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Research and development of a high-performance oxy-fuel combustion power cycle with coal gasification

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Abstract Recent climate changes stimulate the search and introduction of solutions for the reduction of the anthropogenic effect upon the environment. Transition to the oxy-fuel combustion power cycles is an advanced method of CO₂ emission reduction. In these energy units, the main fuel is natural gas but the cycles may also work on syngas produced by the solid fuel gasification process. This paper discloses a new highly efficient oxy-fuel combustion power cycle with coal gasification, which utilizes the syngas heat in two additional nitrogen gas turbine units. The cycle mathematics simulation and optimization result with the energy unit net efficiency of 40.43%. Parametric studies of the cycle show influence of the parameters upon the energy unit net efficiency. Change of the cycle fuel from natural gas to coal is followed by a nearly twice increase of the carbon dioxide emission from 4.63 to 9.92 gmCO₂/kWh.

Keywords: Carbon dioxide; Oxy-fuel combustion; Gasification; Energy efficiency; Thermodynamic analysis

Abbreviations

ASU – air separation unit
IGCC – integrated gasification combined cycle

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1 Introduction

Global warming mostly caused by the increase of carbon dioxide (CO_2) atmospheric content is a first range challenge. During the last decade, the mean annual CO_2 increase is 2.5 ppm, which may be related to the anthropogenic effect upon climate [1, 2]. The power industry produces about 25% of the anthropogenic greenhouse gas emissions [3, 4]. The transition to the heat and power production oxy-fuel combustion power cycles may remarkably reduce the carbon dioxide emissions [5–7].

The efficiency and capital investment are the aspects that make the oxy-fuel Allam cycle [8, 9] so attractive. The cycle is a semi-closed Brayton regenerative cycle where the operating fluid is the carbon dioxide and water vapor mixture. The turbine inlet temperature and inlet pressure are 1000–1200°C and 20–40 MPa. The turbine exhaust and the hot air flow from the air separation unit (ASU) provide the combustion chamber inlet flow regenerative heating which allows the net efficiency of 50% at the natural gas operation [8]. The supercritical CO_2 working fluid provides the facility compact structure and highly efficient capture and storage of the CO_2 produced by the fuel combustion.

Numerous papers describe the Allam cycle thermodynamic analysis. In the paper [10] the natural gas-fired Allam cycle has 54.8% efficiency at the initial temperature and pressure of 1123°C and 283.62 bar and the turbine outlet pressure 47.15 bar. Paper [11] also discloses the cycle thermodynamic parameters optimization and the result is the cycle maximal efficiency 56.5% at the initial pressure and temperature 30 MPa and 1083°C and the turbine outlet pressure of 3 MPa. Such a high power production efficiency is due to the simulation conditions of the multi-flow regenerator, which is a key element of the cycle. Also the ASU model remarkably influences the assessments of oxy-fuel combustion power cycle efficiency.

The world coal resources are three times larger than the natural gas ones [12, 13], therefore, the studies of solid fuel Allam cycle are going on. The gas turbine operation on supercritical carbon dioxide requires gasification technologies which usually remarkably reduces the power plant thermal efficiency. Paper [14] compares the Allam cycle with coal gasification and use of the syngas sensible heat in the additional steam turbine cycle with integrated gasification combined cycle (IGCC). The Allam cycle net efficiency is 39.6%, which is a little lower than the 40% net efficiency value of the IGCC without CO_2 capturing. But the nearly complete carbon capture is the Allam cycle advantage against the IGCC. Papers [15, 16] disclose

the efficiency of the Brayton cycle with supercritical CO₂ which uses the sensible heat of syngas in the Rankine steam cycle. This cycle with 98.1% CO₂ capture has 40.6% net efficiency. The IGCC based on the same gasifier captures about 90% of CO₂ and has 31.2% net efficiency. Thus, the transition to oxy-fuel combustion power cycles is reasonable from the points of view of efficient power production and environmental safety. Papers [17,18] propose the Allam cycle with coal gasification where the syngas sensible heat is used for power production in an additional carbon dioxide back-pressure turbine, and the turbine exhaust gas is supplied to a multi-flow regenerator. This technical solution allows the cycle net efficiency of 43.7% at the carbon dioxide turbine inlet temperature 1200°C.

