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Research on oxy-fuel combustion power cycle using nitrogen for turbine cooling

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Abstract One of the problems in Russia Power Sector strategy until 2035 is the technologies development for mitigation of harmful emissions by the heat and power production industry. This goal may be reached by the transition to environmentally friendly generation units such as oxy-fuel combustion power cycles that burn organic fuels in pure oxygen. This paper provides the results of research on one of the most efficient oxy-fuel combustion power cycle, which was modified by the usage of nitrogen for turbine cooling. The computer simulation and parametric optimization approaches are described in detail. The net efficiency of the oxy-fuel combustion power cycle in relationship to the carbon dioxide turbine exhaust pressure is shown. Moreover, the influence of the regenerator scheme and modeling parameters on heat performance is obtained. Particularly, it was found that the transition to a scheme with five two-threaded heat exchangers decrease cycle efficiency by 4.2% compare to a scheme with a multi-stream regenerator.

Keywords: Carbon dioxide; Thermodynamic analysis; Parametric optimization; Multi-stream regenerator; Gas turbine

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1 Introduction

The world's energy consumption is rising over the past 50 years due to population growth and the increasing industrialization of countries in the third tier. The emerging trend has predetermined several serious environmental consequences, among which is global warming. With a high probability, a rising concentration of carbon dioxide in the atmosphere is the main reason for the observed process.

The results of the continuous measurements of the carbon dioxide concentration in the atmosphere indicate a continuous increase in the period from 1958 to 2017: from 318 to 403 ppm [1]. Such a significant change in a relatively short period could not be due to natural causes only. The concern of the world community about global climate change has contributed to the creation of several international agreements that oblige developed countries and countries in transition to stabilize or reduce greenhouse gas emissions. In particular, in 1997 the Kyoto Protocol was adopted, and in 2015 – the Paris Agreement.

About three-quarters of the anthropogenic CO_2 emissions are the result of oil, natural gas, and coal production and combustion [2]. About 25% of global emissions are produced by power plants [3]. In the US, the contribution of the energy industry to the overall structure of anthropogenic CO_2 emissions is 35%, in China – 6%, in Europe – 31%, in Russia – 33% [4, 5]. The reason for such a significant energy industry contribution in the overall structure of carbon dioxide emissions is the prevalence of generating power plants operating by the typical Rankine and Brayton-Rankine cycles, with the heat supply due to the combustion of a hydrocarbon in the air.

The problem of carbon dioxide precipitation in thermal power plants may be solved by the introduction of oxy-fuel combustion power cycles [6–9]. These technologies differ from traditional cycles by the oxy-fuel combustion and the multi-component working fluid that mostly consists of carbon dioxide and water vapor. This provides the possibility of water component thermodynamic capture by condensing in a cooler.

The Allam cycle is a widely known oxy-fuel version [10]. Its key advantages are high-power production efficiency and compact equipment. According to the developers, the Allam cycle has the natural gas firing net efficiency up to 58.9%, the specific installed power cost 800–1000 $/kW. The coal firing facility has the net efficiency and installed power cost equal to 51.4% and 1500–1800 $/kW, respectively and the carbon dioxide capture degree nearly 100%.

The Allam cycle thermodynamic analysis is disclosed in numerous papers [11–15] but a lot of problems concerned with its parametric optimization are still not clear. Many papers consider the multi-flow regenerator as a single heat exchanger which overestimates the cycle thermodynamic efficiency. Hence, it is reasonable to build a reasonable scheme for the multi-flow heat exchanger and evaluate its influence upon power production efficiency. Moreover, the available papers don't disclose the influence of the wide range of turbine exhaust temperatures upon the cycle efficiency. This parameter also influences the gas turbine dimensions so its optimization is an important task.

It is worth mentioning that many works consider the useful heat utilization in the regenerative heat exchanger. This specific feature remarkable determines the high efficiency of this technology. On the other side, the useful application of the compressed nitrogen that is the air separation unit (ASU) secondary product is not yet described.

