Co-published by
Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Committee on Thermodynamics and Combustion
Polish Academy of Sciences

Copyright©2026 by the Authors under licence CC BY-NC-ND 4.0

http://www.imp.gda.pl/archives-of-thermodynamics/

Experimental verification of the effectiveness of CO_2 capture from flue gas after pulverised coal combustion

Adam Pawłowski*, Wiesław Zima, Sławomir Grądziel, Artur Cebula, Monika Piwowarczyk, Ewa Kozak-Jagieła

Faculty of Environmental Engineering and Energy, Department of Energy, Cracow University of Technology, Warszawska 24, 31-155 Cracow, Poland
*Corresponding author email: adam.pawlowski@pk.edu.pl

Received: 28.02.2026; revised: 02.07.2026; accepted: 21.07.2026

Abstract

This article presents experimental verification of CO_2 capture from flue gases generated in a pulverised coal-fired power boiler. The tests were carried out using a pilot-scale moving bed temperature swing adsorption system installed in an operating coal-fired power plant (Skawina Power Plant). Activated carbon in the form of beads was used as the adsorbent due to its developed microporous structure, large specific surface area and excellent mechanical resistance under conditions of continuous circulation. The installation enables treatment of a flue gas stream with a volumetric flow rate of up to 50 m³/h. The supplied flue gas, composed mainly of N_2 and CO_2, was extracted downstream of the plant's gas-cleaning system. Two recent measurement campaigns were analysed under variable inlet CO_2 concentrations (4.81–7.16 vol.%; it depends on the operation of the power plant, so it cannot be controlled by researchers), different flue gas flow rates and varying sorbent mass flow rates. Under quasi-steady-state operating conditions, a capture efficiency of 50–60% was achieved at an inlet CO_2 concentration of 6–7% by volume, with an average energy consumption of 55.3 MJ/kgCO_2. A second series of measurements confirmed the high sensitivity of capture efficiency to the ratio of sorbent mass flow rate to flue gas flow rate and to regeneration conditions. The results demonstrate the technical feasibility of moving bed temperature swing adsorption operation under actual coal-fired power plant conditions; however, significant optimisation of heat integration, process configuration and sorbent management is necessary to reduce energy requirements to a level compatible with industrial implementation.

Keywords: Experimental tests; CO_2 capture; Research facility; Moving bed temperature swing adsorption

Vol. 47(2026), No. 3, 5–14; doi: 10.24425/ather.2026.3648

Cite this manuscript as: Pawłowski, A., Zima, W., Grądziel, S., Cebula, A., Piwowarczyk, M., & Kozak-Jagieła, E. (2026). Experimental verification of the effectiveness of CO_2 capture from flue gas after pulverised coal combustion. *Archives of Thermodynamics*, 47(3), 5−14.

1. Introduction

Anthropogenic carbon dioxide (CO_2) emissions remain a primary driver of climate change and continue to pose a direct challenge for the power sector and other energy intensive industries. Even under accelerated deployment of renewable energy and electrification, large stationary point sources such as coal and gas fired power plants, cement kilns, steelworks and refineries are expected to contribute substantially to residual emissions over the coming decades. For this reason, carbon capture, utilisation and storage (CCUS) is widely recognised as a key bridging technology to enable deep decarbonisation while maintaining security of supply and industrial competitiveness. A comprehensive review by Markewitz et al. [1] emphasised that CCUS deployment must be assessed not only in terms of capture efficiency, but also in terms of system integration, energy penalty and the implications for the entire energy chain.

From an engineering and policy perspective, the major barrier to large-scale CCUS implementation has consistently been the cost and energy demand of capture, particularly for post-

Nomenclature

CO_2– CO_2 concentration in the flue gas, %
m_{CC}– mass of CO_2 captured from the flue gas, kgCO_2
Q – thermal energy supplied via steam for sorbent regeneration, MJ

Greek symbols

ζ – energy consumption of CO_2 capture, MJ/kgCO_2
η – CO_2 capture efficiency, %

Subscripts and Superscripts

in – before contact with adsorbent
out – after contact with the adsorbent

Abbreviations and Acronyms

BAC – ball-shaped activated carbon
CCS – carbon capture and storage
CCUS – carbon capture, utilisation and storage
CO_2 – carbon dioxide
IGCC – integrated gasification combined cycle
MBTSA– moving bed temperature swing adsorption
MEA – monoethanolamine
MOF – metal-organic frameworks
PSA – pressure swing adsorption
SCADA– supervisory control and data acquisition
TSA – temperature swing adsorption
VSA – vacuum swing adsorption
VTSA – vacuum temperature swing adsorption

combustion flue gas streams where CO_2 is diluted in nitrogen, and where the treated gas flow rates are large. Rubin et al. [2] showed that capture dominates the levelised cost of carbon capture and storage (CCS) for power generation and that cost reductions depend strongly on both process intensification and integration opportunities at the plant level. For pulverised coal units, retrofitting post-combustion capture remains an attractive route because it can, in principle, be implemented without radical modifications to the boilers and turbines system.

Aqueous amine absorption (most commonly monoethanolamine (MEA) based) remains the benchmark technology for post-combustion CO_2 capture due to its technological maturity and demonstrated performance. Rochelle's [3] widely cited review pointed out that amine scrubbing is robust and industrially proven, but also highlighted the fundamental thermodynamic minimum work and the practical need to reduce energy consumption through solvent and process improvements. In practice, the regeneration duty and the associated steam extraction reduce power output and may complicate part-load operation. These limitations motivate continuous research into alternative capture concepts that could reduce the energy penalty, mitigate solvent degradation, and simplify operation and maintenance.

At the industrial scale, the Shell CANSOLV process provides an important reference point for post-combustion CO_2 capture based on regenerable amine absorption. The first commercial applications of this technology demonstrated high CO_2 capture performance and high product purity [4].

Post-combustion capture options include chemical absorption, physical adsorption, membrane separation, and hybrid configurations combining several mechanisms. In a broad review of post-combustion carbon capture, Chao et al. [5] underlined that no single technology is universally optimal; instead, performance depends on flue gas composition, required CO_2 purity and recovery, integration constraints, and site-specific economics. Within this landscape, adsorption-based approaches have attracted increasing attention because regeneration can be driven by temperature and/or pressure changes, and because solid sorbents can potentially avoid some drawbacks of liquid solvents (corrosion, solvent losses, and oxidative/thermal degradation).