It is possible to notice the main problems concerned with the studies of the Allam cycle with gasification. The transition from gas fuel to coal is followed by a remarkable efficiency reduction of about 8–12%. This problem may be solved by the integration of an efficient coal gasifier into a supercritical CO₂ cycle because the syngas has a high potential heat at the outlet of a gasifier.

This investigation aim is the improvement of efficiency and environmental performance of the coal-fired oxy-fuel combustion power cycles. The investigation includes an analysis of the oxy-fuel combustion power cycle losses. The new proposed cycle with coal gasification utilizes the syngas sensible heat in additional nitrogen gas turbines. Besides, there is research on the effect of gasification steam temperature and the first gas turbine pressure on the cycle thermal efficiency in the parametric study.

2 Research object

Figure 1 shows the heat flow chart of the Allam cycle with coal gasification. The cycle operation principle is the following. Gasification block is supplied with coal and gasification agents, oxygen and steam. In the block the solid fuel is transformed to the gaseous one and the gas is cleaned from its solid impurity. Then the syngas passes preliminary preparation system which connects the gasification block to the Allam cycle. Then the fuel is compressed in the fuel compressor and enters the combustion chamber.

In the combustion chamber, the syngas is fired in nearly pure oxygen. The oxygen is produced in ASU and compressed upstream the combustor by compressor and pump. After the combustion chamber, the working fluid enters the carbon dioxide turbine, where it makes its useful work that is

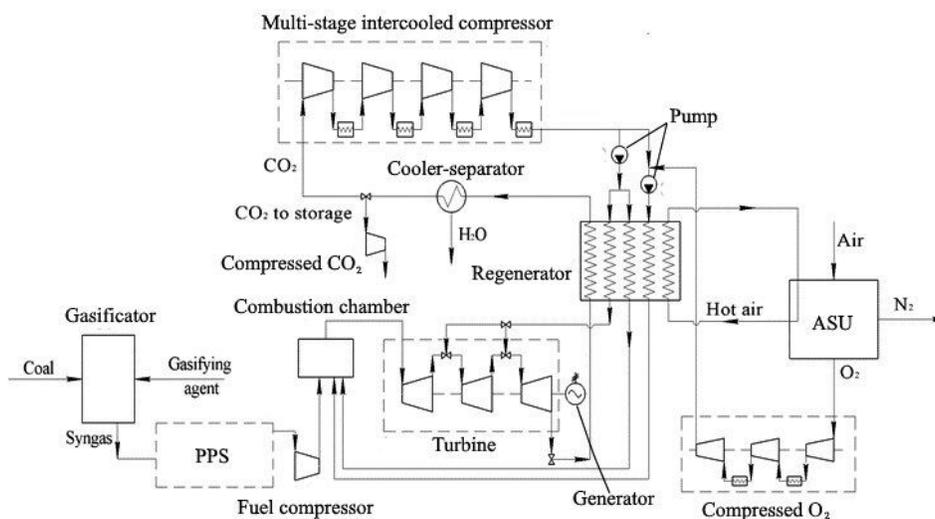


Figure 1: Flowchart of the Allam cycle with coal gasification.

used for the power generator. Then the gas enters the multi-flow regenerator where it heats the CO_2 , the coolant flows and the CO_2/O_2 mixture flow. Also, the regenerator utilizes the low-potential heat of the ASU air accumulated in the air compression. After the multi-flow regenerator, its exhaust gas enters the cooler-separator, where the water vapor is condensed. Then the CO_2 flow is split into two parts, the main part goes to the multi-stage intercooled compressor and the other part produced by the fuel combustion is compressed in the compressor and is then sent to storage. After the multi-stage intercooled compressor the CO_2 flow is again split into two parts, one part is mixed with oxygen. After pump, the main CO_2 flow is again split. The smaller part is the gas turbine coolant and is heated up to $100\text{--}400^\circ\text{C}$ in the multi-flow regenerator. The main CO_2 flow also is heated in the multi-flow regenerator together with the CO_2 and O_2 mixture up to the maximal temperature determined by the regenerator temperature difference. The hot flows leave the multi-flow regenerator, enter the combustion chamber and reduce the fuel consumption needed for the working fluid heating up to $1000\text{--}1500^\circ\text{C}$. The cycle is thus closed.