This paper contains the results of structure and parameters' optimization of the Allam cycle for efficiency improvement.

2 Research object

The gas firing Allam cycle flow chart shown in Fig. 1 is similar to the chart presented in [11]. The gas fuel compressor *1* supplies fuel to the combustor *2* where is also supplied the high purity oxygen produced in the air separation unit *9* and compressed up to the proper pressure by the oxygen compressor *10*. The oxy-fuel mixture burns in the combustor *2* and then the high-temperature flow enters turbine *3*, expands and drives the turbine and the electric generator *4*. The exhaust gas flow enters the multi-stream high-temperature regenerator *11*, where it transfers its heat to the following three flows:

- oxygen and carbon dioxide mixture traveling to the combustor *2*,
- carbon dioxide recirculation flow upstream the combustor *2* to control the maximal temperature,
- carbon dioxide flow to the turbine *3* cooling.

The regenerator *11* also transfers the low potential heat of the compressed hot air from the air separation unit *9*. After the regenerator *11*, the cooled exhaust gas enters the condenser *12* where the two-component mixture is

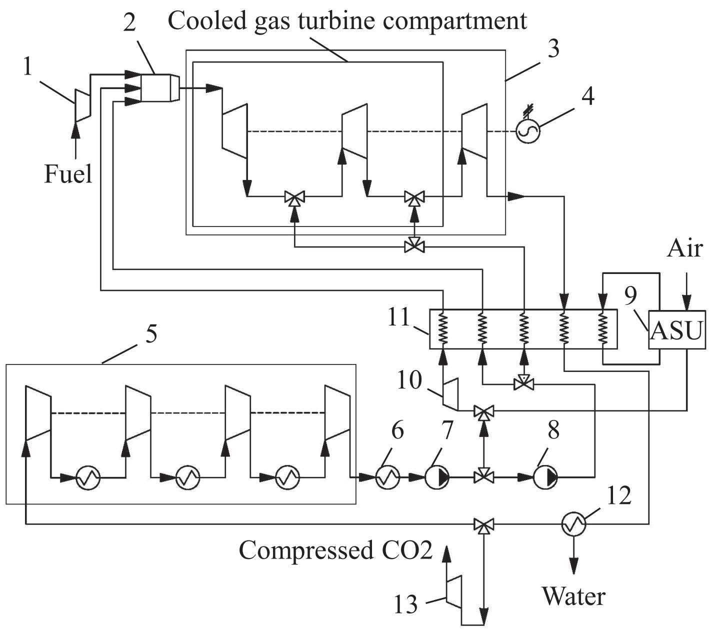

Figure 1: Scheme of the NetPower cycle.

cooled, water is condensed and removed from the cycle flow. After the condenser *12*, the mixture enriched with carbon dioxide enters the multi-stage intercooled compressor *5*. Upstream the compressor *5* some fluid is taken to the carbon dioxide compressor *13* for its further storage. Downstream compressor *5* the flow enters cooler *6* and then the first stage pump *7*. Apart of the fluid flow is mixed with oxygen on its way to the oxygen compressor *10* and the other part travels to the second stage pump *8*. After the final compression, the flow is split into two parts, one part goes to the combustor and another part is supplied to the turbine cooling. Thus, the cycle is closed.

3 Modeling approach

The commercial AspenONE code [16] was used for the Allam cycle parametric optimization. The NIST REFPROP database [17] was used for the calculation of thermophysical parameters of the multi-component working fluid.

The fuel was a pure methane at temperature 15 °C and 0.7 MPa pressure. The oxidizer was pure oxygen with the power consumption for its production of 900 kWs/kg [18,19]. The carbon dioxide storage pressure and temperature were assumed as 100 MPa and −28 °C, respectively [20,21]. Table 1 summarizes the heat flow chart simulation input data.

Table 1: Input data for modeling.

