https://doi.org/10.7494/miag.2023.1.553.19

TOMASZ KUŚ
NAVANEETHAN SUBRAMANIAN
PAWEŁ MADEJSKI
MICHAŁ KARCH

Assessment of the potential for CO_2 capture using post-combustion methods

The combustion of fossil fuels in the process of generating electricity causes the emission of carbon dioxide, which is considered the main anthropogenic reason for global warming. The paper's subject is to assess the potential for CO_2 capture using post-combustion methods. Post-combustion methods such as chemical absorption, physical separation, membrane separation, and chemical looping, are described. The thermodynamic modeling of a coal-fired supercritical power plant integrated with a post-combustion carbon capture installation using the solvent method is performed. The results obtained from the model are used to investigate the impact of the power plant when carbon capture is performed.

Key words: *CO_2 emissions, PCCS, amine technologies*

1. INTRODUCTION

Reducing CO_2 emissions is a crucial part of contemporary energy policy. To reduce the negative impact of climate change, 195 countries signed the Paris Agreement. This agreement defines achieving climate neutrality by 2050 as essential [1]. Considering all greenhouse gases, CO_2 is perceived as the main emission caused by human activity, in which 40% of the global emissions of CO_2 are connected with fossil fuel-fired power generation [2]. Despite a significant increase in the share of renewable energy power generation in total energy production, global CO_2 emissions from power generation and industrial processes reached the highest level in 2022: 36.8 Gt CO_2 [3]. Considering the last several years in Poland, a significant decrease in CO_2 emissions of 16% from fossil fuel-fired power generation and a slight increase in CO_2 emission of 2% from industrial processes can be observed, respectively, by comparing the years 2021 and 2005 [4]. The European Union introduced an emission trading system to promote a gradual and rational reduction of greenhouse gas emissions. The system is based on a financial mechanism (the purchase and sale of emissions) that forces countries to develop and use low-emission technologies.

The aforementioned ecological and political factors make the reduction of CO_2 emissions one of the most important scientific and research challenges. In countries where power is mainly produced based on fossil fuels, CCUS (Carbon, Capture, Utilization and Storage) technology is a promising option to overcome this problem. This technology aims to reduce emissions by capturing carbon dioxide and then storing or converting it into other useful products [5]. In the case of CCUS technology, three basic methods of CO_2 capture can be distinguished: pre-combustion, post-combustion, and oxy-combustion [6, 7].

The post-combustion method is the most suitable for use in existing installations. This solution seems to be particularly important in the Polish power system, where coal and lignite-based units predominate.

Despite the rapid development of renewable energy systems, fossil fuels will be the basic energy carrier in the Polish power system for a long time [8].

2. POST COMBUSTION CO_2 SEPARATION TECHNOLOGIES

Post-combustion carbon capture methods are based on capturing carbon dioxide from the exhaust gas from fuel combustion. The technology scheme is presented in Figure 1. Exhaust gas produced as a result of fuel combustion is initially purified by the removal of nitrogen, sulfur and dust, and then directed to the CO_2 capture installation. The gas consists mainly of nitrogen and carbon dioxide, with a concentration of carbon dioxide about 4–14% [9]. This results in a low CO_2 partial pressure in the gas mixture and complicates the separation process. An additional challenge related to the design of this type of installation is the high temperature of the exhaust gases.

The main advantage of the post-combustion method is the possibility of using it in both new and existing installations without introducing drastic changes [10]. In addition, it is possible to achieve purity of the produced carbon dioxide above 99% [11]. Units with post-combustion installation are highly flexible: it is possible to regulate the amount of the captured CO_2 as well as to completely disable the capture, which enables the control of power plant power per market demand [12]. Post-combustion installations should be designed to achieve the lowest possible carbon dioxide emission at the lowest energy cost. Depending on the method of carbon dioxide capture, the following separation methods can be distinguished in the post-combustion technology: chemical absorption, physical separation, membrane separation and chemical looping.

