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THE THERMODYNAMIC ANALYSIS OF THE COMBINED CYCLE GAS TURBINE UNITS WITHOUT AND WITH CARBON CAPTURE INSTALLATION

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Abstract

This paper presents the thermodynamic analysis of a combined cycle gas turbine units without and with the carbon capture installation (CCS). The characteristics of the combined cycle units and the carbon capture technology were discussed. The operation methods of the oxy - combustion and the post - combustion technology was presented. The three units: combined cycle gas turbine without CCS, the combined cycle gas turbine with oxy - combustion and the combined cycle gas turbine with post - combustion were analyzed. The emission of carbon dioxide from above mentioned units also was compared.

1. Introduction

Combined cycle gas turbines (CCGT) are a combination of a gas turbine cycle with a steam turbine cycle by a heat recovery steam generator (HRSG), what makes them one of the most efficient technologies of electricity generation from fossil fuels. These units are also one of the fastest developing solutions, with efficiency already reaching above 60%. CCGT units are also distinguished by a number of advantages, such as short construction time, low investment cost, high reliability and flexibility of operation, favorable ecological characteristics – with 60% efficiency CO_2 emission is about 330 $kgCO_2$/MWh. This value is around 2.5-times lower than CO_2 emission of modern coal-fired power plants, equal to over 800 $kgCO_2$/MWh. Currently, CCGT are not popular in Poland due to a high natural gas prices in Poland [1,2].

The energy sector is facing the new challenges to reduce the CO_2 emission level. Recently developed Carbon Capture and Storage technologies (CCS) are expected to allow near zero-emission production of electricity from fossil fuels. The aim of CCS technologies is to separate carbon dioxide followed by its transportation and storage. There are 3 basic technologies of CO_2 separation:

- post-combustion
- pre-combustion

- oxy-combustion

The post-combustion technology is based on CO_2 separation from the flue gas, so it does not interfere with the combustion process and the basic structure of the power unit. That makes the post-combustion technology easy to implement, and even possible to install in existing power units, so-called "*capture-ready*". Separation of CO_2 may be realized by various methods, but now the optimal solution is chemical absorption, which confirms the literature review, e.g. [3,4,5,6]. This method is also applied in one of the analyzed units, described in pt. 2.3.

Chemical absorption is based on the absorption of the gas molecules by the liquid sorbent. The process is conducted in the absorber-desorber system. A high level of recovery and high carbon dioxide purity proves the effectiveness of this method. Realization of the CO_2 capture process based on chemical absorption requires to provide a suitable amount of heat energy to the desorber column for regeneration of the sorbent. To provide required heat, a steam extraction is performed in the low pressure steam turbine. This procedure lowers the steam turbine power, and hence, decreases the efficiency of the CCGT unit. In order to reduce this power drop new sorbents are searched, which would be characterizes by low energy consumption.

The oxy-combustion is an alternative CO_2 separation technology, which concept is based on the combustion of fuel in an oxidant with increased oxygen content. The elimination of nitrogen from the combustion process makes the flue gas consist mainly of carbon dioxide and water vapor, allowing for the CO_2 separation with a relatively low energy demand. In spite of the simplified CO_2 separation in relation to other CCS technologies, in this case the oxygen separation process is associated with a significant demand for electric energy. Due to the requirement of a high performance and sufficient oxygen purity, currently the use of cryogenic air separation unit is considered. In the worldwide available literature there are few positions about oxy-combustion technology in CCGT plants, and those are often concerning customized units, e.g. [7,8].

2. The structures of analyzed units

2.1. The combined cycle gas turbine unit without carbon capture installation (CCGT)

The structure of the combined cycle gas turbine without carbon capture installation is presented in Fig. 1. This unit is further identified as the CCGT case and it is a reference unit for the compared systems presented in point 2.2 and 2.3, which are extended with the installations associated with the application of selected CCS technology. The class G gas turbine for the analyzed combined cycle power plants is proposed. The gas turbine has a net electrical power equal to 200 MW, a combustion chamber outlet temperature is t_{3a} = 1500°C and the pressure ratio is β_K = 23. The open-air film cooling in the gas turbine is used. The gas turbine outlet flue gas is sent to the heat recovery steam generator producing the steam to supply the steam part. The triple-pressure heat recovery steam generator with the steam reheating is decided to use. The most important parameters for the gas turbine and the steam cycle of the CCGT unit in are presented in point 2.4.