Parameter	Unit	Value
Atmospheric temperature	°C	15
Fuel temperature	°C	15
Fuel pressure	MPa	0.7
Fuel net calorific value	kJ/kg	50025
O_2 temperature	°C	30
O_2 pressure	MPa	1
Power consumption for O_2 production	kWs/kg	900
Compressed air temperature (the flow from the ASU to regenerator)	°C	280
Compressed air temperature (the flow from the regenerator to ASU)	°C	100
Compressed air pressure	MPa	1.2
CO_2 storage pressure	MPa	10
Minimal cycle temperature	°C	40
Gas turbine inlet pressure	MPa	30
Gas turbine efficiency	%	90
Gas turbine coolant temperature	°C	200
Minimal temperature difference at the pinch point of the regenerator	°C	5
Compressor efficiency	%	90
Power generator efficiency	%	98.5
Mechanical efficiency	%	99

Calculation of the carbon dioxide compressor and turbine involved the isentropic expansion method with the following input data: turbomachine pressure / expansion ratio, turbomachine mechanical, and internal efficiencies.

The combustor model was a stoichiometric reactor with the following input data: fuel, working fluid, and oxygen mass flows. The heat losses for the combustion chamber were not considered and the combustion efficiency was assumed equal to 100%.

The considered method for calculation of gas turbine cooling losses is described in [22]. The analysis assumed seven turbine stages with four of them cooled. The heat drop distribution along the stages is taken as uniform. The turbine flow path efficiency drops due to mixing the coolant and working fluid was evaluated by the method described in [23].

4 Modeling results

4.1 Influence of the multi-stream regenerator scheme on cycle net efficiency

The simulation scheme, parameters, and conditions influence the amount of utilized heat and thus they influence the cycle thermal efficiency. This analysis also must involve the heat exchanging scheme practical applicability. The cycle charts shown in Fig. 2 are created in the AspenONE code for the power production efficiency parametric study at varying multi-flow regenerator schemes. The chart in Fig. 2a includes a regenerator presented as a multi-flow heat exchanger. This scheme allows the evaluation of the cycle maximal efficiency.

The model of a multi-stream heat exchanger assumes that the hot and cold flow temperatures are averaged on their heat capacity. This approach is a pinch-analysis element [24]. Here the regenerator has five flows: two hot flows (turbine exhaust gases and compressed air from the ASU) and three cold flows (turbine coolant, oxidizer supplied to the combustor, and heated flow to the combustor).

The chart in Fig. 2b includes a regenerative heat exchanging system that consists of five double-stream heat exchangers. In each of the heat exchangers, the heated and heating flows direction is assumed as counterflow. As to efficiently utilize the maximal heat amount the scheme provides air cooling in three double-stream heat exchangers.

Simulation results of the two charts shown in Fig. 2a and 2b show that the net efficiency of five two-flow heat exchangers chart is remarkably lower than the multi-flow one. At the turbine inlet temperature and pressure of 1100 °C and 30 MPa and the turbine outlet pressure 3 MPa this net efficiency drops down from 54.1% to 49.9%. The pinch point temperature difference of 5 °C in the regeneration system was kept constant. This efficiency reduction is mostly due to the ~5% smaller regenerator thermal power concerned with the chart change.

Nevertheless, further optimization analysis involves the cycle chart with five heat exchangers because it may be practically applied.