Physical separation uses the phenomenon of absorption, adsorption or cryogenic separation [7]. Physical adsorption is based on the use of porous materials such as activated carbon, silica, zeolites or organometallic frameworks (MOFs) [13]. In case of membrane separation, a membrane is used for the separation or absorption process. Membrane separation is usually connected with low energy consumption, low operating costs and the possibility of easy scalability [14]. The method of fuel combustion in a chemical loop is based on the use of two reactors: air and fuel, and a metal oxide compound circulating between them. The metal oxide is a source of oxygen during the combustion reaction. As a result of combustion in pure oxygen, the flue gases consist mainly of carbon dioxide and steam [15].

Carbon dioxide separation using chemical absorption uses a chemical reaction between CO_2 and solvent. This method is characterized by high investment and operating costs [16]. Chemical absorption based on the use of amines is considered to be the most mature CO_2 separation technology [17]. It application covers mainly pilot power plants [18–21].

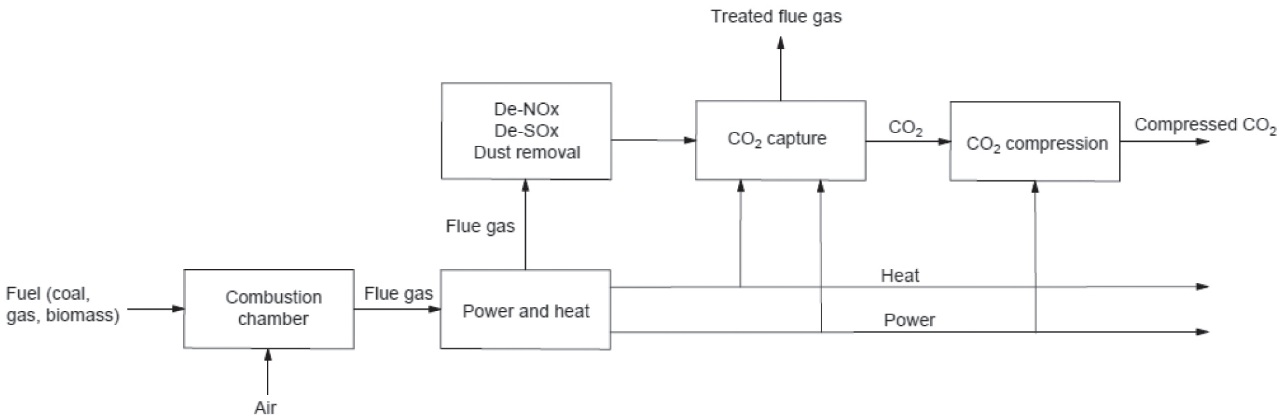

Fig. 1. Post-combustion technology scheme [6]

3. CHEMICAL ABSORPTION

Separation of carbon dioxide using chemical absorption is based on the reaction between the carbon dioxide contained in the flue gas and the chemical solvent in the absorption column. Amines, aqueous ammonia solution and potassium carbonate are used as solvents [22]. The reaction products of amines and carbon dioxide are carbamates or bicarbonates.

Considering power-generation and industrial processes, the following ethanolamines are widely used:

MEA monoethanolamine, DEA diethanolamine and MDEA methyl diethanolamine. The main advantage of ethanolamines is their high ability to capture CO_2, while the main weakness is the high energy consumption of the regeneration process. In addition, amines are easily oxidized, which results in the formation of corrosive compounds such as carboxylic acids or ammonia. It is necessary to use the appropriate concentration of amines to avoid their degradation. Research is being conducted on improving the efficiency of capture and reducing the energy consumption of the process by selecting appropriate mixtures of chemical solvents [23].

The scheme of the chemical absorption process using amines is shown in Figure 2. After passing through the boiler, flue gases are directed to the absorber chamber. A chemical reaction takes place with the solvent, which absorbs CO_2. The solvent is typically a 30% aqueous solution of ethanolamies [24, 25]. The solvent enriched with carbon dioxide is directed to the stripper (desorber), where the regeneration process takes place. The stripper is made of two vertical columns. After passing through one of them and preheating, the solvent is directed to the reboiler. By supplying steam, the temperature of the solvent rises to a level that allows separation. Water vapor and carbon dioxide flows upwards, and the regenerated liquid solvent flows downwards, before being cooled and directed back to the absorber. The mixture of steam and carbon dioxide is cooled, which allows for steam condensation and separation. Next, the carbon dioxide is compressed to a storage pressure level.

