

Pulverized coal gasification with steam and flue gas

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Abstract. The study presents the concept and numerical calculations of the coal dust gasification in the entrained flow reactor with power of 16 MW. The gasification process in the reactor can be performed in the atmosphere of O₂, CO₂ and H₂O. The combustible gases obtained during gasification are composed mainly of CO and H₂ and can be used to feed pulverized coal-fired boilers. Integration of the reactor (reactors) for coal dust gasification with the pulverized coal-fired boiler allows for improved flexibility, especially in the range of low loads if stabilization of coal dust combustion in pulverized-fuel burners or support for their work with ignition burners fed with gas or light fuel oil is necessary. The concept of the gasification reactor assumes strong eddy motion of the coal dust, which substantially allows for elongation of the time of fuel remaining in the reactor and obtaining a high reaction level. The concept of the entrained flow reactor presented in this study and the results of numerical calculations can be helpful for development of the devices with greater powers which in the nearest future should be integrated in the systems of pulverized coal-fired boilers in order to reduce their minimum load without using the ignition burners.

1 Introduction

Ensuring uninterrupted supplies of electricity and heat is mainly obtained in energy processes by combustion of fossil fuels (hard and brown coal, petroleum and natural gas). With the development of nuclear energy and renewable energy technologies, the demand for non-renewable fuels is gradually decreasing. Despite numerous benefits, such as low costs of electricity production, low level of waste and insignificant demand for fuel and huge resources of the fuel, nuclear energy has also some drawbacks, such as high costs of construction of nuclear power plants, generation of waste that is very dangerous to humans and the environment, and risk of failures. The risk of failures, terrorist attack and nuclear disasters that have occurred (Fukushima, Chernobyl) substantially limited the trust to the nuclear energy. Many countries with nuclear power plants plan to shut them down and return to the use of fossil fuels.

A dynamic development of renewable energy based mainly on the use of wind power allows for limitation of the use of fossil fuels. The major problem with renewable energy is the lack of stability of energy supplies, whose production depends substantially on atmospheric conditions (wind). In such cases, conventional power plants (coal-fired) have to be prepared for the replenishment of the electricity deficit in the electric power system. In many cases, operation of high-performance power units with minimal power (minimum load) or temporary shutting down the units is necessary due to the surplus of electricity in the electric power system.

Therefore, it is critical that modern power units are characterized by a low value of minimum load and high

dynamics of changes in the load [1]. Technology of fluidized-bed furnaces allows for operation of the unit in the range of 40-100%, with minimal power of the unit limited by the necessity of maintaining the fluidization process inside the furnace [2]. In the case of pulverized-fuel boilers, minimal load depends on the design and specifications of the boiler and ranges from 40% to 60%. This is connected with stabilization of the coal dust process at low boiler loads (lower temperatures inside the combustion chamber) and ensuring the minimal water circulation rate in the radiant tubes of the boiler. Reduction of the pulverized-fuel boiler power below the minimal level requires starting the ignition burners in order to ensure a stable coal dust combustion process. The use of the ignition burners fuelled by light fuel oil, mazut or natural gas increases the costs of steam power unit operation and emissions of harmful substances.

The increase in flexibility of steam power units equipped in pulverized-fuel boilers can be achieved by replacing ignition fuels (fuel oil, mazut, natural gas) with the gas generated during coal gasification. This solution allows for utilization of the basic fuel in the power plant (hard coal and brown coal) for production of the syngas. Installation of burners in pulverized-fuel boilers fuelled with synthesis gas allows for stabilization of the combustion of coal dust at low loads of the power unit and maintaining the boiler in the state of hot reserve using gas burners fuelled by synthesis gas. The use of burners fuelled with synthesis gas during power unit start up is also possible (replacing the ignition burners). This proposal of the use of synthesis gas allows for limitation of consumption of expensive ignition fuels, especially if the steam power unit has to be operated over the broad range of changes in the load.

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The achievement of such a goal requires a reactor design that ensures control over the coal gasification process. In the case of actual power facilities, it is important that unit power of the reactor should allow for replacing of one or several ignition burners.

