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Łukasz Bartela[*]
Anna Skorek-Osikowska
Marcin Rożek

Silesian University of Technology
Institute of Power Engineering and Turbomachinery
Gliwice

Thermodynamic evaluation of a combined heat and power plant with carbon dioxide capture installation integrated with a gas turbine

The paper presents the results of a thermodynamic analysis carried out for a coal-fired combined heat and power plant (CHP) working at supercritical parameters, integrated with an absorption-based carbon dioxide capture installation. The power of a plant was set at 320 MW, and it was assumed that it produces heat in accordance with heat demand characteristics. It was also assumed that in order to obtain heat for the desorption unit, the plant was integrated with a gas turbine installation, at the outlet of which a recovery heat exchanger was mounted. For the analysis, the values of the characteristic quantities of the gas turbine were adopted. Power of the machine, in turn, depended on the heat demand of the desorption process. For the evaluation of the integration of a CHP plant, the defined in the paper average annual thermodynamic quantities and unit carbon dioxide emissions were used.

1 Introduction

Production of electricity and heat in cogeneration leads to significant savings of primary energy, which in turn reduce emission of harmful substances, including carbon dioxide. Polish energy sector, as compared to others European Union (EU) countries, is characterized by a relatively high share of electricity produced in cogeneration. Approximately 23% of the electricity produced in Poland comes from combined heat and power (CHP) plants [1]. Combined production of electricity in Poland is based on the operation of relatively small units (BC-50 and BC-100) and even smaller industrial plants. A size of these blocks corresponds in most cases, to the demands of district heating networks. However, in more extensive networks, in the near future, it may be purposeful to construct the modern

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[*] Corresponding Author. E-mail: lukasz.bartela@polsl.pl

supercritical unit, with the power rates corresponding to the CHP plants working in large amounts in countries such as Germany or Denmark (250–400 MW_e) [2]. What is important, this type of units would allow to meet growing environmental requirements. In the systems with such high power rates, the integration of CHP plants with the installations of separation of carbon dioxide could be justified [3].

European support mechanisms are favorable for the development of cogeneration plants. The Directive 2004/8/EC, transposed into national legislation, and thereby establishing a certification of the electricity produced in the so-called high-efficiency cogeneration should be mentioned. However, it seems that another mechanism may be a barrier for increasing the share of electricity produced in cogeneration, which may in the near future condition the requirement of the integration of power plant with carbon dioxide capture installations, i.e., *European Union Emission Ttrading Scheme.*

The most mature carbon dioxide separation technology is a technology that uses a chemical absorption method, which is an energy-intensive technology, due to the need for the heat for desorption process. In the case of a condensing plant, heat uptake is possible by extracting of steam from a passage channel of the steam turbine. Extracting in such a way large amounts of steam can result, in the case of newly designed blocks, in certain changes in the turbine construction. In turn, in case of adapting of the existing machines for such an extraction, it may be required to carry out profound modernization [4]. In the case of combined heat and power plants, due to the extraction of steam for heating purposes, this type of integration is possible only for the units newly designed and must lead to a very significant oversizing of the steam turbine parts. The results of the analysis of such an adaptation of a unit for integration with a carbon dioxide capture installation the authors presented in [5,6].

Another solution considered in literature, permitting the operation of an absorption-based separation installation, may be by satisfying the needs of the desorption process by an external heat source [7,8]. Here, the development of a biomass-fired boiler can be considered or, as in this paper, of a gas turbine installation with a recovery heat exchanger mounted at the outlet, recovering heat from the exhaust gas in the amount needed for solvent regeneration.

2 Characteristic of the analyzed system

In this paper two combined heat and power plants were analyzed separately; a system operating without CO_2 capture and compression plant and a system integrated with such an installation. Basic integration was evaluated, which assumes only supplying of exhaust gases generated within the boiler to the absorber column, in which CO_2 is bound with a sorbent. Two integrated systems, i.e., heat and power plant and the carbon dioxide capture and compression installation together with a gas turbine (gray background in Fig. 1) were considered.

