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CO_2 capture from flue gases in a temperature swing moving bed

SŁAWOMIR GRĄDZIEL[a*]
WIESŁAW ZIMA[a]
ARTUR CEBULA[a]
MONIKA RERAK[a]
EWA KOZAK-JAGIEŁA[a]
ADAM PAWŁOWSKI[a]
RICHARD BLOM[b]
LARS OLOF NORD[c]
VIDAR TORARIN SKJERVOLD[c]
GIORGIA MONDINO[b]

[a] Cracow University of Technology, Faculty of Environmental Engineering
and Energy, Warszawska 24, 31-155 Kraków, Poland

[b] SINTEF Industry, P.O. Box 124 Blindern, N0314 Oslo, Norway

[c] Norwegian University of Science and Technology, Department of Energy
and Process Engineering, P.O. Box 8900, NO-7491 Trondheim, Norway

Abstract This paper presents a test stand for the capture of CO_2 from flue gases arising due to firing pulverised hard coal. The stand, financed from the 2014–2021 Norway Grants, is installed at a Polish power plant. The innovation of the proposed CO_2 capture method, developed by the Norwegian partner in the project (SINTEF Industry), lies in the use of activated carbon in the process of temperature swing adsorption in a moving bed. The paper also presents preliminary results of numerical simulations performed using the General PROcess Modelling System (gPROMS) software. The simulations concerned the operation of a supercritical power unit combined with a system for capturing CO_2 from flue gases. Transient operation of the system was analysed, assuming rapid changes in the power unit load. Special attention was paid to the CO_2 capture process energy consumption at an

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[*] Corresponding Author. Email: slawomir.gradziel@pk.edu.pl

increase in load by 5% of the power unit nominal capacity in 30 s. It is found that the proposed CO_2 capture method "keeps up" with such rapid load changes at the method energy consumption smaller than 2 MJ/kg CO_2.

Keywords: Innovative CO_2 capture method; Activated carbon; Test stand; Numerical simulations; Energy consumption; Energy consumption of the method

1 Introduction

According to an International Energy Agency report, as much as 36.8 billion tons of CO_2 were produced in 2022, which is the highest amount ever [1]. Meanwhile, the Intergovernmental Panel on Climate Change predicts that if greenhouse gas emissions continue at the current rate, we are likely to reach a warming of 1.5°C in the years 2030–2052 [2]. In order to limit the warming to 1.5°C (as per the Paris Agreement), CO_2 emissions would have to fall by 45% by 2030 compared to 2010, and finally reach zero in 2050 [2]. The CO_2 capture and storage technologies have thus become some of the most promising solutions for combating climate change. Carbon capture technologies include three main methods, i.e. oxy-combustion, pre-combustion capture and post-combustion capture [3].

This paper is devoted to the last of the above-mentioned methods, which is most often realised using absorption, adsorption, cryogenic separation or membrane processes [4–6]. The main advantage of post-combustion capture methods is that they do not require extensive modifications to the power plant [7]. Moreover, the ease of regeneration of adsorbent materials is also important. Carbon dioxide removal from flue gases is considered the most advanced CO_2 separation technique among the available carbon capture and storage (CCS) technologies [8].

Three kinds of CO_2 adsorption are distinguished: pressure/vacuum swing adsorption (PSA/VSA), temperature swing adsorption (TSA) and electric swing adsorption (ESA). This paper puts forward the use of temperature swing adsorption based on the moving bed temperature swing adsorption (MBTSA) technology.

The operation of CO_2 adsorption in the TSA process is analysed in [9–12]. In these processes, the adsorbent is usually in the shape of balls or granules packed in a series of columns that are located cyclically, alternating between adsorption and regeneration stages. One of the main downsides of fixed bed processes is the requirement to ensure high flue gas flow rates and the high pressure drop occurring in the packed bed. This can be overcome by using appropriate shapes of the adsorbent granules. Another important factor hindering the commercialisation of TSA systems for post-combustion CO_2 capture is that a large temperature change is often needed to achieve the required CO_2 purity and the process adequate efficiency [13, 14].

In [15], the TSA performance indices are shown in terms of CO_2 purity, CO_2 capture efficiency and energy consumption in the process. Respectively, they total 96.22%, 86.5% and 663.8 kWh per ton of captured CO_2 (2.39 MJ/kg CO_2). It should be mentioned that the testing was performed using the Mg-MOF-74 adsorbent.