Table 1 presents the fuel composition assumed according to [19]. The input data for the cycle arrangement analysis are given in Table 2. The initial temperature and the carbon dioxide turbine inlet and outlet pressures are similar to the optimal values [11] calculated for the gas-fired cycle. Equal pa-

parameter values allow correct comparison of the oxy-fuel combustion power cycles operating different fuels. The syngas is fired in the 95.6% pure oxygen produced in the cryogenic low-pressure ASU.

Table 1: Coal composition.

Parameter	Value
Moisture, %	8.10
Ash, %	14.19
Carbon, %	72.04
Hydrogen, %	4.08
Nitrogen, %	1.67
Oxygen, %	7.36
Sulphur, %	0.65
Chlorine, %	0.01
Volatile matter, %	28.51

Table 2: Input data for modeling.

Parameter	Value
Atmospheric pressure, MPa	0.1
Atmospheric temperature, °C	15
Syngas pressure, MPa	4
Turbine inlet temperature, °C	1083
Turbine inlet pressure, MPa	30
Turbine outlet pressure, MPa	3
Turbine coolant temperature, °C	200
CO ₂ compressor massflow, kg/s	600
Gas turbine and compressors isentropic efficiency, %	90
Pumps isentropic efficiency, %	75
Multi-flow regenerator pinch-point temperature difference, °C	5
Turbine, power generator, compressors mechanical efficiency, %	99
Pumps mechanical efficiency, %	95
Power generator and electric motor efficiency, %	99
Cooler-separator exit working fluid temperature, °C	55
Working fluid temperature at the compressor inter-cooler outlet, °C	30
Oxygen purity, %	95.6

3 Modeling approach

Thermodynamic studies of oxy-fuel combustion power cycles are carried out with AspenONE code. The facility simulation model consists of three sub-models, Allam cycle, air separation unit, and gasification block (Fig. 2). Input data for studies of the steam-oxygen blow gasification unit are the following: coal parameters, ASU output oxygen parameters, water from Allam cycle parameters. The output syngas parameters are calculated by the methods disclosed in [19]. The flow with syngas parameters and the ASU output oxygen flow are used in the Allam cycle model. The power produced in the Allam cycle is partly spent for the separation process in ASU. The air parameters were also used to calculate the ASU model according to the method presented in [20].

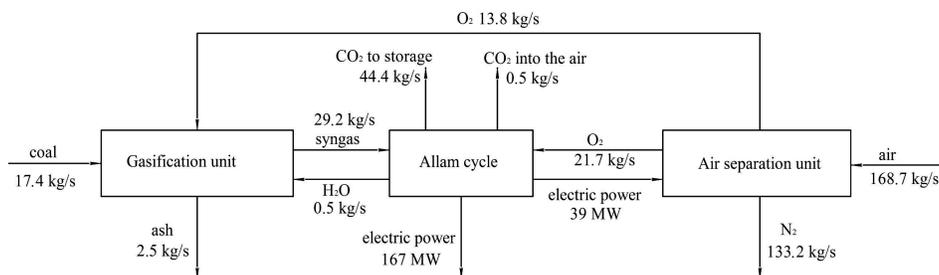


Figure 2: Scheme of energy and material flows of the oxy-fuel combustion power cycle with gasification.

Figure 3 presents the Allam cycle simulation flowchart modeled in AspenONE code. Analysis of the carbon dioxide compressor and turbine is based on the isentropic expansion with the following input data: pressure/expansion ratio, mechanical and internal turbo-machine efficiency.

The combustion chamber model is a stoichiometric reactor with the input data: fuel, working fluid and oxygen massflow values. The heat losses are not considered, therefore, the combustion chamber efficiency is equal to 100%.

The coolant massflow and its distribution to the cooled turbine parts are calculated by the method [21].

The multi-flow regenerator model involves the following assumptions: the pinch-point temperature difference above 5°C, flows of CO₂ and CO₂/O₂ mixture at the regenerator output have equal temperatures, gas turbine cooling flow temperature 200°C, air temperature at the regenerator output above 30°C.