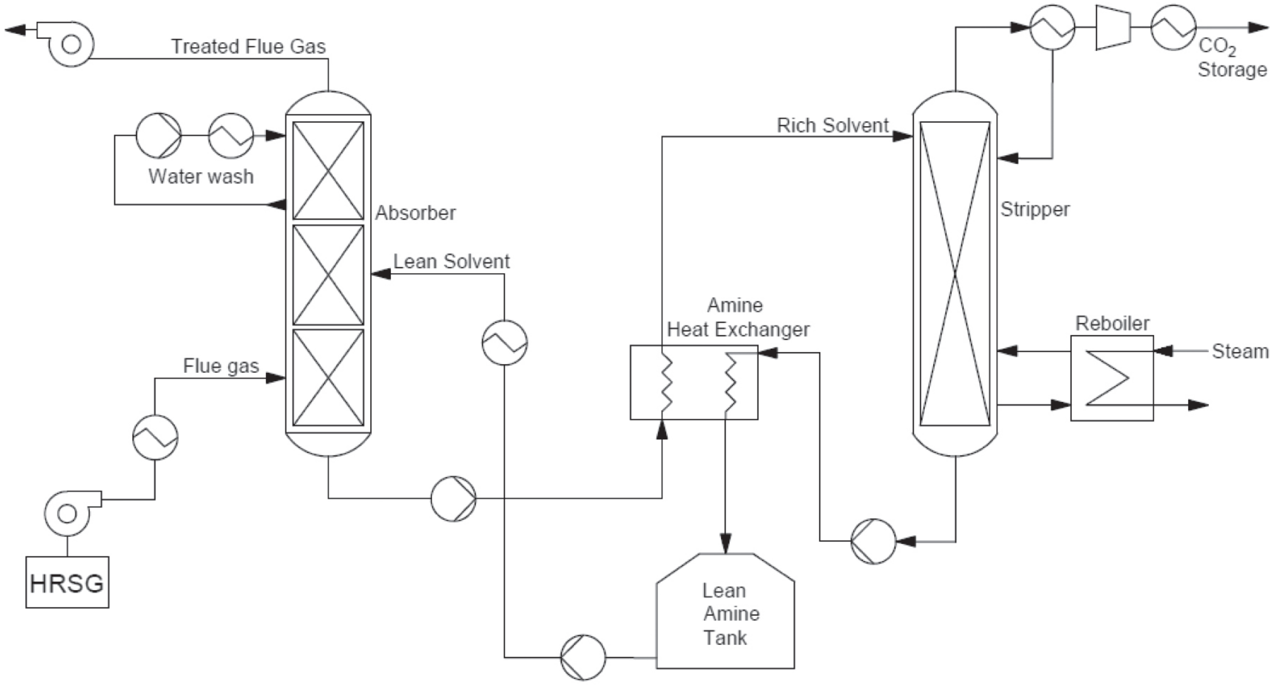

Fig. 2. Scheme of the PCCS installation using the chemical absorption method with the use of amines

4. CALCULATIONS OF CO_2 CAPTURE FROM A SUPERCRITICAL COAL-FIRED POWER PLANT USING AMINE TECHNOLOGY

Calculations of CO_2 capture using the PCCS installation with amine technology were carried out based on the results of CO_2 emissions from the supercritical coal-fired power plant presented in [6]. Simulation results for different load conditions are presented in Table 1. For a 100% load, a power plant produces 808.96 MW with coal consumption of 92.31 kg/s and the amount of exhaust gases emitted is 879.38 kg/s. By reducing the load, the output power, coal consumption, gross and net efficiency decrease.

Table 2 shows the composition of the coal which is used in the calculations of the exhaust gas compositions directed to the CO_2 capture installation. The exhaust gas content (mass and molar shares) is presented in Table 3. The flue gas consists mainly of nitrogen (69.5% mass fraction) and carbon dioxide (20.98% mass fraction). The mass fraction of oxygen and water are 3.39% and 5.50%, respectively. For different loads of the unit, the composition of the exhaust gases remained the same (the mass flow of gases changed).

