Analysis of a gas system with a recirculation of the flue gases and carbon dioxide capture

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Abstract:

EU regulations in the field of climate policy imposes strict limits on the emission of pollutants such as NO_x, SO_2, dust and mercury. In addition, there are ongoing work on systems to CO_2 capture, which is considered a major cause of global warming on Earth. During gas combustion emits significantly less pollution and carbon dioxide which ifs their advantage. However, because of the limited CO_2 emission it is possible to introduce the uptake of said compound by chemical absorption, predisposed to be used for the coal-fired plants. Low concentrations of carbon dioxide in the exhaust gas can be increased by using exhaust gas recirculation system of a gas turbine, while reducing energy consumption during capture. In addition, the second topic discussed in the article relates to the use of hydrogen fuel for gas system. It has been shown that hydrogen admixture injection for natural gas affect considerable reduction emission carbon dioxide. This article presents the change in the operating parameters of the combined cycle with installation of CO_2 capture and exhaust gas recirculation. Built a mathematical model of the system using the code of Ebsilon Professional and performed parametric calculations. In the report, there was conducted an analysis of the dependence of the change of LHV of gaseous fuel which is a mixture of natural gas and hydrogen for proper work of the gas turbine installation. The article analyzed the effect of exhaust gas recirculation on indicators of the combined cycle and the opportunities of cooling the exhaust gas in order to reduce the energy consumption of the compressor of a gas turbine. Moreover in this work, shows chosen issues of adaptation of gas installations and usage of hydrogen as an alternative fuel for natural gas.

The built model and obtained results are useful in the analysis of combined cycle systems integrated with separation of carbon dioxide from the flue gas.

Keywords:

Gas turbine, exhaust gas recirculation, carbon dioxide concentration, carbon dioxide capture, CCS, hydrogen fuel, fuel mixture.

1. Introduction

There are many uncertainties related to the power engineering technology development. It takes a place not only because of the new and strict exploitation laws and influence of the production units on a natural environment. Also because of the disturbance in the safety of the supply of natural resources or overstating of the prices of their purchase, there is an increased risk related to the certain technology classes. Therefore, more and more often actions taken in order to diversify electrical energy production sources can be observed.

Decisions about strategies which have on their purpose introduction of so called energetical mix, are made not only by the energy companies guided by the economical profit but also because of the central policy of the state which tends to maintain constant electrical energy supply.

Predictably, there will be a growth of share of usage of gas turbines technologies in the polish electrical energy production sector. This prognosis is associated with the new requirements for power engineering technologies with relation to the energy market development, new emission targets and growth of importance of technologies with random production nature (mainly wind and solar energy). Autonomous gas turbine and gas-steam combined units are better than coal technologies in dealing with the increase of heat flexibility demands (defined as a dynamic change of load with the maintenance of stability of main modules of installation) and also improvement of efficiency and reliability.

From an ecological point of view, an important advantage of gaseous fuel is lower, in comparison with other fuels, carbon dioxide generation in the combustion process per unit of the chemical energy contained in the fuel. During the combustion of the carbon compound 0,112 kgCO_2/MJ is released, while during burning of the methane emission per unit equals 0,055 kg CO_2/MJ. After taking into account the additional difference between electrical energy production efficiencies for coal and gas technologies, it reveals a significant ecological vantage of gas technologies which distinguish by a much smaller emission. With currently achievable efficiencies of gas – steam combined cycles emission reaches 325 kgCO_2/MWh. Undeniable advantage of gas systems is also relatively low investment cost. Construction costs of described system is around 800-900 €/kWel.netto, which is lower than in case of build of units based on other technologies. Exemplary, construction costs of condensation steam power plant supplied by hard coal is around 1500 €/kWel.netto [1].

Rate of implementing of gas technologies to the power system and the political situation in the international arena which translates into fuel supply security lowers the high prices of natural gas. An alternative for a natural gas may be hydrogen, often called as a fuel of "future".

In case of further development of power engineering from renewable energy sources, balance of shortages of wind and solar energy has to be considered. That's why there is an idea to use the excess of energy from the wind to produce hydrogen. Energy stored in this way may be used in gas turbines to produce electricity. Another source of hydrogen are chemical plants e.g. refineries, which generate surplus of this gas, and because of that co-combustion of hydrogen with natural gas in gas turbines is proposed.

In Poland, in 2012, 3,9% of the electricity was produced from natural gas. High amount of planned investments indicative of not only the climate targets realization imposed by the EU directives but also is shown by the Polish Energy Policy up to 2030, which assume natural gas share in production of electrical energy at the level of 6,6%. It has to be noticed that Energy Market Agency [1] assume share of this fuel in the electricity production in 2030 at the level of 10%. [1, 2, 3].

The article shows chosen issues of adaptation of gas installations for carbon dioxide separation from flue gases and usage of hydrogen as an alternative fuel for natural gas

2. CO_2 emission reduction

Energy branch of the polish economy, because of the great share of coal in energy-mix, is characterized by an huge amount of environment pollution. EU regulations require reduction of the emissions of nitrogen oxides(NO_x), sulfur dioxide, dusts and what is more because of the alleged greenhouse effect, carbon dioxide. Because of this there are investments in methods which increase the efficiency of the energy generation from coal, technologies for CO_2 capture from flue gases, and construction of low emission units.