The authors of [16] consider the use of the moving bed temperature swing adsorption (MBTSA) process for CO_2 capture as an alternative to commercial absorption-based technologies in the context of a natural gas combined cycle (NGCC) power plant. The power plant operation was simulated using the gPROMS software. Two cases with different regeneration temperatures were analysed. In both of them, the CO_2 capture purity was achieved in the range of 95.1%–95.8%, while the CO_2 capture efficiency was included in the range of 96.0%–98.2%.

In [17], simulations are performed of CO_2 capture from a waste treatment plant based on the MBTSA technology. The heat transfer coefficients of the heating section of an MBTSA demonstration unit using activated carbon balls were investigated. The obtained results were used as input data for the process simulation. The outcome was satisfactory: the CO_2 capture efficiency of about 90% and the CO_2 purity above 95%. However, the CO_2 capture energy consumption was rather high, totalling about 5.7 MJ/kg CO_2. The MBTSA technology offers the opportunity to internally recover part of the heat needed for the sorbent regeneration and thus reduce the demand for external energy [13, 18].

Many works focus on the development of general models of entire power plants and on the use of computer programs, both for steady-state and transient conditions [19, 20]. However, most of them fail to achieve the desired accuracy. Mesarovic [21] presented a case for the power plant emergency states using mass, momentum and energy balance equations.

Many works are also devoted to modelling the thermal and flow phenomena occurring in the boiler heating surfaces. A method for modelling the boiler evaporator dynamics is proposed in [22]. The proposed distributed parameter model, based on solving balance equations describing the principles of mass, momentum and energy conservation, enables an analysis of transient-state processes.

In the literature to date, much attention has been given to modelling transient operation of steam superheaters in large power boilers. The first mathematical models were very simple, with lumped thermal parameters [19, 20]. It should be noted that simple lumped parameter models are still used to simulate water heaters (economisers), boiler evaporators and steam superheaters/reheaters with a complex structure [23–25], mainly for the needs of automatic control systems in boilers.

A distributed parameter mathematical model of the steam superheater and the feed water heater is proposed in [26–29]. The model was built using mass, momentum and energy balance equations.

A mathematical model is developed in [30] to enable thermal and flow analysis of the phenomena occurring in the waterwalls of furnace chambers of supercritical boilers. The aim of the numerical calculations was to determine the temperature distributions of the medium and of the metal of the waterwall tubes. The model results were compared with the results obtained from computational fluid dynamics (CFD) testing.

The authors of [31] present a mathematical model of a natural circulation boiler which makes it possible to simulate the thermal and flow phenomena occurring in power boilers in conditions of rapid changes in thermal loads. The analysis of the results obtained from the proposed model shows very good agreement between the calculated and the measured values. The mathematical models presented in the paper can be used to develop comprehensive models of other boilers, including supercritical ones. In addition, they can prove helpful in the development of power unit simulators.

A mathematical model simulating the dynamics of a supercritical boiler is presented in [32]. Distributed parameter models of the boiler heating surfaces (the evaporator, steam superheaters and reheaters, the feed water heater, the selective catalytic reduction (SCR) reactor, the air heater) were developed. The performed numerical testing results allow the statement that the developed model is suitable for the simulation of rapid changes in the boiler thermal load.

Analysing the above literature, it can be seen that all the CO_2 capture models are simulated using computer programs, but there are no experimental tests carried out on real facilities operating in power plants.

This paper presents a test stand for the capture of CO_2 from flue gases arising due to firing pulverised hard coal. The test stand is installed at a Polish power plant on a natural circulation boiler.

The paper also presents a numerical simulation of the operation of a supercritical power unit combined with a system for capturing CO_2 from flue gases. Transient operation of the system is analysed, assuming rapid changes in the power unit load. Special attention is paid to the energy consumption of the CO_2 capture process at a rise in the power unit load. The simulation is performed using the gPROMS software [33].