Table 1

Parameters of supercritical coal-fired power plant under different load conditions [6]

Load condition	Total power generation	Efficiency		Coal consumption	Exhaust mass flow
		Gross	Net		
[%]	[MW]	[%]	[%]	[kg/s]	[kg/s]
100	809.96	48.02	46.43	92.31	879.38
90	734.33	47.79	46.38	83.20	793.24
80	657.25	47.51	46.28	74.24	707.23
70	584.12	47.39	46.26	65.53	624.23
60	509.14	47.23	46.20	56.79	540.94
50	434.52	47.14	46.15	47.73	454.67
40	356.39	46.92	45.98	38.62	367.85

Table 2

Content of coal used for analysis

Content	Mass fraction [%]
C	0.5497
H	0.0350
O	0.0463
N	0.0100
S	0.0080
Cl	0.0000
Moisture	0.1275
Ash	0.2235
Total	1.0000

Table 3

Exhaust gas content

Content	Mass [%]	Mol [%]
Nitrogen (N_2)	69.489460	73.169940
Oxygen (O_2)	3.388145	3.123258
Argon (Ar)	0.402427	0.297147
Water (H_2O)	5.501076	9.007125
Carbon dioxide (CO_2)	20.984630	14.064830
Sulphur dioxide (SO_2)	0.166130	0.076492
Elemental carbon (C)	0.057712	0.141735
Elemental hydrogen (H)	0.003675	0.107536
Elemental oxygen (O)	0.004861	0.008962
Elemental nitrogren (N)	0.001050	0.002211
Elemental sulphur (S)	0.000840	0.000773
Total	100.000000	100.000000

The model developed of the CO_2 capture installation using the amine method is shown in Figure 3. The main components of the installation are the system for supplying and discharging the treated flue gases, the absorber-desorber system enabling CO_2 capture and solvent regeneration, and the CO_2 separation and compression system. The fuel mass flow as well as the fuel composition, are input data. The solvent used in the study is a 30% aqueous monoethanolamine (MEA) solution. The supercritical power plant only produces electricity, therefore, the heat needed to regenerate the PPCS solvent is taken from the auxiliary boiler, producing steam at a temperature of 135°C and a pressure of 3 bar. Steam is delivered to the reboiler.

Table 4 shows the simulation results of CO_2 capture with the PCCS installation for various supercritical coal-fired power plant load conditions. CO_2 capture capacity decreases as the load is reduced, which is connected with a lower stream of exhaust gases. The maximum achieved capture is 166.06 kg/s of CO_2 at 100% load and 89.32 MW electric power consumption.

Electric power for the installation's needs is taken from the power plant, directly affecting the overall efficiency. This can be noticed in Figure 4, where the efficiency of the power plant with/without the PCCS installation for different unit load conditions is presented. By reducing the load, the gross efficiency is decreasing from 48.02% at 100% load to 46.92% at 40% load. As the load decreases, the net efficiency without the PCCS installation falls, respectively 46.43% and 45.98% for 100% and 40% loads. The net efficiency of the unit with the PCCS installation remains relatively constant at 41.1%. The steam supplied to the reboiler is generated by the auxiliary boiler. The input power needed to generate it at full load is 647.1 MW. It is assumed that this power is supplied from outside the system and does not affect the operation of the installation.