The viability of adsorption-based CO_2 capture depends on two coupled elements: the intrinsic properties of the sorbent (capacity, selectivity, kinetics, stability) and the process design (contactor configuration and regeneration strategy). Choi et al. [6] provided an early, influential review of sorbent classes for large point sources, discussing activated carbons, zeolites, alkaline oxides, hydrotalcites, amine-functionalised solids and metal-organic frameworks (MOFs), and highlighted that process design constraints often dominate material selection when moving from laboratory to industrial scales. In a later review focused specifically on post-combustion capture using solid sorbents, Samanta et al. [7] stressed the importance of cyclic stability, tolerance to moisture and impurities, and the practical challenges of scaling fixed-bed systems, including pressure drop and heat management. More recently, Raganati et al. [8] summarised the state of adsorption-based post-combustion capture, emphasising that regeneration strategy and heat integration determine much of the overall energy penalty and capture cost.

The development of advanced sorbents remains an active area of research, especially for low CO_2 partial pressures where high selectivity is required. D'Alessandro et al. [9] discussed the prospects and limitations of new porous materials for CO_2 separation, noting that improved materials must be evaluated under realistic operating conditions, including temperature, humidity and exposure to contaminants. In a recent review, Kong et al. [10] compared carbon sorbents, zeolites and MOFs for post-combustion capture, highlighting recurring trade-offs: zeolites and some MOFs exhibit high efficiency and selectivity but can be sensitive to water, while carbonaceous materials are generally more resistant to moisture and contamination but may exhibit lower selectivity and operating efficiency under flue gas conditions.

From a process standpoint, adsorption cycles can be broadly classified as pressure swing adsorption (PSA), vacuum swing adsorption (VSA), temperature swing adsorption (TSA), and combined VTSA cycles. TSA is particularly relevant for near-atmospheric flue gas because it avoids deep vacuum operation and can allow us to use waste heat; yet, TSA can suffer from slow heating and cooling rates, large thermal inertia and high heat demands. Clausse et al. [11] performed a numerical parametric study on indirect TSA for post-combustion capture, and demonstrated that cycle performance is strongly affected by the regeneration temperature, purge conditions and heat transfer characteristics, with energy consumption being a central constraint for industrial relevance. Earlier, Bonjour et al. [12] investigated a TSA process with indirect heating and cooling, and dis-

cussed how internal heat exchanger design and scaling influence specific heat consumption, providing a process-intensification perspective directly relevant to pilot- and industrial-scale systems.

Thermodynamic analyses of integrated gasification combined cycle (IGCC) systems with pre-combustion, post-combustion and oxy-fuel configurations make a significant contribution to the assessment of the efficiency of coal-fired power plants integrated with CCS systems. Kindra's et al. [13] work provides a comparative analysis of these variants using simulation models, showing that the highest net efficiency (47.2%) can be achieved in an IGCC system with pre-combustion capture, assuming effective thermal integration of the synthesis gas preparation section, while the oxy-fuel configuration minimises CO_2 emissions (approx. 9 g/kWh), but at the cost of a significant drop in efficiency to 36.3%. These results clearly indicate that the competitiveness of CCS technology is primarily determined by the energy balance of the system and the extent of heat recovery. However, it should be emphasised that the presented analyses are model-based and refer to fixed operating conditions, which justifies the need for experimental research conducted under real conditions, allowing for the verification of the assumptions made and the assessment of operational limitations, in particular with regard to adsorption processes.

Beyond the choice of the cycle, it is increasingly recognised that meaningful comparisons between the capture technologies require consistent performance metrics: capture rate, product purity, productivity and specific energy consumption (thermal and/or electrical), ideally evaluated under comparable boundary conditions. Zhao et al. [14] proposed performance analysis frameworks for TSA systems and emphasised the role of thermodynamic benchmarking when interpreting reported energy demands. In a comprehensive evaluation of TSA for post-combustion capture, Zhao et al. [15] further highlighted that the apparent energy penalty depends not only on the heat of adsorption but also on the heat capacity of the sorbent and the overall heat management of the contactor and auxiliaries. This is particularly important for systems aiming at continuous or quasi-continuous operation, where thermal integration is an explicit design objective.

Moving bed temperature swing adsorption (MBTSA) has been proposed as an approach to overcome some intrinsic limitations of fixed-bed TSA. The key concept is continuous circulation of the adsorbent through spatially separated sections for adsorption, heating (desorption) and cooling, which can reduce pressure drop in the adsorption zone and potentially improve heat transfer by decoupling the thermal front from the gas-phase pressure constraints. Mondino et al. [16] developed and analysed MBTSA configurations for post-combustion capture in a coal-fired power plant context and showed that process modifications, particularly gas recirculation from the desorption section, can substantially improve CO_2 purity and capture rate compared to simple baseline configurations. In a later study, Mondino et al. [17] investigated MBTSA as an alternative to absorption for natural gas combined cycle plants, where the CO_2 partial pressure is typically low, demonstrating that MBTSA can be competitive when integrated at the plant level and when the capture process auxiliaries are fully accounted for. More recently, MBTSA was assessed for a waste-to-energy application, with a clear focus on internal heat recovery and experimentally informed heat-transfer correlations, reinforcing that heat transfer and thermal integration remain decisive factors for the practical feasibility of the concept [18].

A concept utilising a fixed sorbent in continuous mode for CO_2 capture has also been developed by Kawasaki; in this system, the process relies on a porous, amine-impregnated material regenerated with low-temperature steam, which differs significantly from the spherical activated carbon used in the current MBTSA plant. In early moving-bed tests, CO_2 was captured from coal-combustion exhaust gas using steam at approximately 60°C, with a reported CO_2 product concentration of at least 95%, whereas later parametric tests were performed on a 5 t_{CO_2}/day moving-bed unit [19,20]. These studies indicate that the moving-bed configuration itself can be technically feasible, but they also show that process performance is strongly dependent on sorbent chemistry, regeneration strategy and heat integration.