The study presents the concept and numerical computations of the reactor operation to perform coal gasification process in the atmosphere of recirculating flue gas and water steam.

2 The concept of reactor for coal gasification

Coal gasification process can be performed using one of the three types of reactors (Fig. 1):

- moving bed reactors;
- fluidized-bed reactors;
- entrained-flow reactors.

Moving bed reactors (Fig. 1a) (Lurgi) are designed to gasify solid fuels with grain size ranging from 5 to 80 mm. Time of fuel gasification process depends on the gasification medium (oxygen, air, water steam) and pressure at which the process is performed (environmental pressure, overpressure) and ranges from several minutes to several hours. The most popular reactors include counter-current flow of fuel and gasifying agent with their power reaching 350 MW_t. Heat needed for the gasification process originates from partial combustion of the charge. Gasification in a stationary bed requires fuel and low agglomerating capacity of coal. The main problem connected with operation of moving bed reactors is the disposal of fragmented fuel and liquid hydrocarbons [4-9].

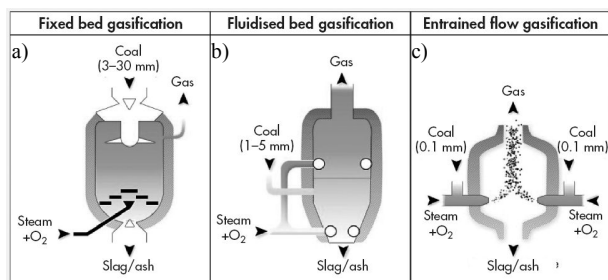


Fig. 1. Gasification process for coal [3].

In fluidized-bed reactors (Fig. 1b) (Winkler), it is necessary to prepare fuel through its fragmentation in the range of 0.5-6 mm in order to ensure efficient fluidizing. Time of fuel remaining in the reactor ranges from 10 to 100 s while its temperature has to be lower than the softening point of the ash contained in the coal. Unit powers of fluidized-bed reactors reach 700 MW_t. Gasifying agents include oxygen, air and water steam introduced from the bottom. The major problem with operation of fluidized-bed reactors is poor conversion of the C element resulting from low process temperatures limited by the ash softening point [4-9].

In entrained flow reactors (Fig. 1c) (Koppers-Totzek), fragmented coal is transported in the streams of the gasifying agent (oxygen and water steam mixture).

With fragmentation of fuel to grains of below 0.1 mm and the temperature during the gasification process ranging from 1200-1600°C, time of fuel grain remaining amounts to several seconds, which allows for reaching high unit gas efficiency and reactor power of 700 MW_t. One benefit of this type of generators is the opportunity to use caking coals as raw materials and no temperature limits caused by ash composition. The main problems connected with operation of entrained flow reactors is to ensure continuous supply of the gasifying agent and fuel with the specific ratio and cooling of the gas generated during gasification [4-9].

The biggest potential connected with the achievement of high efficiencies of synthesis gas, rate of changes in efficiency and opportunity to control coal gasification process is observed for entrained flow reactors for coal gasification [9]. They allow for coal dust gasification in the atmosphere of recirculated flue gas and in the presence of water steam. Ash vitrification can also be performed [10-16].

Fig. 2 presents a design of entrained-flow reactor for coal gasification with power output of 16 MW_t. The reactor is composed of seven main components presented in Fig. 2. The C1 dome contains one burner nozzle with diameter of 50 mm and four nozzles for supplying gases with specific content to the reactor. Below the C1 dome there is C2 with diameter of 2 m, composed of ten cylindrical segments with the height of 0.5 m each. Each segment has eight nozzles with diameter of 50 mm at the angle of 45°. The nozzles were installed so that their distance from the symmetry axis of the chamber C2 in each lower segment is incremented by 50 mm. This design allows for a strong eddy motion of the gas and fuel supplied to C2. Below the C2 chamber there is the C3 chamber with the height of 1 m and reducing diameter to 1.8 m, where three levels of nozzles with diameter of 50 mm are located. Each level contains eight nozzles (distributed every 90°). This system of nozzles ensures a strong eddy motion of the gas and fuel. Below the chamber C3 there is the C4 chamber with special design, composed of ten segments with the height of 0.5 m each. Each segment has four levels of nozzles distributed every 90° with diameter of 50 mm. Side walls of each segment in the C4 chamber were shaped so that the nozzles are installed tangentially to the chamber walls. The nozzles are also inclined at the angle of 5°.