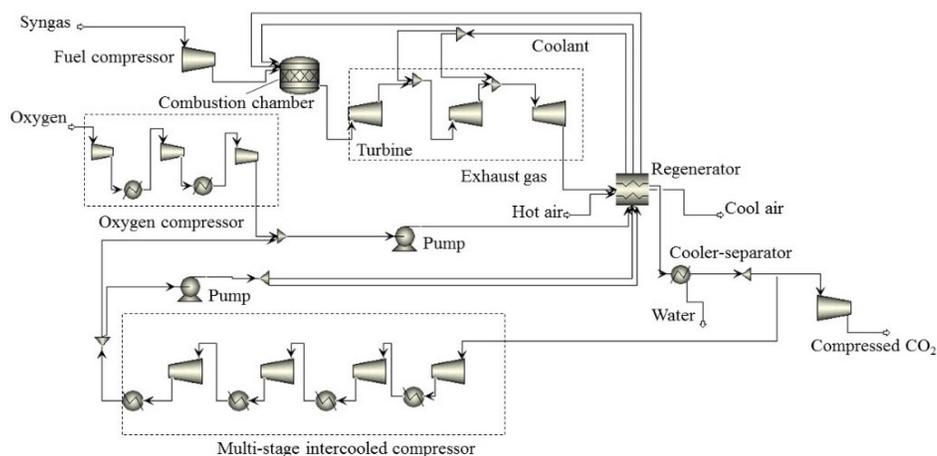


Figure 3: Simulation flowchart of the Allam cycle working on syngas.

4 Modeling results

The beginning investigation stage was the cycle arrangements analysis of the oxy-fuel combustion power cycles with coal gasification to assess their efficiency and determine directions for the efficiency improvement.

The first cycle arrangement version uses the cooler for integration of gasification unit with Allam cycle. The cooler cools syngas before the fuel compressor, after which gas enters the cycle combustion chamber (Fig. 4a). Downstream the gasification unit the gas temperature and pressure are 1000°C and 4 MPa, therefore, the gas cooling before compression reduces the compressor power. This cycle arrangement disadvantage is the losses in the cycle cold sources.

The second cycle arrangement version involves the useful utilization of syngas sensible heat before its compression in the fuel compressor (Fig. 4b). After the gasification unit, the syngas releases its heat in the surface heat exchangers of additional nitrogen gas turbines, which allows the production of additional electric power. The nitrogen for additional gas turbines is the result of air separation in ASU. The first gas turbine has an inlet temperature of 750°C , which allows its non-cooled type. The gas turbine has a pressure ratio of 20, which is typical for powerful gas turbine units. The second gas turbine's main function is not the power production but the syngas cooling because the syngas temperature after the first heat exchanger is remarkably high due to the high nitrogen temperature after

