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The improvement of environmental characteristics of the combined cycle power plant by the implementation of the carbon capture installation

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Abstract

The paper describes a combined cycle power plant with carbon capture installation in a post-combustion technology. Carbon dioxide is separated from flue gas by using a chemical absorption method with monoethanolamine (MEA) as a sorbent. Separated carbon dioxide is compressed in order to prepare for transportation to the storage place. This paper identifies the electric efficiencies and other characteristic parameters of power plants before and after implementation of CO_2 capture installation, as well as the power plant efficiency drop, and the improvement of ecological characteristics related to the implementation of this installation. The implementation of the installation described herein is associated with the efficiency loss caused by the auxiliary power for additional installations. The CO_2 separation installation is powered by heat energy required for reclaiming the sorbent. This energy is taken in the form of steam extracted from the steam cycle, thus reducing the steam turbine power output, while the CO_2 compression installation is powered by electric energy.

Introduction

A combined cycle power plant is a combination of a gas turbine installation working at high temperatures with a steam cycle operating at a lower temperature range. The result of the combined work cycle is a high net efficiency of power generation, currently exceeding 60%, and very low emissions of carbon dioxide: lower than 330 $kgCO_2/MWh$, a value more than twice as low as the emission values of modern supercritical coal-fired power plants. Low investment costs and short construction times are favorable, as are such other ecological characteristics as low emissions of NO_x and no emissions of SO_X or dust (Szargut and Ziębik, 1988; Chmielniak, 2008; Kotowicz, 2008). Therefore, the global contribution of natural gas to electricity production is constantly growing, having reached 22.5% in 2012 (European Commission, 2014).

Anthropogenic CO_2 emissions alter the balance of the carbon cycle in nature, which may cause unfavorable climatic changes. Therefore the policy objective of many global economies, including the European Union, is to reduce greenhouse gas emissions, especially carbon dioxide. To meet growing demands for the reduction of such emissions, it is necessary that electricity produced from fossil fuels be produced with high efficiency and low emissions. As with coal fired power plants, combined cycle power plants will not be able to meet these demands without significant changes (Directive 2009/29/EC of the European Parliament).

Carbon capture and storage (CCS) technology has been suggested as an emissions solution, allowing for near zero-emission operation of these units. The aim of CCS is to capture, prepare, transport and store the captured CO_2. There are three main groups of CO_2 separation technologies:

- pre-combustion;
- post-combustion;
- oxy-combustion.

Post-combustion technology is closest to commercial implementation. It is based on the separation of CO_2 from flue gases, and therefore does not affect the combustion process or the basic structure of the power unit. Installation based on post-combustion technology the easiest to implement, and can occur in existing "CCS ready" power units. Among the many techniques of carbon dioxide separation from flue gases described in the literature, such as membrane techniques (Kotowicz & Bartela, 2012), physical adsorption and absorption (Maurstad, 2005), thermo-acoustic techniques (Remiorz, 2014) and chemical absorption (Duan, Zhao & Yang, 2012), the last method is the most mature technology. Currently, it is the optimal solution.

Model of the combined cycle gas turbine unit

A combined cycle (CC) power plant, the subject of this analysis, is a connection of two separate thermal cycles: a gas turbine (GT) and steam cycle (SC) connected through a heat recovery steam generator (HRSG). Units with carbon capture capabilities are equipped with such additional components as installations to separate CO_2 from flue gas using the chemical absorption method (CSU), and a carbon dioxide compression installation (CCU). The structure of the described unit, with individual installations highlighted, is shown in Figure 1. Mathematical models of the gas tur-