The chamber C5, composed of two truncated cones is located in the lower part, with a step between each other aimed to extend the time of fuel remaining in the boiler. Nozzles are tangentially installed in the side walls of the C5 chamber, at five steps, distributed every 90°. Below them there is the C6 chamber, cylindrically-shaped, with diameter of 3 m and tangentially installed channel used to discharge gases from the reactor. A plunger is installed inside the C6 chamber. Below this point there is the C7 chamber composed of two truncated cones and a cylindrical chamber. The chambers C6 and C7 act as a cyclone that allows for separation of solid particles from the gas generated in the reactor.

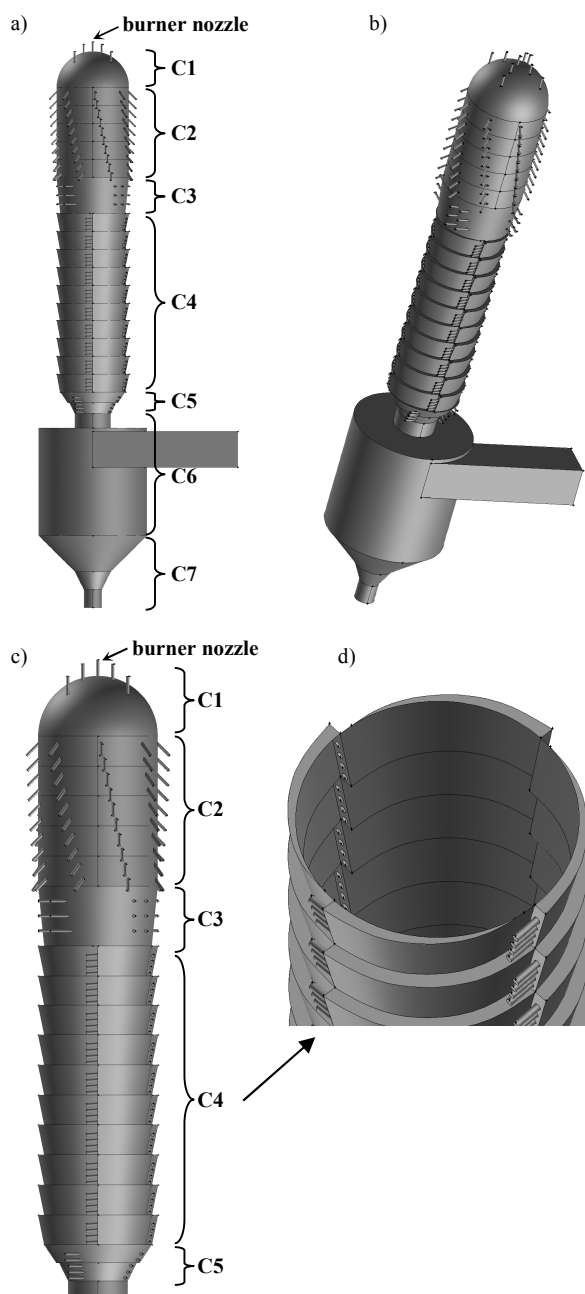


Fig. 2. Entrained flow reactor for coal gasification.

3 Numerical analysis of coal dust gasification process

Geometry and the grid used for computation of the coal dust gasification reactor (Fig. 2) was developed using the GAMBIT software. The ANSYS FLUENT 14 software was used to compute coal dust gasification process.

Calculations of coal dust and gas flow were performed using the Reynolds Stress turbulence model. Modelling of flow of coal dust 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 [17-22]. The Single-Rate fuel devolatilization model was employed. Calculations were based on the radiation model termed Discrete Ordinate

(DO). A numerical model of the process allows for computation of combustion, fuel devolatilization and fuel gasification in the atmosphere of air, O₂, CO₂ and water vapour.