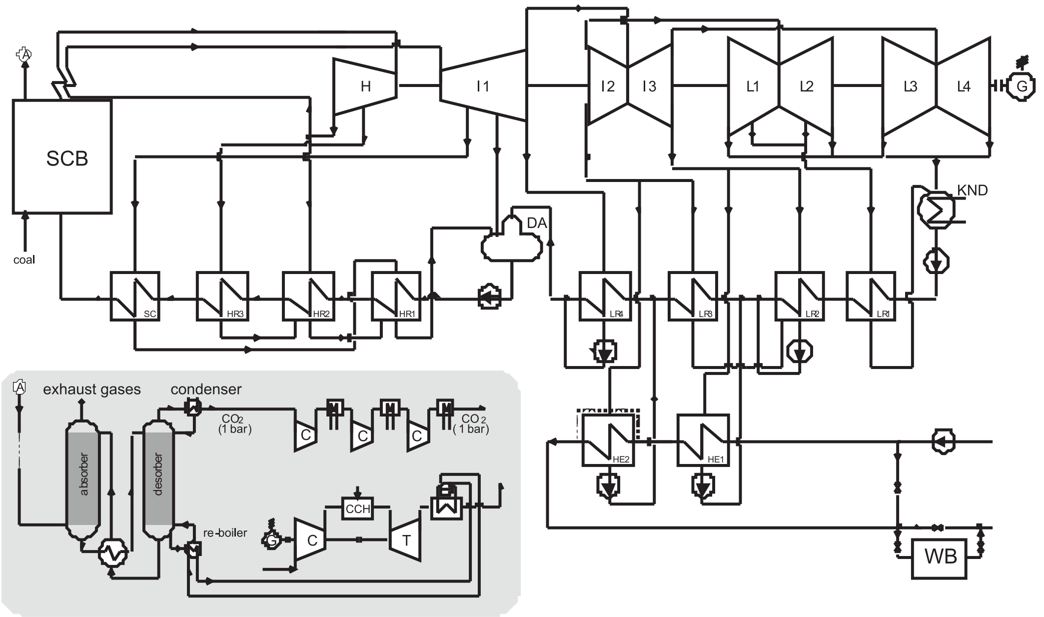

Figure 1. Scheme of a heat and power plant integrated with CO_2 capture and compression installation and a gas turbine: H,I,L – high, intermediate and low-pressure part of steam turbine, DA – deaerator, KND – condenser, G – generator, SCB – supercritical coal-fired boiler, SC – steam cooler, HR – high-pressure regenerative heat exchanger, LR – low-pressure regenerative heat exchanger, HE – district heating network heat exchanger, WB – water boiler, A – link, C – compressor, T – expander, CCH – combustion chamber.

2.1 Combined heat and power plant

Steam boiler produces live steam at parameters: 650 °C, 30 MPa and a reheated steam at parameters: 670 °C, 5.9 MPa. The boiler efficiency was assumed at 94.5%. A steam turbine consists of five parts. From the outlets of the intermediate pressure double-stream steam turbine two district heating heat exchangers are supplied. The model built allows to carry out calculations in a design mode, and also for simulation of the operation, during which the model automatically adapts the load of the system to the requirements of the district heating net-

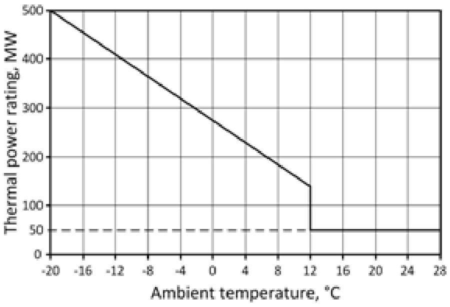

Figure 2. Heat demand characteristic.

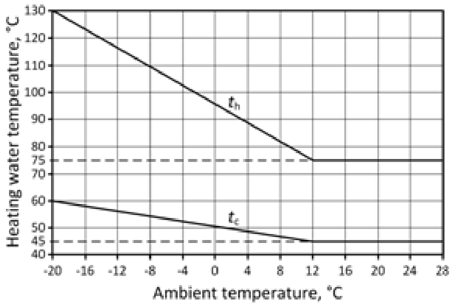

Figure 3. Temperature characteristic of the network.

work, determined by the characteristics shown in Figs. 2 and 3. The mass flow rate and concentrations of individual components in flue gases leaving the boiler were: $\dot{m}_A = 298.9$ kg/s, $CO_2 = 14.16\%$, $SO_2 = 0.09\%$ $O_2 = 3.29\%$, $N_2 = 73.78\%$, $H_2O = 7.80\%$, Ar=0.88%.