Directive 2009/28/WE which is commonly called "3x20 package" contains a obligation to increase energy efficiency by 20%, achieve of 20% share of renewable sources in overall energy consumption and reduction of greenhouse gases emission by 20% with comparison to the level from 1990. In order to fulfill given criteria, especially CO_2 emissions, under development are direct methods of reduction of carbon dioxide emissions by means of technologies of capture of this compound combined with its transport and storage (*Carbon Capture and Storage* – CCS).

One of the CO_2 emissions reduction method is usage of the chemical absorption technology (*post-combustion*). This process bases on the absorption of the carbon dioxide from the dust, NO_x and

SO_2 free flue gases stream, with a solution of the amines. It is highly energy-intensive process because of the necessity of CO_2-amines solution regeneration by usage of large heat flux. The average net electrical energy efficiency drop also for hard coal fired units equals 10%. High degree of energy intensity depends of the carbon dioxide concentration in the exhaust gases directed to absorber. Relationship, shown in the fig. 1, leads to the conclusion, that the greater share of CO_2 in exhaust gases the lower the energy consumption, and as an aftermath, smaller net efficiency drop in the system. Algorithm (1) shown in [5] allowed to determinate the minimal output energy of carbon dioxide from the flue gases of the simplified composition (CO_2, N_2) and assumed carbon dioxide capture efficiency Θ = 90% [4, 5, 6].

$$W_{min} = -\frac{RT_0}{\Theta}\left(\ln\left(\frac{1}{x_{CO_2}}\right) + \frac{\left(1-\Theta x_{CO_2}\right)}{x_{CO_2}}\ln\left(\frac{1}{\left(1-\Theta x_{CO_2}\right)}\right) + \left(1-\Theta\right)\ln\left(\left(1-\Theta\right)x_{CO_2}\right)\right) \tag{1}$$

Values shown at the chart (Fig. 1) are related to 1 kg of CO_2 and they are calculated with usage of the simplified model which takes into account the second law of thermodynamics, constant and reversible flow of the substance and what is more, negligible influence of the potential and kinetic energy. Current technology state allows to reach energy consumption at the level of 3,5 MJ/kg CO_2 with the CO_2 mass share at around of 21% [4, 5].

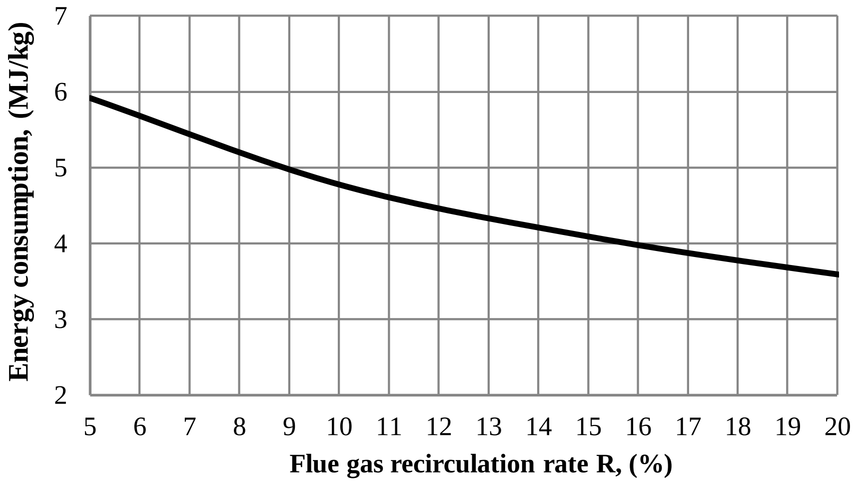

Fig. 1. Energy consumption of chemical absorption of 1 kg CO_2 in function of CO_2 concentration in flue gases.

3. Recirculation and cooling of the flue gases

When designing gas-steam system integrated with the carbon dioxide capture installation the ability of own needs reduction of the power unit should be analyzed. A significant part of the needs is related with the functioning of the CO_2 capture system and here the embodied energy may be reduced. Gas combustion installations are characterized by low mass share of CO_2 in the exhaust gases which shapes up at 6 ÷ 8% and this amount is three times lower than for carbon burning units. As it is shown in the Fig. 1 concentration of the carbon dioxide is meaningful if it goes about carbon capture installation energy usage and in order to obtain better indicators, CO_2 concentration has to be increased. It can be conducted with the usage of recirculation of the part of flue gases flux from the outlet of the waste heat boiler to the node where it is mixed with primary air before it goes to the compressor.

Stream of exhaust gases at the outlet of waste heat boiler has a temperature of 80 ÷ 100°C, and because of that it has to be cooled down before it is mixed with the primary air. High temperature of the flue gas-air mixture would cause increase of the power of gas turbine compressor and decrease of the efficiency of the system. To prevent this, flue gases cooling on the basis of water injection was used, thereby achieving a predetermined temperature of 30 °C. After that the stream of exhaust gases is directed to the dryer and divider, which is responsible for the degree of recirculation.

