MODELING OF OXY-COMBUSTION AND GASIFICATION LIGNITE DUST IN A CYCLONE FURNACE

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Abstract – This study presents the results of numerical calculations of the process of combustion and gasification of brown coal in a cyclone furnace. The design of the cyclone furnace allows for separation of the processes of heating, drying and coal dust devolatilization from the processes of combustion and gasification. The process of gasification of the carbon residue was performed in the atmosphere of O_2/CO_2 (substoichiometric conditions), whereas in the bottom part of the cyclone furnace, combustion (superstoichiometric conditions) of the non-reacted carbon residue was conducted, thus ensuring the required amount of heat and the gasification factor in the form of CO_2 sufficient for the gasification process. Combustion of the carbon residue allows for achievement of the temperatures that allow for vitrification of the ash contained in the coal. Gasification process helps control temperature under conditions of elevated oxygen concentration. The process also makes it possible to obtain the gases with content of CO exceeding 80%, which can be used for energy purposes e.g. for feeding the ignition burners in the boilers.

INTRODUCTION

The constant development of civilization is followed by the increasing demand for electricity and heat. In Poland, generation of electricity and heat is connected with combustion of fossil fuels in the form of hard coal and brown coal. Processes of combustion of fossil fuels are one of the main factors to affect the status of natural environment. Despite the development of technologies that limit the negative impact of the energy sector on the natural human environment, the emissions of CO_2 during combustion of fossil fuels have failed to be limited so far. Recent years have seen explorations aimed to find new technologies that allow for a more effective utilization of the chemical energy contained in fuel at the lowest possible impact on the natural environment. The solutions that have been used include oxy-fuel combustion technologies in both pulverized coal-fired boilers and fluidized-bed boilers (Nowak and Czakiert, 2012; Nowak et al., 2013; Nowak et al., 2014; Nowak et al., 2015;), building high-performance energy power units that are operated at supercritical conditions (Chmielniak and Łukowicz, 2015; Rusin, 2015) or initial fuel processing that consists in its underground or on-ground gasification (Borowiecki et al., 2008).

One of the major problems faced by the industrial energy sector is the rapid development of the renewable energy based on the use of wind. It concerns the necessity to improve flexibility of coal-fired power units connected with fast changes in generation of electricity from renewable sources and opportunities for reduction in the minimum load of the coal-fired power units. Reduction in the minimum load to the level of 15 to 20% from the current 40% is impossible without using the ignition burners fed by light fuel oil or gas. The use of ignition burners to maintain boiler operation at a low level of minimum load or during its start-up is connected with the increase in costs of fuel (fuel oil, gas).

One of the solutions that can be used as an alternative to ignition burners is to build cyclone furnaces. The design of a cyclone furnace allows for performance of the process of coal dust gasification in substoichiometric conditions (O_2, CO_2) while the combustible gases obtained during the process (CO, H_2, CH_4) can be supplied to the boiler chamber through e.g. nozzles of the ignition burners or, after adequate preparation, used in the chemical processes as a raw material. The use of the cyclone furnace fed by coal dust should allow for a substantial reduction in the costs of maintenance of the boiler in the state of a hot reserve or the load of ca. 15 to 20%. This study presents numerical calculations of operation of the furnace for gasification of brown coal for the purposes of supplying fuel to the boiler in the power unit.

CYCLONE FURNACE

Cyclone furnaces are power-generating devices with fuel combustion or gasification processes occurring in a strong eddy flow of gases. These furnaces have a relatively small combustion chambers compared to the equipment used in the energy sector. This allows for reaching high temperatures during the combustion process or during fuel gasification and for utilization of the furnaces for melting of the ash contained in the fuel. Due to high temperatures that occur in cyclone furnaces, it is recommended to replace air with other oxidizing agents without nitrogen in order to limit NO_x emissions. The use of recirculation of oxygen-rich flue gas or, additionally, water steam, substantially limits the emissions of NO_x.

