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Evaluation of Bleed Flow Precooling Influence on the Efficiency of the E-MATIANT Cycle

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This study aims to present a method for precooling bleed flow by water injection in the E-MATIANT cycle and to estimate its impact on the overall efficiency. The design parameters of the cycle are set up on the basis of the component technologies of today's state-of-the-art gas turbines with a turbine inlet temperature between 1100 and 1700 °C. Several schemes of the E-MATIANT cycle are considered: with one, two and three combustion chambers. The optimal pressure ratio ranges for the considered turbine inlet temperatures are identified and a comparison with existing evaluations is made. For the optimal initial parameters, cycle net efficiency varies from 42.0 to 49.8%. A significant influence of turbine stage cooling model on optimal thermodynamic parameters and cycle efficiency is established. The maximum cycle efficiency is 44.0% considering cooling losses. The performance penalty due to the oxygen production and carbon dioxide capture is 20–22%.

Keywords: oxy-fuel combustion cycle, gas turbine, cooling scheme, thermodynamic optimization.

1. Introduction

The world's energy consumption is rising over the past 50 years due to population growth and increasing industrialization of countries in the third tier. The emerging trend has predetermined a number of serious environmental consequences, among which is the global warming. With a high probability, a rising concentration of CO_2 in the atmosphere is the main reason for the observed process.

The results of the continuous measurements of the CO_2 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 time 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 a number of 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-quarter 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 CO2 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 CO_2 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 cycles [6, 7]. 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.

Published papers usually consider oxy-fuel combustion cycles with the carbon dioxide recirculation into the combustor. Specifically are widely known Allam cycle, E-MATIANT cycle and SCOC-CC [8–10]. The mentioned cycles have their advantages and shortages. The Allam cycle obvious advantages are its high efficiency and the power production facility compactness. The SCOC-CC cycle advantage is the simple thermal scheme that provides the highest reliability between all cycles. The modified E-MATIANT thermal scheme cycle is similar to the Allam cycle but it differs remarkably in the parameters levels in combustors, turbines, and regenerators.

Numerous works are devoted to optimization of the SCOC-CC cycle parameters [11–12] and the Allam cycle [13–14]. On the other side, the E-MATIANT structural and parametric optimization aspect did not attract proper attention. The results of the sensitivity analysis of the MATIANT cycle presented in [15]. Steam injection in the low-pressure combustion chamber (LPC) was considered to increase cycle efficiency in [16].

This work contains the results of structure and parameters optimization of the E-MATIANT cycle for the efficiency improvement.

2. Thermal schemes and modeling approaches

The main investigation method was the computer simulation in the Microsoft Excel code that allows an iterative calculation algorithm. The multi-component working fluid was presented as an ideal mixture of real gases. The mixture components thermodynamic parameters were assumed with the NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) code. The components partial pressures were determined by Dalton law. The components extensive thermodynamic parameters, enthalpy, entropy, etc. were taken from the material and thermal balance equations written for an ideal mixture of real gases. Each element in the flowchart was described with a specific mathematical model.

The investigation first stage consisted of the working fluid initial thermodynamic parameters optimization. The aim was to find an optimal compressor pressure ratio for different turbine inlet temperatures from the range of 1100–1700°C. On this stage, the cooling losses were not considered. The compressor pressure ratio optimization was carried out for the E-MATIANT cycle with one, two and three combustion chambers (CC) (Fig. 1).

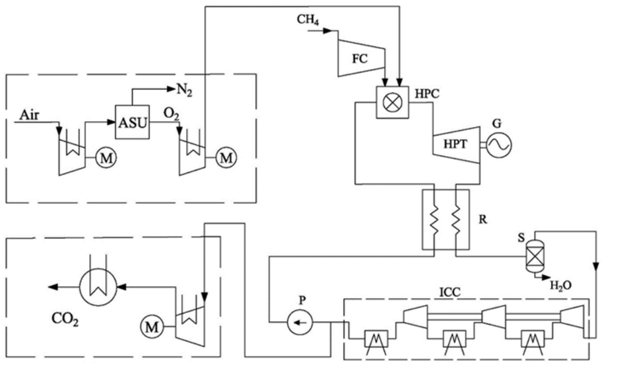
The investigation second stage included evaluation of the E-MATIANT cycle with the cooling losses. The aim was to find optimal turbine inlet parameters from the best cases obtained on the first stage. Thermal scheme of the E-MATIANT cycle with turbine cooling presented in the Fig. 2.