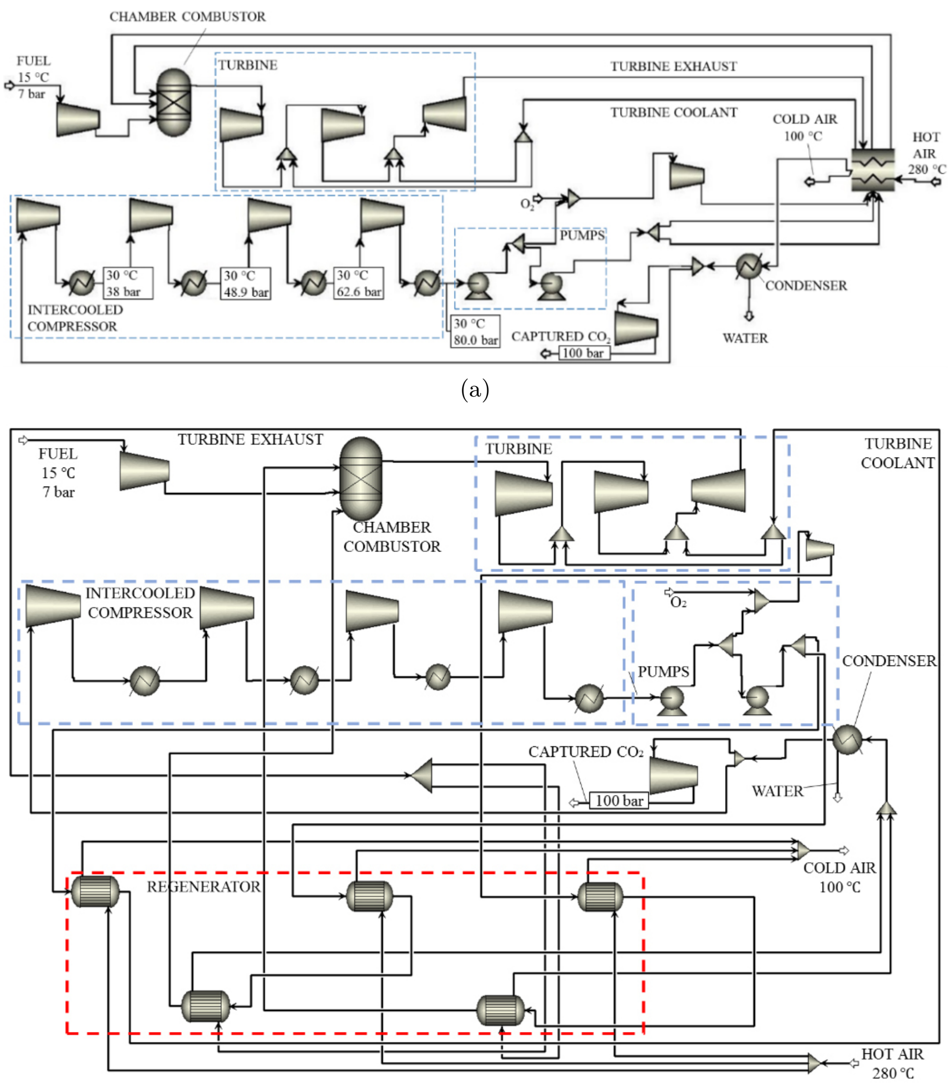

Figure 2: Simulation flowchart of the Allam cycle a) single multi-stream regenerator, b) regenerator consisting of five double-stream heat exchangers.

4.2 Influence of gas turbine outlet pressure on cycle net efficiency

Parametric optimization involved the enumerative method. The turbine inlet pressure was equal to 30 MPa for all the considered cases. The varying parameters were gas turbine inlet temperature and outlet pressure. The results of cycle parametric optimization are presented in Fig. 3.

