Swirl chamber for vitrification of fly ashes

Robert Zarzycki[1,*]

[1]Czestochowa University of Technology, Department of Energy Engineering, ul. Brzeznicka 60a, 42-201, Poland

Abstract. The study presents the concept of a swirl chamber used for vitrification of fly ashes. It assumes the use of coal dust 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 and H_2O allows for obtaining combustible gases composed of CO and H_2, which are burnt with the pneumatically supplied fly ash. The above process allows for obtaining a product in the form of a molten slag which does not contain coal grains. The study presents numerical calculations for the process of combustion and gasification of coal dust and opportunities for ensuring adequate parameters in the fly ash melting zone. The combustible gases obtained during the process of gasification can be supplied to the chamber of a pulverized-bed boiler.

1 Introduction

The use of fossil fuels for production of electricity and heat leads to the emissions of CO_2, SO_x and NO_x and dust in the form of fly ashes. Development of the flue gas allows for a substantial reduction in the emissions of pollutants (including dusts) to the atmosphere. Fly ashes are used to fill the excavations in mines and are often discharged to landfill sites. They can also be used to manufacture building materials (cement, granular materials), as they have to meet specific requirements specified by the constructional standards PN-EN 450-1:2012, PN-EN 206:2014-04 concerning mainly coal content. In many cases, fly ashes generated in the combustion processes contain, apart from considerable amounts of carbon, also CaO and other components in the amounts that do not allow for their industrial use and which cannot be safely stored. Therefore, fly ash may represent a serious problem for electricity and heat power plants. One of the solutions proposed for this problem is vitrification and the use of the product for production of construction materials. This study presents the concept of a melting chamber for vitrification of fly ashes.

2 Fly ash vitrification

Vitrification is a technological process that consists in controlled heat supply [1] 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 [2,3,4]. The energy of around 2 MJ/kg [1,2] 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 [3]. 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), aluminium compounds (e.g. Al_2O_3), iron compounds (e.g. Fe_2O_3), calcium compounds (CaO) and magnesium compounds (MgO) [1]. 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 [1]. 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.

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* Corresponding author: zarzycki@is.pcz.czest.pl

3 The concept of operation of the chamber for vitrification of fly ashes

As indicated above, the precondition for vitrification of fly ashes is to ensure adequate level of temperature and supply of heat necessary for heating and, consequently, melting of the mineral substance contained in the ash.

The required conditions of the vitrification process can be obtained through combustion of fuel in the form of the natural gas, fuel oil or coal dust. From the standpoint of the easiness of control of the combustion process, the best fuels are those in the liquid and gaseous forms. However, they are characterized by substantially higher unit energy costs compared to coal dust. On the other hand, the use of coal dust in the vitrification process may lead to the presence of non-combusted coal grains (molten slag), which substantially deteriorates properties of the product. The solution for this problem is offered by coal dust gasification in the strong eddy stream of oxidant and then controlled combustion of the part of combustible gases with pneumatically supplied fly ashes. 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 fly ash vitrification. The chamber is composed of the stepped chamber SC1, with the ignition burner fuelled with methane and designed in the roof. The inlets of coal dusts are distributed centrically around the burner. The nozzles that supply gas are installed on side walls (tangentially), with the gas leading to formation of a strong eddy of coal dust and allowing for controlled combustion and gasification. The used of the stepped chamber SC1 allows for elongation of the time of coal

dust presence while reducing the falling rate. The products which leave the chamber SC1 include gases containing CO and H_2 and insignificant amounts of CO_2 and H_2O.
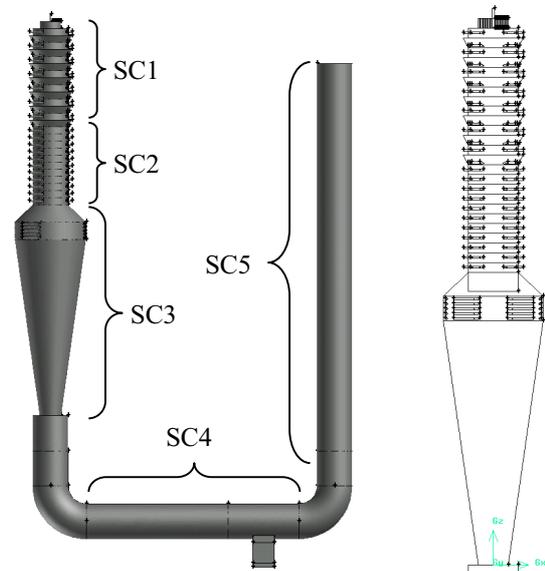

Fig. 1. The design of the chamber for vitrification of fly ashes.