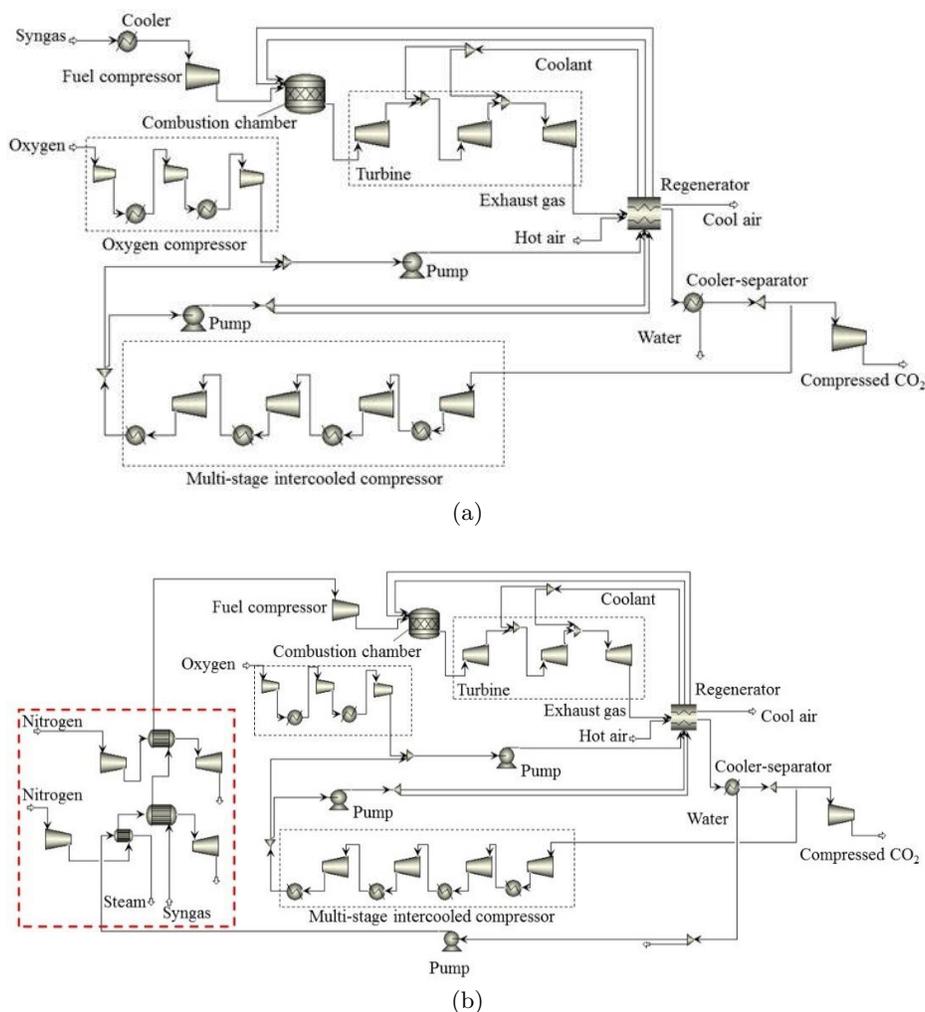


Figure 4: Cycle arrangements of oxy-fuel combustion power cycle with coal gasification: (a) utilization of the syngas heat in the cooler, (b) utilization of the syngas heat in the heat exchangers of nitrogen gas turbine units.

the first compressor. Besides, this cycle arrangement includes the heat exchanger that produces steam for the coal gasification using heating water from the Allam cycle after the cooler-separator. Table 3 presents the input data for modeling additional gas turbine units running on nitrogen.

Results of the cycle arrangement analysis allow calculation of the heat balance of the cycle with syngas heat utilization in the cooler (Fig. 5a) and

Table 3: Input data for modeling additional gas turbine units running on nitrogen.

Parameter	Value
Pinch-point temperature difference in the nitrogen-water heat exchanger, °C	5
First syngas compressor pressure ratio	6
Second syngas compressor pressure ratio	1.75
Nitrogen temperature at the inlet of the first gas turbine, °C	650
Nitrogen temperature at the inlet of the second gas turbine, °C	250
Nitrogen massflow at the inlet of the first gas turbine, kg/s	69.1
Nitrogen massflow at the inlet of the second gas turbine unit, kg/s	35.3
Turbines outlet pressure, MPa	0.1

in additional nitrogen gas turbines (Fig. 5b). The results show the energy losses and the possibility to improve efficiency by the additional nitrogen gas turbines that utilize the syngas heat. The additional losses include electric motors and power generators, oxygen compressor cooler, carbon dioxide storage losses, and water losses downstream of the cooler-separator. Large parts of losses are the 35% losses in the multi-stage intercooled compressor intermediate coolers and the 11% losses with the syngas cooling upstream the fuel compressor (Fig. 5a). When the syngas heat is utilized for the addi-