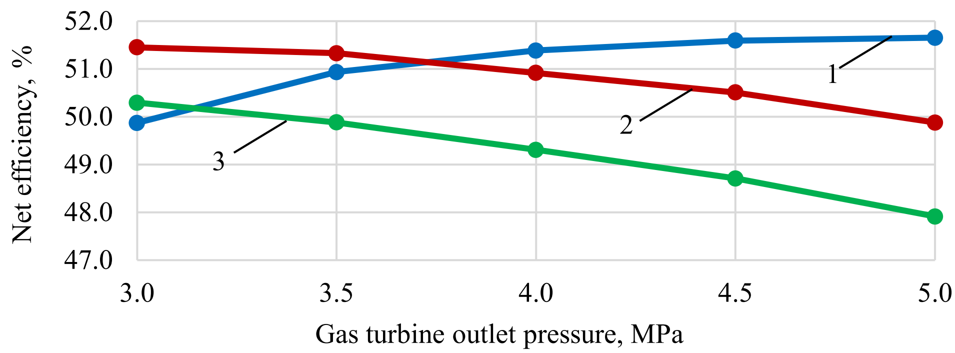

Figure 3: The results of parametric optimization of the Allam cycle. 1 – gas turbine inlet temperature of 1100 °C, 2 – gas turbine inlet temperature of 1200 °C, 3 – gas turbine inlet temperature of 1300 °C.

The turbine inlet temperature and outlet pressure ambiguously influence the thermal efficiency. The cycle net efficiency reaches its maximum at outlet pressure of 5 MPa for the inlet temperature of 1100 °C and at outlet pressure below 3 MPa for the inlet temperature range of 1200–1300 °C. This optimal outlet pressure reduction at the constant inlet pressure is caused by the higher optimum value of the turbine expansion ratio, which reduces the exhaust temperature increase together with acceptable losses in the cold source.

Finally, the Allam cycle reaches its maximal net efficiency of 51.7% for the initial working fluid temperature of 1100 °C and the turbine exhaust pressure of 5 MPa.

4.3 Using nitrogen for gas turbine cooling system

The nitrogen with pressure and temperature of 0.6 MPa and 30 °C is a by-product of the cryogenic air separation unit. This produces excessive pressure and its low temperature allow its application for the Allam cycle turbine cooling. This technical solution requires the application of the closed cooling concept that eliminates the nitrogen and working fluid mixing. The available turbine blade alloys withstand temperatures above 1000 °C [25, 26] so the closed cooling may be used at working fluid temperature below 1300 °C.

Figure 4 illustrates the Allam cycle with closed turbine cooling with the nitrogen produced by the air separation unit. The nitrogen from ASU passes the turbine cooling channels, heats up, and enters the turbo-expander where it produces additional power. A specific feature of this scheme is the smaller number of double-stream heat exchangers, four instead of five. The fifth heat exchanger that pre-heats the turbine cooling agent, in this case, is absent.

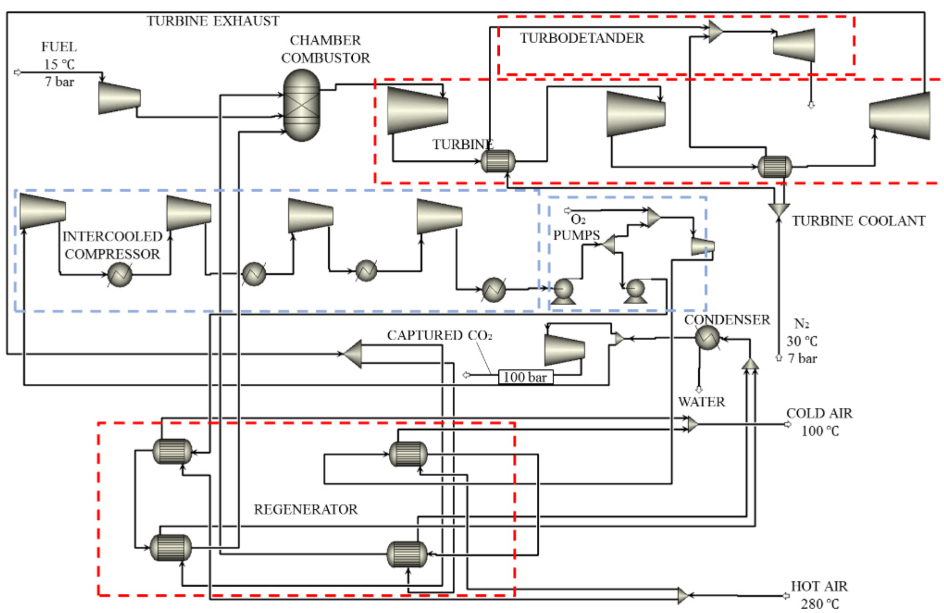

Figure 4: Simulation flowchart of the Allam cycle with a closed-loop nitrogen cooling system.