It is also possible that tiny coal dust grains and ashes flow out from this chamber. The role of the cylindrical chamber SC2 with tangentially installed nozzles is to burn and gasify the tiniest fractions of coal dust and partial combustion of the gases generated in the SC1 chamber in order to ensure optimal conditions for the gasification process. No coal dust grains (only gaseous compounds and ash) are expected to be present at the outlet from the chamber SC2. The chamber SC3 below the SC2 is used as a chamber for melting of the fly ash, which, through nozzles installed in its upper part, is transported pneumatically to its interior. Gas composition (O_2, CO_2) can be used to control the degree of gas combustion for the gas generated in the chambers SC1 and SC2 and the temperature in the chamber SC3. The molten slag flows to the horizontal chamber SC4 in the form of a bath filled with molten slag with high-temperature gas flying over its surface. The second part of the chamber SC4 features outlet of molten slag. Hot gases containing combustible compounds are supplied through the channel SC5 to the chamber in the pulverized-bed furnace for afterburning.

4 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 [5,6,7,8,9]. Calculations were based on the radiation model termed Discrete Ordinate (DO).
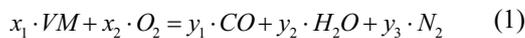
Calculations of the combustion process and gasification of coal dust with replacement diameter of 500 μm were carried out for the fuel with physicochemical parameters presented in Table 1. For simplification purposes, it was adopted that the fuel does not contain sulphur. Reaction rate constants were derived from the studies [5,6]. 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
$$x_1 \cdot VM + x_2 \cdot O_2 = y_1 \cdot CO + y_2 \cdot H_2O + y_3 \cdot N_2 \quad (1)$$
where x_1, x_2, y_1, y_2, y_3 are stoichiometric coefficients
- Reaction of oxidation of carbon oxide
$$CO + 0.5O_2 = CO_2 \quad (2)$$
- Reaction of oxidation of fixed carbon (FC)
$$C_{(s)} + 0.5O_2 = CO \quad (3)$$
- Boudouard's reaction
$$C_{(s)} + CO_2 = 2CO \quad (4)$$
- Synthesis of water gas
$$C_{(s)} + H_2O = CO + H_2 \quad (5)$$
- Hydrogen oxidation reaction
$$H_2 + 0.5O_2 = H_2O \quad (6)$$
- Methane oxidation reaction
$$CH_4 + 1.5O_2 = CO + 2H_2O \quad (7)$$
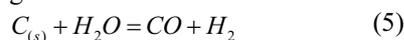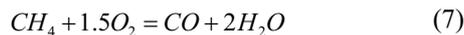
5 Analysis of the results of calculations for the coal dust combustion and gasification processes

The results of calculations presented in this chapter were obtained for the flow rate that is supplied with the nozzles installed near the methane ignition burners for coal dust of 15 g/s. The gas for SC1, SC2 and SC3 chambers was supplied with the rate of 20 m/s with temperature of 600 K through the nozzles with diameter of 20 mm. The volumetric fractions of the gas supplied to the chamber SC1 were 40% for O_2 and 60% for H_2O. The gas supplied to the chamber SC2 contained 30% of O_2 and 70% of CO_2, whereas the gas supplied to the chamber SC3 was characterized by 40% of O_2 and 60% of CO_2. The nozzle installed in the roof of the chamber SC1 was used to supply the mixture of 80% of O_2 and 20% of CH_4 in order to initiate the coal gasification process and its stabilization.

Adoption of the above compositions of the gaseous mixtures resulted from the assumptions concerning coal dust gasification in the chamber SC1, where CO and H_2 are produced. Gasification or combustion of tiny fuel

grains in the atmosphere of gases generated in the chamber SC1 in order to limit their flow to the chamber SC3 were assumed for the chamber SC2. The final combustion and gasification of the tiniest fuel grains and combustion of a part of the products of coal gasification in order to obtain the temperature required for fly ash heating and melting (depending on fly ash composition) occur in the chamber SC3, with the fly ash supplied with the gas stream flowing to this chamber.