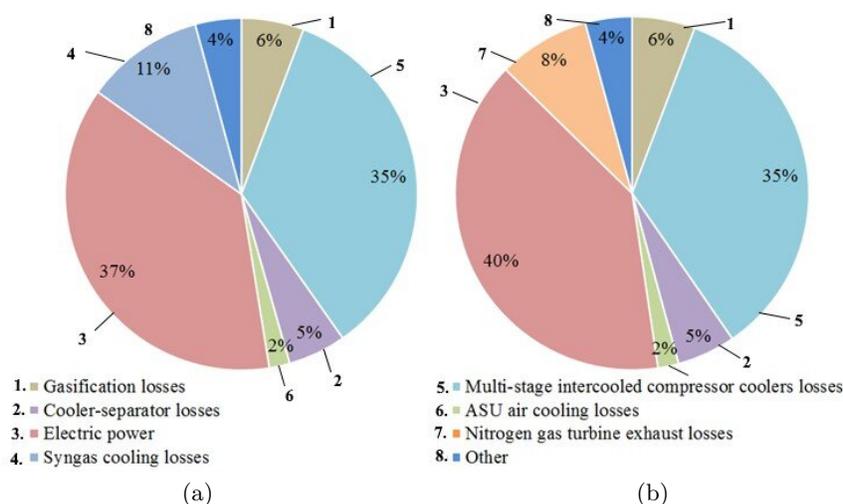


Figure 5: Heat balances of oxy-fuel combustion power cycles with coal gasification: (a) utilization of the syngas heat in the cooler; (b) utilization of the syngas heat in the heat exchangers of nitrogen gas turbine units.

tional power production its cooling losses drop down to 8%. The additional gas turbine units increase the facility efficiency by 3% (Fig. 5b).

The nearly zero carbon dioxide emissions are an important feature of the oxy-fuel combustion power cycles, almost 99% of the CO₂ formed in combustion is stored. The cycle transition to coal fuel increases this emission because coal has a lower heating value and thus the fuel consumption is higher. There was evaluated the CO₂ emission of the syngas-fired cycle in this work (Fig. 6). The emissions were compared with the natural gas-fired cycle described in [11].

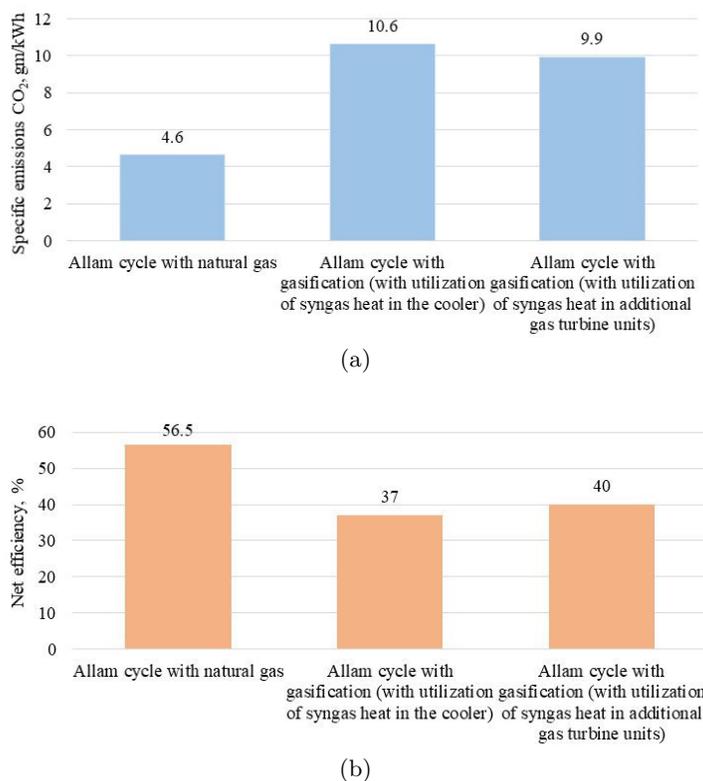


Figure 6: Comparison of oxy-fuel combustion power cycles' parameters with different types of fuel: (a) specific CO₂ emissions of oxy-fuel combustion power cycles, (b) net efficiency of oxy-fuel combustion power cycles.

The analysis results in Fig. 6a show that the fuel change from natural gas to coal increases the CO₂ emission almost twice which is mostly concerned with the cycle net efficiency reduction (Fig. 6b) caused by the coal gasifica-

tion losses. In the cycle arrangement with syngas sensible heat utilization in the cooler, the emission is $10.63 \text{ gmCO}_2/\text{kWh}$. When the syngas sensible heat is utilized in additional nitrogen gas turbine units the CO_2 emission is $9.92 \text{ gmCO}_2/\text{kWh}$ which may be explained by the higher electricity production at the same CO_2 storage losses, the amounts of fuel consumption in both versions are equal. It is worth mentioning that although the gasification oxy-fuel combustion power cycle CO_2 emission is higher it is still remarkably lower than the $400 \text{ gmCO}_2/\text{kWh}$ emission in the combined cycle power plants without CO_2 capture.