2 Test stand

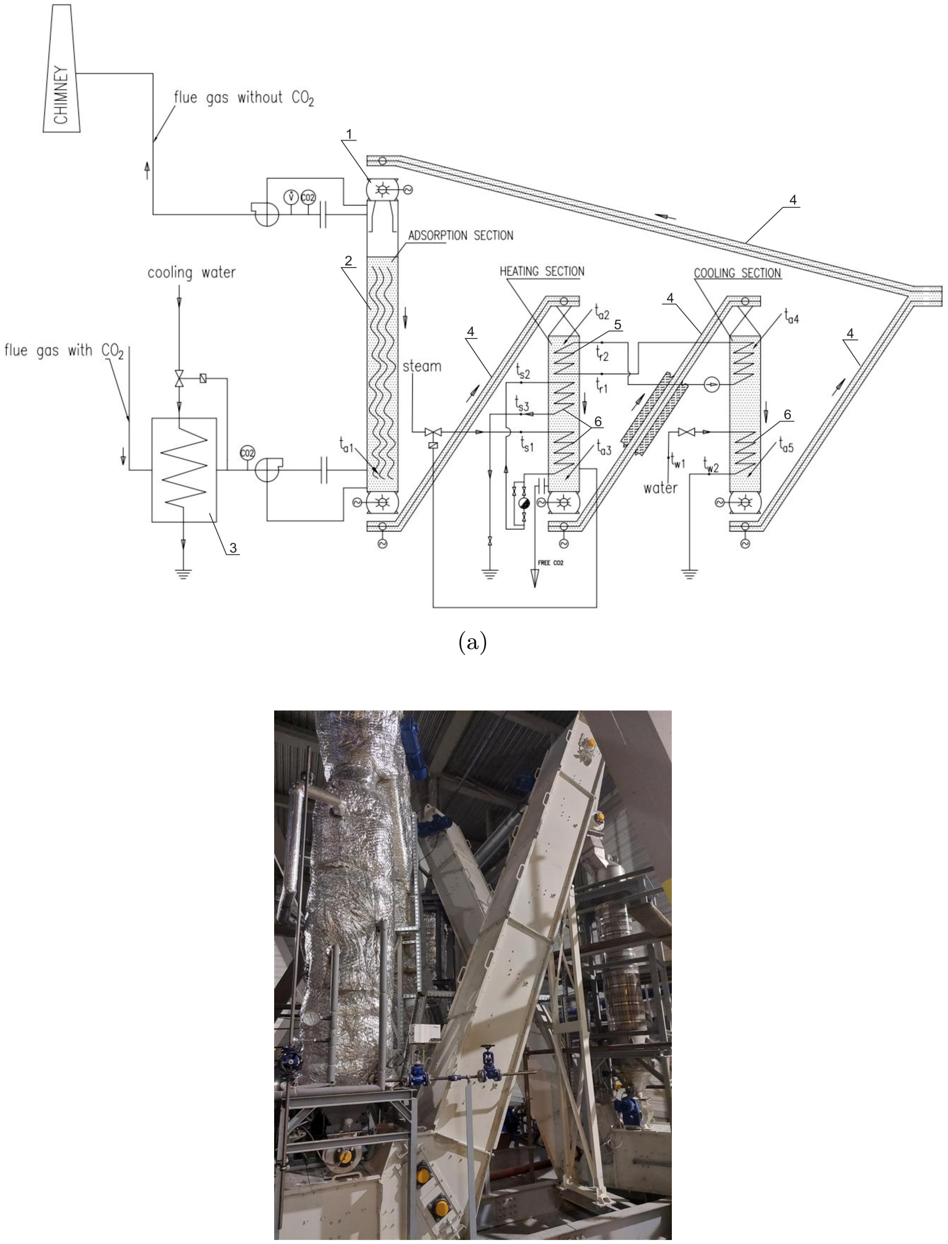
A test stand for CO_2 capture from flue gases (based on MBTSA) was installed at a Polish power plant (at a subcritical boiler with a steam output of 210 Mg/h). The stand is shown schematically in Fig. 1a, with an example photo in Fig. 1b. It consists of three basic components: a reactor (adsorption section), a heating section (desorption section) and a cooling section. The reactor is made in the form of a polycarbonate column with the height of 1.5 m and the inner diameter of 0.5 m, filled with Mellapak structured packing [34] ensuring a uniform distribution of the sorbent flow.

The adsorbent is fed by a rotary-valve feeder into the reactor from above. Rotary-valve feeders are also installed downstream of the reactor, the heating section and the cooling section. The BKRV150 feeder is intended for collection and proportioning of bulk materials and materials with small-sized particles. The feeder consists of the following components: a gear-motor, the rotor assembly, a steel body (Fig. 2). The rotor is driven by a shaft passing through the side lids and supported by two bearing units. This feeder type is characterised by good tightness and infinitely variable adjustment of the amount of fed adsorbent. The basic data of the BKRV150 feeder are listed in Table 1.

Table 1: Basic data of the BKRV150 feeder type.

Output	kg/h	1000
Working temperature	°C	–20–+60
Gear-motor power	kW	0.18
Output speed	1/min	13
Weight	kg	19
Motor rotational speed	1/min	1385

Activated carbon was chosen as the adsorbent due to, among other things, high values of the heat transfer coefficient on its side, totalling 69–117 $W/(m^2K)$ [17]. Activated carbon appears to perform satisfactorily



(a)

(b)

Figure 1: The test stand scheme (a) and photo (b): 1 – feeder, 2 – reactor, 3 – flue gas cooler, 4 – conveyor belts, 5 – heat exchanger intended for heat recovery, 6 – heat exchangers.