The E-MATIANT cycle specific feature is the multistage expansion of the working fluid with high carbon dioxide content. The carbon dioxide is compressed in a multi-stage inter-cooled compressor (ICC) and supplied into a regenerator (R) for heating. The flow heated by a part of the low-pressure turbine (LPT) exhaust enters the high-pressure combustor (HPC) where its temperature grows. Oxygen from the air separation unit (ASU) enters the combustion chambers. After the HPC the hot flow expands in the high-pressure turbine (HPT) and enters the low-pressure combustor (LPC). After the LPC, the flow expands in the LPT and is supplied to the regenerator. Thus, the cycle is closed.

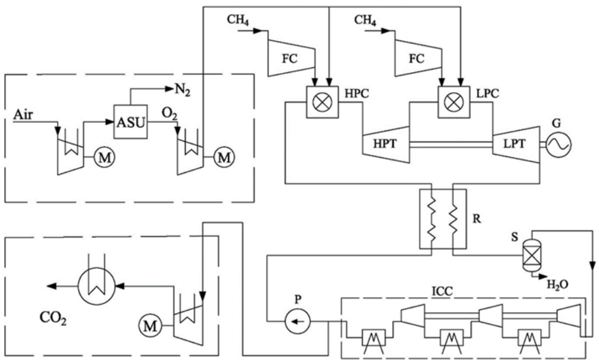
The coolant source must provide proper coolant pressure and temperature. The coolant pressure must be as high as to overcome the cooling channels resistance, and the coolant temperature must keep the given airfoil metal surface temperature at adequately low mass flow. The E-MATIANT schemes presented in the Fig. 1 shows that the HPT coolant may be taken only from upstream, inside or downstream regenerator because only here the pressure is sufficiently high.

An influence of the coolant temperature on cycle efficiency is not obvious. The coolant bleeding upstream the regenerator heating allows its small mass flow and causes the turbine power increase. On the other side, the heated substance flow in the regenerator drops down, which reduces the regeneration efficiency and increases the combustor fuel consumption. If the coolant is taken after its heating in the regenerator keeps the regeneration efficiency but the coolant mass flow grows which reduces the turbine power. Thus, the choice of coolant temperature needs optimization thermodynamic studies.

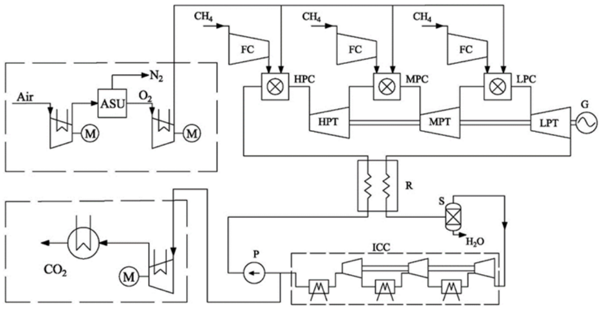
The initial data for cycles modeling are presented in Table 1. The turbine cooling model used for the calculations of the E-MATIANT cycle is described in the next section.