Calculations of coal dust gasification process for the dust with mean size of 0.25 mm were carried out for coal dust with physicochemical parameters as presented in Table 1.

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

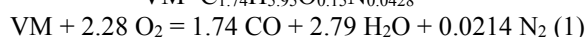
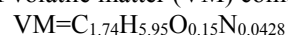
M	A	VM	FC	C	H	N	O	HHV
[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[MJ/kg]
5	5	45	45	85	10	1	4	24.7

A - ash
 M - moisture
 VM - volatile matter
 FC - fixed carbon
 HHV - higher heating value

For simplification purposes, it was adopted that the fuel does not contain sulphur. Reaction rate constants were derived from the studies [17,18].

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

- Reaction of volatile matter (VM) combustion



- Reaction of oxidation of carbon oxide



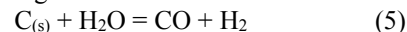
- Reaction of oxidation of fixed carbon (FC)



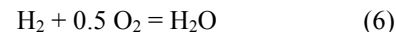
- Boudouard's reaction



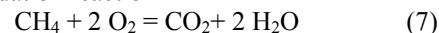
- Synthesis of water gas



- Hydrogen oxidation reaction



- Methane oxidation reaction



Numerical computations were performed for two variants:

- V1 - gasification in the atmosphere of O₂/CO₂,
- V2 - gasification in the atmosphere of O₂/H₂O.

In both cases (V1 and V2), the conditions of fuelling the C1 and C2 chambers were identical. The burner located in the C1 chamber was fuelled by the O₂/CH₄ mixture at the rate of 15 m/s with volumetric ratios of 80/20%. The nozzles were fuelled by the mixture of O₂/CO₂ at the speed of 5 m/s with volumetric ratios of 80/20%. The C2 chamber was fuelled by the O₂/CO₂ mixture with the speed of 5 m/s, with volumetric ratio of 70/30%. With this gas, coal dust was also supplied to the C2 chamber. Total flux of the coal dust was 0.65 kg/s, whereas 0.11 kg/s was supplied at the highest step, and reduced for each step down by 0.01 kg/s. The lowest step of the C2 chamber was fuelled at a rate of 0.02 kg/s.

For the V1 variant, the C3 chamber was fuelled with the O₂/CO₂ mixture with the rate of 7 m/s and volumetric ratio of 50/50%. The C4 chamber was fuelled with the gas with every second step of nozzles with the parameters similar to the C3. The chamber C5 was

fuelled by the O_2/CO_2 mixture at a rate of 10 m/s, with volumetric ratio of 50/50% only in the upper cone.

The difference between V1 and V2 variants is connected with replacement of the carbon dioxide supplied to C3, C4 and C4 (variant V1) with water steam (variant V2).

Temperature of gas mixtures supplied with nozzles to the reactor was identical for both cases (V1 and V2), i.e. 300°C.

The results of the gasification process in the O_2/CO_2 atmosphere (variant V1) are presented in Fig. 3. Fig. 3a presents distribution of the peripheral gas rate in the vertical cross-section resulting from the supply of the gas with tangentially designed nozzles. The highest levels of the peripheral component are observed near the reactor walls in the chamber C4 and C5. Concentration of the fuel supplied to the reactor with nozzles installed in the C2 chamber is presented in Figs. 3b, 3c and 3d. With the nozzles installed in the C2 chambers at the angle of 45° and their shift with respect to axes at individual steps, the fuel supplied to the chamber is decomposed in the form of the rings observed inside the C2 chamber along its height (Fig. 3b, Fig. 3c).