While modelling studies provide critical insights into process design space, experimental evidence under real flue gas conditions remains essential. Flue gas contains water vapour and trace contaminants, exhibits temporal variability and imposes operational constraints that are often simplified or ignored in simulations. Pilot scale adsorption capture using multi-layer VSA/VPSA or MBTSA configuration (described in the next chapters) has been demonstrated at coal-fired power plants, providing valuable benchmarks for actual performance. Liu et al. [21] reported on onsite CO_2 capture from coal-fired flue gas using an adsorption process after dehydration, demonstrating high CO_2 purity and recovery in a multi-bed cycle and reporting experimentally measured energy consumption under plant integrated conditions. In a related short communication, Wang et al. [22] experimentally evaluated adsorption capture in an existing coal-fired power plant and showed that dehumidification and real-gas operation are central to stable performance and energy consumption. These studies underscore the importance of plant-level constraints and provide context for interpreting energy metrics obtained in pilot systems.

For adsorption-based capture from flue gas, moisture is a dominant factor affecting cycle performance. Activated carbons are often considered advantageous in wet conditions due to their relatively hydrophobic character compared to many zeolites. Xu et al. [23] investigated the effects of water vapour on CO_2 capture using activated carbon in VSA operation and demonstrated that, even when CO_2/N_2 separation remains feasible, moisture can increase energy consumption and complicate cycle optimisation. Consequently, pilot-scale evaluation under real flue gas conditions should clearly consider humidity management, thermal inertia and the stability of the sorbent under repeated cycling.

Another central but frequently underestimated contributor to energy penalty in TSA/MBTSA systems is the sensible heat required to raise and lower the temperature of the circulating solid phase. Even when the heat of adsorption is moderate, a high sorbent heat capacity or excessive thermal mass in the contactor can lead to large regeneration duties. Querejeta et al. [24] sys-

tematically measured heat capacities of activated carbons in the temperature range relevant for TSA-based CO_2 capture and concluded that selecting and/or modifying carbon materials to reduce heat capacity can be an effective strategy to lower regeneration energy demand. This insight is directly relevant for moving bed concepts, where continuous sorbent circulation amplifies the impact of solid-phase thermal properties.

In addition to the international studies discussed above, Polish pilot and demonstration projects provide important quantitative benchmarks for assessing post-combustion CO_2 capture processes under real-world flue gas conditions. Pilot tests based on the amine process, carried out at the Łaziska Power Station, enabled the removal of over 19 000 kg of CO_2 over approximately 550 hours of operation and demonstrated the practical significance of mobile pilot installations integrated with coal-fired units [25]. Earlier Polish studies on amine-based post-combustion CO_2 capture reported a pilot plant capacity of up to 200 Nm³/h of flue gas [26].

These studies are complemented by national energy and economic analyses of CO_2 capture installations using monoethanolamine and ammonia, which indicate that the choice of absorbent significantly affects the heat demand for regeneration and the cost of the process [27]. In the case of adsorption-based capture methods, Polish research into DR-VPSA was carried out using actual flue gases, a four-column adsorption system and a complete gas pre-treatment line, comprising dust removal, cooling, desulphurisation, denitrification, drying and compression [28]. The long-term performance of activated carbon in a pilot DR-VPSA plant was also analysed over 808 hours under real flue gas conditions [29]. These results are relevant to the present MBTSA study, as they show that capture efficiency must be interpreted in conjunction with gas conditioning, sorbent durability, regeneration stability, pressure drops, heat recovery and auxiliary energy requirements.

In the next chapters, this paper presents an experimental performance of CO_2 capture using a pilot MBTSA system installed in an operating pulverised coal-fired power plant (Skawina Power Plant, Poland). The installation processes actual flue gas taken from the end of the existing purification installation and uses ball-shaped activated carbon (BAC) as a mechanically robust sorbent suitable for continuous circulation. The scope of the experiment focuses on determining the capture efficiency at different CO_2 inlet concentrations and flow conditions, and calculating the energy consumption associated with thermal regeneration using a heat source integrated with the power plant and operating data recorded by the SCADA system. This experimental analysis complements previous work comparing MBTSA simulations with experimental observations for the same installation [30].

2. Description of the research facility

As part of the conducted research, a specially designed pilot installation for CO_2 capture from flue gas was employed. The system enables treatment of a flue gas stream with a volumetric flow rate of up to 50 m³/h. The process was implemented using the MBTSA technology. The installation was connected to the flue gas duct of a pulverised coal-fired boiler downstream of the existing gas-cleaning units. As a result, the supplied gas stream consisted predominantly of N_2 and CO_2. A specially prepared ball-shaped activated carbon (BAC), manufactured by Kureha [31], was used as the adsorbent. The sorbent circulates continuously between three main process sections: the adsorption section, where CO_2 and partially N_2 are captured; the regeneration section, in which the sorbent undergoes thermal desorption; and the cooling section. Material transport between the columns is carried out by insulated belt conveyors, which receive the sorbent after its passage through each process section.

2.1. Description and purpose of individual sections of the facility

The pilot installation consists of three main process sections enabling continuous CO_2 capture from flue gas using the temperature swing adsorption concept. Each section is equipped with a rotary valve that ensures controlled sorbent flow by allowing gradual discharge at the bottom of the column. The combination of bed level sensors and frequency inverters enables automatic adjustment of the rotational speed of the rotary valves. Since the belt conveyors operate at constant speed, regulation of sorbent dosing via the rotary valves makes it possible to vary the sorbent mass flow rate while maintaining predefined filling levels in each process section.

The three principal sections of the installation (Fig. 1) are described below in the order corresponding to sorbent circulation, excluding mechanical transport elements:

1. Adsorption section (reactor).
   The adsorption section consists of a sealed, cylindrical column with plastic walls and filled with Mellapak™ structured packing. Within the column, upward-flowing flue gas comes into contact with adsorbent particles descending under gravity, resulting in adsorption of CO_2 onto the sorbent surface. The flue gas is introduced at the bottom of the column and, under slight overpressure, exits at the top. The sorbent is supplied from the top and flows downward to the bottom of the column. The application of Mellapak™ structured packing ensures uniform distribution of both gas and solid phases and extends gas–solid contact time.
2. Regeneration/heating section.
   The regeneration section consists of a thermally insulated column in which the sorbent undergoes thermal desorption at a temperature of approximately 180°C, required for effective regeneration of the activated carbon. Three shell and tube heat exchangers are installed inside the column. The upper heat exchanger forms part of a closed internal heat recovery loop. It transfers energy between the regeneration and cooling sections, enabling preheating of the incoming sorbent while simultaneously recovering heat from the cooling column. The remaining two heat exchangers operate in series. Saturated steam extracted from the turbine, with parameters of approximately 190°C and 1.3 MPa, is supplied to the lower exchanger. The steam condenses while transferring heat to the sorbent. The resulting condensate is then directed to the middle exchanger, where its temperature decreases to approximately 121°C. The desorbed gas stream, consisting primarily of CO_2 and

N_2, is removed through an outlet equipped with a fan generating slight underpressure, ensuring stable evacuation of the desorption gases from the system.