a) E-MATIANT cycle with one combustion chamber



b) E-MATIANT cycle with two combustion chambers



c) E-MATIANT cycle with three combustion chambers

Figure 1 Thermal schemes of the E-MATIANT cycles without turbine cooling

Table 1 Initial data for modeling

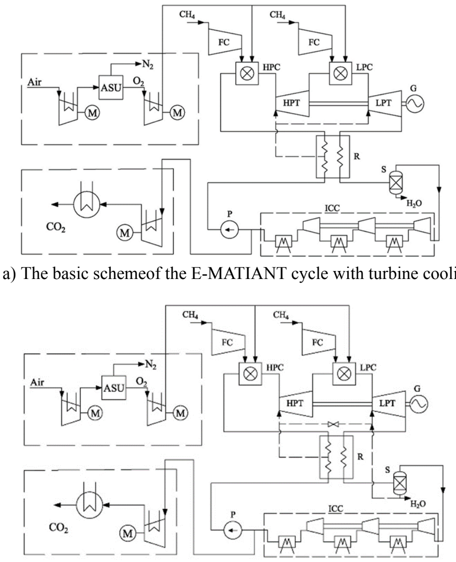
Parameter	Value	Parameter	Value
Ambient temperature, °C	15	Minimum cycle temperature, °C	30
Ambient pressure, bar	1.013	Regenerator pressure drop, %	2
Ambient humidity, %	60	Coolers pressure drop	1
Fuel	CH4	Regenerator minimum pinch point temperature, °C	20
Lower heating value for fuel (at 15 °C and 7 bar), kJ/kg	50025	Pump polytropic/ mechanical efficiency, %	70/90
Fuel temperature/pressure, °C/bar	15/7	ASU delivery pressure, bar	1.2
Fuel compressor isentropic/ mechanical efficiency, %	80/99	ASU delivery temperature, °C	30
CO_2 compressor/turbine polytropic efficiency, %	90/90	ASU power consumption, kW/(kg/s)	900
Turbines mechanical efficiency, %	99	O_2 purity, %	99.8
Generator electricity/ mechanical efficiency, %	98.5/ 99.4	O_2 compressor polytropic/mechanical efficiency, %	88/99
Molar oxygen concentration at the outlet of the combustion chamber, %	1	The specific power consumption of a compressor for CO_2 disposal, kW/(kg/s)	350
Combustor pressure drop, %	4	Condenser efficiency	0.8

3. Turbine cooling model

An open cooling scheme of the gas turbine compartment was proposed. If the difference between working fluid and blade wall temperatures is less than 300 °C, the convective cooling type is considered, otherwise, the film cooling type is adopted. In the mathematical model, the maximum permissible average temperature of the blade outer surface is 850°C.

The method described in [17, 18] was selected for the estimation of relative coolant mass flow (cooling flow fraction). According to the chosen method, the relative coolant mass flow for each vane/blade row is defined as follows (1):

$$\Psi = \frac{K_{\text{cool}}}{1+B}\frac{\varepsilon_0 - \varepsilon_f[1-\eta_{\text{int}}(1-\varepsilon_0)]}{\eta_{\text{int}}(1-\varepsilon_0)} \tag{1}$$



a) The basic schemeof the E-MATIANT cycle with turbine cooling

b) Scheme of the E-MATIANT cycle with water injection in coolant flowsof the LPT

Figure 2 Thermal schemes of the E-MATIANT cycles with turbine cooling

where: K_{cool} represents cooling flow factor; B *';lkm n*represents coefficient depending on the metal and TBC BIOT number; ε_0 represents vane/blade cooling effectiveness, η_{int} represents internal cooling efficiency (it was taken equal to 0.7 in the model); ε_f represents film-cooling effectiveness.

After determining the cooling flow factor for each vane/blade row of the gas turbine, the polytropic efficiency of the cooling stages is defined as follows (2) [11]:

$$\eta_{\text{oi.cool}} = \eta_{\text{oi}} - S \ln\left(\frac{p_{\text{in}}}{p_{\text{out}}}\right) \frac{p_i(G_{0\text{out}} - G_{0\text{in}})}{(p_{\text{in}} - p_{\text{out}})G_{0\text{in}}} \tag{2}$$

where: η_{oi} represents polytropic efficiency of the stage without cooling losses; S represents the turbine efficiency factor ($S = 0.1$–0.5; 0.1 – for high-efficient turbines, 0.5 – for low-efficient turbines); p_{in} represents stagnation pressure at the turbine inlet; p_{out} represents stagnation pressure at the turbine outlet; $G_{0\text{in}}$ represents working fluid mass flow at the turbine inlet; $G_{0\text{out}}$ represents working fluid mass flow at the turbine outlet; p_i represents the stagnation pressure at the inlet of the rotor blade row of the i-th stage.

4. Turbine inlet parameters optimization for the E-MATIANT cycle

The results of the turbine inlet parameters optimization for the E-MATIANT cycle without considering cooling losses are presented in Fig. 3 by continuous lines.

For the cycle with one combustion chamber, maximal net efficiency may be obtained at the following turbine inlet parameters:
1100–1200°C and 30 bar; 1300–1400°C and 40 bar; 1500–1600°C and 50 bar; 1700°C and 60 bar.

For the cycle with two combustion chambers, maximal net efficiency may be obtained at the following flow parameters at the HPT and LPT inlets:
1100°C and 30/9 bar; 1200°C and 30/12 bar; 1300°C and 40/16 bar; 1400°C and 40/20 bar; 1500–1600°C and 50/25 bar; 1700°C and 60/30 bar.