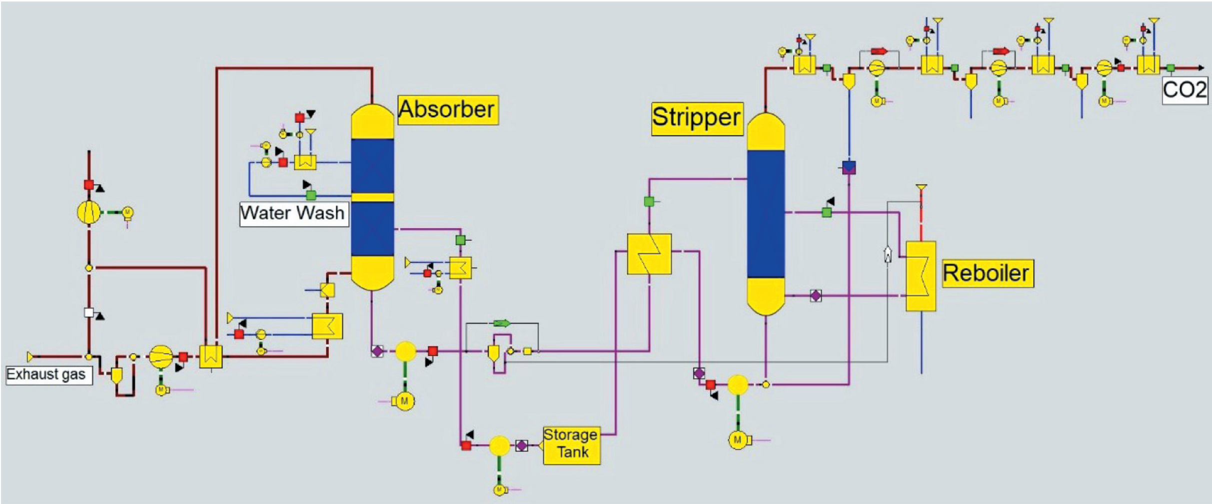

Fig. 3. Model of PCCS amine-based chemical absorption installation

Table 4

Simulation results of CO_2 capture with the PCCS installation for different loads of a supercritical coal-fired power plant – mass streams and power consumption

Load condition	Lean amine	Rich amine	Reboiler steam		Power consumed	Captured CO_2
[%]	[kg/s]	[kg/s]	[kg/s]	[t/h]	[MW]	[MW]
100	1724.24	1890.30	300.80	1082.880	89.32	422.26
90	1554.06	1703.73	271.12	976.032	80.53	380.58
80	1386.70	1520.24	241.90	870.840	71.83	311.02
70	1224.00	1341.88	213.53	768.708	63.41	299.75
60	1060.75	1162.90	185.05	666.180	54.95	259.77
50	891.53	977.38	155.53	559.908	46.20	218.33
40	721.36	790.83	125.84	453.024	37.37	176.66

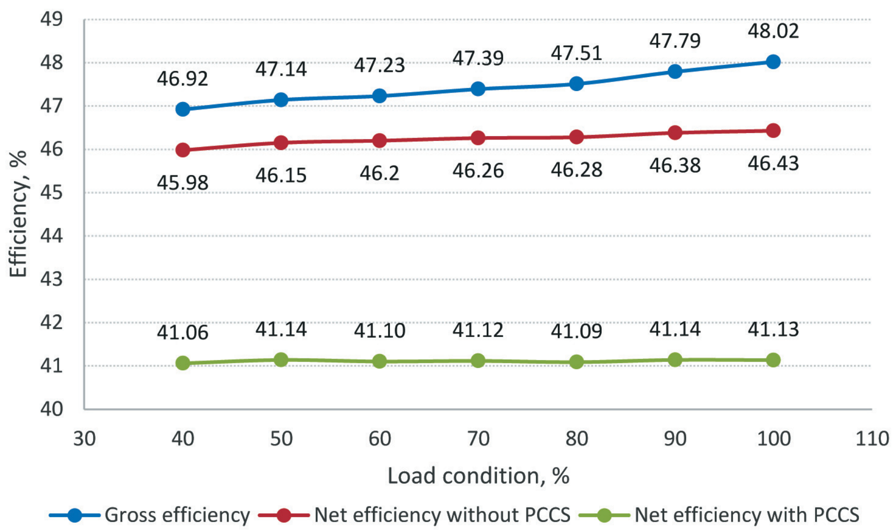

Fig. 4. Efficiency of a power plant with and without PCCS

The net power and efficiency reduction for different loads are presented in Table 5. The efficiency reduction due to the operation of the PCCS installation ranges from 5.30 to 4.92 pp. (i.e. 11.41–10.70%). The higher the load, the greater the decrease in efficiency.