The results of the performance evaluation of the Allam cycle with a closed-loop nitrogen cooling system presented in Table 2. The usage of the nitrogen cooling leads to an increase of the Allam cycle net efficiency by 1.2% and 2.4% at the initial temperatures 1100 °C and 1200 °C respectively. This is followed by the additional power production of 20.6 MW. This power may be used for a part of the internal power consumption.

Table 2: Performance evaluation of the Allam cycle with a closed-loop nitrogen cooling system for the turbine inlet temperature of 1200 °C.

Parameter	Unit	Value
Thermal energy of feedstock	MW	435.7
Turbine power	MW	325.3
Intercooled compressor and pumps consumption	MW	51.5
Fuel compressor consumption	MW	8.6
Oxygen compressor consumption	MW	18.1
Carbon dioxide compressor consumption	MW	2.0
Turboexpander power	MW	20.6
Air separation unit	MW	31.3
Net electric power output	MW	234.4
Net electric efficiency	%	53.8
Total coolant flow rate	%	12.6

5 Conclusion

1. The Allam cycle is a promising technology for electricity production with near-zero emissions. A scheme of the multi-stream regenerator and a coolant source have a significant influence on cycle net efficiency. To evaluate the thermodynamic effect, simulation models of oxy-fuel combustion power cycles were developed using the commerical code for the power production efficiency parametric study.

2. Particularly, it was found that the transition to a scheme with five double-stream heat exchangers decreases the Allam cycle efficiency by 4.2% compared to a scheme with a multi-stream regenerator.

3. An increase of the Allam cycle initial fluid temperature at a constant initial pressure causes a reduction of the turbine exhaust optimal pressure. The initial temperature increase from 1100 to 1300 °C at the initial pressure 30 MPa reduces the turbine exhaust optimal pressure for more than 2 MPa.

4. The closed cooling scheme of the supercritical carbon dioxide turbine with the nitrogen produced in the air separation unit increases the Allam cycle net efficiency for 2.4%.

5. In high-temperature blades, if the difference between the coolant nitrogen and working fluid temperatures needs a reduction the nitrogen may be pre-heated in the regenerator fifth heat exchanger.

6. If the initial working fluid temperature is above 1300 °C it is possible to apply a pre-cooling of the coolant flow with nitrogen in an intermediate heat exchanger.

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References

[1] Keeling R.F., Piper S.C., Bollenbacher A.F., Walker J.S.: *Atmospheric carbon dioxide record from Mauna Loa.* Carbon Dioxide Research Group, La Jolla 2008.

[2] *Global Environment Outlook. 2012*, United Nations Environment Programme, Progress Press, Malta, 2012.

[3] *Climate change 2014: Mitigation of climate change.* Intergovernmental Panel on Climate Change, Cambridge University Press, New York 2014.

[4] Marchal V., Dellink R., Van Vuuren D., Clapp C., Chateau J., Magné B., Van Vliet J.: *OECD environmental outlook to 2050.* Organization for Economic Co-operation and Development, 2011.

[5] Feng K., Davis S.J., Sun L., Hubacek K.: *Drivers of the US CO_2 emissions 1997–2013.* Nat. Commun. **6**(2015), 7714.

[6] Buhre B.J., Elliott L.K., Sheng C.D, Gupta R.P., Wall T.F.: *Oxy-fuel combustion technology for coal-fired power generation.* Prog. Energ. Combust. **31**(2005), 4, 283–307.

[7] Liang Y., Cai L., Guan Y., Liu W., Xiang Y., Li J., He T.: *Numerical study on an original oxy-fuel combustion power plant with efficient utilization of flue gas waste heat.* Energy **193**(2020), 116854.