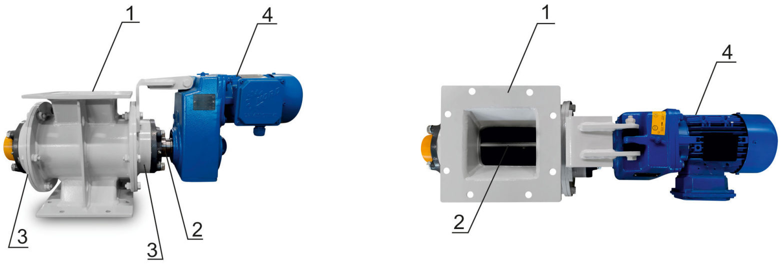


Figure 2: Diagram of the BKRV150 feeder: 1 – body, 2 – rotor assembly, 3 – side lids, 4 – gear-motor.

as an adsorbent also in the presence of water vapour, when regeneration takes place at temperatures of 150°C and higher [35]. Keeping the regeneration temperature possibly low is necessary to minimise the energy consumption of the method. The basic properties of activated carbon are listed in Table 2.

Table 2: Activated carbon basic parameters [36].

Mean size of particles	mm	~ 0.7
Coal dust content	ppm	> 600
Specific heat	J/(kgK)	880
Specific surface	m^2/g	1100–1300
Bulk density	g/ml	~ 0.6

After passing through the adsorption section, activated carbon is supplied to the rotary-valve feeder driven by a gear-motor connected to the power supply using a frequency converter (inverter). In this way, by adjusting the motor rotational speed, it is possible to control the amount of the fed activated carbon.

The feeder carries the sorbent to a belt conveyor which transports activated carbon to the heating section. Such conveyors are also used between individual sections. Due to internal heat recovery, the heating section and the cooling section are thermally insulated. Basic information on the conveyors used on the stand is given in Table 3.

The heating section consists of a series of (shell-and-tube) heat exchangers in which the sorbent is heated indirectly by steam drawn from the turbine bleed. For the adsorbent regeneration, the temperature of the bed in the heating section should be between 180°C and 200°C.

Table 3: Basic data of the BKBC400L belt conveyor.

Output	kg/h	1000
Total length	mm	6100–6650
Lift height	mm	4400–4800
Lift angle	deg	64–67
Belt width	mm	400
Total weight	kg	1165–1310
Belt speed	m/s	0.8

The adsorbent temperature is measured using five thermocouples placed at different locations in the reactor, in the heating and cooling sections (t_{a1}–t_{a5} in Fig. 1). In addition, three thermocouples to measure the steam temperature at the inlet and outlet of the heat exchangers (t_{s1}–t_{s3} in Fig. 1), two thermocouples at the inlet and outlet of the heat exchanger cooling the sorbent in the cooling section (t_{w1} and t_{w2} in Fig. 1) and two thermocouples at the inlet and outlet of the heat exchanger intended for heat recovery (t_{r1} and t_{r2} in Fig. 1) are installed. The mass flow rates of water and steam in the cooling section and in the heating section are also measured.

The cooling section is similar to the heating section. Municipal water is used as the cooling agent. Having passed the cooling section, the sorbent is transported by belt conveyors to the upper feeder located above the reactor.

The flue gases collected from the boiler and containing CO_2 flow through a heat exchanger where they are cooled to the temperature of about 30°C and then directed to the reactor lower part. The content of CO_2 in flue gases is measured at the reactor inlet and outlet by the Vaisala CARBOCAP GMP251 carbon dioxide probe. The probe is based on the patented second-generation CARBO-CAP technology and enables full temperature compensation of the measurement results, according to the temperature of the surroundings. The probe basic characteristic data are listed in Table 4.

All measurements collected from the stand are recorded using a data acquisition system, stored on a computer and visualised in a SCADA system. A diagram of the test stand is shown in Fig. 3.

The test stand was designed and the sorbent characteristics were selected so that the MBTSA process should meet the requirements for the CO_2 purity level of at least 95% and a capture rate higher than 90%. These are the parameters typically required for CCS applications [37, 38].

Table 4: Characteristic data of the Vaisala CARBOCAP GMP251 probe.