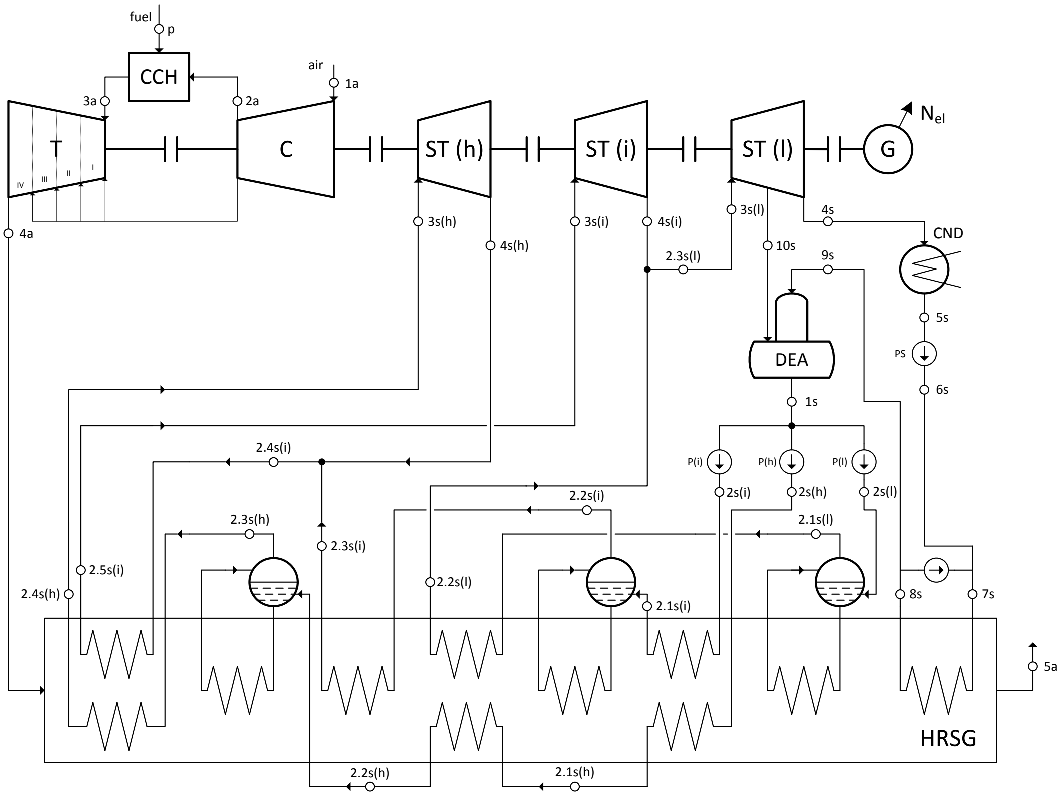

Fig. 1. A scheme of the combined cycle gas turbine unit without carbon capture installation – CCGT case (G - generator, C - compressor, EX - expander, CMB – combustion chamber, HRSG - heat recovery steam generator, CND - condenser, DEA - deaerator, P – pump, ST - steam turbine ((h) - high-pressure, (i) - intermediate-pressure, (l) - low-pressure level)

2.2. The combined cycle gas turbine unit with oxy-combustion technology (OXY)

The structure of the CCGT unit with oxy-combustion is presented in Fig. 2. This unit is further identified as the OXY case. In the unit a higher pressure ratio than in the air-combustion units is applied, equal to $\beta_K = 50$. This high pressure ratio has for example the turbine Rolls Royce Trent 1000, the unit with the same pressure ratio value is also analyzed in [10]. The main assumptions are listed in pt. 2.4. In the oxy-combustion it is necessary to introduce the flue gas recirculation, so to the compressor is directed the flue gas from the cooler (FC) outlet. After compression its mixed with the oxidant and sent to the combustion chamber. The possible influence of the steam part on the gas turbine work parameters is eliminated by maintaining the constant temperature of the recirculated flue gas by the FC. This temperature is set so as to avoid the moisture condensation ($t_{5.1a}$ = 90°C). The oxidant consists of 99.5% O_2 and 0.5% N_2. Streams of the mixed recirculated gas and oxidant are set so as to provide the constant O_2 content equal to 2% in the flue gas at the combustion chamber outlet.