[8] Ziebik A., Gładysz P.: *System approach to the analysis of an integrated oxy-fuel comustion power plant.* Arch. Thermodyn. **35**(2014), 3, 39–57.

[9] Kotowicz J., Michalski J.: *Modeling of a supercritical power plant with an oxy type pulverized fuel boiler, a carbon dioxide capture unit and a 'four-end' type membrane air separator.* Arch. Energetyki **42**(2012), 2, 73–83.

[10] Allam R.J., Palmer M.R., Brown Jr. G.W., Fetvedt J., Freed D., Nomoto H., Jones Jr. C.: *High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide.* Enrgy Proced. **37**(2013), 1135–1149.

[11] Scaccabarozzi R., Gatti M., Martelli E.: *Thermodynamic analysis and numerical optimization of the NET Power oxy-combustion cycle.* Appl. Energ. **178**(2016), 505–526.

[12] Sifat Najmus S., Yousef Haseli: *Thermodynamic modeling of Allam cycle.* Int. Mechanical Engineering Congr. Expos., ASME, Pittsburgh 2018.

[13] Rogalev A., Kindra V., Osipov S., Rogalev N.: *Thermodynamic analysis of the net power oxy-combustion cycle.* ETC13, Euroturbo Society, Lausanne 2019.

[14] Rogalev A., Grigoriev E., Kindra V., Rogalev N.: *Thermodynamic optimization and equipment development for a high efficient fossil fuel power plant with zero emissions.* J. Clean. Prod. **236**(2019), 117592.

[15] Zhao Y., Zhao L., Wang B., Zhang S., Chi, J., Xiao Y.: *Thermodynamic analysis of a novel dual expansion coal-fueled direct-fired supercritical carbon dioxide power cycle.* Appl. Energ. **217**(2018), 480–495.

[16] Aspen Technology Corporation, AspenOne, Bedford, United States.

[17] Lemmon E., Huber M., McLinden M.: *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP*, Version 9.0, 2018.

[18] Rogalev A.N., Kindra V.O., Rogalev N.D., Sokolov V.P., Milukov I.A.: *Methods for efficiency improvement of the semi-closed oxy-fuel combustion combined cycle.* J. Phys. Conf. Ser. 012003, 2018.

[19] Hnudiuk-Stefan A., Składzień J.: *The analysis of parameters of the cryogenic oxygen unit cooperating with power plant to realize oxy-fuel combustion.* Arch. Thermodyn. **36**(2015), 1, 39–54.

[20] Araújo O.D.Q.F., de Medeiros J.L.: *Carbon capture and storage technologies: present scenario and drivers of innovation.* Curr. Opin. Chem. Eng. **17**(2017), 22–34.

[21] Selosse S., Ricci O.: *Carbon capture and storage: Lessons from a storage potential and localization analysis.* Appl. Energ. **188**(2017), 32–44.

[22] Rogalev A., Kindra V., Zonov A., Rogalev N., Agamirov L.: *Evaluation of bleed flow precooling influence on the efficiency of the E-MATIANT cycle.* Mechanics Mechanical Eng. **22**(2018), 2, 593–602.

[23] Thorbergsson E., Grönstedt T.: *A thermodynamic analysis of two competing mid-sized oxyfuel combustion combined cycles.* J. Energy 2438431, 2016.

[24] Kemp I.C.: *Pinch analysis and process integration: a user guide on process integration for the efficient use of energy*, Elsevier, Oxford 2011.

[25] Vaferi K., Nekahi S., Vajdi M., Moghanlou F. S., Shokouhimehr M., Motallebzadeh A., Asl M.S.: *Heat transfer, thermal stress and failure analyses in a TiB2 gas turbine stator blade*, Ceram. Int. **45**(2019), 15, 19331–19339.

[26] Khryashchev I.I., Danilov D.V., Logunov A.V.: *Developing a sparingly doped high-temperature nickel alloy for gas turbine blades.* Metallurgy **26**(2019), 2, 205–218.