4. Description of the analyzed gas turbine

The object of the analysis is gas turbine system with the flue gases recirculation, which scheme was shown at fig. 2. Main purpose in paper is determine influence of flue gas recirculation in plant working. Mathematical model was created in EBSILON Professional [10] software. That allowed to determine the basic parameters and characteristics of considered installation including determination of electrical power as well as consumed energy indicator. Additionally, using EBSILON's software made possible to assess the impact of flue gas recirculation on individual components of the system.

What is more, in the report, there was conducted an analysis of the dependence of the change of Lower Heating Value of gaseous fuel which is a mixture of natural gas and hydrogen (with usage of varying degrees of hydrogen addition) for proper work of the gas turbine installation.

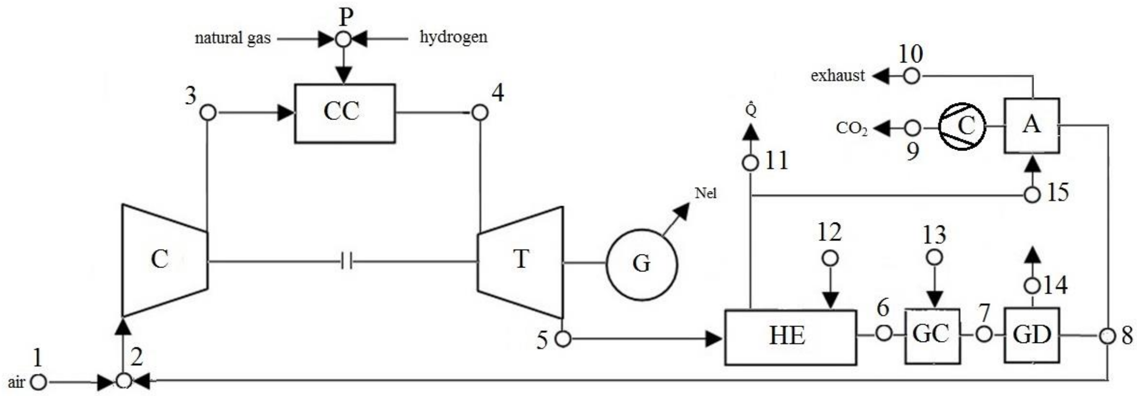

Fig. 2. Scheme of the analyzed gas turbine with exhaust gas recirculation (S – compressor, KS-combustion chamber, T – turbine, G – generator, KO – heat recovery steam generator, GC – exhaust gas cooler, GD – exhaust gas dryer, p – fuel preparation point, CC - CO_2 absorber, WC – heat exchanger, SPR - CO_2 compressor)

System, apart from the basic components such as compressor, combustion chamber and gas turbine comprise necessary elements for proper work of the flue gases recirculation and what is more heat exchanger which simulates heat recovery steam generator or heat distribution centre which is prevalent in heat and power plants.

Flue gases exiting boiler, of a temperature 70°C , are directed to the cooler that have two main functions. Firstly, it lowers the flue gases temperature to a required by CSS installation level in order to ensure the proper reaction between CO_2 and amine. Secondly, due to reduction of f.g. temperature and as a consequence change of specific volume of that medium, it allows to decrease the gas turbine unit's compressor energy consumption. Decrease of f.g. temperature is done by implementation of heat exchanger with water injection.

Cooled mixture of flue gas and water is directed to the dryer in order to separate water prior to delivery to the gas turbine's compressor. To separate water from the mixture the cyclone separators have been employed. Operation of such cyclone is based on the principle of mass forces(inertia and gravity). Use of recuperative non-direct heat exchangers is not recommended due to a significant heat transfer area in comparison to considerably small temperature difference of coolant and flue gases to be cooled. Temperature of cooled flue gases was estimated at the level of 30°C according to the analysis made in [7]. Stream of cooled flue gases is being separated and directed to the CCS installation in order to separate CO_2 and to the mixing node with the primary air before compressor.

Ratio of exchanged streams of flue gases is described by the recirculation rate R defined as a quotient of flue gases stream directed to the compressor ($\dot{m}_{gas\_R}$) to the total flue gases stream emitted by the gas turbine ($\dot{m}_{gas}$).

$$R = \frac{\dot{m}_{gas\_R}}{\dot{m}_{gas}} \times 100\% \tag{2}$$

Flue gases recirculation ratio R is the input value in described model. Whereas the flue gases stream directed to the CO_2 absorber $\dot{m}_{gas\_CCS}$ is the result value equal to:

$$\dot{m}_{gas\_CCS} = \dot{m}_{gas} - \dot{m}_{gas\_R} \tag{3}$$

Initially, for the preliminary calculation of mathematic model, R value was equal to 0% and $\dot{m}_{gas\_CCS}$ was directed completely to the chimney and then to the atmosphere, bypassing the CCS installation. Such set of input parameters is corresponding to the operation of combined cycle without flue gases recirculation and CCS installation.