The inlet, captured and emitted CO_2 mass flow for different loads is presented in Figure 5. The lower the load, the smaller the CO_2 mass flow, which is directly related to the amount of exhaust gas. For a 100% load, the captured CO_2 mass flow is 166.06 kg/s and the emitted CO_2 mass flow is 16.46 kg/s.

Table 5

Comparison of the net power with/without PCCS and the reduction of the plant's efficiency for different load conditions

Load condition	Net power without PCCS	Net power with PCCS	Efficiency reduction	
[%]	[MW]	[MW]	[pp.]	[%]
100	783.14	693.82	5.30	11.41
90	712.66	632.13	5.24	11.30
80	640.23	568.40	5.19	11.22
70	570.19	506.78	5.14	11.12
60	498.04	443.09	5.10	11.03
50	425.39	379.19	5.01	10.86
40	349.25	311.88	4.92	10.70

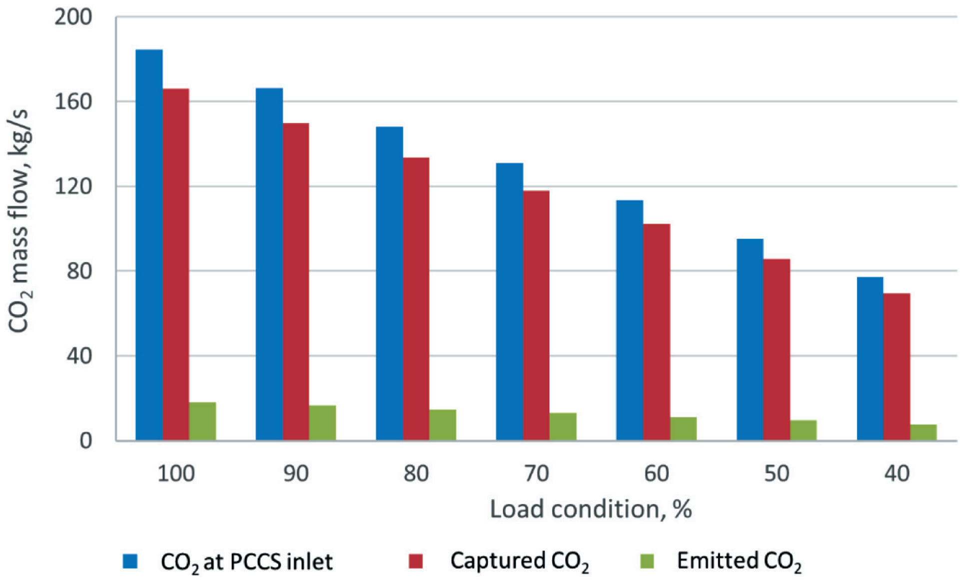

Fig. 5. Inlet, captured and emitted CO_2 mass flow for different load conditions

5. SUMMARY

The paper presents an assessment of the possibility of capturing CO_2 using post-combustion methods based on the review of the current state of technology development and the results of thermodynamic analysis of the operation of the supercritical coal-fired power plant. The power plant is equipped with a PCCS installation using an amine-based chemical absorption method. The social and economic factors that accelerate the development of technology were discussed. The amine-based PCCS technology is indicated as the most mature and suitable for existing power plants. Based on the assumed coal composition, the composition of exhaust gases directed to the PCCS installation was calculated. For different power plant load conditions, the captured CO_2 mass flow and the efficiency drop due to the presence of the PCCS installation were calculated. Under nominal load conditions (block capacity 809.96 MW), CO_2 capture was 166.06 kg/s with an electric power consumption of 89.32 MW. In this case, the efficiency of the power plant compared to the efficiency without the PCCS installation decreased by 11.41%. For lower load values, the efficiency reduction slightly decreased to 10.7% at 40% load. The analyzed technology of CO_2 capture using amines is characterized by high CO_2 capture efficiency, but this is strictly connected with a significant decrease in efficiency. The CO_2 capture process requires a large amount of energy to be supplied to the reboiler, which will also reduce the effectiveness of the post-combustion installation in power units. Further development of the technology for application in large power plant units should focus on reducing the energy consumption of carbon dioxide capture.