A more detailed characteristic of the system was presented in [5,6,9].

2.2 Carbon dioxide capture and compression installation

By the name of a carbon dioxide capture and compression installation a system composed of three units is understood, i.e., separation installation, of which the essential part is an absorber and a stripper column, a gas turbine system with a heat exchanger at the outlet of the expander and a three-section compressor installation with intersection coolers. The calculations of the chemical absorption system were carried out by introducing significant simplifications. It was assumed that the separation leads to a capture of 90% of the CO_2 contained in the exhaust gas stream supplied to the installation. After the CO_2 separation the drying process proceeds, which is generally required for a transport of the gas for long distances. It was assumed that the gas prepared in such a way is a pure carbon dioxide, which is subsequently compressed. A compressor preparing CO_2 for further transport to the storage location is a three-section machine with interstage coolers. It was assumed that the gas is compressed from 0.1 MPa to 20 MPa. Total pressure ratio is realized by three sections, assuming the same pressure ratios for each section. Cooling in each interstage heat exchanger leads to cooling of the carbon dioxide to 40 °C. Important, for the integration of the separation installation with the gas turbine unit, is the energy intensity of the desorption process. Currently used sorbents allow to conduct the process of regeneration by supplying the heat in the range from 2 to 6 MJ/kg CO_2 [10,11] but the research in the world are carried out aiming to limit this value even more. In the analysis specific heat of desorption (q_{des}) was changed from 1 to 6 MJ/kg of CO_2 captured.

In the calculation, the power of a gas turbine was adjusted in such a way to meet the thermal needs of the adsorption process. Regardless the power of a turbine, the values of basic quantities characterizing the work of the machine were kept constant. It was assumed that the exhaust gas temperature at the exit of the combustion chamber was at 1200 °C, the compression ratio was equal to 20, the isentropic efficiency of a compressor and an expander were equal to 90%, and electromechanical efficiency equal to 95%. In addition, the relative pressure losses at the inlet to the compressor at 0.7% and during the gas flow through the combustion chamber at 2.5% were assumed. The main task of the heat exchanger located at the exhaust gas stream is to produce saturated steam at 130 °C. The heat exchanger efficiency was assumed at 90%.

3 Evaluation indices

During analyzes for the two CHP systems, the calculation of the selected energetic and ecological evaluation indices were made. The net (η_{el,b_R}) and gross (η_{el,n_R}) efficiency of electricity production were determined:

$$\eta_{el,b_R} = \frac{E_{elST} + E_{elGT}}{E_{chc} + E_{chg}} = \frac{\int\limits_0^{\tau_R} (N_{elST} + N_{elGT}) d\tau}{V_{dc} \int\limits_0^{\tau_R} \dot{m}_c d\tau + V_{dg} \int\limits_0^{\tau_R} \dot{m}_g d\tau} , \tag{1}$$

$$\eta_{el,n_R} = \eta_{el,b_R} - \frac{E_{elpw}}{E_{chc} + E_{chg}} = \eta_{el,b_R} - \frac{\int\limits_0^{\tau_R} N_{elpw} d\tau}{W_{dc} \int\limits_0^{\tau_R} \dot{m}_c d\tau + V_{dg} \int\limits_0^{\tau_R} \dot{m}_g d\tau} , \tag{2}$$

where:

E_{elST}, E_{elGT} – annual electricity production realized by steam and gas turbines (gross),

E_{elpw} – annual auxillary power,

E_{chc}, E_{chg} – annual use of chemical energy of coal and gas,

V_{dc}, V_{dg} – lower heating value of coal and gas,

N_{elST}, N_{elGT} – actual power of steam turbine and gas turbine,

N_{elpw} – actual auxiliary power,

$\dot{m}_w, \dot{m}_g$ – streams of coal and gas,

τ, τ_R – time and annual operations time.