The results of numerical computations for gas and fuel flow and the process of its gasification are presented in Figures 4, 5 and 6. 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 (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. 2b and 2c). The steps of the chamber SC1 (Figs. 2b and 2c) allow for maintaining the eddy of the greater fuel mass near the wall, which substantially extends the time of its remaining in the gasification zone. Tiny and the tinniest grains are transported with the flow to the chamber SC2, where strong eddy is also maintained (see Fig. 2b). With the gaseous mixture with oxygen supplied to the chambers SC1 and SC2 and with adequate temperatures, it is possible to perform combustion and gasification of the fuel, which can be observed in Fig. 2d that presents the parameter responsible for fuel conversion rate. It is noticeable that the highest values of this parameter occur near the walls of the chambers SC1 and SC2 in the location of gas supply. The values of this parameter in the chamber SC2 are reduced, which reflects fuel conversion from the solid state to gaseous products of combustion or gasification.

The fuel supplied in the upper part of the SC1 chamber (see Fig. 2c) is quickly heated by the central methane burner flame and the burnt and gasified fuel present near the walls. Fuel devolatilization process is presented in Figs. 3a and 3b which present the rate of devolatilization process and volumetric fraction of volatile matter, respectively. Through fragmentation of fuel to the form of dust and its eddy motion, devolatilization occurs very intensively (see Fig. 3a), which is reflected by high concentration of volatile matter (Fig. 3b). While increasing the distance from the location of fuel supply, the concentration of volatile matter declines through their partial oxidation and dilution in the gaseous component of the coal gasification process in the chamber SC1.

The process of fuel gasification requires adequately high temperature and the amount of heat for endothermic reaction. Consequently, the gas with oxygen is supplied at the level of the chambers SC1 and SC2. Partial combustion of coal dust and gasification products occurs in this case in order to maintain the assumed temperature (see Fig. 4a). The amount of oxygen supplied to SC1 and SC2 is substoichiometric (Fig. 3c) and allows only for maintaining the assumed temperature that guarantees performing the processes of coal dust gasification. The function of the SC3 chamber is to melt fly ash. For this purpose, gas is supplied to the chamber SC3 with the oxygen content (see Fig. 3c) such that the conditions that

ensure melting of fly ash are obtained (see Fig. 4a). Then, a part of flue gas is burnt in the chambers SC1 and SC2, which is reflected by the increase in CO_2 and H_2O concentrations in the upper part of the chamber SC3. The temperature in the chamber SC3 can be adjusted by changing oxygen concentration in the supplied gas so that the performance of this chamber (connected with the amount of the vitrified fly ash) can be controlled.
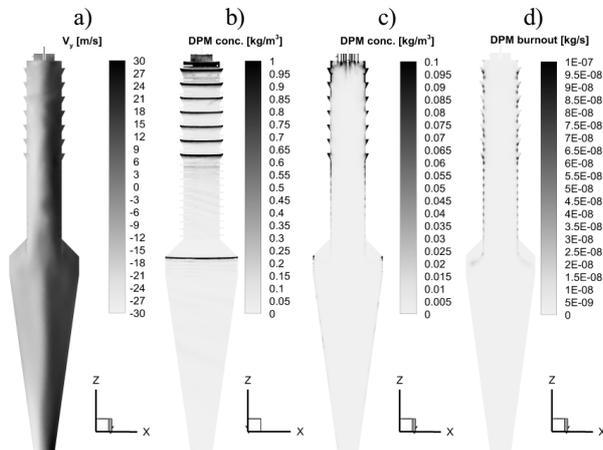
Fig. 2. Distribution of (a) peripheral velocity component, (b) fuel concentration on chamber walls and (c) in vertical cross-section of the chamber and (d) combustion rate.
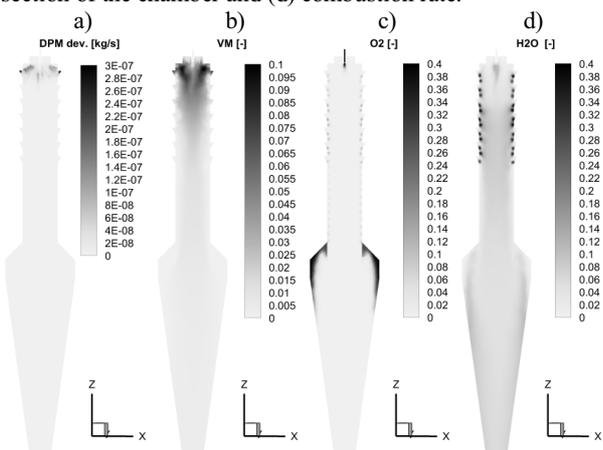
Fig. 3. Distribution of (a) devolatilization rate, (b) molar fractions for volatile matter, (c) molar fractions for O_2 and (d) molar fractions for H_2O.
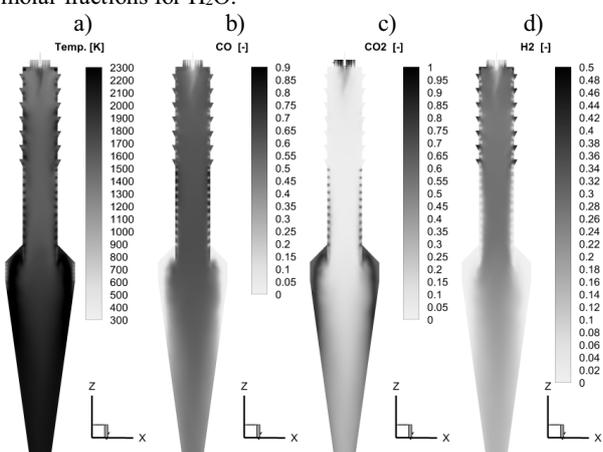
Fig. 4. Distribution of (a) temperature, (b) molar fractions for CO, (c) molar fractions for CO_2 and (d) molar fractions for H_2.