Combustion in the oxygen-rich atmosphere leads to a considerable increase in temperature, with its values exceeding thermal strength of the ceramic materials used for construction of the furnace. Therefore, with higher oxygen concentrations, the temperature that can be obtained has to be controlled through: flue gas recirculation, combustion in the substoichiometric conditions (gasification), injection of water or water steam in order to reduce temperature (evaporation of water, overheating the steam) or the use of water steam in the process of coal gasification. Control of temperature through gasification of fuel inside the cyclone furnace helps obtain combustible gases composed mainly of CO and H_2 with contents that depend on process conditions. Strong eddy makes it possible to elongate time of fuel stay in the combustion or gasification zone, thus limiting the waste of incomplete burning. With strong eddy motion, ash separation and vitrification in cyclone furnace is also feasible. After moving to the pulverized coal-fired boiler, hot combustible gases generated in the process of gasification (CO, H_2) can support its operation or stabilize coal dust combustion process at low load. It is possible to supply gases generated to cyclone furnace in order to maintain the hot reserve state.

PROCESS OF COAL DUST COMBUSTION AND GASIFICATION IN CYCLONE FURNACE

The process of brown coal dust combustion and gasification was conducted in a furnace presented in Fig. 1. It is composed of the three chambers: upper chamber (PC2) and lower chamber (PC1) and the chamber (PC3) for the afterburning of generated gases. Chamber PC3 can be a combustion chamber of the boiler dust. The PC2 chamber is cylindrical, with its upper part featuring tangentially installed channels which supply coal dust pneumatically in a stream of CO_2 (recirculated flue gas). The PC1 chamber is also cylindrical and is composed of six levels with reducing diameters. There are nozzles on lateral surfaces of the chamber PC1 which allow for supply of the "driving" gas with assumed composition of O_2 and CO_2. The chambers PC1 and PC2 are connected with a channel with a plunger used to separate the flow of flue gas from the chamber PC1 to PC2 and the fuel flow (carbon residue) from the chamber PC2 to PC1 (Fig. 1).

With the cyclone furnace divided into two chambers, it is possible to perform the processes of heating, drying and devolatilization of fuels in the upper chamber (PC2) and processes of combustion and gasification of the devolatilized fuel in the lower chamber (PC1) to which the recirculated flue gas rich in oxygen (CO_2 and O_2) can be supplied. The gasification process requires an adequate temperature and supplying the heat to ensure endothermic gasification reactions. Therefore, it is necessary to burn a part of fuel in the lower part of PC1 chamber (superstoichiometric conditions) in order to maintain the conditions of the brown coal gasification process in upper part of PC1 chamber (substoichiometric conditions). The concept and design of the cyclone furnace was developed within the Strategic Program "ADVANCED TECHNOLOGIES OF ENERGY GENERATION" (Zarzycki et al., 2016; Zarzycki and Bis, 2016a; Zarzycki and Bis, 2016b; Zarzycki and Bis, 2017).

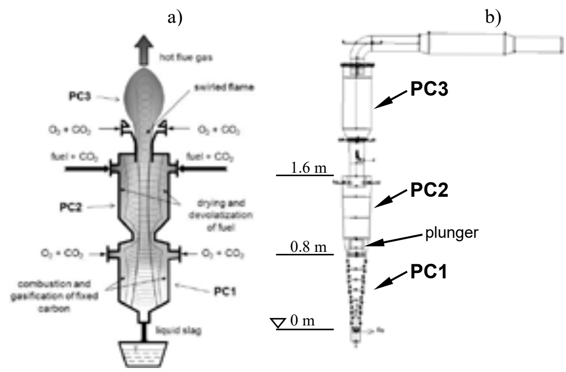


Fig. 1. Diagram a) and view b) of the model of a cyclone furnace with after-burner chamber

The geometry of the cyclone furnace was designed using the Gambit software (Fig. 1b). Furthermore, the ANSYS FLUENT 14 software was also used for the calculations. Calculations of gas and fuel flow were performed using the Reynolds Stress turbulence model. Discrete Phase Model software was employed to model coal grain flow. Coal dust combustion and gasification was modelled using Species Transport model, which allows for modelling of chemical reactions both in the solid phase and gaseous phase can be found in (Toporov at al., 2008; Vascellari and Cau, 2009; Chen at al., 2010; Warzecha and Bogusławski, 2012). 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 300 [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 (Vascellari and Cau, 2009; Chen at al., 2010). Model of fuel devolatilization in the FLUENT software allows for *VM* (volatile matter) component responsible for the content of volatile matter. In the model not taken into account the formation of tar during devolatization fuel. Table 1 presents the parameters of the fuel used in the study.