Another calculated energetic evaluation index was the efficiency of useful heat production:

$$\eta_{q_R} = \frac{Q_R}{E_{chc} + E_{chg}} = \frac{\int\limits_0^{\tau_R} \dot{Q}\, d\tau}{V_{dc} \int\limits_0^{\tau_R} \dot{m}_c d\tau + W_{dg} \int\limits_0^{\tau_R} \dot{m}_g d\tau}\,, \tag{3}$$

where: Q_R – annual heat production, $\dot{Q}$ – actual heat load of the system.

The most classic indicator of ecological evaluation of carbon dioxide emissions in the power plants is the average CO_2 emission incriminating a unit of net electricity produced. For the analyzed systems it was defined by the following formula:

$$\varepsilon_{CO_2} = \frac{(1 - R_{CO2})\, m_{CO_{2w}} + m_{CO_{2g}}}{E_{elST} + E_{elGT} - E_{elpw}} = \frac{(1 - R_{CO2}) \int\limits_0^{\tau_R} \dot{m}_{CO_{2c}} d\tau + \int\limits_0^{\tau_R} \dot{m}_{CO_{2g}} d\tau}{E_{elST} + E_{elGT} - E_{elpw}}\,, \tag{4}$$

where:

$m_{CO_{2c}}$, $m_{CO_{2g}}$ – annual CO_2 emission resulting from combustion of coal and gas,

$\dot{m}_{CO_{2c}}$, $\dot{m}_{CO_{2g}}$ – actual CO_2 mass flow rates resulting from combustion of coal and gas,

R_{CO2} – CO_2 recovery rate.

Calculation of the defined annual indicators required the determination, for the analyzed range of temperatures (-20 °C to 28 °C), of the electric power, heat fluxes, fuels streams, streams of carbon dioxide, and then, presenting of these values as a function of time of occurrence of each value within a year and, eventually, integration of these values in time. For such a transformation for the calculations an appropriate ordered diagram of the ambient temperatures was adopted [12].

4 Results of calculation

The applied simulations have made it possible to obtain, for the two analyzed systems, several characteristics of the main quantities as a function of ambient temperature $(N_{elST}, N_{elGT}, N_{elpw}, \dot{Q}, \dot{m}_c, \dot{m}_g, \dot{m}_{CO2_c}, \dot{m}_{CO2_g} = f\,(t_{ot}))$. Using of the assumed ordered diagram of the ambient temperatures allowed for the presentation of these quantities as a function of time of occurrence within a year $(N_{elST}, N_{elGT}, N_{elpw}, \dot{Q}, \dot{m}_c, \dot{m}_g, \dot{m}_{CO2_c}, \dot{m}_{CO2_g} = f\,(\tau))$. Additional integration allowed for obtaining the characteristics: $E_{elST}, E_{elGT}, E_{elpw}, Q_R, E_{chc}, E_{chg}$, $m_{CO2_c}, m_{CO2_g} = f(\tau_R)$, where τ_R is a time of operation of CHP plant in the year. Prepared in such a way characteristics were the basis for the development of a set of characteristics shown in Figs. 4–7.

During the analyses for the different specific heat of desorption indicators nominal power of the gas turbine was determined. The change of the heat of desorption was accompanied by a linear change of its value. For extreme values of the heat of desorption, namely 1 and 6 MJ/kgCO$_2$, nominal gas turbine power was determined at the levels of, respectively, 44.6 MW and 267.6 MW. Energy intensity of the carbon dioxide compression process was calculated at 23.89 MW. It was also needed to define the auxiliary power of the particular installations. It allowed for the determination of the net power of the system.

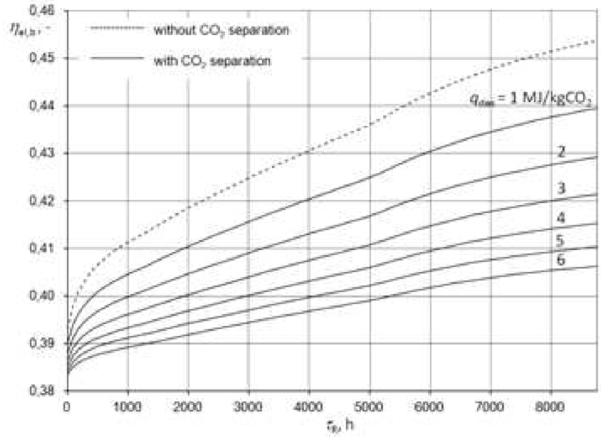

Figure 4. Efficiency of the gross electricity production for the system with and without CO$_2$ separation for different values of the specific heat of desorption.