3. Cooling section.
   The final section of the installation is a thermally insulated column designed to reduce the sorbent temperature to restore its adsorption capacity prior to re-entry into the adsorption section. Two shell and tube heat exchangers are installed within this column. The upper exchanger is integrated into the previously described internal heat recovery loop, while the lower exchanger provides direct cooling of the sorbent. Cooling water at approximately 15°C flows through the lower heat exchanger, enabling reduction of the sorbent temperature to below 25°C before it returns to the adsorption section.

Figure 1 presents the pilot installation viewed from the conveyor connecting the cooling section, visible as the insulated column on the left, with the adsorption section, visible as the column on the right. The regeneration section is located on the opposite side of the facility and is only partly visible in the photograph. One belt conveyor transfers the activated carbon from the adsorption section to the regeneration section, while another conveyor transports the regenerated sorbent from the regeneration section to the cooling section. The silver-coloured cladding visible on the regeneration section, the cooling section and the conveyor between these sections protects and stabilises the mineral-wool insulation, ensuring continuity and high effectiveness of thermal insulation. Due to the presence of supporting structures and other power plant equipment, capturing a complete view of the installation in a single photograph is not feasible.



Fig. 1. Illustrative photograph of research facility.

A simplified process scheme of the installation is shown in Fig. 2. The scheme illustrates the main circuits present in the CO_2 capture system, including the flue gas path, sorbent circulation loop, heating medium circuit, cooling-water circuit and CO_2-rich gas outlet. The sections connecting the bottom of one column with the top of the next column represent belt conveyors used for transporting the activated carbon between the process sections.

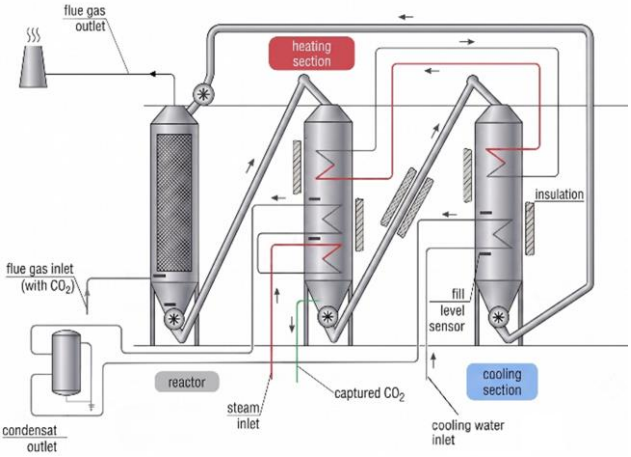


Fig. 2. Scheme of research facility.

The flue gas is introduced into the lower part of the adsorption reactor and is withdrawn from the upper part of the reactor under a slight negative pressure. In the upper parts of the regeneration and cooling sections, heat exchangers filled with circulating water form an internal heat-recovery loop between these two sections. In the middle and lower parts of the regeneration section, additional heat exchangers are installed. Saturated steam extracted from the turbine is supplied to the inlet of the lower heat exchanger, where it condenses while transferring heat to the activated carbon. The condensate then flows through the middle heat exchanger and is subsequently discharged to the condensate tank, where it is cooled before being released to the drainage system. The CO_2-rich gas released from the activated carbon during thermal desorption is extracted by a small fan and discharged from the installation. In the lower part of the cooling section, a heat exchanger supplied with cold water is used to reduce the temperature of the regenerated sorbent before it returns to the adsorption section. After leaving the cooling section, the water is directed to the condensate tank, where it assists in reducing the condensate temperature before discharge to the drainage system.

2.2. Structural layout of the research facility

The pilot installation was designed in a triangular configuration, in which the three main process sections (adsorption, regeneration and cooling) are located at the vertices of a triangle, while the sorbent transport system forms its sides. This arrangement enabled efficient utilisation of the available space and ensured compliance with structural constraints associated with installing the system inside an existing building. The adopted layout also provides protection of the installation components against adverse environmental conditions and facilitates operation and maintenance. A vertically stacked configuration was initially considered, as it would have theoretically reduced the number of required belt conveyors. However, this option exceeded the available floor height and permissible structural load limits, and was therefore rejected at the design stage.

2.3. Characteristics of flue gases feeding the system

The flue gas supplied to the adsorption section originated from a power boiler operating under real plant conditions. Consequently, its chemical composition exhibited continuous variability, resulting in significant fluctuations in the carbon dioxide (CO_2) concentration within the analysed stream. The recorded volumetric CO_2 concentrations ranged from 4,81% to 7.16%, which is considerably lower than the values assumed at the design stage of the pilot installation. The CO_2 concentration in the flue gas was measured using a Vaisala CARBOCAP® GMP251 probe based on infrared (IR) absorption technology.

2.4. Information about the adsorbent

Activated carbon was selected as the sorbent material primarily due to its favourable thermo-physical properties, in particular its relatively high heat transfer coefficient on the solid side, reported in the range of 69–117 W/(m^2·K) [17]. An additional factor influencing this choice was its superior mechanical strength compared with alternative sorbents such as zeolite 13X.

Although zeolites exhibit more favourable adsorption characteristics, resulting in lower specific energy consumption in MBTSA processes, their practical applicability remains limited. Simulation studies indicate that the specific energy demand for zeolite 13X may reach approximately 2.3 MJ/kg CO_2 [16], whereas for activated carbon it is estimated at approximately 5.7 MJ/kg CO_2 [17]. However, commercially available zeolites are characterised by relatively low mechanical strength and high brittleness, leading to rapid degradation under continuous circulation conditions. This makes their application in MBTSA systems currently impractical.

The thermo-physical properties of the activated carbon have been reported in the literature [17,31]. Its principal characteristics are summarised in Table 1, while a photograph of the material in its original packaging is presented in Fig. 3.

Table 1. Selected parameters of activated carbon [32].