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

Technical analysis	[-]	Elemental analysis	[-]
VM (volatile matter)	0.345	C	0.48
FC (fixed carbon)	0.320	H	0.05
A (ash)	0.220	O	0.46
M (moisture)	0.115	N	0.01

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

- Reaction of volatile matter combustion

$$1\ VM = C_{0.13}\ H_{2.92}\ O_{1.55}\ N_{0.0422}$$
$$1\ VM + 0.02\cdot O_2 = 0.13\cdot CO + 1.46\cdot H_2O + 0.0211\cdot N_2 \tag{1}$$

- Reaction of oxidation of carbon oxide

$$CO + 0.5O_2 = CO_2 \tag{2}$$

- Reaction of oxidation of fixed carbon (FC)

$$C_{(s)} + 0.5O_2 = CO \tag{3}$$

- Boudouard's reaction

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

- Synthesis of water gas

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

- Hydrogen oxidation reaction

$$H_2 + 0.5O_2 = H_2O \tag{6}$$

- Methane oxidation reaction

$$CH_4 + 1.5O_2 = CO + 2H_2O \tag{7}$$

Conditions of coal dust gasification process modelling were as follows: flow of coal dust with mean grain size of 300 [µm] of 1.5 [g/s] supplied tangentially with two inlets located at the opposite sides of the chamber PC2 (Fig. 1) in the CO_2 with temperature of 350 [K] and the velocity of 3 [m/s]. Following a helical line, the fuel moves downwards in the chamber PC2 as it is heated, dried and devolatilized through the effect of hot flue gas that flows in the furnace axis and contact with hot walls of the chamber PC2. Fuel gasification occurs through partial combustion of fixed carbon (FC) in the chamber PC1 can be found in (Zarzycki and Bis, 2016a; Zarzycki and Bis, 2016b; Zarzycki and Bis, 2017). The driving nozzles were used to supply (tangentially) the driving gas composed of the mixture of O_2/CO_2 with volumetric content of 45/55% with the velocity of 3.5 [m/s] and temperature of 600 [K]. The numerical model takes into consideration the heat transfer through furnace walls to its surroundings. Actual thickness of individual components of the laboratory furnace was also assumed during calculation of heat loss, with coefficients of heat penetration and conduction for the materials. It was adopted that air temperature around the furnace is 300 [K].

ANALYSIS OF COAL DUST COMBUSTION AND GASIFICATION

The aim of this study was to analyse the process of combustion and gasification of brown coal dust in oxy-fuel conditions. The process of modelling of oxy-fuel combustion of coal dust starts from supplying the fuel to the upper part of the chamber PC2 through two tangential inlets located at the opposite sides of the chamber. The fuel flow rate of 1.5 [g/s] was ensured pneumatically at the speed of 3 [m/s] in the CO_2 stream with the temperature of 350 [K]. A set of nozzles were used to supply "driving" gas tangentially to the chamber PC1 at the rate of 3.5 [m/s], with molar fractions ranging from 45% O_2 to 55% H_2O and the temperature of 900 [K]. A nozzle was built in the lower part of the PC1 chamber, used to supply the mixture of O_2/CH_4 with volumetric ratio of 80/20% at the speed of 10 [m/s] in order to initialize the process of coal dust combustion and stabilization. The excess oxygen supplied with the nozzle was used in the process of combustion and gasification of the coal dust.

The results of the calculations of the process of coal dust combustion and gasification are presented in Figs. 2 and 4. Fig. 2 shows selected process values in the vertical cross-section and on the lateral surface of the cyclone furnace. Furthermore, Fig. 4 presents the profiles of selected process values along the furnace axis (line *z0*) and along two lines presented in Fig. 3, located near the driving nozzles (line *z1*) and along the line shifted by the angle of 90^o (line *z2*).