In the subsequent simulations the influence of flue gases recirculation rate R (0%÷50%) as well as directing the whole stream of $\dot{m}_{gas\_CCS}$ to the CCS installation on the simple cycle operation parameters was determined. The base value for the simulations was constant fuel stream (methane, LHV~49,5 MJ/kg) of 1kg/s. Additionally all characteristic parameters of gas turbine unit like: compressor pressure ratio and temperature at the inlet of the gas turbine were adopted according to analysis done in [7].

Natural gas with high methane share of E type [8] is assumed as a primary fuel. It has a composition: methane CH_4 98%, ethane C_2H_6 1%, nitrogen N_2 1%, and its lower heating value is around 49,5 MJ/kg. Hydrogen H_2 was used as an alternative fuel, which was supplied within the range 0÷50% of the total fuel mass stream directed to the combustion chamber of the analyzed installation. Lower Heating Value of the hydrogen H_2 equals about 120 MJ/kg, so usage of hydrogen as a compound of the gas fuel leads to the increase of the Lower Heating Value of the mixture. New parameter X_{H2} which defines mass share of hydrogen inside the fuel supplied to the combustion chamber was implemented.

$$X_{H2} = \frac{\dot{m}_{H2}}{\dot{m}_{CH4} + \dot{m}_{H2}} \times 100\% \tag{4}$$

Basic assumptions to the calculations of combined cycle are presented in Table 1 below.

The major indicator of the efficiency of the work conditions of gas turbine assessment is net electrical energy produce efficiency $\eta_{el\,GT}$, which is described by equation:

$$N_{elGT} = \left(N_{iT} \times \eta_{mT} - \frac{N_{iC}}{\eta_{mC}}\right) \times \eta_G \tag{5}$$

$$\eta_{el\,GT} = \frac{N_{elGT}}{\dot{m}_f \times LHV} \tag{6}$$

$$\eta_{T\_GT} = \frac{N_{elGT} + \dot{Q}}{\dot{m}_f \times LHV} \tag{7}$$

where:
- N_{elGT} – net electrical power gas turbine,
- $\dot{m}_f$ – fuel stream,
- LHV – Lower Heating Value
- N_{iT} – gas turbine internal power,
- η_{mT} – gas turbine mechanical efficiency
- N_{iC} – compressor internal power,
- η_{mS} – compressor mechanical efficiency
- $\eta_{T\,GT}$ - total efficiency of gas system
- Q - heat flux in HE (useful)

Table1. Assumptions for calculations of combined cycle.

Parameter	**Quantity**
Fuel stream, $\dot{m}_f$ (X_{H2}=0%)	1 kg/s
Lower Heating Value of natural gas, LHV_{CH4}	49,49 MJ/kg
Lower Heating Value of hydrogen, $LHV_{\_H2}$	119,98 MJ/kg
Flue gas recirculation rate, R	0÷50%
Hydrogen inside the fuel share, X_{H2}	0÷50%
Steam stream to the CCS, ($\dot{m}_{15}$), $\dot{m}_{CCS}$	0÷31,92 kg
Flue gas cooling temperature in SS,	30°C
Temperature at discharge of combustion chamber,	1400°C
Pressure ratio in compressor, β	18
Isentropic efficiency of Gas Turbine, η_{iGT}	90%
Mechanical efficiency of Gas Turbine , η_{mGT}	99%
Isentropic efficiency of compressor, η_{iC}	88%
Mechanical efficiency of compressor, η_{mC}	99%
Generator efficiency, η_G	99%
Discharge pressure of gas turbine, p_5	1,16 bar
Compression pressure of CO_2, p_9	150 bar
Pressure losses of flue gas in boiler (HE),	0,01 bar
Flue gases temperature at the outlet of HE, t_6	70°C
Temperature of water injection at GC, t_{13}	12°C
Ambient temperature, t_1	15°C
Ambient pressure, p_1	1,15 bar

For above mentioned assumptions, from the mathematical model, characteristic work parameters of combined cycle was obtained (without flue gases recirculation X_R=0%, without CCS installation $\dot{m}_{CCS} = 0 kg/s$, when supplied by a natural gas X_{H2}=0%),

Table 2. Selected operating parameters of the gas turbine.

Parameter	**Value**
Electrical energy produce efficiency. $\eta_{el\ GT}$	39,38%
Total efficiency of gas turbine system, $\eta_{T\ GT}$	90,55%
Net electrical power GT, N_{elGT}	19,51 MW
Compressor mechanical power, N_{mC}	17,14 MW
Heat flux, $\dot{Q}_{11}$	26,84 MW
Flue gases stream, $\dot{m}_5$	40,01 kg/s
Flue gases temperature, t_5 (°C)	566°C
CO_2 share in the flue gases, X_{CO2}	6,84%

5. Influence of chosen parameters on the system work conditions

In order to most faithfully reproduce work of the actual gas system, sensitivity analysis was conducted due to change in the value of chosen input data to the model, particularly taking into account: flue gases recirculation degree, heat flux which supplies CCS and in another analysis change of the Lower Calorific Value caused by addition of the hydrogen.

5.1. Degree flue gases recirculation influence on gas turbine work

Model input variables and basic indicators of the system operation have been shown in the Table 3. First, specified column containing data shows figures for gas system (without flue gases recirculation, without CCS installation, supplied by natural gas).