Measurement range	% CO_2	5–10
Operating temperature	°C	–40–+60
Calibration uncertainty	%	±0.05% CO_2 (at 5% CO_2)
		±0.19% CO_2 (at 20% CO_2)
Accuracy (at 25°C, 1013 hPa)	%	±0.2% CO_2 (at 0–8% CO_2)
		±0.4% CO_2 (at 8–20% CO_2)

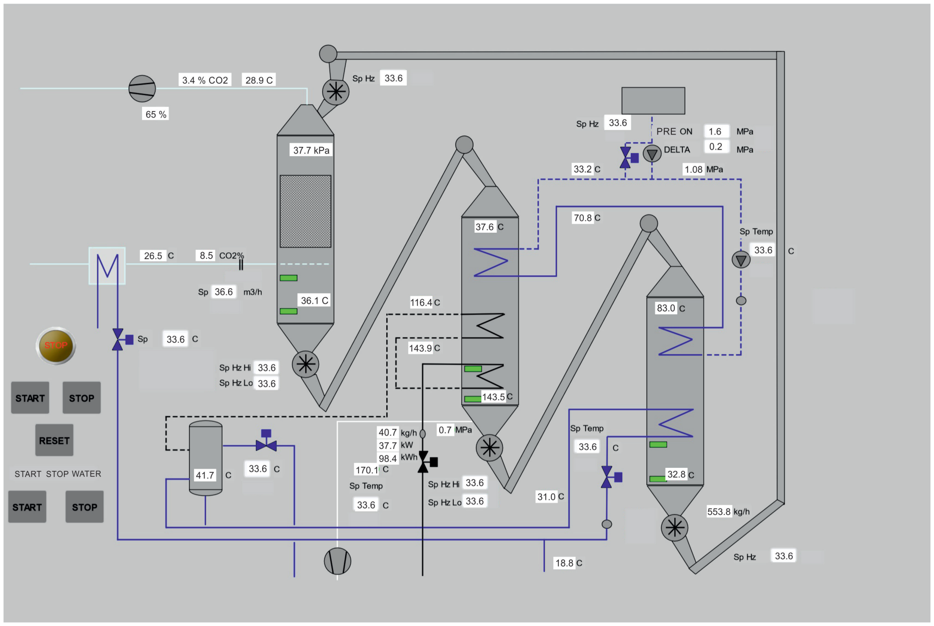


Figure 3: Visualisation of the test stand with preliminary measurement results.

3 Selected simulation results

A simulation was performed of the process of CO_2 capture from flue gases arising due to firing pulverised hard coal in a supercritical boiler (CCS-ready power unit) operating in a power plant in Poland. The simulation was carried out using the gPROMS software [33], which makes it possible to model both the boiler system and the CO_2 capture process.

The basic part of the designed dynamic computational model of CO_2 capture from flue gases is the model of the boiler section (Fig. 4).

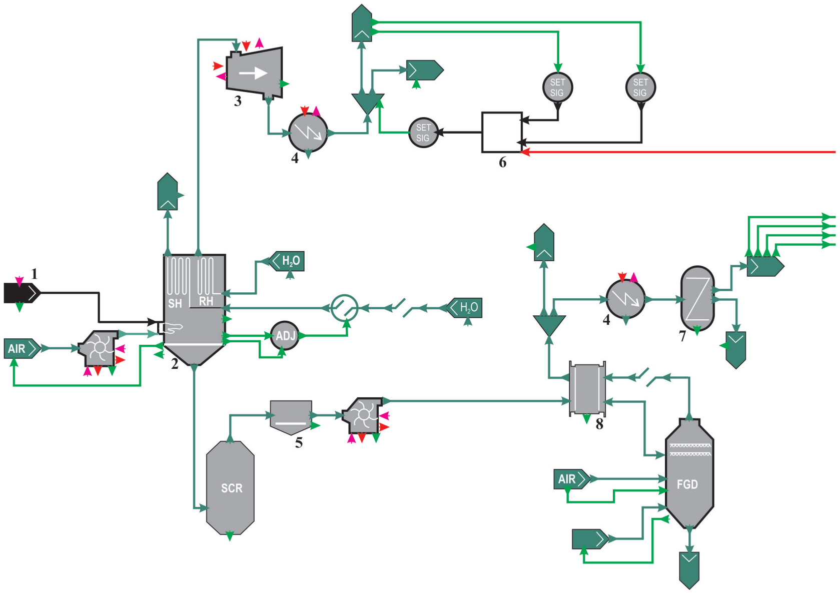


Figure 4: Boiler section of the computational model of CO_2 capture from flue gases created in the gPROMS Process environment: 1 – coal supply, 2 – pulverised coal boiler, 3 – turbine, 4 – cooler, 5 – electrostatic precipitator, 6 – calculation block, 7 – component splitter, 8 – gas-gas heater, SH – superheater, RH – reheater, SCR – selective catalytic reduction, GET SIG – change of signal type, SET SIG – change of signal type, FGD – flue gas desulphurisation, ADJ – adjust.