Fig. 2 presents distribution of selected process values for the analysed case of coal dust combustion and gasification. Using the nozzles located in the chamber PC1 (lower chamber), the driving gas was supplied, causing formation of eddies of gas (Fig. 2a) and the fuel. With the effect of the centrifugal force, the fuel in the form of the coal dust is accumulated at individual levels of the chamber PC1 (Figs. 2b, c, d). Spurts of the fuel supplied are noticeable in Fig. 2c in the upper part of the PC2 chamber. With the design of the internal plunger between the PC2 and PC1 chambers, the transport of the fuel flowing to the PC1 chamber is limited (Fig. 2d). Substoichiometric amount of the oxidant was supplied to the chamber PC1, which is illustrated in Fig. 2e. The elevated oxygen concentration is observed only near the driving nozzles (see Fig. 4a) and near the lower nozzle (see Fig. 4a) fed by the mixture of O_2/CH_4 with volumetric ratio of 80/20% (lower part of the PC1 chamber). With strong eddy motion of the gas and fuel in the PC1 chamber (see Fig. 2a) and substoichiometric amount of oxygen supplied to the PC1 chamber, the temperature distribution was as shown in Fig. 2f. High values of temperature can be observed in the lower part of the PC1 chamber (Fig. 4b). They result from afterburning of the fuel residue which was not gasified in the upper part of the PC1 chamber. With strong eddy motion and presence of oxygen in the lower part of the PC1 chamber (Fig. 2e), the increase in the temperature can be observed in the axis of the cyclone furnace (Figs. 2f, 4b). This increase in the temperature is very beneficial since the process of coal gasification requires that the heat is supplied. Figs. 2g and 4b present the values of temperature near the cyclone furnace walls. It can be observed that the highest values of temperature are observed in the lower part of the PC1 chamber, which was demonstrated above (Fig. 2f). With the temperature present in this location of around 1600-2000 [K], it is possible to ensure the process of ash vitrification contained in the fuel and its supply to the slag tank located below in a liquid state. Due to the substoichiometric conditions present in the PC1 chamber, the temperature in the upper part of the chamber ranges from 900 to 1400 [K] (2f, 2g, 4b) and declines only in the locations of supplying driving gas with temperature of 600 [K] (Fig. 2g). The gases flowing from the PC1 chamber allow for reaching the mean temperature in the PC2 chamber of 1000-1200 [K] (see Fig. 4b). These conditions ensure that the fuel supplied in the upper part of the PC2 chamber, which moves near the wall, is heated, dried and devolatilized, which is presented in Figs. 2h and 2i. The area of high rates of fuel devolatilization (Fig. 2h) is coincident with the elevated fuel concentration in the upper part of the PC2 chamber (see Fig. 2c). Fig. 2j presents the distribution of molar fractions of volatile matter generated through fuel devolatilization. The highest concentrations of volatile matter are observed in the lower part of the PC2 chamber near the internal plunger. This is connected by strong heating of the circulating large mass of fuel in this area (see Figs. 2b, 2c, 2d). Through strong heating and strong eddy motion of the fuel in the PC2 chamber the fuel is almost entirely devolatilized and, in the PC1 chamber, the process virtually does not occur, which is additionally illustrated by the distribution of the concentration of the volatile matter in the axis and near the furnace wall (Fig. 4e). The highest rates of fuel burning are observed in the lower part of the PC1 chamber (Fig. 2k) in the area of the highest oxygen concentration (Fig. 2e, 4a) and the highest temperatures (Fig. 2f, 2g, 4b). As mentioned before, this location is the place of afterburning of the carbon residue that was not reacted in the gasification processes in the upper part of the PC1 chamber. Consequently, a substantial increase in CO_2 concentration is observed in the lower part of the PC1 chamber (Figs. 2l, 4c), with its value gradually reducing with the height. This decline is connected with the fact that the CO_2 obtained in the lower part through combustion of the carbon residue participates in the above gasification reactions (the Boudouard's reaction). The gasification process is noticeable in Fig. 2m that presents the distribution of the molar fraction of CO. The very high CO concentration that occurs in the lower part of the PC1 chamber and results from the coal gasification reaction can be observed (the Boudouard's reaction). The gasification process results from the presence of the devolatilized fuel in this part, supply of the O_2/CO_2 mixture through driving nozzles and supply of heat from combustion of carbon residue in the lower part of the PC1 chamber. The gasification process in the PC1 chamber can be analysed in detail based on the temperature profiles (Fig. 4b), molar fractions of O_2 (Fig. 4a), CO_2 (Fig. 4c), CO (Fig. 4d) in the axis and near the cyclone furnace walls. The driving gas composed of O_2 and CO_2 leads to local increases of oxygen concentration near the walls (see Fig. 4a, line *z1*, *z2*), which consequently leads to local increases in temperature (see Fig. 4b, line *z1*, *z2*). Due to the composition of the driving gas and substoichiometric volume of the oxygen supplied to the PC1 chamber near the driving nozzles, the local increase in CO_2 concentration is observed, resulting from the composition of the gas supplied and combustion of fuel in these areas. It is noticeable that the CO_2 concentration near the PC1 chamber decreases as the height rises. Furthermore, in the case of distributions of CO concentration (Fig. 4d) near the walls of the PC1 chamber, this concentration increases noticeably with the height. Local decreases of CO concentration are observed only in the locations of supply of the driving gas (see Fig. 4d).