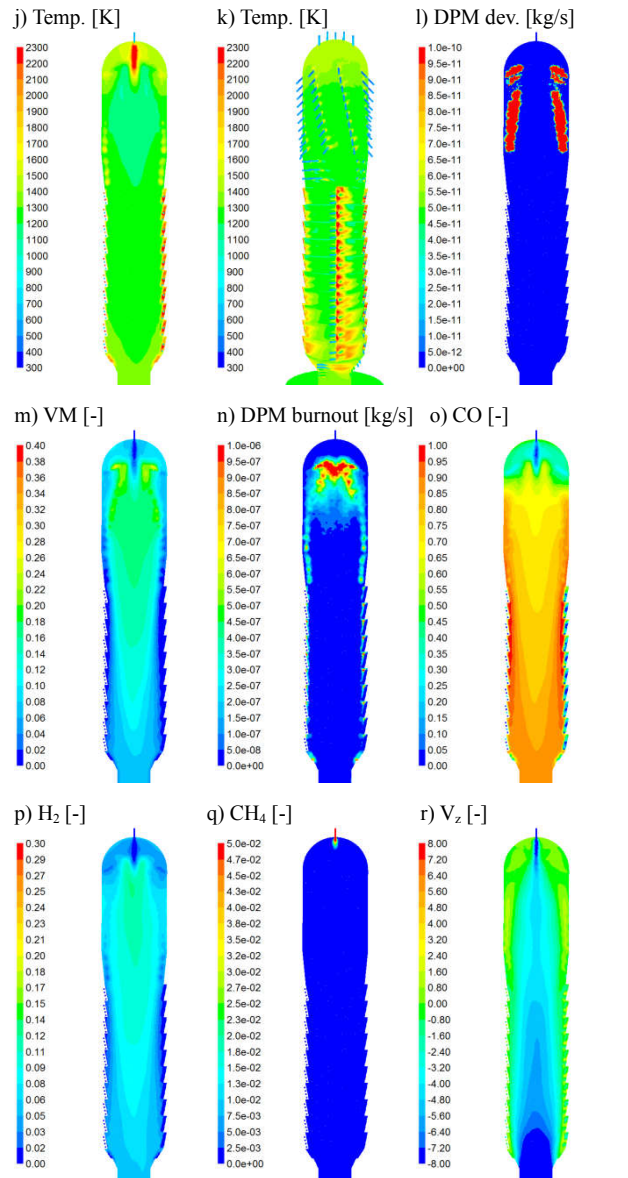
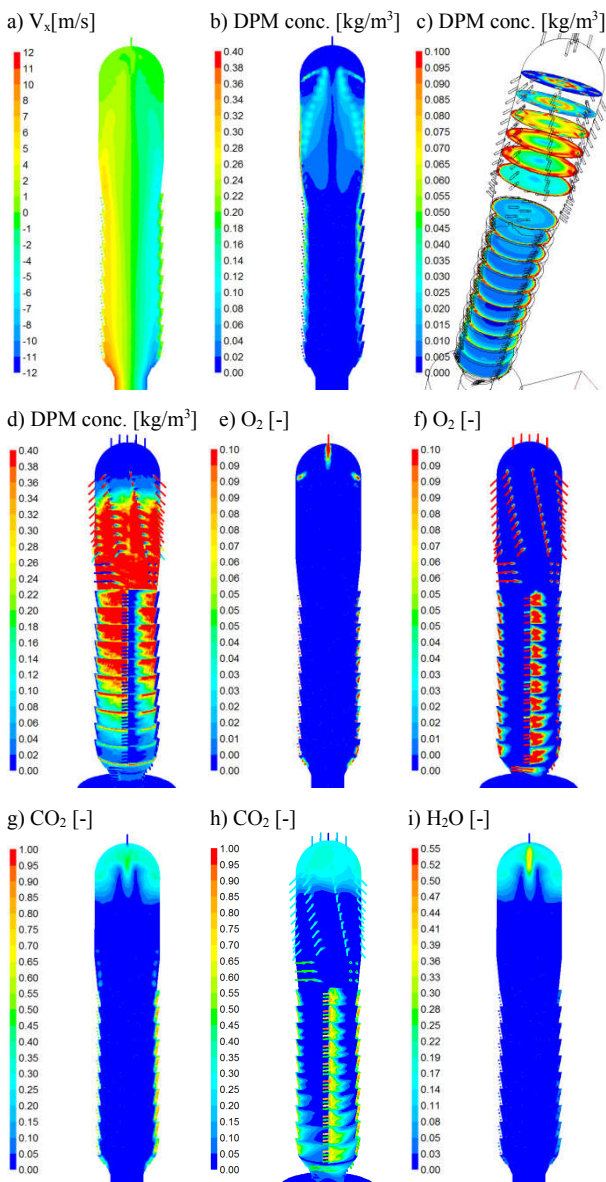