This is the part where flue gases are produced. Depending on the boiler load, the molar content of individual chemical compounds and elements, including CO_2, changes. Carbon dioxide is then captured in the next section. The designed model takes detailed account of the fuel feeding method, the fuel composition, the air heating and supply to the boiler, the boiler operating parameters and the flue gas purification system before flue gases are entered into the CO_2 capture section. The steam and the boiler feed water circulation systems were designed using some simplifications. The next stage was to introduce a "block" calculating the amount of steam that should be drawn from the turbine bleed to the CO_2 capture section to regenerate the adsorber in the heating (regeneration) column. The steam mass flow is calculated in the block called "Calc_steam_flow", which was additionally created in the program to meet the project needs. The block is fed on-line with the steam enthalpy and pressure values, as well as the demand for heat from the CO_2 capture station (red line in Fig. 4).

The CO_2 capture section was also created using the gPROMS software, not in the “Process” environment, however, but in “ModelBuilder” due to the chemical capabilities of this part of the program (Fig. 5). Using the available tools, a model was made of the system removing carbon dioxide from flue gases. The diagram shows the flue gases flowing through the system (turquoise line), while the flue gases still to enter the capture section are marked with a black line. The purple colour indicates the closed loop of the adsorbent purifying the flue gases. The grey lines mark the information transfer between the system various components and PID (proportional–integral–derivative) controllers. The transfer of information on the heat demand for the adsorbent regeneration from the heating column to the model calculating the demand for steam from the turbine bleed is marked in red.

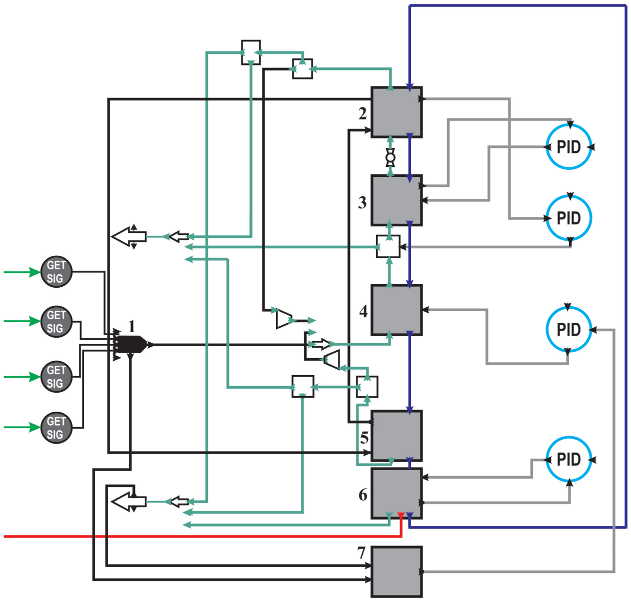


Figure 5: Diagram of the MBTSA stand created in the gPROMS ModelBuilder environment: 1 – flue gas feed, 2 – precooling section, 3 – cooling section, 4 – adsorption section, 5 – preheating section, 6 – desorption section, 7 – signal ratio, PID – proportional-integral-derivative controller, GET SIG – change of signal type.

In the central part of the model there is a block that represents the reactor column of the real system (Point 3, Fig. 5). The injected flue gases come into contact with the adsorbent, giving up a significant amount of CO_2 and a small amount of N_2 (the ratio between these two quantities determines the capture purity). Below the column, two more blocks can be seen (Points 5 and 6, Fig. 5). Together they form a heating column consisting of a part for the sorbent preheating and a desorption (regeneration) part. In this part, the turbine bleed steam is used to preheat the adsorbent to a temperature of about 180°C, at which the bed is regenerated. On the adsorbent further path, a cooling column was also modelled. It consists of precooling and proper cooling parts (Fig. 5, Point 2 and Point 3, respectively). Owing to the water circulating in the heat exchangers, the adsorbent temperature drops to 30°C. In this temperature the adsorbent demonstrates sufficient purity of the CO_2 captured from flue gases.

Performing a dynamic simulation in the gPROMS program after the two sections are combined makes it possible to analyse the results accurately. The results of the simulation calculations can be checked for all necessary parameters in each component of the system.