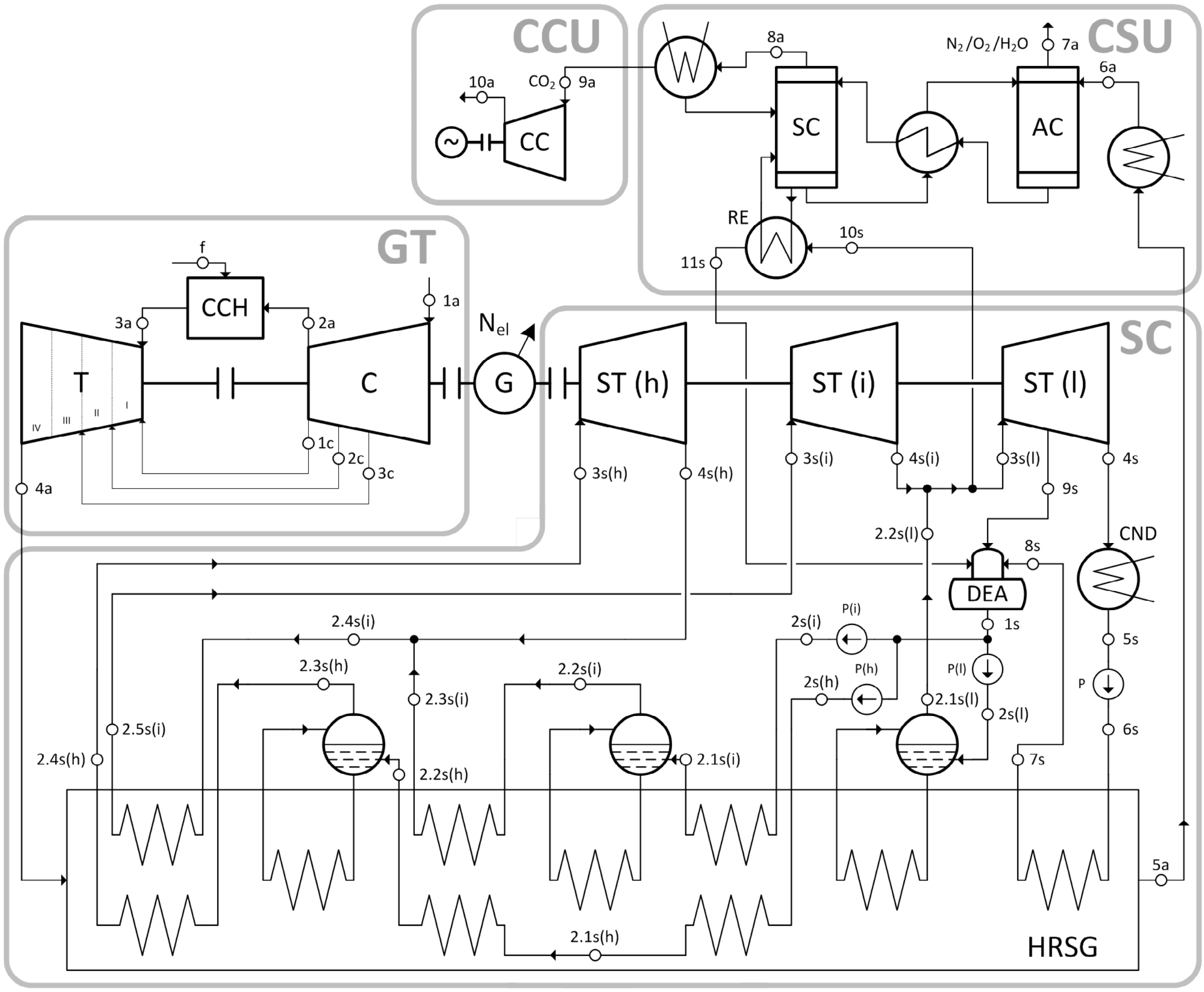

Figure 1. Schematic of a combined cycle gas turbine integrated with a carbon dioxide capture and compression unit; T – turbine, CCH – combustion chamber, C – compressor, G – generator, DEA – deaerator, CND – condenser, P – pump, SC – stripper column, AC – absorber column, RE – reboiler, ST – steam turbine; h – high-pressure, i – intermediate--pressure, l – low-pressure level

bine, the steam cycle, and the CO_2 compression installation were generated with GateCycle software (GateCycle Version 5.40).