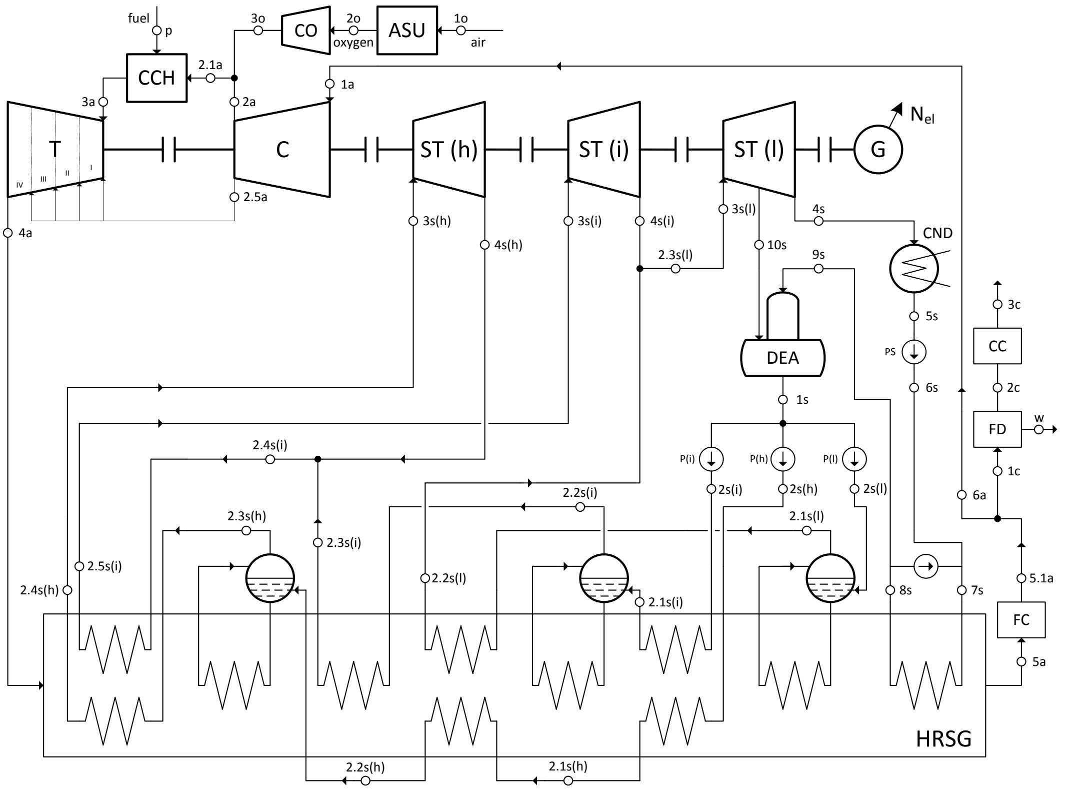

Fig. 2. A structure of the CCGT unit with oxy-combustion – OXY case (ASU – cryogenic air separation unit, CO – oxidant compressor, FC – flue gas cooler, FD – flue gas dryer, CC – installation of CO_2 compression)