Table 3.Chosen parameters of modeled gas system with flue gases recirculation.

Parametr	**Unit**			**Input data**			
R	%	0	0	12	25	38	50
X_{H2}	%	0	0	0	0	0	0
$\dot{m}_{CCS}$	kg/s	0	31,92	31,63	29,89	27,77	24,91
Parametr	**Unit**			**Output data**			
$\eta_{el\ GT}$	%	39,38	36,37	36,10	35,77	35,40	34,93
$\eta_{T\ GT}$	%	90,55	62,18	62,38	63,86	65,72	68,27
N_{elGT}	MW	19,51	19,51	19,37	19,21	19,02	18,79
Q	MW	26,84	12,78	13,02	13,91	15,01	16,51
N_{mC}	MW	17,14	17,14	17,19	17,21	17,16	16,98

During data analysis, it can be noticed, that CO_2 capture installation causes net electricity production efficiency decrease of 3,01 percentage points to the value of 36,37% (the decrease in total efficiency η_{T_GT} of 28,38 percentage points to the value of 62,18%). Given value of efficiency drop is lower than for coal fired units mainly because of the twice lower CO_2 particles generation per unit of chemical energy of fuel (0,055 CO_2/MJ). Simultaneously against gas system works nearly three times lower concentration of CO_2 in the flue gases.

On the basis of the data from Table 3, decrease in electrical power of the gas turbine and mechanical of the compressor can be observed. Changes of values of power can be explained by two phenomena. Firstly, the growth of share of recirculated flue gases causes the change of gas mass ratios (mainly N_2 and CO_2) directed to the gas turbine. Those gases have different values of the adiabatic exponent, and as an aftermath, in accordance to Poisson's law, which determines the adiabatic transformation, differences in expansion curves of gases of different quantity of particles are possible, therefore, differences in gas turbine work.

Secondly, along with the change of the R parameter there is also a change of the temperature of the gases directed to the compressor, which is a sum of an ambient and cooled flue gases temperatures with consideration of the magnitude of streams. The lowest temperature which is 15°C was obtained with R = 0%, while the highest, 23°C when R = 50%.

Additionally, different build of three, and diatomic molecules, along with the previously mentioned adiabatic exponent, contribute to obtain different flue gases temperatures behind the gas turbine. At the fig. 3 the flue gases temperature with dependence of the degree of recirculation R is shown.

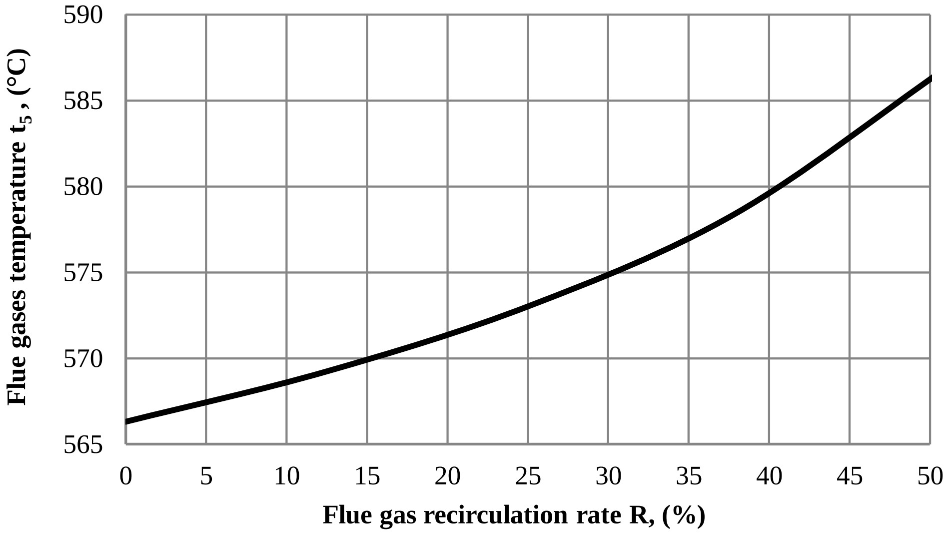

Fig. 3 Dependence between the gas turbine flue gases outlet temperature and their degree of recirculation.

Furthermore, it has been noticed that there is a dependence of mass share of CO_2 in the flue gases in function of the degree of recirculation what is shown at the fig. 4. Results of the conducted simulation are consistent with the information included at the introduction of the report. Usage of the recirculation of the half of the flue gases stream generated by combustion chamber contributes to the twofold increase of the CO_2 share in flue gases, finally reaching value $X_{CO2} = 14{,}93\%$ when R = 50%. Simultaneously on the basis of data shown at fig. 1, energy intensity decrease of CCS by nearly 30% is possible and what is more, it was implemented to the model coherent with the table 3.