Analysis of the two cycles' arrangements (Fig. 5) makes the base for the further improvement of the coal-fired cycle net efficiency. The improvement is investigated in the cycle with syngas sensible heat utilization in two additional gas turbine units. The steam-oxygen coal gasification for its efficient functioning needs high parameters steam. Nowadays are not yet available data on the influence of the gasification steam temperature upon the facility efficiency.

Below is described the influence of steam temperature at the steam-oxygen gasifier inlet upon the efficiency of the oxy-fuel combustion power cycle with two additional gas turbines. The study is carried out for the $300\text{--}400^\circ\text{C}$ steam temperature range because this temperature may be provided by the nitrogen flow compressed in the first compressor up to 2 MPa pressure with 419°C temperature. Figure 7 shows the dependence of the efficiency of the oxy-fuel combustion power cycle with the gasifier inlet steam temperature. The cycle net efficiency increase from 39.922% to 39.929% results from the temperature increase from 300°C to 400°C , which is caused by a small reduction of fuel consumption. This shows that the steam temperature change does not remarkably improve the efficiency and the change is within the calculation accuracy.

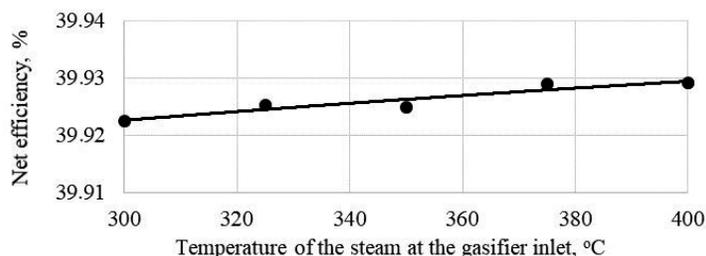


Figure 7: Dependence of the efficiency of the oxy-fuel combustion power cycle with gasification on the temperature of the steam at the gasifier inlet.

The further cycle efficiency study is devoted to the additional nitrogen gas turbine parameters optimization. The first gas turbine inlet temperature of 750°C was fixed and the compressor pressure ratio was variable. The compressor outlet nitrogen temperature must be above 305°C , which allows steam heating at the gasifier inlet. Fig. 8 shows the oxy-fuel combustion power cycle efficiency on the first additional gas turbine unit compressor outlet pressure. The minimal pressure value to keep the nitrogen temperature above 305°C is 0.87 MPa. This pressure also provides the maximal cycle net efficiency of 40.43%. Thus, the result of the first gas turbine pressure optimization is increasing the net efficiency by 0.5%.

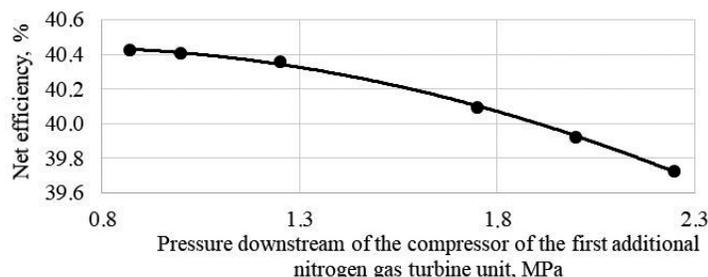


Figure 8: Dependence of the net efficiency of the oxy-fuel combustion power cycle with gasification on the pressure downstream of the first additional nitrogen gas turbine unit compressor.

5 Conclusions

The cycle arrangement of the oxy-fuel combustion power cycle with coal gasification and utilization of the syngas heat in two additional nitrogen gas turbines is developed. This cycle's maximal net efficiency is 40.43%.

The transition from natural gas to coal fuel of oxy-fuel combustion power cycle increases the carbon dioxide emissions from 4–5 to 9–10 gmCO_2/kWh . Although the coal gasification cycle emissions are high they are still lower than the 400 gmCO_2/kWh that is typical for a combined cycle power plant.

The gasification steam temperature increase from 300°C to 400°C increases the facility net efficiency from 39.922% to 39.929% which difference is within the analysis accuracy.

The nitrogen gas turbine pressure reduction from 2.25 to 0.87 MPa increases the oxy-fuel combustion power cycle net efficiency from 39.72% to 40.43%.

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