Gas turbine

The G-class gas turbine with an electric power of 260 MW was used in the combined cycle unit described here. The most important assumptions for the gas turbine installation are summarized in Table 1. Isentropic efficiency values for the compressor and expander were assumed on the basis of the calculation algorithms developed by Kotowicz, Job and Brzęczek (2015). The gas turbine is fuelled by natural gas comprised of 96% CH_4, 2.5% C_2H_6, 1% N_2 and 0.5% CO_2. This gas has a lower heating value of 48.419 MJ/kg. The gas at the combustion chamber inlet has a temperature of 15°C and a pressure of 3.5 MPa. The air at the compressor inlet has a composition consistent with ISO-2314 (ISO, 2009), a temperature of 15°C, a pressure of 101.325 kPa, and a relative humidity, φ, of 60%.

Table 1. Assumptions for gas turbine installations

Parameter	Symbol	Value
Gas turbine electric power	N_{elGT}, MW	260.0
Turbine inlet temperature	t_{3a}, °C	1500.0
Compression ratio	β, –	20.0
Compressor isentropic efficiency	η_{iC}, %	87.9
Turbine isentropic efficiency	η_{iT}, %	90.3
Mechanical efficiency	η_m, %	99.5
Generator efficiency	η_G, %	98.5
Compressor inlet pressure loss (air filter)	ζ_{in}, %	1.0
Combustion chamber pressure loss	ζ_{CCH}, %	4.5
Gas turbine outlet pressure	p_{4a}, kPa	105.5
Gas turbine and steam cycle own needs ratio	δ_{el}, %	2.0

Convection air cooling of the turbine blades protects elements exposed to the highest temperatures. The turbine consists of four blade stages, the first three of which are cooled. The air taken from the compressor outlet is used to cool the first stage, while the cooling of second and third stage air is taken from compressor bleeds. The cooling model results from the heat flow balance between the hot flue gases, the turbine blades, and the cooling air, as described by Jonsson et al. (Jonsson et al., 2005), Sanjay, Singh and Prasad (Sanjay, Singh & Prasad, 2008), and Kotowicz, Job and Brzęczek (Kotowicz, Job & Brzęczek, 2015). Based on that heat flow balance, the individual mass flows of cooling air required for each turbine stage is determined by the following equation:

$$\dot{m}_c = \dot{m}_g \cdot \frac{k \cdot St}{\eta_c} \cdot \left(\frac{t_{g.in} - t_b}{t_b - t_{c.in}} \right) \cdot \frac{c_{p.g}}{c_{p.c}} \tag{1}$$

where:

$\dot{m}_c$, $\dot{m}_g$ – mass flows of the cooling gas and the hot gas, respectively, at the turbine stage inlet;

η_c – cooling efficiency (assumed $\eta_c = 0.5$);

St – Stanton number (approximately 0.005);

k – ratio between the heat transfer area and the hot gas cross-section area (k is about 6–10, here $k = 10$);

$c_{p.c}$, $c_{p.g}$ – the average specific heat capacity between inlet and blade temperatures of the cooling gas and the hot gas, respectively;

$t_{c.in}$, $t_{g.in}$ – the respective cooling gas and the hot gas temperature at the turbine stage inlet;

t_b – blade temperature (assumed $t_b = 900$°C).

Steam cycle

The steam cycle is based on a tri-section steam turbine, which is powered by the steam generated in the heat recovery steam generator (Figure 1). A three-pressure heat recovery steam generator with intermediate-pressure steam reheating utilizes the hot flue gases from the gas turbine to produce steam. The deaeration economizer in the construction of HRSG is used, replacing the low-pressure economizer. The high-pressure economizer has two parts. The deaerator is fed by the steam extracted from the low-pressure steam turbine section. The operating parameters and other assumptions for the steam cycle of the unit are summarized in Table 2.