Acknowledgements

Research project supported by the program, "Excellence initiative – research university" for the AGH University of Krakow.

The research leading to the results received funding from the subsidy of the Ministry of Education and Science No. 16.16.130.942 (Faculty of Mechanical Engineering and Robotics, AGH University of Krakow).

References

[1] Parlament Europejski, Dyrekcja Generalna ds. Komunikacji: *Czym jest neutralność emisyjna i jak możemy ją osiągnąć do 2050 r.?* 14.04.2023. https://www.europarl.europa.eu/news/pl/headlines/society/20190926STO62270/czym-jest-neutralnosc-emisyjna-i-jak-mozemy-ja-osiagnac-do-2050-r.

[2] International Energy Agency: *The role of CCUS in low-carbon power systems*. IEA, Paris 2020. https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems.

[3] International Energy Agency: *CO_2 emissions in 2022*. IEA, Paris 2023. https://www.iea.org/reports/co2-emissions-in-2022.

[4] Crippa M., Guizzardi D., Banja M., Solazzo E., Muntean M., Schaaf E., Pagani F., Monforti-Ferrario F., Olivier J., Quadrelli R., Risquez Martin A., Taghavi-Moharamli P., Grassi G., Rossi S., Oom D., Branco A., San-Miguel J., Vignati E.: *CO_2 emissions of all world countries – JRC/IEA/PBL 2022 Report*. Publications Office of the European Union, Luxembourg 2022. https://doi.org/10.2760/730164.

[5] International Energy Agency: *Energy Technology Perspectives 2020*. IEA, Paris 2021. https://www.iea.org/reports/energy-technology-perspectives-2020.

[6] Madejski P., Chmiel K., Subramanian N., Kuś T.: *Współczesne metody i technologie wychwytu CO_2*. In: *Mechanizacja, automatyzacja i robotyzacja w górnictwie 2021: monografia: praca zbiorowa*, K. Krauze (red. nauk.). Wydawnictwa AGH, Kraków 2022: 29–36.

[7] Madejski P., Chmiel K., Subramanian N., Kuś T.: *Methods and techniques for CO_2 capture: Review of potential solutions and applications in modern energy technologies*. Energies 2022, 15, 3: 887. https://doi.org/10.3390/en15030887.

[8] Ministerstwo Gospodarki: *Polityka energetyczna Polski do 2030 roku*. Warszawa 2009.

[9] Olajire A.A.: *CO_2 capture and separation technologies for end-of-pipe applications – A review*. Energy 2010, 35, 6: 2610–2628. https://doi.org/10.1016/j.energy.2010.02.030.

[10] Więcław-Solny L., Ściążko M., Tatarczuk A., Krótki A., Wilk A.: *Czy CCS może być tańszy? W poszukiwaniu nowych sorbentów CO_2*. Polityka Energetyczna 2011, 14, 2: 441–453.

[11] Porter R., Fairweather M., Pourkashanian M., Woolley R.: *The range and level of impurities in CO_2 streams from different carbon capture sources*. International Journal of Greenhouse Gas Control 2015, 36: 161–174. https://doi.org/10.1016/j.ijggc.2015.02.016.

[12] Pandey S.N., Gupta S.K., Tomar A., Kumar A.: *Post combustion carbon capture technology*. In: *National Conference on Eco friendly Manufacturing for Sustainable Development: November 19–21, 2010, GLA University, Mathura, U.P., India*, 2010, paper no. 56.

[13] Li J.-R., Ma Y., McCarthy M.C., Sculley J., Yu J., Jeong H.-K., Balbuena P.B., Zhou H.-C.: *Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks*. Coordination Chemistry Reviews 2011, 255, 15–16: 1791–1823. https://doi.org/10.1016/j.ccr.2011.02.012.

[14] Vakharia V., Salim W., Wu D., Han Y., Chen Y., Zhao L., Winston Ho W.: *Scale-up of amine-containing thin-film composite membranes for CO_2 capture from flue gas*. Journal of Membrane Science 2018, 555: 379–387. https://doi.org/10.1016/j.memsci.2018.03.074.