The following parameters of the boiler were adopted for the simulation: the boiler nominal thermal power – 1838 MW (the power unit gross capacity: 910 MW), which corresponds to the live steam mass flow of 2368×10^3 kg/h (at the steam pressure of 28.5 MPa and temperature of 603°C).

The boiler transient operation was analysed, assuming changes in the boiler load at the rate of 5% of the nominal load in 30 s (Fig. 6).

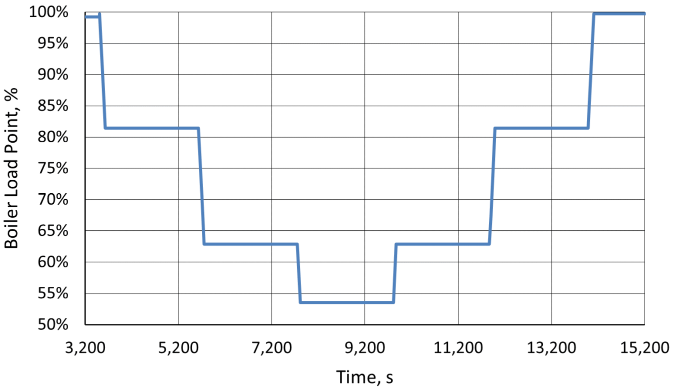


Figure 6: Changes in the power boiler load.

The calculated history of changes in the flue gas mass flow at the reactor inlet is shown in Fig. 7, whereas Fig. 8 illustrates changes in the CO_2 molar concentration in flue gases. These histories were treated as input data for the CO_2 capture section (MBTSA) in the gPROMS ModelBuilder program.

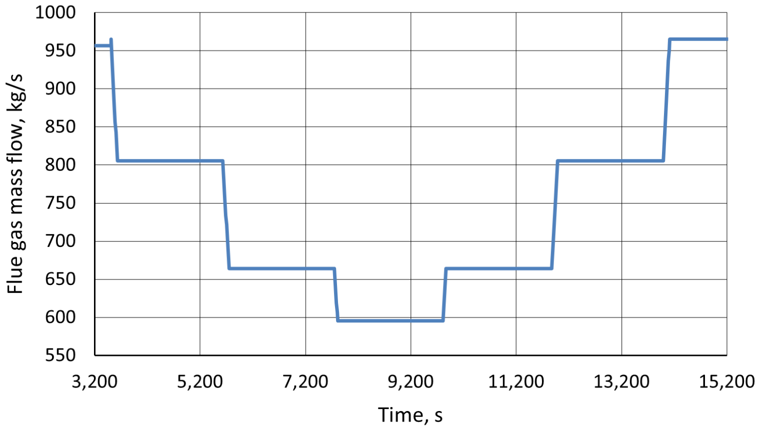


Figure 7: History of changes in the flue gas mass flow.

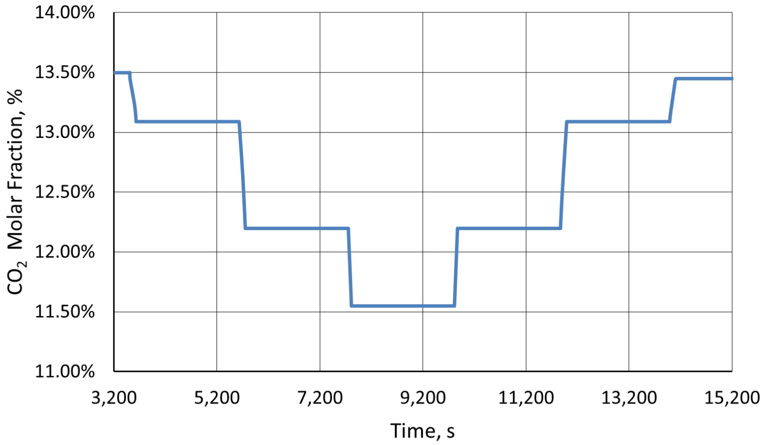


Figure 8: History of changes in the CO_2 molar concentration.

In order to calculate the steam demand for the heating section, the steam parameters available from the turbine bleed were analysed, assuming 100% load of the power unit. Figure 9 shows the history of changes in the demand for heating power for the heating section, whereas Fig. 10 illustrates the changes in the steam mass flow needed to heat the adsorbent. In the case of the analysed bleed, the heating power demand totals $\sim$ 265 MW. This results from the need to heat approx. 2700 kg/s of the adsorbent from the temperature of about 30°C to the temperature of about 180°C.