The not recirculated part of flue gas is cooled in the dryer (FD) to the temperature of t_{2c} = 20°C, resulting in condensation of almost all the moisture content. Subsequently the flue gas (consisting about 90% of CO_2) is compressed to the pressure of 15 MPa in the CC installation and sent to the place of storage. The CO_2 capture effectiveness is assumed at the level of 98%, remaining 2% is emitted to the atmosphere. Design and working parameters of the cryogenic air separation unit and CC installation are not analyzed. There have been made assumptions of the unit energy consumption, for the oxygen production in ASU equal to $E_{N(ASU)}$ = 0,2 kWh/kgO_2 [10], and for the carbon dioxide compression in CC installation equal to $E_{N(CC)}$ = 0,1 kWh/kgCO_2 [1]. The own needs of the ASU installation N_{ASU}, and of the CC installation N_{CC} are equal to:

$$N_{ASU} = \dot{m}_{2o} \cdot E_{N(ASU)} \tag{1}$$

$$N_{CC} = \dot{m}_{2c} \cdot E_{N(CC)} \tag{2}$$

Where $\dot{m}_{2o}$ and $\dot{m}_{2c}$ are the mass flows of the oxidant from ASU and compressed CO_2, respectively.

2.3. The combined cycle gas turbine unit with post-combustion technology (ABS)

The integration of the combined cycle power plant with the carbon capture installation in post - combustion technology is presented in Figure 3. This unit is further identified as the ABS case. The optimization process and analysis of this structure is presented in [11]. The main assumptions for the ABS unit are listed in pt. 2.4.