Supplying the gas with content of O_2 and H_2O to the chamber SC1 (see Fig. 3d) yields CO through fuel gasification (see Fig. 4b, Table 2) and H_2 (Fig. 4d, Table 2). Supplying the mixture of O_2 and CO_2 to the chamber SC2 allows for control of temperature through combustion of a certain part of the gases generated during gasification and the tiniest grains of the coal dust.

Table 2 presents means values of volumetric fractions of the main gaseous components and mean temperatures at the outlet from the chambers SC1, SC2 and SC3. The results demonstrated generation of CO and H_2 in the SC1 chamber as a result of coal dust gasification with the mixture of O_2 and H_2O. A decline in concentration of CO and H_2 is observed at the outlet from the chamber SC2, resulting from their partial combustion and leading to the temperature increase. Further decline in CO and H_2 concentrations is observed at the outlet from the chamber SC3, which is connected with combustion for the purposes of generation of heat necessary for melting of fly ash. Hot gases that leave the chamber SC3 and contain combustible components in the form of CO and H_2 can be supplied to the pulverized-bed furnace chamber in order to ensure afterburning.

Mean temperatures in the chambers SC1, SC2 and SC2 were 1,579 K, 1,645 K and 2,131 K, respectively. The mean temperature in the chamber SC3 ensures the required conditions of fly ash melting.

Table 2. Volumetric fractions of gaseous components in cross-sections located at the outlet from the chambers SC1, SC2, SC3.

At the outlet from the chamber	CO [%]	CO_2 [%]	H_2 [%]	H_2O [%]	O_2 [%]	VM [%]	Temp. [K]
SC1	63.32	2.31	24.67	8.83	0.42	0.45	1658.8
SC2	55.65	21.79	16.45	4.29	1.42	0.4	1789.9
SC3	43.44	36.94	12.93	6.39	0	0.3	2160.4

6 Conclusion

The concept of the system 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 three chambers, the process of coal dust gasification can be successfully performed in the chamber SC1 while yielding high concentrations of CO and H_2. In order to ensure complete combustion of coal dust in the chamber SC2, the coal dust is burned or gasified with simultaneous combustion of a part of combustible gases while increasing the temperature. The role of the chamber SC3 is to increase the temperature to the expected level that depends on the composition of fly ash (its melting temperature) through combustion of a part of volatile gases (CO and H_2). The temperature in the chamber SC3 can be controlled through adjustment of oxygen concentration in the supplied gas. Similar method can be used to control fly ash melting efficiency. Hot gases that leave the chamber SC3 and contain CO and H_2 can be supplied to the pulverized-bed furnace in order to ensure afterburning.

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