Shape	Specific surface area	Average particle diameter	Hardness
Spherical	1100-1300 m^2/g	≈0,7 mm	≥95%



Fig. 3. BAC-type activated carbon: a) in its original packaging; b) spilled out on a paper.

3. Analysis of experimental results

The experimental results are presented in graphical form and include both direct measurements obtained from the pilot installation and values calculated on the basis of these measurements. All data were acquired and archived using a SCADA (supervisory control and data acquisition) system, which enables continuous monitoring of process parameters based on signals from sensors installed throughout the installation.

Figures 4 and 5 present selected measurement data recorded during operation of the pilot unit, including:

- CO_2 concentration in the flue gas at the inlet and outlet of the adsorption section (Figs. 4a and 5a),
- mass flow rate of the activated carbon (Figs. 4b and 5b),
- volumetric flow rate of the supplied flue gas (Figs. 4b and 5b).

In addition, two key performance indicators were determined based on the recorded data:

- CO_2 capture efficiency (η), defined as the relative reduction in CO_2 concentration in the flue gas after contact with the sorbent. This parameter was calculated according to the following equation:

$$\eta = 1 - \frac{CO_{2,out}}{CO_{2,in}}, \quad (1)$$

where: η – CO_2 capture efficiency [%], $CO_{2,out}$ – CO_2 concentration in flue gas after contact with the adsorbent [%], $CO_{2,in}$ – CO_2 concentration in flue gas before contact with the adsorbent [%],

- energy consumption of the CO_2 capture process (ζ), defined as the ratio of the total heat supplied for sorbent regeneration to the mass of captured CO_2:

$$\zeta = \frac{Q}{m_{CC}}, \quad (2)$$

where: ζ – energy consumption of CO_2 capture [MJ/kgCO_2], Q – thermal energy supplied via steam for sorbent regeneration [MJ], m_{CC} – mass of CO_2 captured from the flue gas [kgCO_2].

Figure 4 presents the results of measurements and calculations performed on 8 March 2024. Although these are not the earliest available datasets, it should be noted that the activated carbon used during this campaign had already been subjected to significant prior operation (several dozen hours of circulation within the system). Consequently, partial sorbent degradation and a reduction in adsorption performance were expected.

The results presented correspond to an approximately 30-minute segment of measurement data selected from the analysed day. This period was chosen because it represented the longest uninterrupted operation of the installation under a constant activated carbon mass flow rate and a relatively stable flue gas volumetric flow rate (Fig. 4b). This approach limited the influence of transient operating conditions on CO_2 capture efficiency and specific energy consumption. As shown in Fig. 4a, the CO_2 concentration in the flue gas entering the adsorption column varied within the range of 6–7%, while the outlet concentration averaged approximately 3%. This corresponded to a capture effi-

ciency of 50–60% during most of the analysed interval. At the same time, a high specific energy consumption was observed (Fig. 4c), with a median value of 55.3 MJ/kgCO_2, which must be considered unfavourable from the standpoint of energy performance.