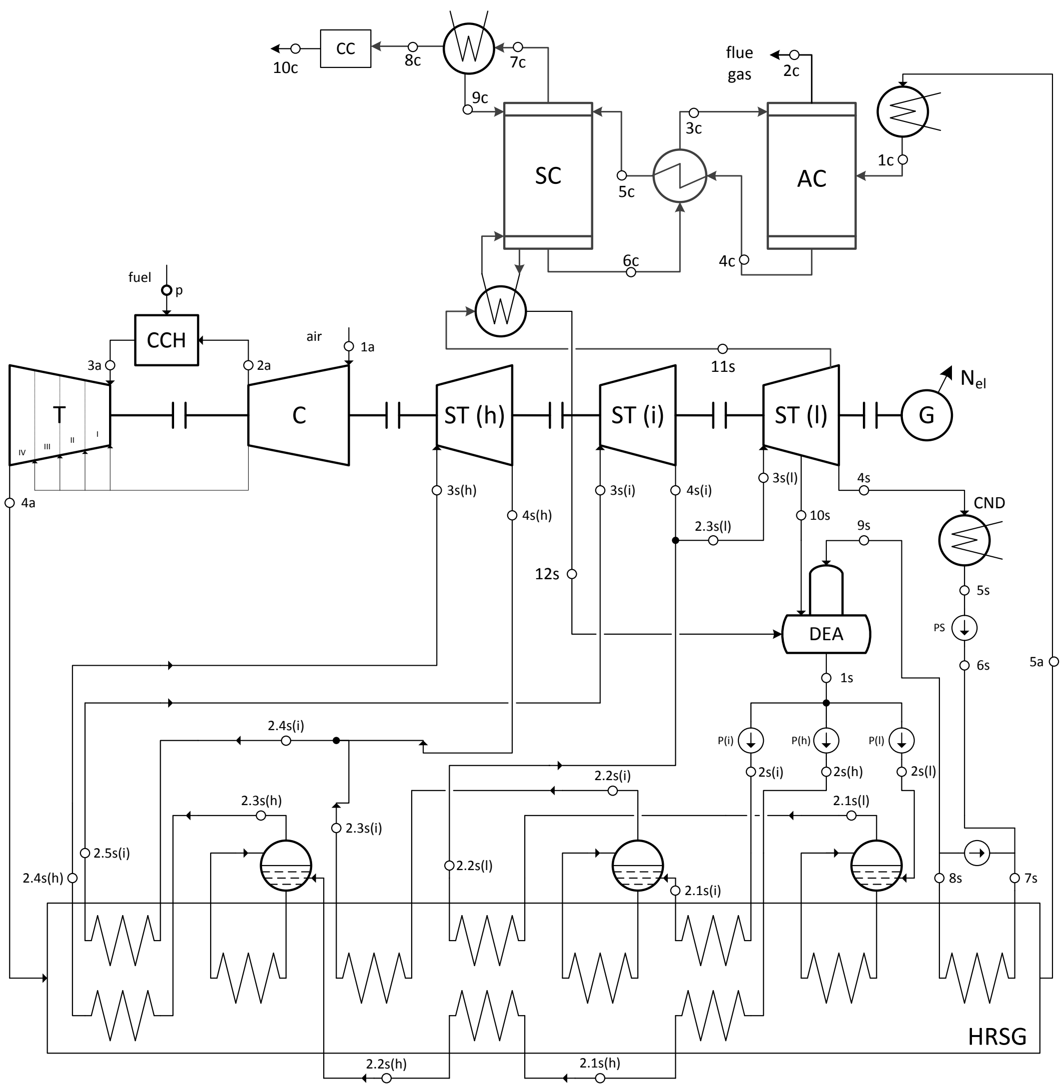

Fig. 3. A scheme of the combined cycle gas turbine unit with post - combustion technology – ABS case (AC - absorber column, AS - stripper column)

The flue gas from the HRSG is directed to the absorber column, where it is cooled to the temperature of 40 °C. The CO_2 recovery rate is R = 90%, which means that 10% of the CO_2 is emitted into the atmosphere. MEA (*monoethanolamine*) is used as the sorbent, whose energy consumption equal to 4 MJ/kgCO_2 is assumed. The chemical absorption process takes place in the absorber column. The MEA and CO_2 mixture is directed to the stripper column. It is necessary to provide a suitable amount of the heat energy for the sorbent regeneration. For this purpose the steam extraction is performed. The medium in the stripper heat exchanger is heated to the temperature of 125 °C. The pressure of the steam extraction used for regeneration of the MEA equals p_{11s} = 0,287 MPa.

The steam extraction for the sorbent regeneration causes a significant decrease of the steam turbine power, and in consequence decrease in the unit's power and efficiency. The CO_2 compression in CC installation causes further decrease in the efficiency and power of the ABS unit. Similarly to the OXY case, the energy consumption of the CO_2 compression equal to $E_{N(CCS)}$ = 0,1 kWh/kgCO_2 is assumed. In this case the auxiliary power of the CC installation N_{CC} is equal to:

$$N_{CC} = \dot{m}_{8c} \cdot E_{N(CC)} \tag{3}$$

Where $\dot{m}_{8c}$ is the mass flow of the separated carbon dioxide.

2.4. Operation parameters of the units

The main assumptions for the gas turbine part and steam part of the analyzed cases CCGT, OXY and ABS are presented in Tab. 1. To the units air is supplied at a temperature of 15 °C, pressure of 101,325 kPa, and a relative humidity of $\varphi = 60\%$. The combustion chambers are powered by the natural gas with the lower heating value $LHV = 50{,}18$ MJ/kg and volumetric composition: 98,21% CH_4, 1,27% N_2 and 0,52% CO_2. The models of the analyzed cases have been made in a GateCycle[TM] software [12]. Selection of the steam parameters was preceded by the optimization by means of genetic algorithm. Optimization process and detailed results are presented in other author's papers, for the CCGT and ABS cases in [11], and for OXY case in [9].

Table 1. The parameters of the gas turbine and steam part of the CCGT, OXY and ABS cases