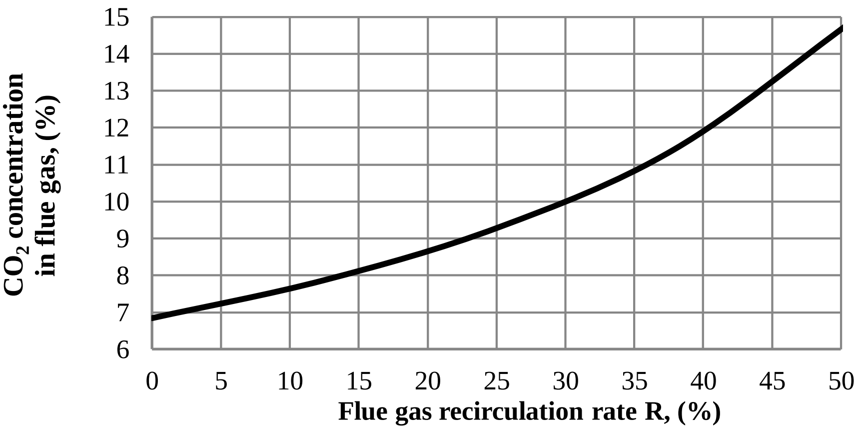

Fig. 4 Dependence between CO_2 concentration in flue gases and their degree of recirculation.

The major indicator of the gas turbine efficiency assessment is net electricity production efficiency. During analysis of the fig. 5 it can be noticed that usage of the flue gases recirculation (with CCS) at the degree of R = 50% leads to the about one and a half percentage point reduce of the efficiency. Drop of the efficiency $\eta_{el\,TG}$ results in net electrical power decrease by nearly 0,72 MW. In connection with the use of flue gases recirculation, we can observe increase of flue gases heat flux $\dot{Q}_5$ and their recirculation degree. For described case $\Delta\dot{Q}_5$ equals 3,73MW for R=50%.

Considering gas-steam combined cycles, it can be rightly assumed that partial decrease of obtained electrical power will be replaced by the electrical power from the steam cycle, thanks to the surplus heat provided by the flue gases to the waste heat boiler. In the Fig. 5 there are shown curves which illustrate the change of the electrical power and flue gases heat in the function of the recirculation degree.

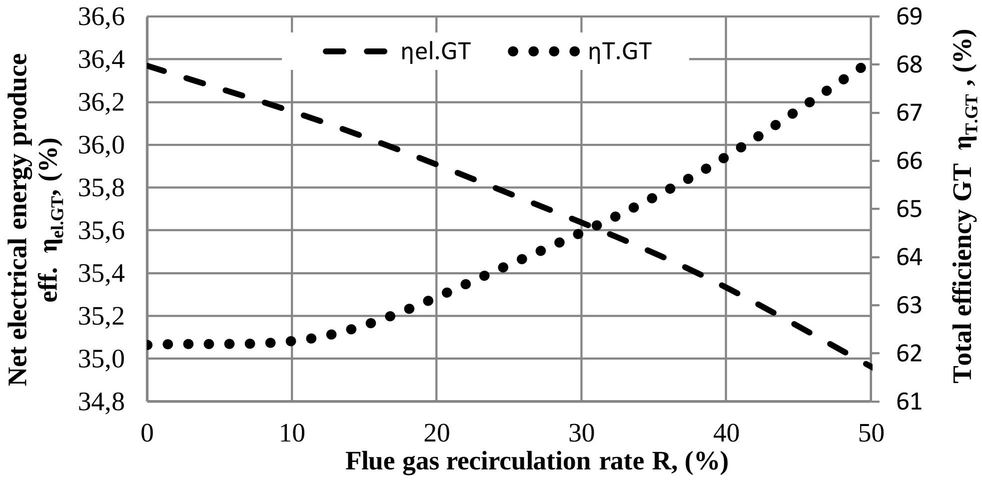

Fig. 5 Dependence between the net electrical energy efficiency production and heat flux compared to flue gases recirculation degree.

At the actual stage of work it is hard to say if described increase of the efficiency is adequate to make a decision about implementing of such solution to the commercially build installations. It has to be taken into account , that assumption made in the report, negatively affects obtained data.

Among others, assumed desorption energy demands in certain range are empirical values and in fact they can reach lower levels. Furthermore, researches of obtaining of synthetic amines are conducted. Those amines will be characterized by regeneration heat at the level of 1,3 MJ/kg CO_2 [9], and this value is two and the half times lower than the assumed in this report. (MEA – monoethanolamine , 3,5 MJ/kg CO_2).

Negative aspects of the analysis includes difficulties, which can occur during effective flue gases cooling to a relatively low temperature, which is needed not only to ensure faultless compressor work but also proper work of CCS installation.

In order to provide a clear decision on the use of flue gases recirculation additional should be made detailed analysis using the real object

5.2. Hydrogen fuel influence on gas turbine work

In today's world a large amount of research involve hydrogen fuel. It is very characteristic the fuel.

Hydrogen has the highest calorific value of liquid fuels and specific weight. Therefore, it is different from the other gaseous fuels for example methane. In the following part on the article to be analyzed influence on hydrogen fuel gas turbine work

The first part of the article concerned flue gases recirculation and increase CO_2 fraction in the flue gas. According to the equation (9) as a result the burning of hydrogen does not generate carbon dioxide. It is therefore not have to be used carbon capture and storage (without flue gases recirculation R=0%, without CCS installation m_{CCS}=0 kg/s).