Fig. 3. Distribution of selected process values (V1): a) peripheral velocity component, b) fuel concentration in the vertical cross-section, c) fuel concentration on the furnace walls, d) fuel concentration on the furnace walls, e) O_2 concentration on the furnace walls, f) O_2 concentration on the furnace walls, g) CO_2 concentration on the furnace walls, h) CO_2 concentration on the furnace walls, i) H_2O concentration on the furnace walls, j) temperature distribution in the vertical cross-section, k) temperature distribution near furnace walls, l) devolatilization rate distribution in the vertical cross-section, m) volatile matter concentration, n) fuel burning rate, o) CO concentration, p) H_2 concentration, q) CH_4 concentration, r) vertical velocity component.

With the effect of the centrifugal force caused by swirling gas (Fig. 3a), the fuel supplied to the C2 chamber is transported near the reactor walls (Fig. 3c). The gas supplied tangentially to the C3 and C4 chambers at a rate of 7 m/s increases the value of the centrifugal force and, consequently, the fuel remains only near the reactor walls.

This phenomenon is very beneficial due to the extension of time of fuel remaining near the specifically shaped walls of the C4 chamber, whereas the gasifying agent is supplied only near the walls, which allows for

gasification of the fuel in this area. The special shape of the **C4** chamber helps intensify mixing of gas and the fuel swirling inside the reactor (Fig. 4), allowing for an efficient gasification process. Process conditions were set so that fuel concentration at the outlet from the **C5** chamber was equal zero. This means that total stream of the fuel supplied to the reactor is gasified in its interior. In the analysed variant, the gasification agents were O_2 and CO_2 , with distributions presented in Figs. 3e, 3f, 3g and 3h. Distributions of O_2 concentration in the vertical cross-section of the reactor (Fig. 3e) show substoichiometric conditions inside the reactor whereas elevated O_2 concentration is observed only near the nozzles that fuel the **C4** chamber. Analysis of CO_2 distribution reveals elevated concentration of this gas in the **C1** chamber and in the upper part of the **C2** chamber. This is connected with the necessity of combustion (reaction 1) of a specific amount of gases generated through fuel devolatilization (Fig. 3l, 3m) due to the necessity of ensuring heat for the performance of endothermic processes of coal gasification. Furthermore, CO_2 is generated through combustion of the O_2/CH_4 mixture supplied with the burner nozzle. Due to the gasification process (reaction 4), the CO_2 concentration is noticeably reduced, and in the central part of the **C2** chamber, it equals nearly zero. CO_2 concentration near reactor walls is presented in Fig. 3h. Similar to O_2 , its elevated concentration is observed only near the nozzles that supply the O_2/CO_2 mixture. This suggests intensive processes of mixing and coal gasification (reaction 4). Figure 3i illustrates H_2O concentration. Presence of H_2O is due to the combustion of the O_2/CH_4 mixture (reaction 7) in the burner installed in the **C1** chamber and humidity contained in the fuel. Similar to CO_2 distribution, H_2O concentration was significantly reduced in the initial part of the **C2** chamber, which suggests the gasification process (reaction 5) using water steam, which results in the increase in H_2 concentration (Fig. 3p).

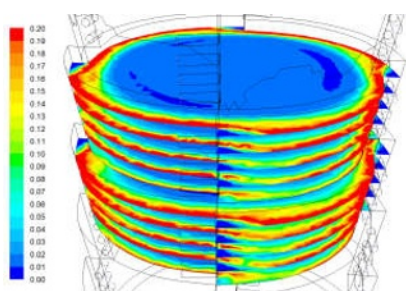


Fig. 4. Distribution of fuel concentration in **C4** (**V1**).