For the cycle with three combustion chambers, maximal net efficiency may be obtained at the following flow parameters at the HPT, MPT and LPT inlets:
1100 °C and 30/9/5.4 bar; 1200°C and 30/15/7.2 bar; 1300°C and 40/20/9.6 bar; 1400○C and 40/20/9.6 bar; 1500°C and 50/30/17.5 bar; 1600°C and 50/30/20 bar; 1700°C and 60/36/24 bar.

The maximum net efficiency is reached for the scheme with two combustion chambers. Using three combustion chambers is not reasonable because of the lower cycle efficiency and the complicated scheme structure. The HPT and LPT inlet parameters increase from 1100°C and 30/9 bar to 1700°C and 60/30 bar is followed by the total efficiency increase from 56.9 to 66.8% and the net efficiency from 42.0 to 49.8%.

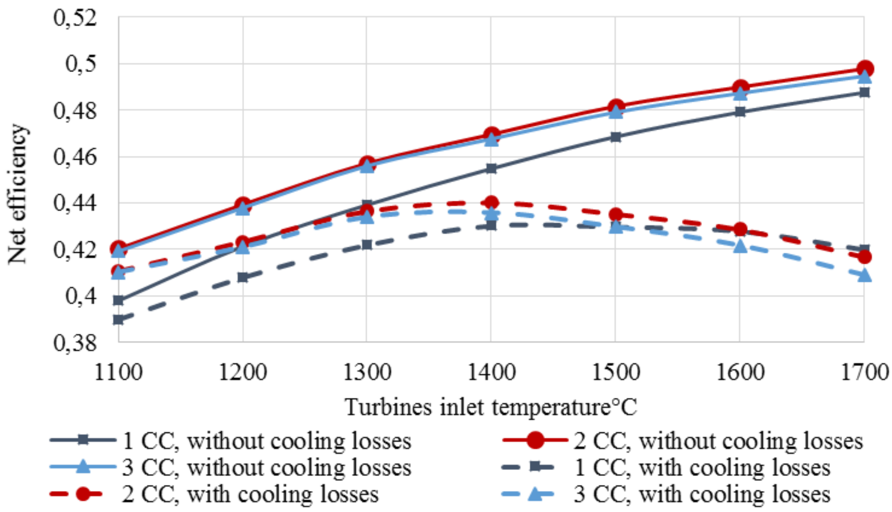


Figure 3 Turbine inlet parameters influence on the E-MATIANT cycle net efficiency with/without cooling losses

The results of net efficiency estimation for the E-MATIANT cycle considering cooling losses are also presented in Fig. 3 (dashed lines). The maximum net efficiency of the E-MATIANT cycle with two combustion chambers equal to 44.0% may be achieved at the HPT and LPT inlet parameters equal to 1400°C and 40/20 bar. The relative coolant flow for the considered cycle parameters is equal to 40.3%. The cooling losses cause the cycle with two combustion chambers net efficiency reduction of 1.0–8.1% (the lower value for 1100°C and 30/9 bar, the upper value for 1700°C and 60/30 bar).

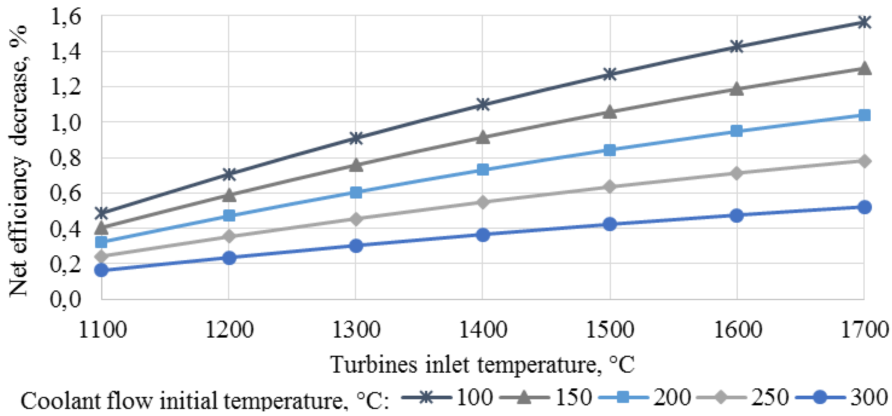


Figure 4 An influence of the turbine inlet temperature on the E-MATIANT cycle net efficiency for the different coolant flow initial temperature