According to the data shown in Tab. 4, mass fluxes of natural gas and hydrogen were controlled in the way which allowed reaching 19,51 MW of power at the generator terminals with the simultaneous keep of the hydrogen share X_{H2} in the fuel between 0÷50% level.

Basic parameter which describes gas turbine work is net electrical energy production efficiency η_{el_GT} which equals 39,38% % (total efficiency η_{T_GT} equal 93,57%) when is supplied by the fuel consisting of natural gas only (X_{H2}= 0%) which Lower Heating Value is 49,5 MJ/kg.

Table 4. Chosen parameters of modeled gas system powered by with natural gas and hydrogen.

Parametr	Unit	Input data					
$\dot{m}_{CH4}$	kg/s	1	0,76	0,63	0,51	0,39	0,29
$\dot{m}_{H2}$	kg/s	0	0,1	0,15	0,2	0,25	0,29
R	%	0	0	0	0	0	0
$\dot{m}_{CCS}$	kg/s	0	0	0	0	0	0
Parametr	**Unit**	**Output data**					
X_{H2}	%	0	12	20	28	39	50
$N_{el\ GT}$	MW	19,51	19,51	19,51	19,51	19,51	19,51
LHV	MJ/kg	49,5	57,7	63,0	69,3	77,1	84,7
$\eta_{el\ GT}$	%	39,38	39,45	39,48	39,52	39,55	39,58
η_{T_GT}	%	93,57	93,53	93,51	93,50	93,48	93,47
Q	MW	26,84	26,74	26,69	26,65	26,60	26,56
N_{mC}	MW	17,14	17,03	16,98	16,92	16,87	16,83
$\dot{m}_{air\_1}$	kg/s	39,01	38,71	38,56	38,42	38,27	38,15
λ	-	2,29	2,37	2,42	2,47	2,52	2,56
$\dot{m}_{gas\_4}$	kg/s	38,68	37,87	37,46	37,07	36,67	36,34
t_5	°C	566	566	566	566	566	566

According to the assumptions, there has been an analyze of modeled system sensitivity due to change of the Lower Heating Value of the fuel by the admixture of hydrogen within the range X_{H2}= 0÷50%. Fig. 6 shows the electricity production efficiency η_{el_GT} and total efficiency $\eta_{T\ GT}$ in function of hydrogen share in the fuel X_{H2}. Usage of the hydrogen addition at the level of X_{H2}= 50% results in $\Delta\eta_{el\_GT}$=0,2 percentage point growth of the efficiency ($\Delta\eta_{T\_GT}$= -0,1 percentage point) . Dependence between Lower Heating Value of fuel delivered to the combustion chamber and the hydrogen share in this fuel X_{H2} was shown in Tab. 4.

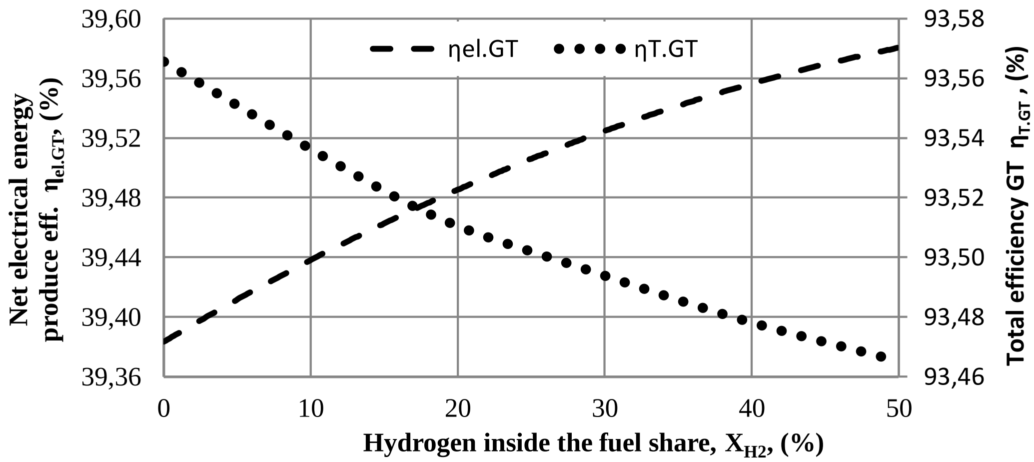

Fig. 6. Gas system electricity production efficiency η_{el_GT} and total efficiency η_{T_GT} relation to the hydrogen share X_{H2}.

Lower Heating Value of fuel mixture increased from the base 49,5 MJ/kg for X_{H2}=0% up to 84,7 MJ/kg for X_{H2}=50% with simultaneous decrease of the mass flux, what is necessary because of the need to maintain constant chemical energy of the fuel at the level of m_f*LHV=49,48 MJ/s supplied to the combustion chamber.

Flue gases temperature at the outlet of the combustion chamber t_4 is being maintained at the constant level of 1400°C due to air flow regulation at the inlet of the system. This flow is reduced because of the fuel stream level drop in order to provide proper conditions for stoichiometric combustion in the combustion chamber. As a consequence it leads to the mechanical power drop on the compressor shaft, and with maintenance of power at the level of 19,51 MW leads to the micro turbine electric efficiency increase.