[15] Rakowski J., Bocian P., Celińska A., Świątkowski B., Golec T.: *Zastosowanie pętli chemicznych w energetyce*. Energetyka 2016, 4: 208–213.

[16] Kárászová M., Zach B., Petrusová Z., Červenka V., Bobák M., Šyc M., Izák P.: *Post-combustion carbon capture by membrane separation, Review*. Separation and Purification Technology 2020, 238: 116448. https://doi.org/10.1016/j.seppur.2019.116448.

[17] Zanco S.E., Pérez-Calvo J.-F., Gasós A., Cordiano B., Becattini V., Mazzotti M.: *Postcombustion CO_2 capture: A comparative techno-economic assessment of three technologies using a solvent, an adsorbent, and a membrane*. ACS Engineering Au 2021, 1, 1: 50–72. https://doi.org/10.1021/acsengineeringau.1c00002.

[18] Patil M., Vaidya P., Kenig E.: *Bench-scale study for CO_2 capture using AMP/PZ/water mixtures*. Chemical Engineering Transactions 2018, 69: 163–168. https://doi.org/10.3303/CET1869028.

[19] Feron P.H.M., Cousins A., Jiang K., Zhai R., Garcia M.: *An update of the benchmark post-combustion CO_2-capture technology*. Fuel 2020, 273: 117776. https://doi.org/10.1016/j.fuel.2020.117776.

[20] Spietz T., Dobras S., Chwoła T., Wilk A., Krótki A., Więcław-Solny L.: *Experimental results of amine emission from the CO_2 capture process using 2-amino-2-methyl-1-propanol (AMP) with piperazine (PZ)*. International Journal of Greenhouse Gas Control 2020, 102: 103155. https://doi.org/10.1016/j.ijggc.2020.103155.

[21] Xue B., Yu Y., Chen J., Luo X., Wang M.: *A comparative study of MEA and DEA for post-combustion CO_2 capture with different process configurations*. International Journal of Coal Science & Technology 2017, 4: 15–24. https://doi.org/10.1007/s40789-016-0149-7.

[22] Mazurkiewicz M., Uliasz-Bocheńczyk A., Mokrzycki E., Piotrowski Z., Pomykała R.: *Metody separacji i wychwytywania CO_2*. Polityka Energetyczna 2005, 8 (spec.): 527–538.

[23] Ávila S.G. de, Logli M.A., Silva L.C.C., Fantini M.C.A., Matos J.R.: *Incorporation of monoethanolamine (MEA), diethanolamine (DEA) and methyldiethanolamine (MDEA) in mesoporous silica: An alternative to CO_2 capture*. Journal of Environmental Chemical Engineering 2016, 4, 4, part A: 4514–4524. https://doi.org/10.1016/j.jece.2016.10.015.

[24] Pinto D.D.D., Knuutila H., Fytianos G., Haugen G., Mejdell T., Svendsen H.F.: *CO_2 post combustion capture with a phase change solvent. Pilot plant campaign*. International Journal of Greenhouse Gas Control 2014, 31: 153–164. https://doi.org/10.1016/j.ijggc.2014.10.007.

[25] Bernhardsen I.M., Knuutila H.K.: *A review of potential amine solvents for CO_2 absorption process: Absorption capacity, cyclic capacity and pKa*. International Journal of Greenhouse Gas Control 2017, 61: 27–48. https://doi.org/10.1016/j.ijggc.2017.03.021.

TOMASZ KUŚ, M.Sc.
kus@agh.edu.pl
NAVANEETHAN SUBRAMANIAN, M.Sc.
subraman@agh.edu.pl
PAWEŁ MADEJSKI, PhD., DSc., Eng.
madejski@agh.edu.pl
MICHAŁ KARCH, PhD., Eng.
karch@agh.edu.pl

AGH University of Krakow
Faculty of Mechanical Engineering and Robotics
al. A. Mickiewicza 30, 30-059 Krakow, Poland