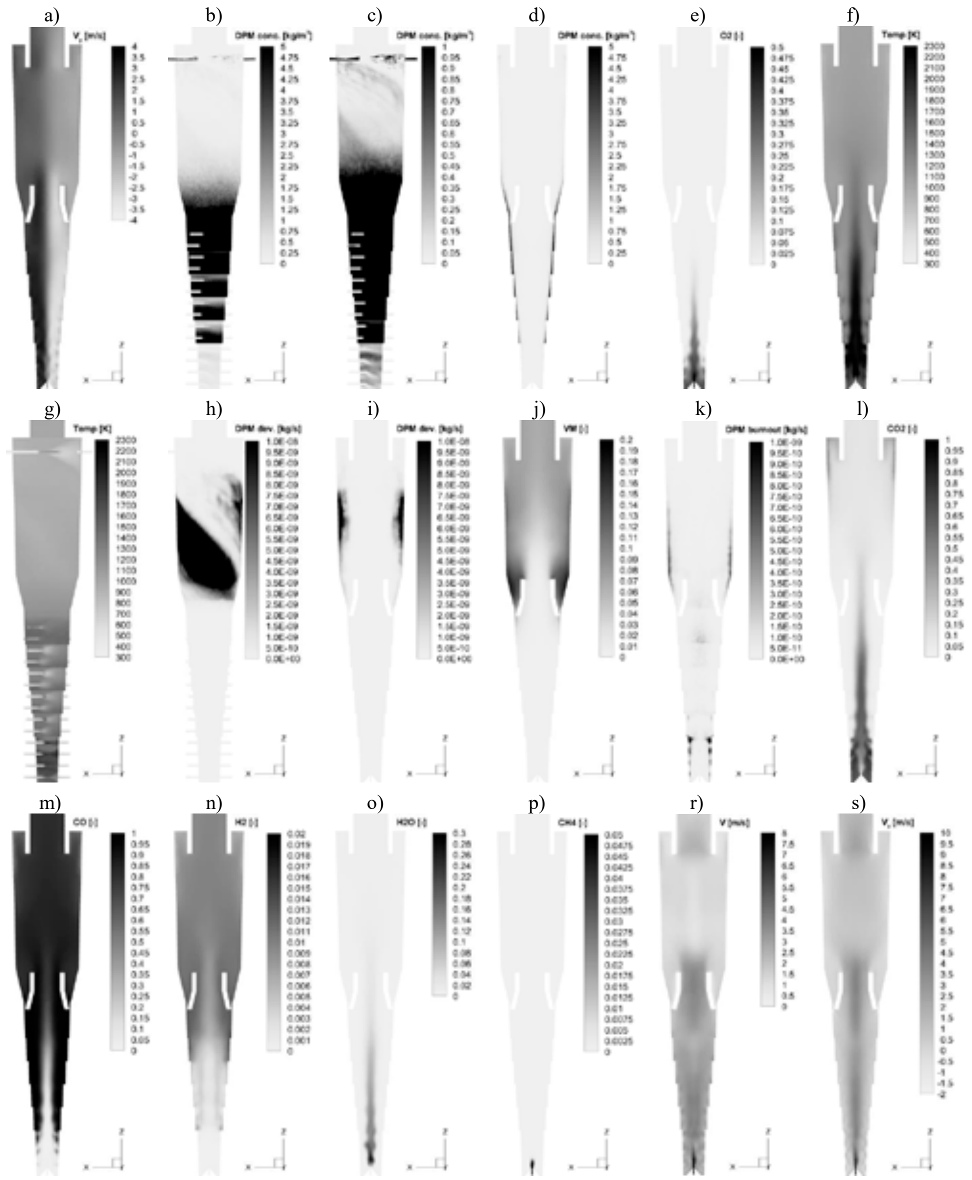


Fig. 2. Distribution of selected process values: a) peripheral velocity component, b) and c) fuel concentration on the furnace walls, d) fuel concentration in the vertical cross-section, e) O_2 concentration, f) temperature distribution in the vertical cross-section, g) temperature distribution near furnace walls, h) devolatilization rate distribution near furnace walls, i) devolatilization rate distribution in the vertical cross-section, j) volatile matter concentration, k) fuel burning rate, l) CO_2 concentration, m) CO, n) H_2, o) H_2O, p) CH_4, r) total velocity, s) vertical velocity component

Figure 2n presents distribution of H_2 concentration along the height of the cyclone furnace; the highest H_2 concentration of 1% is observed in the upper part of the PC1 chamber and in the whole PC2 chamber. Presence of H_2 in this area results from devolatilization of the fuel, which contains 5% of hydrogen, and reaction of water gas synthesis Eq. (5). Distribution of H_2O concentration was presented in Fig. 2o. A noticeable high concentration in the lower part of the PC1 chamber results from the combustion of the O_2/CH_4 mixture. With greater heights, this concentration declines as a result of dilution in the gases generated in the process of gasification. Furthermore, as mentioned above, the reaction of the water gas synthesis occurs according to the equation (5). Figure 2p presents distribution of CH_4 concentration in the cyclone furnace. The only observation is the high concentration of CH_4 near the nozzle, which then declines rapidly due to the superstoichiometric conditions in this part of the PC1 chamber. Figures 2r and 2s present values of total velocity and vertical velocity component. It can be observed that the highest values of the vertical component (Fig. 2s) occur in the axis of the furnace in the PC1 chamber. The distributions of the vertical velocity component near the internal plunger should be emphasized. High velocities are observed inside the plunger, resulting from the flow of gas from the PC1 chamber to the PC2 chamber, whereas these velocities are close to zero outside the plunger, making the fuel flow from the PC2 to PC1 chambers easier.