Table 2. Assumptions for steam cycle

Parameter	Symbol	Value
Live steam temperature at the turbine inlet	$t_{3s(h)}$, °C	560.0
Live steam pressure at the turbine inlet	$p_{3s(h)}$, MPa	18.0
Reheated steam temperature at the turbine inlet	$t_{3s(i)}$, °C	560.0
Reheated steam pressure at the turbine inlet	$p_{3s(i)}$, MPa	4.0
Low-pressure level steam pressure at the turbine inlet	$p_{3s(l)}$, MPa	0.3
Condenser pressure	p_{CND}, MPa	0.005
Steam turbine isentropic efficiency	η_{iST}, %	90.0
Steam turbine mechanical efficiency	η_{mST}, %	99.0
Heat exchangers efficiency in HRSG	η_{HE}, %	99.0
Pinch point temperature differences in evaporators	Δt_{pp}, °C	5.0
Underheating of water at the economizers outlet (approach point)	Δt_{ap}, °C	5.0

Carbon dioxide separation unit

At present, the optimal method for capturing CO_2 from flue gases in post-combustion technology is absorption using chemical sorbents. This is based on a comparison of carbon dioxide capture methods described in the literature (Kotowicz & Janusz, 2007; Chmielniak & Wójcik, 2010). A CSU installation which separates CO_2 from flue gases by means of a chemical absorption process is shown in Figure 1. Installation of carbon dioxide capture capability entails two basic processes – separation of CO_2 from flue gases in an absorber column (AC), and reclaiming of the amines in a stripper column (SC).

Monoethanolamine (MEA) and methyldiethanolamine (MDEA) are the most commonly used amines. MDEA is used to selectively absorb H_2S in the presence of CO_2. MEA has a higher alkalinity, a high reactivity and stability, and a low price. An installation using MEA allows for the removal of about 75–96% of carbon dioxide, and for achieving an almost pure CO_2 stream (> 99%). The CO_2 chemical absorption process with MEA takes place by the following reactions (Kohl & Nielsen, 1997):

$$2\mathrm{RNH_2} + \mathrm{CO_2} + \mathrm{H_2O} \Leftrightarrow (\mathrm{RNH_3})_2\mathrm{CO_3}$$

$$(\mathrm{RNH_3})_2\mathrm{CO_3} + \mathrm{CO_2} + \mathrm{H_2O} \Leftrightarrow 2\mathrm{RNH_3HCO_3}$$

$$2\mathrm{RNH_2} + \mathrm{CO_2} + \mathrm{H_2O} \Leftrightarrow \mathrm{RNHCOONH_3R}$$

The flue gas stream leaving the HRSG is pre-cooled to a temperature of approximately 40°C, and is then directed to the absorber column. The liquid absorbent, MEA, requires a high heat of absorption, which is reflected in the need to supply the required heat energy to break the complex of MEA with CO_2 in the desorption process. The process of sorbent reclamation takes place in the stripper column at a temperature of approximately 120°C. For the process of reclaiming sorbent, the steam is taken from a bleed from the low-pressure steam turbine section. The required steam mass flow for sorbent reclamation was determined by the following relationship:

$$\dot{m}_{10s} = \frac{q_S \cdot \dot{m}_{CO2} \cdot R}{(h_{10s} - h_{11s}) \cdot \eta_{RE}} \tag{2}$$

where:

h_{10s}, h_{11s} – steam enthalpy at the reboiler (heat exchanger of the stripper) inlet, and the water enthalpy at the reboiler oulet.