Parameter	Symbol	CCGT	OXY	ABS	unit
GAS TURBINE					
Gas turbine gross electric power	N_{elGT}		200		MW
Combustion chamber outlet temperature	t_{3a}		1500		°C
Compressor pressure ratio	β	23	50	23	-
Turbine cooling air flow	$m_{2.5a}$		0,20*m_{1a}		kg/s
Cooling air flow ratio of the expander stages: I stage: II stage: III stage: IV stage:	δ_I δ_{II} δ_{III} δ_{IV}		0,52 0,38 0,10 0,00		-
Compressors isentropic efficiency	η_{iC} η_{iCO}		0,88		-
Expander isentropic efficiency	η_{iT}		0,90		-
Compressors and expander mechanical efficiency	η_{mC} η_{mT}		0,99		-
Mechanical efficiency of the generator	η_g		0,99		-
Efficiency of the combustor chamber	η_{CCH}		0,99		-
Compressor inlet pressure loss rate	ζ_{1a}		0,007		-
Combustion chamber pressure loss rate	$\zeta_{2a\text{-}3a}$		0,045		-
Lower heating value	LHV		50,18		MJ/kg
Expander outlet pressure	p_{4a}		103		kPa
Gas turbine and steam part own needs ratio	δ_{el}		0,02		-
STEAM CYCLE					
High-pressure steam turbine inlet temperature	$t_{3s(h)}$	560	600	560	°C
High-pressure steam turbine inlet pressure	$p_{3s(h)}$		17500		kPa
Intermediate-pressure steam turbine inlet temperature	$t_{3s(i)}$	560	600	560	°C
Intermediate -pressure steam turbine inlet pressure	$p_{3s(i)}$	3600	3360	4200	kPa
Condenser inlet pressure	p_{CND}		5		kPa
Steam turbine isentropic efficiency	η_{iST}		0,90		-
Steam turbine and generator mechanical efficiency	η_{mST} η_g		0,99		-

3. Thermodynamic efficiency evaluation

3.1. Evaluation methodology

Gas turbine gross electric power N_{elGT} is determined by the relationship:

$$N_{elGT} = \left(N_{iT} \cdot \eta_{mT} - \frac{N_{iC} + N_{iCO}}{\eta_{mC}} \right) \cdot \eta_G \tag{4}$$

where: N_{iT} – expander internal power, η_{mT} – expander mechanical efficiency, N_{iC} – compressor internal power, N_{iCO} - oxidant compressor internal power (appears only in the OXY case, in the remaining cases N_{iCO} is 0), η_{mC} – compressors mechanical efficiency, η_G – generator efficiency

Effectiveness of the CCGT unit is evaluated by the efficiency of electric energy production. Gross electric efficiency $\eta_{el.gross}$ is defined by the relation:

$$\eta_{el.gross} = \frac{N_{el.gross}}{\dot{m}_f \cdot LHV} = \frac{N_{elGT} + N_{elST}}{\dot{m}_f \cdot LHV} \tag{5}$$

gdzie: $N_{el.gross}$ – electric power of the CCGT unit, N_{elST} – steam turbine electric power, $\dot{m}_f$ - fuel mass flow, LHV – lower heating value of the fuel.

Electric efficiency of the gas turbine η_{elGT} and steam part η_{elST} are given by:

$$\eta_{elGT} = \frac{N_{elGT}}{\dot{m}_f \cdot LHV} \tag{6}$$

$$\eta_{elST} = \frac{N_{elST}}{\dot{Q}_{4a}} \tag{7}$$

Where $\dot{Q}_{4a}$ is the heat flow at the HRSG inlet.

By using the ratio of heat flow at the expander outlet $\dot{Q}_{4a}$ to the gas turbine electric power, indicated as α, equation (5) can be written as:

$$\eta_{el.gross} = \eta_{elGT} \cdot (1 + \alpha \cdot \eta_{elST}) \tag{8}$$

$$\alpha = \dot{Q}_{4a} / N_{elGT} \tag{9}$$

The net electric efficiency of the combined cycle unit is defined with analogy to (5), taking into account the own needs of individual installations within the unit:

$$\eta_{el} = \frac{N_{elGT} + N_{elST} - \sum \Delta N_i}{\dot{m}_f \cdot LHV} \tag{10}$$

$$\sum \Delta N_i = \Delta N_{el} + \Delta N_{ASU} + \Delta N_{CC} \tag{11}$$

The applied additional installations vary depending on the analyzed case. In equation (11) all occurring installations are listed, but if the analyzed case is not equipped with selected installation, then its own needs are equal to zero. The total own needs rate of the unit δ is equal to:

$$\delta = \sum \delta_i = \delta_{el} + \delta_{ASU} + \delta_{CC} = \frac{\Delta N_{el} + \Delta N_{ASU} + \Delta N_{CC}}{N_{el.gross}} \tag{12}$$

where: δ_{el} – gas turbine and steam part own needs ratio, δ_{ASU} – air separation unit own needs ratio, δ_{CC} – carbon dioxide compression installation own needs ratio.