As it can be seen an increase in the operation time of the CHP plant is accompanied by a corresponding increase in efficiency of gross and net electricity generation and a decrease in the heat generation efficiency. It can be explained by a decrease in the thermal power of the system with increasing ambient temperature and a consequent increase in generated electric power. Integration of a combined heat and power plant with a capture installation, according to the assumed variant, leads to a reduction of the efficiency of electricity and useful heat production, while the decrease in heat production is relatively higher here. For real time of operation of the combined heat and power plant in the year (over 5000 h), a decrease in electricity generation efficiency at a specific heat of desorption q_{des}=1 MJ/kgCO$_2$, is equal to 1–1.4 pp only, while a decrease in the

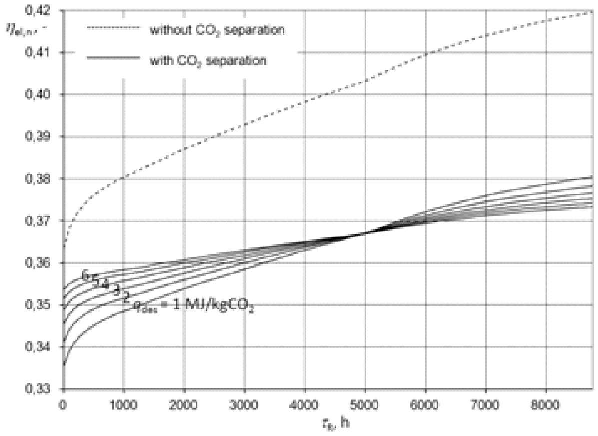

Figure 5. Efficiency of the net electricity production for the system with and without CO_2 separation for different values of the specific heat of desorption.

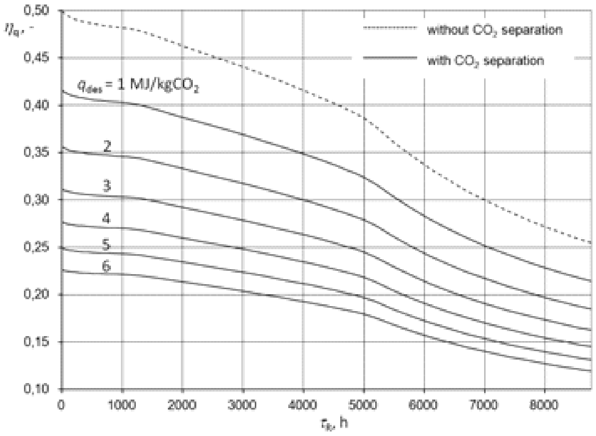

Figure 6. Efficiency of the useful heat production for the system with and without CO_2 separation for different values of the specific heat of desorption.

efficiency of net electricity generation is equal to 3.6–3.9 pp. Decreases in efficiency of electricity generation are the result of the introduction to the production of a gas turbine with lower efficiency of electricity production than the efficiency of the coal unit. An analogical decrease in the efficiency of useful heat generation is equal to 4.1–6.1 pp. Here, after the introduction of a gas turbine, a significant increase in fuel consumption without increasing the thermal capacity of the system is observed. It is worth noticing that while the growth of the specific heat of desorption significantly affects the efficiency of the gross electricity generation,

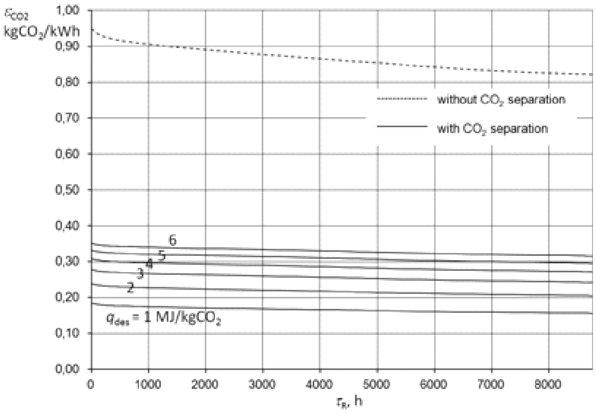

Figure 7. Average annual CO_2 emission index incriminating the unit of net electricity produced for the system with and without CO_2 separation at different values of the specific heat of desorption.