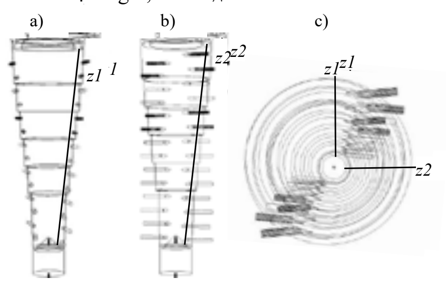
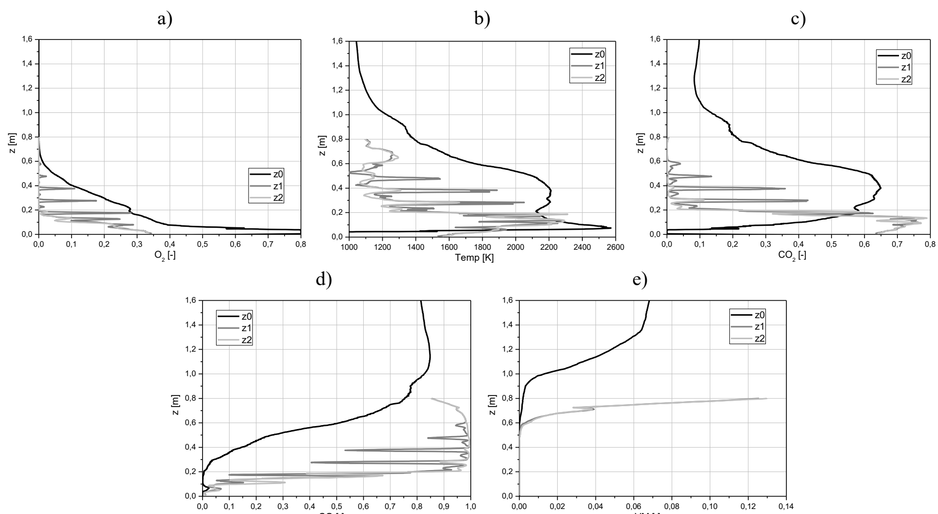


Fig. 3. Location of lines along which the analysis of temperature profiles and molar fractions of flue gas components was performed: view of the lines near "driving" nozzles *z1* a), view of the lines in the plane which is perpendicular to the plane of the "driving" nozzles *z2* b), top view of line location *z1* and *z2* c)



Rys. 4. Distributions of selected process values in the axis of the cyclone furnace *z0* and lines *z1* and *z2*: a) O_2 concentration, b) temperature, c) CO_2 concentration d) CO, e) VM

Table 2 compares mean values of select process parameters in the plane located at the outlet from the PC1 chamber (0.8 m) and the plane located at the outlet from the PC2 chamber (1.6 m). An insignificant decline in gas temperature can be observed between the outlet from the PC1 and PC2 chambers. It results from the fuel supplied pneumatically to the PC2 chamber in the stream of gas with temperature of 350 [K] and heat loss through the PC2 chamber walls. The observed decline in CO concentration and the increase in CO_2 concentration at the outlet from the PC2 chamber results from the CO_2 stream supplied to the PC2 chamber. On the other hand, higher values of volatile matter concentration are observed at the outlet from the PC2 chamber, which, rather than the PC1 chamber, seems to be the location of the main stage of fuel devolatilization. Due to the substoichiometric oxygen amount supplied to the cyclone furnace, the concentration of this gas is close to zero in both control planes. Similar values are observed for other gaseous components. It was found that the transport of tiny fuel grains or devolatilized fuel from the PC2 chamber is also very low. Vertical velocity component in the analysed planes is ca. 1-1.1 [m/s].

Table 2: Selected mean process parameters at the outlet from the PC1 and PC2 chambers

	z	Temp	CO	CO_2	VM	O_2	H_2	H_2O	N_2	CH_4	DPM conc.	V_{mag}	V_z
	[m]	[K]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[kg/m^3]	[m/s]	[m/s]
PC1	0.8	1192.8	0.9369	0.0345	0.0129	6,05E-05	0.0110	0.0041	4.20E-04	4.36E-14	0.0442	2.72	1.12
PC2	1.6	1033.2	0.8020	0.1082	0.0717	1,11E-17	0.0093	0.0063	0.0025	9.40E-14	1.67E-04	1.63	1.03

CONCLUSION

The results presented in the paper support the correctness of heat and flow assumptions for the new design of the cyclone furnace based on simultaneous processes of fuel combustion and gasification. Maintaining substochiometric amount of oxygen in the chamber PC1 allows for temperature control under conditions of oxy-fuel combustion. Coal gasification reaction according to Bouduard's reaction is possible in the above conditions. The use of a methane burner in the lower part of the chamber PC1 stabilizes the process of coal combustion and gasification. This burner allows for supplying an additional amount of oxygen for afterburning of carbon residue, which substantially limits the loss of the incomplete combustion.

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