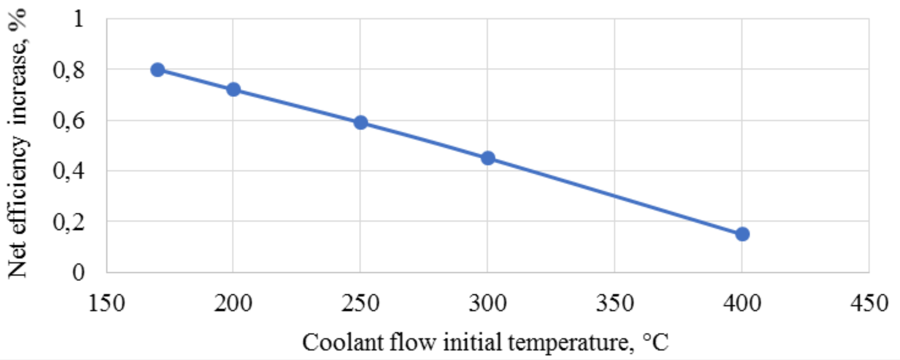


Figure 5 An influence of the coolant flow initial temperature on the net efficiency increase of the E-MATIANT cycle

5. An analysis of methods to increase the efficiency of the E-MATIANT cycle

The investigation results of the coolant temperature on the efficiency of the E-MATIANT cycle with two combustion chambers are presented in Fig. 4.

The investigation results show that the decrease of the coolant temperature accompanied by the decrease of the cycle net efficiency despite the reduction of the coolant flow and turbine cooling losses. The decrease in the amount of heat transferred in the regenerator is the reason. That's why the thermal scheme with water injection in the coolant of the LPT was proposed (Fig. 2b).

The E-MATIANT net efficiency can be increased by injection of water taken from the cooler-separator in the coolant flows. When the cold water contacts hot streams of coolant the evaporation occur and the coolant temperature decreased. In order to avoid the danger of moisture contact with the details of the hot flow path, water injection is carried out only in the low-pressure turbine, where the partial pressure of water is relatively low.

The relative mass flow of the injection water should be in the range from 2.3 to 2.7% (regarding the mass flow at the inlet of the LPT). The E-MATIANT cycle with two combustion chambers at turbine inlet temperatures from 1100 to 1700 °C has a possibility for the 0.15–0.80% net efficiency increase by means of water injection into the LPT coolant (Fig. 5).

6. Conclusion

The mathematical modeling of thermal schemes was performed to analyze the effect of the structure by changing the number of combustion chambers of the E-MATIANT cycle on the net efficiency.

For the cycle with one combustion chamber maximal net efficiency may be obtained at the following turbine inlet parameters:
1100–1200°C and 30 bar; 1300–1400°C and 40 bar; 1500–1600°C and 50 bar; 1700°C and 60 bar.

For the cycle with two combustion chambers maximal net efficiency may be obtained at the following flow parameters at the HPT and LPT inlets:
1100°C and 30/9 bar; 1200°C and 30/12 bar; 1300°C and 40/16bar; 1400°C and 40/20 bar; 1500–1600°C and 50/25 bar; 1700°C and 60/30 bar.

For the cycle with three combustion chambers maximal net efficiency may be obtained at the following flow parameters at the HPT, MPT and LPT inlets:
1100°C and 30/9/5.4 bar; 1200°C and 30/15/7.2 bar; 1300°C and 40/20/9.6 bar; 1400°C and 40/20/9.6 bar; 1500°C and 50/30/17.5 bar; 1600°C and 50/30/20 bar; 1700 °C and 60/36/24 bar.

The maximum net efficiency is reached for the scheme with two combustion chambers. Using three combustion chambers is not reasonable because of the lower cycle efficiency and the complicated scheme structure. The HPT and LPT inlet parameters increase from 1100°C and 30/9 bar to 1700°C and 60/30 bar is followed by the net efficiency increase from 42.0 to 49.8%. The performance penalty due to the oxygen production and carbon dioxide capture is about 20–22%.

The cooling losses cause the cycle with two combustion chambers net efficiency reduction of 1.0–8.1%, the lower value for 1100°C and 30/9 bar, the upper value for 1700°C and 60/30 bar. The maximal net efficiency of the E-MATIANT cycle with two combustion chambers of 44.0% may be obtained at the HPT and LPT inlet parameters equal to 1400°C and 40/20 bar and the coolant flow of 40.3%.

The cycle structure with water bleeding from the cooler-separator and injection into the LPT coolant flow allows the coolant flow reduction and 0.15–0.80% net efficiency increase.

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