Energy consumption of the sorbent, q_s, was assumed to be 3 MJ/kgCO2. The carbon dioxide recovery rate from the carbon dioxide stream contained in the flue gases, $\dot{m}_{CO2}$, has an R of 90%, and the efficiency of the reboiler, η_{RE}, is assumed to be 0.99. MEA is heated in the reboiler by the steam to temperature $t = 125$°C. The steam bleed pressure, p_{10s}, is 0.287 MPa, and was determined from the following relationship:

$$p_{10s} = \frac{q_S (t + \Delta t_{RE})}{1 - \varsigma_{RE}} \tag{3}$$

where:

ζ_{RE} – relative loss of the vapor pressure in the reboiler;

Δt_{RE} – minimal temperature difference in the reboiler ($\Delta t_{RE} = 5$°C).

The steam bleed from the steam turbine to reclaim MEA in the CO_2 capture unit causes a significant loss of the steam turbine power. Therefore, the efficiency of the steam cycle and combined cycle unit decreases.

Carbon dioxide compression unit

Because the separated CO_2 stream in the chemical absorption installation is has a purity exceeding 99%, it is directed to a carbon dioxide compression unit (CCU in Figure 1) without any additional purification. Such prepared gas is compressed to a pressure of 13 MPa in an eight-section compressor with intercooling to a temperature of 30°C. In the first seven sections the gas is compressed to 6.5 MPa using the same pressure ratios in each section. After the seventh section, the pressurized carbon dioxide is condensed during cooling, and the last section is a liquid CO_2 pump. Isentropic efficiency of the compressors is assumed to be 80%. Compressed carbon dioxide in the supercritical state is then ready for transport to the storage facility.

Results of the thermo-ecological analysis

The effectiveness of the analyzed combined cycle unit is evaluated by electricity generation efficiency. Net electrical efficiency, η_{elCC}, is determined by the relationship in Eq. (4). The results of thermo-ecological analysis are presented in Table 3. The CO_2 emission and net electrical efficiency of the combined cycle power plant as a function of sorbent energy consumption is shown in Figure 2.

$$\eta_{elCC} = \frac{N_{elCC}}{\dot{m}_f LHV} = \frac{N_{elGT} + N_{elSC} - (\Delta N_{CC} + \Delta N_{CCU})}{\dot{m}_f LHV} \tag{4}$$

where:

N_{elCC} – electrical power of the unit;

N_{elGT}, N_{elSC} – electrical power of the gas turbine and steam cycle;

ΔN_{CC} – combined cycle own needs ratio;

ΔN_{CCU} – carbon dioxide compression unit own needs ratio;

$\dot{m}_f$ – mass flow of the fuel;

LHV – lower heating value.

Electrical efficiency of the gas turbine, η_{elGT}, and the steam cycle, η_{elSC}, are expressed by the following relationships:

$$\eta_{elGT} = \frac{N_{elGT}}{\dot{m}_f LHV} \tag{5}$$

$$\eta_{elSC} = \frac{N_{elSC}}{\dot{Q}_{4a}} \tag{6}$$

where:

$\dot{Q}_{4a}$ – heat flux at the HRSG inlet.

Table 3. The results of the thermo-ecological analysis

Parameter	Symbol	Value	
		CC	CCS
Gas turbine electric power	N_{elGT}, MW	260.0	260.0
Chemical energy flux of the fuel	$\dot{m}_f LHV$, MW	653.1	653.1
Electrical efficiency of the gas turbine	η_{elGT}, %	39.8	39.8
Heat flux at the HRSG inlet	Q_{4a}, MW	377.6	377.6
Energy flux rate of the flue gases at the gas turbine outlet	α, –	1.45	1.45
Flue gas temperature at the HRSG inlet	t_{4a}, °C	601.0	601.0
Electrical power of the steam turbine	N_{elSC}, MW	129.7	105.6
Electrical efficiency of the steam cycle	η_{elSC}, %	34.3	28.0
Gross electrical power of the combined cycle unit	$N_{el.gross}$, MW	389.7	365.6
Gross electrical efficiency of the combined cycle unit	$\eta_{el.gross}$, %	59.7	56.0
Gas turbine and steam part own needs	ΔN_{CC}, MW	7.8	7.3
Carbon dioxide compression installation own needs	ΔN_{CCU}, MW	0	10.5
The total own needs rate of the unit	δ, %	2.0	4.9
Net electrical power of the combined cycle unit	N_{elCC}, MW	381.9	347.7
Net electrical efficiency of the combined cycle unit	η_{elCC}, %	58.5	53.3
CO_2 production in combustion process	u_{CO2}, kg/MWh	319.5	350.9
CO_2 emissions	e_{CO2}, kg/MWh	319.5	35.1