to a much lower extent, with the change of the specific heat of desorption change the values of efficiency of net electricity generation. Of a principal importance is the high energy demand needed to drive the compressor of carbon dioxide, which does not depend on the energy intensity of the desorption process. The change of the values of the specific heat of desorption has the most significant impact on the efficiency of the useful heat production. Here, for $q_{des} = 6$ MJ/kgCO_2 a reduction in the efficiency in relation to the system without separation for $\tau_R > 5000$ h was even up to 20.2 pp. The use of separation installation and a gas turbine allows for a significant reduction in CO_2 emissions per unit of net electricity produced. When using sorbents with the specific heat of desorption $q_{des} = 1$ MJ/kgCO_2 the emission indicator, over the entire range of working time, is much less than the 0.2 kgCO_2/kWh. The use of sorbents with higher specific heat of desorptioncontributes to the increase of the emission indicator, but in any case, its value does not exceed 0.35 kgCO_2/kWh.

5 Summary

The need to produce heat in a combined heat and power plant according to the characteristics of demand causes that the introduction of steam extraction for the implementation of the desorption process is impossible. In this case, for the heat supply to the stripping column, it is necessary to find an external source of heat. The use of a gas turbine and a heat exchanger, producing saturated steam, allows to achieve high efficiencies of power generation. A decrease in the efficiency of net electricity generation in relation to the system without the capture installation is a result of the introduction of an additional component to the system, with an efficiency lower than the efficiency of the coal unit and the consequence of a relatively high energy consuming process of compression of captured CO_2. An important limitation of the useful heat generation efficiency is, in turn, caused by an increased consumption the chemical energy of fuel in the absence of useful heat production based on additionally introduced natural gas. Undoubtedly, the integration of a CHP plant with a carbon dioxide capture installation according to the analyzed variant allows to reduce significantly the carbon dioxide emissions. A reduction of emissions incrementing the unit of produced electricity is a result of the separation of CO_2 formed in the coal boiler, as well as of the implementation of an additional electricity production based on the fuel burdened with lower unit emissions of this popular greenhouse gas. A further reduction of carbon dioxide emissions in the analyzed system may be the result of subjecting them to the CO_2 capture of the exhaust gases arisen in the combustion chamber of a gas turbine. Reduction of efficiency losses resulting from the integration should be searched for in the heat integration of particular installations aiming to use a waste heat [13]. About the justification of the integration of carbon dioxide capture installation with a combined heat and power plant working at supercritical parameters will determine the result of economic analysis, which will depend significantly on the development of the price of carbon dioxide emission allowances.

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Ocena termodynamiczna bloku elektrociepłowni współpracującej z instalacją wychwytu dwutlenku węgla przy jej integracji z turbiną gazową

Streszczenie

W artykule przedstawiono rezultaty analizy termodynamicznej przeprowadzonej dla bloku elektrociepłowni węglowej na parametry nadkrytyczne zintegrowanej z absorpcyjną instalacją wychwytu dwutlenku węgla. Moc elektrociepłowni określono na poziomie 320 MW, zakładając, że produkuje ona ciepło zgodnie z przyjętymi charakterystykami zapotrzebowania. Założono ponadto, iż dla potrzeb pozyskania ciepła dla procesu desorpcji blok elektrociepłowni zintegrowany został z instalacją turbiny gazowej, na wylocie której zabudowano wymiennik odzyskowy. Dla celów analizy określono odpowiednie wielkości charakteryzujące turbinę gazową. Moc maszyny z kolei zależała od ciepłochłonności procesu desorpcji. Przy ocenie integracji elektrociepłowni posłużono się zdefiniowanymi w pracy średniorocznymi wskaźnikami termodynamicznymi oraz emisją jednostkową dwutlenku węgla.