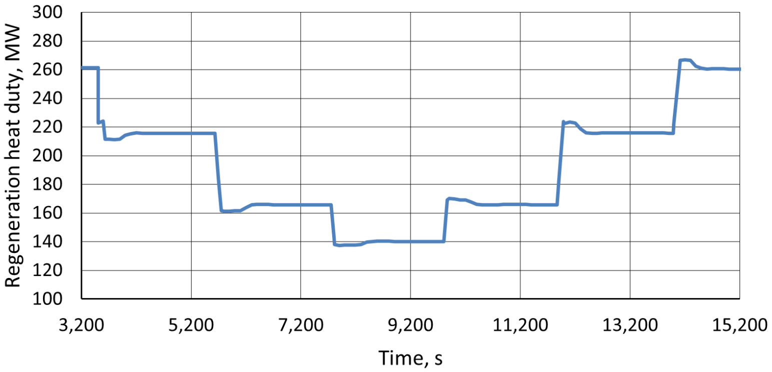


Figure 9: Heating section demand for heating power.

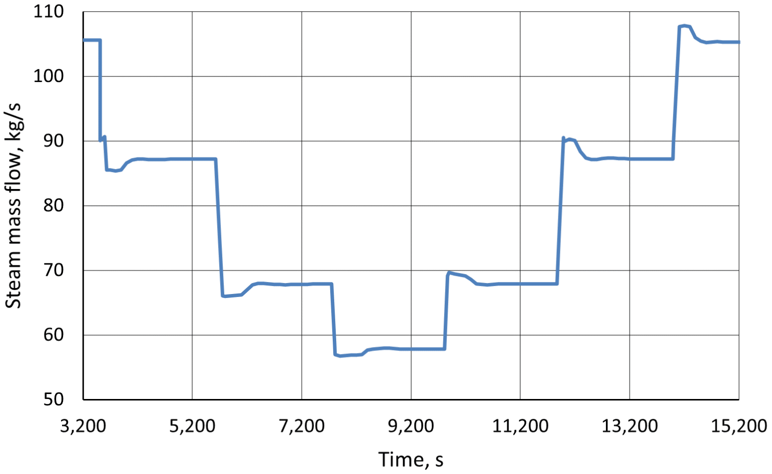


Figure 10: Heating section demand for the steam mass flow.

Figure 11 presents the history of the calculated demand for energy needed to capture 1 kilogram of CO_2 (the method energy consumption). From this figure it can be seen that the method energy consumption varies between ~ 1.4 MJ/(kg CO_2) and ~ 1.7 MJ/(kg CO_2), which is very promising compared to the energy consumption of other methods of CO_2 capture [39]. The figure also shows the time needed for the CO_2 capture section stabilisation (after a change in the boiler load).

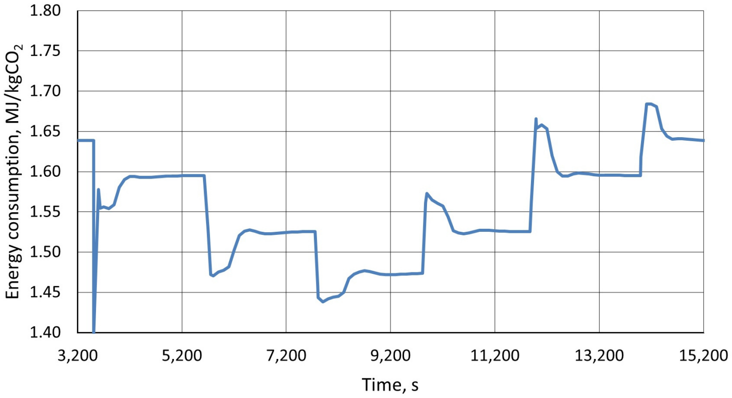


Figure 11: Energy consumption of the method.

4 Summary and conclusions

The paper presents a stand intended for CO_2 capture from flue gases based on the moving bed temperature swing adsorption (MBTSA) process using activated carbon as the adsorber. The stand, built in a Polish power plant, is a research station which enables CO_2 adsorption only from a part of the flue gases produced in the boiler. The main advantages of the MBTSA method are low pressure drops in the adsorption zone and the possibility of a faster rate of the adsorbent heating compared to standard adsorption technologies.

In order to estimate the method energy consumption, simulation calculations were performed of the CO_2 capture from flue gases arising due to firing pulverised hard coal in a supercritical boiler (the boiler is a part of a CCS-ready power unit). The simulations were carried out using the gPROMS software, which makes it possible to combine the boiler section with the CO_2 capture section. The simulation results indicate that the proposed method is characterised by lower energy consumption (about 1.7 MJ/kg CO_2) compared to other methods described in the literature.

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