Figures 3j and 3k illustrate distributions of temperature inside the reactor and near its walls, respectively. The highest temperature values are observed near the burner (chamber **C1**) and near the walls of the **C4** chamber. Gasification processes require ensuring adequate amount of heat to perform them and maintain optimal thermal conditions due to the pattern of coal gasification reaction. Mean temperatures in the reactor are around 1000-1200°C near the reactor walls (**C4** chamber). In the locations where the O_2/CO_2 mixture is supplied, local temperature reaches the level

near 2000°C. This allows for a fast heating of the fuel in this zone and intensification of the gasification processes (reactions 3, 4 and 5). Local temperature of 2000°C also allows for vitrification of ash remaining after the gasification process. It is possible in this case to discharge the molten ash with the combustible gases obtained through gasification to the **C6** and **C7** chambers. The fuel supplied to the **C2** chamber is devolatilized, which can be observed in Fig. 3l, which illustrates fuel devolatilization rate. This results in the distribution of concentration of volatile matter (VM), as presented in Fig. 3m.

The highest VM concentration occurs in the upper part of the **C2** chamber and is insignificantly reduced with the flow towards the **C4** and **C5** chambers. Near the reactor walls, VM concentration is noticeably decreased, which results from partial combustion of volatile matter (reaction 1) and dilution with gasification products (reaction 3, 4 and 5) generated near the reactor walls. The parameter which reflects the rate of fuel conversion in the reactor is presented in Fig. 3n. The highest fuel conversion rates are observed near the burner and near the locations of supply of the gasifying agent (O_2/CO_2). The main product of the gasification process for the **V1** is CO , whose distribution is presented in Fig. 3o. Near the burner nozzle (**C1** chamber), CO concentration is ca. 20-40%, whereas down the stream, the CO content in the reactor axis rises noticeably to the level of 60-80%. The highest values of the CO concentrations are observed near the wall of the **C3** and **C4** chambers, with elevated fuel concentration (see Figs. 3b, 3c, 3d) and places where the gasification factor of O_2/CO_2 is supplied. The other gasification product is H_2 , with its distribution presented in Fig. 3p. Presence of this gas component results on the one hand from gasification of coal dust in the presence of water steam generated due to combustion of CH_4 and humidity contained in fuel. Furthermore, H_2 is partially obtained from combustion of a part of volatile matter (reaction 1) and then gasification of fuels in the generated stream of water vapour (reaction 5). Due to the superstoichiometric conditions of O_2/CH_4 burner operation, methane supplied to the do reactor is quickly burnt (Fig. 3q). Figure 3r presents the vertical component of gas velocity in the reactor. With adequate installation of the nozzles in side walls of the reactor, it is possible to obtain flow of gas towards the **C1** chamber near the walls, whereas in the reactor axis, the flow is noticeably oriented towards the **C5** chamber. This organization of gas flow is beneficial due to the improved mixing of gases in the reactor and, importantly, allows for extension of the time of remaining the tiniest fuel grains through their flow towards the **C1** chamber. This allows for a substantial limitation of the steam of fuel, which, with the molten slag, could flow to the **C6** and **C7** chambers.

The selected results of computations of the gasification process in the presence of water steam (variant **V2**) are presented in Fig. 5. Distribution of temperature for **V2** variant is similar to the distribution for **V1** in chambers **C1**, **C2**, **C3**. Slightly higher temperatures are observed in the **C4** and **C5** chambers,

resulting from the difference in the demand for heat at gasification in the presence of CO₂ (8) and H₂O (9).

- the Boudouard reaction

$$C_{(s)} + CO_2 = 2 CO + 172 \text{ MJ/kmol} \quad (8)$$
- the water gas reaction

$$C_{(s)} + H_2O = CO + H_2 + 131 \text{ MJ/kmol} \quad (9)$$

Analysis of the distribution of CO concentration for V2 (Fig. 5b) reveals that the highest values of CO concentrations occur near the C2 chamber walls whereas the CO concentration decreases down the stream. Analysis of the H₂ distribution (Fig. 5c) reveals a noticeable increase in H₂ concentration near the walls of the C3 and C4 (places of O₂/H₂O mixture supply).