3.2. Results

Characteristic parameters obtained for the analyzed combined cycle gas turbine units are presented in Tab. 2.

Table 2. Characteristic parameters of the CCGT, OXY and ABS cases.

Parametr	CCGT	OXY	ABS
N_{iT}, MW	428,1	520,6	428,1
N_{iC}, MW	219,5	283,3	219,5
N_{iCO}, MW	0,00	27,0	0,0
N_{elGT}, MW	200,00	200,0	200,00
$m_f LHV$, MW	516,3	568,5	516,3
$\eta_{el.GT}$, -	0,3873	0,3518	0,3873
Q_{4a}, MW	301,8	386,0	301,8
α, -	1,509	1,930	1,509
t_{4a}, °C	595,0	642,2	595,0
$N_{el.ST}$, MW	100,1	141,0	74,5
$\eta_{el.ST}$, -	0,3282	0,3654	0,2469
$N_{el.gross}$, MW	301,1	341,0	274,5
$\eta_{el.gross}$, -	0,5813	0,5998	0,5316
ΔN_{el}, MW	6,0	6,8	5,5
ΔN_{ASU}, MW	0,0	32,5	0,0
ΔN_{CC}, MW	0,0	11,6	8,9
δ, -	0,0200	0,1493	0,0525
N_{el}, MW	295,1	290,1	260,1
η_{el}, -	0,5715	0,5103	0,5037
u_{CO2}, kg/MWh	330,1	374,0	382,1
e_{CO2}, kg/MWh	330,1	7,5	38,2

Where u_{CO2} is the CO_2 production in combustion process per every 1 MWh of produced net electric energy, and e_{CO2} is a CO_2 emission per every 1 MWh of produced net energy.

4. Conclusion

- The thermodynamic assessment of the combined cycle gas turbine (CCGT), the combined cycle power plant with the oxy – combustion (OXY) and the unit with the chemical absorption (ABS) indicated the lower gas turbine efficiency in the OXY case than in the other cases with the air - combustion, efficiency were equal to 0.3518 and 0.3873, respectively. However, the heat amount supplied to the heat recovery steam generator in the OXY case is higher than for the other units by about 28%, additionally the flue gas is characterized by the higher temperature, equal 642°C in OXY, related to 595°C in the remaining cases. As a consequence the steam cycle in the OXY case achieves electric power higher by 39.9 MW than the CCGT case, resulting in the gross efficiency of the OXY unit equal to 0.5998, which is the highest value among the analyzed cases. The CCGT unit reaches gross efficiency equal to 0.5813. The steam extraction used in the ABS case causes a drop in the steam cycle power by 25.6 MW in relation to the CCGT case and in consequence significant decrease in the gross efficiency to the level of 0.5316.

- The CCGT case has no additional installations and is affected only by minor own needs of gas turbine and steam turbine installations, thus, it achieves the highest net efficiency, amounting 0.5715. In the cases with CCS technology, apart from mentioned own needs, there are additional installations decreasing the net electric efficiency of those cases. The air separation unit in OXY case is characterized by a high own needs, amounting 32.5 MW. Additionally, in the OXY and ABS cases, the compression of the captured CO_2 increases the own needs of this cases by 11.6 MW and 8.9 MW, respectively. In OXY and ABS cases, due to the application of CCS technology, achieved net efficiency are lower than in the base case (CCGT) by 6.12 percent. points in OXY case, and by 6.78 percent. points in ABS case.
- The use of the less energy consuming air separation unit, e.g. membrane or hybrid (membrane - cryogenic) ASU in the oxy - combustion unit shall cause the net efficiency improvement for the unit. The less energy consumption sorbents and the new concepts to provide the heat to regenerate the sorbent are sought to increase the efficiency of the combined cycle power plant with the CCS installation in post - combustion technology.

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