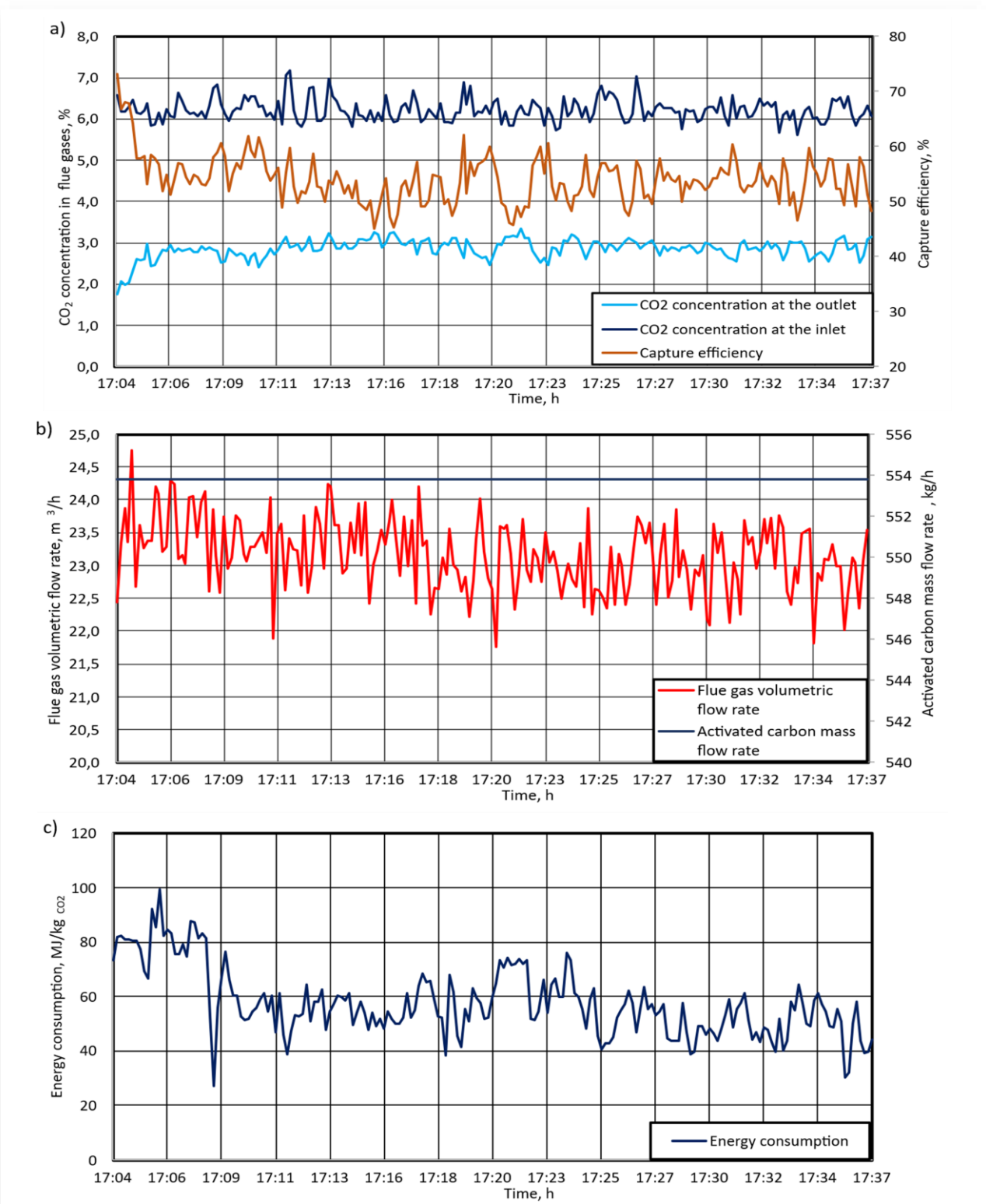
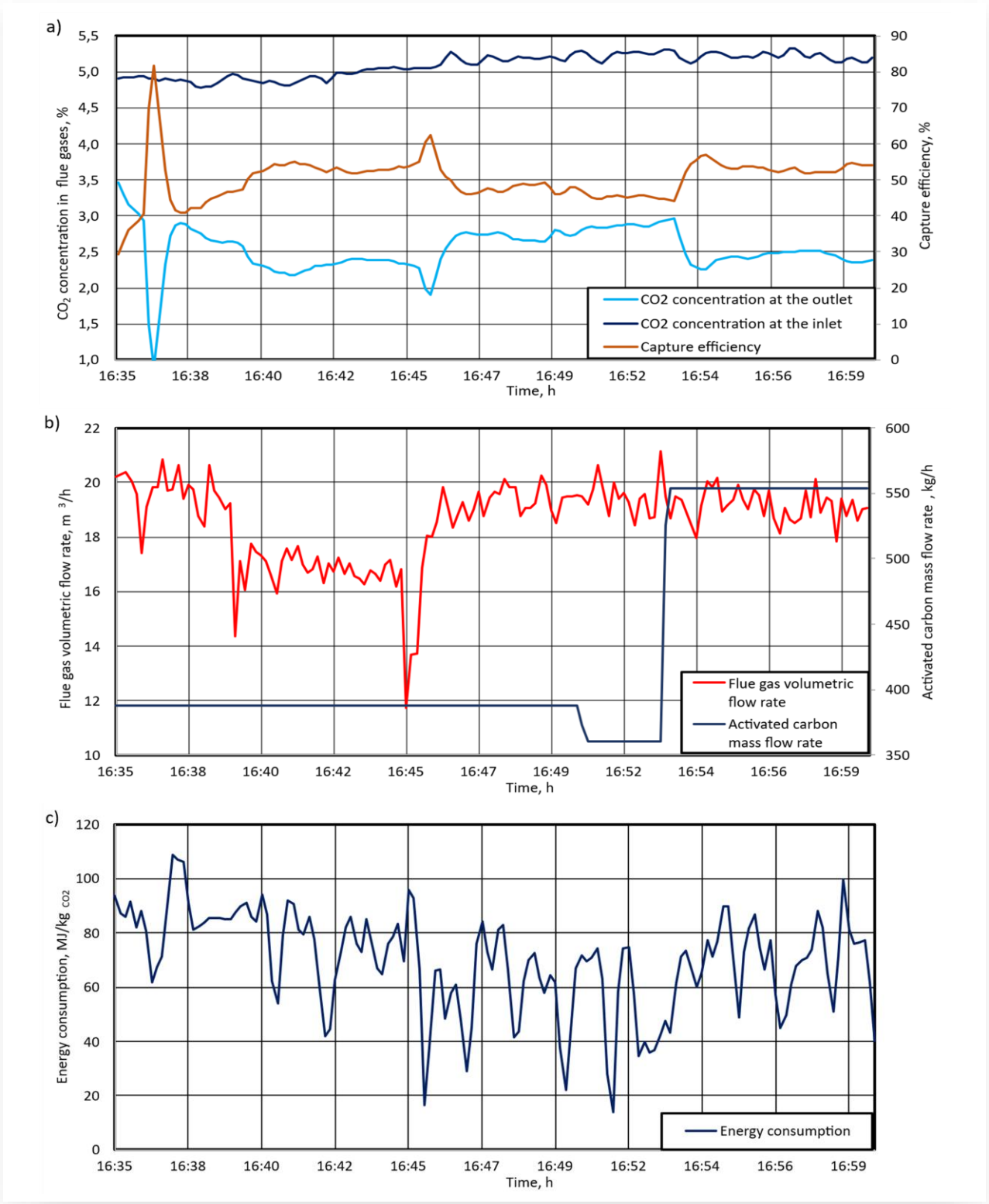


Fig. 4. Results obtained on 8 March 2024: a) CO_2 concentration in the inlet and outlet flue gas streams and corresponding capture efficiency; b) volumetric flow rate of the flue gas and mass flow rate of the activated carbon; c) specific energy consumption of the capture process.

Figure 5 presents the results obtained on 17 April 2024. During the period between the two measurement campaigns, the installation remained inactive, and no fresh sorbent was introduced into the circulation loop, implying further physico-chemical degradation of the activated carbon. In contrast to the relatively stable conditions shown in Fig. 5, the time interval pre-

sented in Fig. 5b exhibits noticeable variability in both the activated carbon mass flow rate and the flue gas volumetric flow rate. These variations directly affected the CO_2 concentration at the reactor outlet. A decrease in flue gas flow rate or an increase in sorbent feed resulted in improved capture efficiency, whereas the opposite changes led to a reduction in performance.

Pronounced changes in specific energy consumption were also observed (Fig. 5c); however, its response was less immediate. The specific energy demand exhibited a delayed reaction to variations in the sorbent mass flow rate, which can be attributed to system inertia, including gradual sorbent dosing through the rotary valve and the dynamic behaviour of the internal heat recovery loop.



Significant variations in the operating parameters of the installation may substantially affect data interpretation, particularly when datasets covering periods longer than two hours are analysed with a time resolution of 30 s. In contrast, results

obtained over shorter intervals with a 15 s sampling step allow for more detailed analysis of transient effects occurring after changes in key operating conditions.

4. Conclusions

The analysis of results obtained from the two measurement series clearly indicates a significant influence of the activated carbon mass flow rate on the efficiency of the CO_2 adsorption process. Although increasing the sorbent feed appears to be a straightforward method for improving capture efficiency, it may simultaneously lead to higher specific energy consumption and an increased risk of insufficient heating of the sorbent to the required regeneration temperature. Under the investigated experimental conditions, the specific energy demand reached very high values, representing a major barrier to potential industrial implementation of the technology. For this method to become attractive from both economic and environmental perspectives, a substantial reduction in regeneration energy consumption is essential. Inadequate heating of the activated carbon results not only in incomplete sorbent regeneration, leading to reduced adsorption capacity, but also in gradual cooling of the internal heat recovery circuit. This effect may further deteriorate the overall energy balance of the installation and hinder the achievement of stable operating conditions.