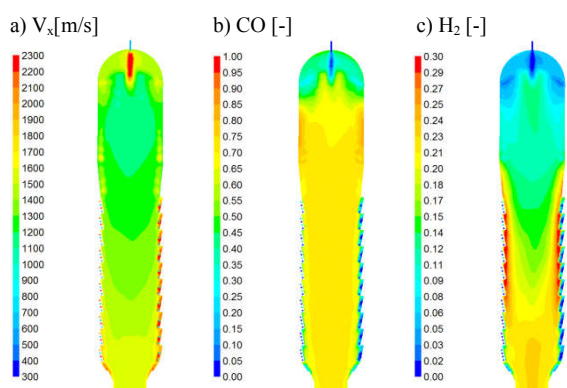


Fig. 5. Distribution of selected process values (V2):
 a) temperature distribution in the vertical cross-section,
 b) CO concentration, c) H₂ concentration.

Table 2 compares composition of gases that leave the C5 chamber. It can be noticed that for the V1 variant, process gas is composed of 86% CO and 5.65% H₂. In the case of V2 (gasification in the presence of water steam) the CO concentration reaches 68.5% whereas H₂ concentration exceeds 21%. Values of other gas components for both cases of V1 and V2 were similar.

Table 2. Selected process parameters at the outlet from C5 for coal dust gasification (V1, V2).

Variant	CO [%]	H ₂ [%]	CO ₂ [%]	H ₂ O [%]	VM [%]	O ₂ [%]	CH ₄ [%]
V1	86.30	5.65	1.25	0.20	6.52	1.61E-04	1.19E-05
V2	68.67	21.37	1.52	2.58	5.84	1.39E-03	1.35E-05

4 Conclusions

The concept and the design of coal dust gasification reactor presented in the study allows for performing the process of coal dust gasification in the atmosphere of O₂/CO₂ and O₂/H₂O. Division of reactor into zones allows for controlling the gasification process. Process of fuel gasification is performed both in the central part of the reactor (the C2 chamber) and near its walls (C3, C4 chambers). Strong eddy motion of the fuel with the special design of the C4 chamber allows for intensification of the process of mixing between the fuel and gasification agent and extension of the time of fuel remaining in the reactor. The proposed solution also allows for ash vitrification in the lower part of the C4

chamber and in the C5 chamber. The computations of the fuel gasification process revealed opportunities to obtain the product containing 86.3% CO and 5.6% H₂ for the V1 variant and 68.7 % CO and 21.4 H₂ for the V2 variant. These gases can be directly used for fuelling pulverized-fuel boilers in order to improve their flexibility, stabilization of the coal dust combustion process at low boiler loads and replacing the ignition burners during boiler start-up.

The gasification process in the atmosphere of O₂/CO₂ and O₂/H₂O allows for the control of temperature inside the reactor and separation of the processes of coal gasification and fly ash vitrification. With changes in the composition of the gasifying agent, it is possible to obtain a product (synthesis gas) with expected composition.

During designing and construction of new pulverized coal-fired boilers, they can be equipped in coal gasification reactors using the solution presented in this study. A compact design of the reactor allows for its installation near a pulverized coal-fired boiler. Using the coal dust as a fuel supplied to a coal gasification reactor allows for a substantial limitation of consumption of fuel oil or gas during operation of the pulverized coal-fired boiler. The design of the reactor should be integrated especially with pulverized coal-fired boilers where oxy-fuel combustion processes are performed.

The installation of the coal gasification reactors in a pulverized coal-fired boiler system allows for:

- increasing the flexibility and dynamics of blocks with dust boilers,
- increase in thermal efficiency of boilers,
- reduction of the minimum technological operation of the dust boiler without the need to start the firing torches,
- implementation of the combustion and/or gasification process of solid fuels,
- carrying out the process of ash refining (e.g. during the period of cheaper night pricing).

The proposed solution constitutes an interesting technological option aimed at retrofitting and modernization of 200 MW_e class of dust mills.

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