Thus, the net electrical efficiency of the combined cycle unit, as described (4), can be condensed as follows:

$$\eta_{elCC} = \eta_{elGT}\left(1 + \alpha \cdot \eta_{elSC}\right) \tag{7}$$

Wherein:

$$\alpha = \frac{\dot{Q}_{4a}}{N_{elGT}} \tag{8}$$

where:

α – energy flux ratio of the gas turbine outlet flue gas.

The CO_2 emissions for 1 MWh of net electrical energy produced may be expressed as follows:

$$e_{CO2} = \frac{\dot{m}_{CO2}}{N_{elCC}} \cdot 3600 \cdot (1 - R) \tag{9}$$

Conclusions

The methodology and calculations for power plant efficiency with and without carbon capture and compression installation is described in this article. The integration of the combined cycle unit with CO_2 capture and compression installations causes a loss of efficiency relative to the power plant without these installations of about 5.3 percentage points. The decrease of the efficiency of the unit with CO_2 capture and compression relative to the unit without this installation is due to two factors:

- From the power reduction of the steam turbine caused by the steam bleed used by the chemical absorption installation. For the adopted energy consumption of sorbent, q_S, of 3 MJ/kgCO_2, the power reduction of the steam turbine is 24.1 MW.
- From the electrical power demand of the CO_2 compression installation. The total compressor

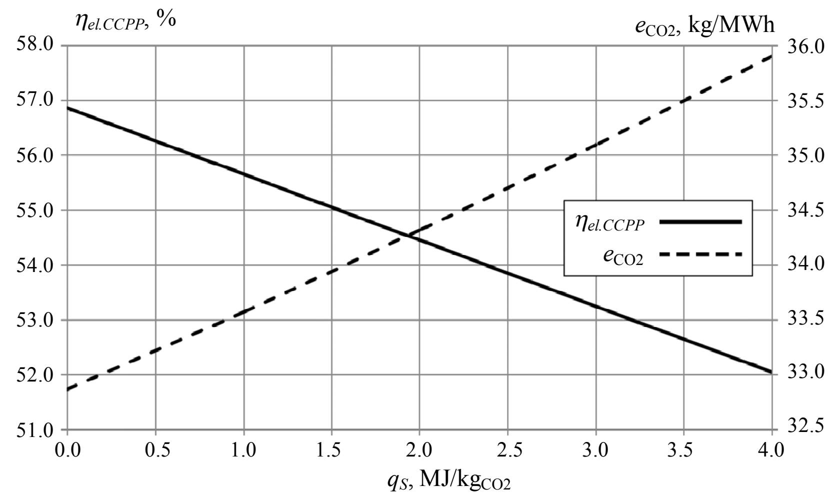

Figure 2. Net electrical efficiency of the combined cycle unit and CO_2 unit emissions as a function of sorbent energy intensity

power in the CO_2 compression unit is equal to 10.5 MW, while the individual need of this installation is 95.98 kWh/MgCO_2.

Reducing the sorbent energy intensity by 1 MJ/kgCO_2 causes an increase of net electrical efficiency of the combined cycle unit by approx. 1.25 pp, and a decrease of the CO_2 unit emissions by approximately 0.73 kg/MWh (Figure 2). The carbon capture installation reduces carbon dioxide emissions by approximately 88.8%.

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