It should also be pointed out that the presented results were obtained using the sorbent that had already operated in the circulation loop for several hours, implying a reduction in its initial adsorption performance. Previous studies [31] have reported significantly higher CO_2 capture efficiencies, reaching approximately 76%, together with lower specific energy consumption of about 25 MJ/kgCO_2, when partial replacement of activated carbon was implemented during operation.

In light of these observations, further optimisation of the MBTSA technology appears justified, both in terms of installation design and sorbent selection. One potential development pathway is the reconstruction of the system into a vertically stacked configuration, in which the individual process sections would be arranged one above another. Such a layout could reduce heat losses associated with sorbent transport between sections and decrease the risk of leakage through flexible components (e.g. seals), which may allow ingress of cold and humid ambient air. In parallel, further investigations of alternative commercial sorbents are recommended, particularly those offering lower regeneration energy demand, higher CO_2 selectivity, and mechanical durability comparable to that of activated carbon.

The obtained results should also be considered in the broader context of Polish pilot and demonstration experience. Compared with Polish pilot tests based on amine processes, in which CO_2 removal above 90% and large cumulative amounts of captured CO_2 were reported [25], the results obtained in the present MBTSA study confirm the technical feasibility of conducting an adsorption-based CO_2 capture process using real flue gas from coal combustion. At the same time, however, they indicate much stronger limitations related to regeneration energy and solid-phase heat management. The measured capture efficiency of approximately 50–60% at an inlet CO_2 concentration of 6–7 % vol. and the median specific energy consumption of 55.3 MJ/kgCO_2 indicate that the investigated configuration is not yet energetically competitive with mature absorption-based processes. At the same time, the previous result of approximately 76% capture efficiency and about 25 MJ/kgCO_2 after partial replacement of the activated carbon shows that this technology is highly sensitive to sorbent condition, heat recovery efficiency and operating parameters. Therefore, the practical assessment of MBTSA technology should include not only instantaneous capture efficiency, but also sorbent ageing, regeneration completeness, steam parameters, cooling demand, heat losses during sorbent transport, internal heat recovery, leaks leading to the intake of cold and humid ambient air, and long-term operational stability [30].

Against the background of the international literature, it should only be noted that mature amine absorption processes, such as Shell CANSOLV [4] and moving-bed systems developed by Kawasaki [19,20], confirm the key importance of sorbent type, regeneration strategy and thermal integration for the achieved CO_2 capture performance.

At the same time, the results obtained in the present MBTSA installation cannot be directly compared on a one-to-one basis with results reported for other pilot and demonstration CO_2 capture installations [25−30]. These installations were based on different capture methods, including primarily amine absorption and cyclic adsorption processes, and they also differed in process configuration, scale, operating pressure, regeneration strategy, heat source, gas pretreatment requirements and performance assessment indicators. Moreover, the experimental campaign described in this study revealed a number of design and construction imperfections in the investigated installation that may have adversely affected the measured capture efficiency and specific energy consumption. These include excessive heat losses during sorbent transport, possible air intake through flexible connections and sealing elements, non-uniform heating of the circulating activated carbon, incomplete regeneration, limitations of the internal heat recovery system and process sensitivity to sorbent ageing and dosing stability. Therefore, before the obtained results can be used for a reliable quantitative comparison with other demonstration studies, the identified design and construction problems should be eliminated, and the installation should be retested under repeatable operating conditions with clearly defined boundary parameters.

Acknowledgements

The research that led to these results received funding from the Norway Grants 2014−2021 through the National Centre for Research and Development (grant NOR/POLNORCCS/0015/2019-00).

References

[1] Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., Schreiber, A., & Müller, T.E. (2012). Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2. *Energy & Environmental Science*, 5, 7281–7305. doi: 10.1039/C2EE03403D

[2] Rubin, E.S., Davison, J.E., & Herzog, H.J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, 40, 378–400. doi: 10.1016/j.ijggc.2015.05.018

[3] Rochelle, G.T. (2009). Amine scrubbing for CO_2 capture. *Science*, 325(5948), 1652–1654. doi: 10.1126/science.1176731

[4] Singh, A., & Stéphenne, K. (2014). Shell Cansolv CO_2 capture technology: Achievement from First Commercial Plant. *Energy Procedia*, 63, 1678–1685. doi:10.1016/j.egypro.2014.11.177

[5] Chao, C., Deng, Y., Dewil, R., Baeyens, J., & Fan, X. (2021). Post-combustion carbon capture. *Renewable and Sustainable Energy Reviews*, 138, 110490. doi: 10.1016/j.rser.2020.110490

[6] Choi, S., Drese, J.H., & Jones, C.W. (2009). Adsorbent materials for carbon dioxide capture from large anthropogenic point sources. *ChemSusChem*, 2(9), 796–854. doi: 10.1002/cssc.200900036

[7] Samanta, A., Zhao, A., Shimizu, G.K.H., Sarkar, P., & Gupta, R. (2012). Post-combustion CO_2 capture using solid sorbents: A review. *Industrial & Engineering Chemistry Research*, 51(4), 1438–1463. doi: 10.1021/ie200686q

[8] Raganati, F., Miccio, F., & Ammendola, P. (2021). Adsorption of carbon dioxide for post combustion capture: A review. *Energy & Fuels*, 35(16), 12845–12868. doi: 10.1021/acs.energyfuels.1c01618

[9] D'Alessandro, D.M., Smit, B., & Long, J.R. (2010). Carbon dioxide capture: Prospects for new materials. *Angewandte Chemie International Edition*, 49(35), 6058–6082. doi: 10.1002/anie.201000431

[10] Kong, M., Song, L., Liao, H., Zhang, S., Wang, Y., Deng, X., & Feng, W. (2024). A review on development of post combustion CO_2 capture technologies: Performance of carbon based, zeolites and MOFs adsorbents. *Fuel*, 362, 132103. doi: 10.1016/j.fuel.2024.132103

[11] Clausse, M., Merel, J., & Meunier, F. (2011). Numerical parametric study on CO_2 capture by indirect thermal swing adsorption. *International Journal of Greenhouse Gas Control*, 5(5), 1206–1213. doi: 10.1016/j.ijggc.2011.05.036