Air–fuel equivalence ratio λ increases from 2,29 up to 2,56 due to change of the stoichiometry of combustion of different compounds of fuel used with maintenance of the similar flow of air supplied to the combustion chamber. According to the equation (11) to obtain the same amount of fuel chemical energy, 9,7 times more oxygen is needed when methane CH_4 is used, than for hydrogen H_2 usage.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{8}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{9}$$

$$2H_2 \rightarrow 240\frac{MJ}{kg} \leftarrow 4{,}85CH_4 \tag{10}$$

$$4{,}85CH_4 + 9{,}7O_2 \rightarrow 4{,}85CO_2 + 9{,}7H_2O \tag{11}$$

Obtained values of the flue gases flow $\dot{m}_{gas\_4}$ approve the correction of the mass balance for analyzed system as well as well-defined combustion process. This flow decreases as a consequence of regulation of fuel supplied to the combustion chamber. Calculated temperature of the flue gases at the outlet of expander t4 is at an constant level in accordance with the design assumptions. At the basis of the gas turbine work simulation and obtained results from the Tab. 2 it can be assumed that proper work of the gas turbine system which combusts the mixture of natural gas and hydrogen is possible. Hydrogen addition at the level up to 50% of the mass flow of fuel supplied doesn't have any negative effects on the system operation.

Usage of hydrogen as an addition to the fuel results in 69% decrease of carbon dioxide emission for X_{H2}=50% what is shown at the Fig. 7. Emissions of other compounds are on the unchanged level irrespectively of the amount of hydrogen delivered to the combustion chamber.

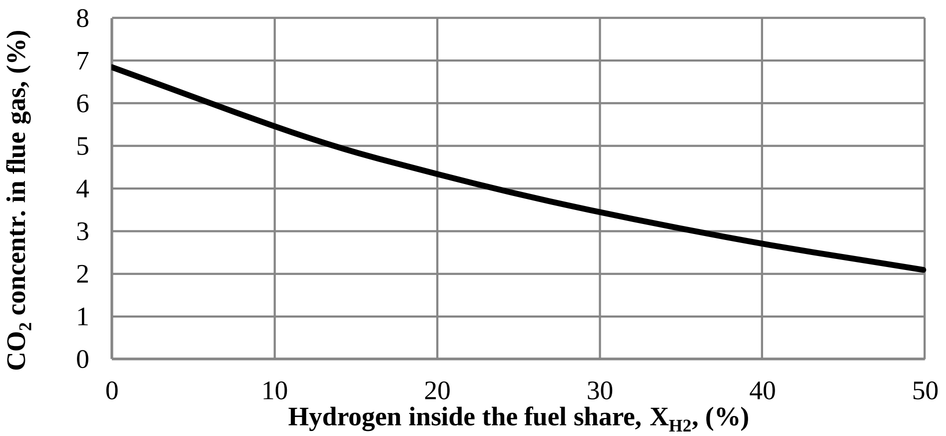

Fig. 7. Concentration of CO_2 in the flue gases in relation to the hydrogen share in fuel X_{H2}.

It is worth emphasizing, that mathematical model of the combustion chamber was not targeted at the generation of thermal nitrogen oxides at the beginning. Calorimetric temperature of hydrogen combustion is much higher than natural gas temperature, so as a result it is possible to reach higher NO_x concentration. However, usage of low emission burners in the gas turbines and recirculation in the combustion chamber allows to decrease the number of unexpected oxides in flue gases. Above mentioned problem has to be under consideration especially during modeling combustion of pure hydrogen, when NOx concentration may rise significantly, but for installations of low power level it is not the most important factor.

6. Conclusion

This article presents the change in the operating parameters of the combined cycle with installation of CO2 capture and exhaust gas recirculation. Built a mathematical model of the system using the code of Ebsilon Professional and performed parametric calculations.

The recirculated exhaust gas from the outlet of heat recovery boiler, after cooled and dried, are fed to the mixer with the primary air, and then to the compressor of the gas turbine. This is leads to increase a carbon dioxide concentration in the exhaust gas which is fed to the installation of CO2 capture. The consequently is a reduction in the demand for a heat to regeneration of the amine solution in the CO2 capture reactor.

In addition, the recirculated exhaust gas stream affects the temperature rise of the exhaust gas at the entrance to the exchanger and allows to produce more heat. These changes have affected in the increase in the efficiency. The main purpose of the article was to reduce the energy intensity the installation of CO_2 capture.The use of flue gas recirculation satisfy these target.

Additionally in this article presents data for hydrogen combustion in the combustion chamber of the gas turbine. It has been shown that hydrogen admixture injection for natural gas affect on small increase net electricity production efficiency.The main effect of the use of hydrogen is considerable reduction emission carbon dioxide

The built model and obtained results are useful in the analysis of gas system and combined cycle systems integrated with separation of carbon dioxide from the flue gas. Also for analysis, which describe an algorithm hydrogen combustion in gas turbine

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