1	0.867	0.010	0.049	0.070	3.70E-06	0.005	1.69E-10	-3.14	1056
SC2	0.840	0.029	0.048	0.072	1.55E-03	0.008	1.76E-10	-8.90	1155
SC3	0.815	0.056	0.040	0.060	1.70E-02	0.010	1.54E-10	-12.30	1491
SC4	0.801	0.091	0.038	0.058	3.23E-17	0.012	9.67E-11	-9.98	1609

CONCLUSION

The concept of the swirl chamber presented in this study allows for the use of the fuel in the form of the coal dust for the process of fly ash melting. With the division of the system into five chambers, the process of coal dust gasification can be effectively performed in the chambers SC1 and SC2 by generating high concentrations of CO. In order to ensure complete combustion of coal dust in the chamber SC3, the coal dust is burned or gasified with simultaneous combustion of a part of combustible gases while increasing the temperature. The role of the SC4 chamber is to increase the temperature to the expected level that depends on the composition of fly ash (its melting temperature) through combustion of the required stream of combustible gases (CO, VM and H_2). The temperature in the SC4 chamber can be controlled through adjustment of the oxygen stream. Similar method can be used to control fly ash melting efficiency. Hot gases that leave the SC4 chamber and contain over 80% CO and VM and H_2 can be supplied to the pulverized coal-fired boiler in order to ensure afterburning.

ACKNOWLEDGEMENTS

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