[12] Bonjour, J., Clausse, M., & Meunier F. (2005). A TSA process with indirect heating and cooling: parametric analysis and scaling-up to practical sizes. *Chemical Engineering and Processing: Process Intensification*, 44(9), 969–977. doi: 10.1016/j.cep.2005.01.002

[13] Kindra, V.O., Milukov, I.A., Shevchenko, I.V., Shabalova, S.I., & Kovalev, D.S. (2021). Thermodynamic analysis of cycle arrangements of the coal-fired thermal power plants with carbon capture. *Archives of Thermodynamics*, 42(4), 103–121. doi: 10.24425/ather.2021.139653

[14] Zhao, R., Deng, S., Zhao ,L., Li, S., Zhang, Y., & Liu, B. (2017). Performance analysis of temperature swing adsorption for CO_2 capture using thermodynamic properties of adsorbed phase. *Applied Thermal Engineering*, 123, 205–215. doi: 10.1016/j.applthermaleng.2017.05.042

[15] Zhao, R., Liu, L., Zhao, L., Deng, S., Li, S., & Zhang, Y. (2019). A comprehensive performance evaluation of temperature swing adsorption for post combustion carbon dioxide capture. *Renewable and Sustainable Energy Reviews*, 114, 109285. doi: 10.1016/j.rser.2019.109285

[16] Mondino, G., Grande, C.A., & Blom, R. (2017). Effect of gas recycling on the performance of a moving bed temperature swing (MBTSA) process for CO_2 capture in a coal fired power plant context. *Energies*, 10(6), 745. doi: 10.3390/en10060745

[17] Mondino, G., Grande, C.A., Blom, R., & Nord, L.O. (2019). Moving bed temperature swing adsorption for CO_2 capture from a natural gas combined cycle power plant. *International Journal of Greenhouse Gas Control*, 85, 58–70. doi: 10.1016/j.ijggc.2019.03.021

[18] Mondino, G., Grande, C.A., Blom, R., & Nord, L.O. (2022). Evaluation of MBTSA technology for CO_2 capture from waste to energy plants. *International Journal of Greenhouse Gas Control*, 118, 103685. doi: 10.1016/j.ijggc.2022.103685

[19] Okumura, T., Ogino, T., Nishibe, S., Nonaka, Y., Shoji, T., & Higashi, T. (2014). CO_2 Capture Test for a Moving-bed System Utilizing Low-temperature Steam. *Energy Procedia*, 63, 2249−2254. doi:10.1016/j.egypro.2014.11.243

[20] Okumura, T., Yoshizawa, K., Nishibe, S., Iwasaki, H., Kazari, M., & Hori, T. (2017). Parametric Testing of a Pilot-scale Design for a Moving-bed CO_2 Capture System Using Low-temperature Steam. *Energy Procedia*, 114, 2322–2329. doi: 10.1016/j.egypro.2017.03.1369

[21] Liu, Z., Wang, L., Kong, X., Li, P., & Yu, J. (2012). Onsite CO_2 capture from flue gas by an adsorption process in a coal fired power plant. *Industrial & Engineering Chemistry Research*, 51, 7355–7363. doi: 10.1021/ie3005308

[22] Wang, L., Liu, Z., Li, P., & Yu, J. (2013). Experimental evaluation of adsorption technology for CO_2 capture from flue gas in an existing coal fired power plant. *Chemical Engineering Science*, 101, 615–619. doi: 10.1016/j.ces.2013.07.028

[23] Xu, D., Xiao, P., Zhang, J., Li, G., Xiao, G., Webley, P.A., & Zhai, Y. (2013). Effects of water vapour on CO_2 capture with vacuum swing adsorption using activated carbon. *Chemical Engineering Journal*, 230, 64–72. doi: 10.1016/j.cej.2013.06.080

[24] Querejeta, N., García, S., Álvarez-Gutiérrez, N., Rubiera, F., & Pevida, C. (2019). Measuring heat capacity of activated carbons for CO_2 capture. *Journal of CO_2 Utilization*, 33, 148−156. doi: 10.1016/j.jcou.2019.05.018

[25] Stec, M., Tatarczuk, A., Więcław-Solny, L., Krótki, A., Spietz, T., Wilk, A., & Śpiewak, D. (2016). Demonstration of a post-combustion carbon capture pilot plant using amine-based solvents at the Łaziska Power Plant in Poland. *Clean Technologies and Environmental Policy*, 18, 151–160. doi: 10.1007/s10098-015-1001-2

[26] Więcław-Solny, L., Stec, M., Tatarczuk, A., Krótki, A., Spietz, T., & Wilk, A. (2013). First Polish Pilot Plant for CO_2 Post Combustion Capture. *Proceedings of the 2nd Post Combustion Capture Conference*, September 17–20, Bergen, Norway.

[27] Bochon, K., & Chmielniak, T. (2015). Energy and economic analysis of the carbon dioxide capture installation with the use of monoethanolamine and ammonia. *Archives of Thermodynamics*, 36(1), 93–110. doi: 10.1515/aoter-2015-0007

[28] Wawrzyńczak, D., Majchrzak-Kucęba, I., Srokosz, K., Kozak, M., Nowak, W., Zdeb, J., Smółka, W., & Zajchowski, A. (2019). The pilot dual-reflux vacuum pressure swing adsorption unit for CO_2 capture from flue gas. *Separation and Purification Technology*, 209, 560–570. doi: 10.1016/j.seppur.2018.07.079

[29] Majchrzak-Kucęba, I., Wawrzyńczak, D., Ściubidło, A., Zdeb, J., Smółka, W., & Zajchowski, A. (2019). Stability and regenerability of activated carbon used for CO_2 removal in pilot DR-VPSA unit in real power plant conditions. *Journal of CO_2 Utilization*, 29, 1–11. doi: 10.1016/j.jcou.2018.11.003

[30] Zima, W., Pawłowski, A., Grądziel, S., Cebula, A., Piwowarczyk, M., & Kozak-Jagieła, E. (2025). CO_2 capture from flue gases in a temperature swing moving bed – simulation results vs. the experiment. *Energy*, 327, 136445. doi: 10.1016/j.energy.2025.136445

[31] Kureha. *Bead-Shaped Activated Carbon*. https://www.kureha.co.jp/en/business/material/bac.html [accessed 22 Feb. 2025].