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Thermodynamic analysis of the double Brayton cycle with the use of oxy combustion and capture of CO_2

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Abstract In this paper, thermodynamic analysis of a proposed innovative double Brayton cycle with the use of oxy combustion and capture of CO_2, is presented. For that purpose, the computation flow mechanics (CFM) approach has been developed. The double Brayton cycle (DBC) consists of primary Brayton and secondary inverse Brayton cycle. Inversion means that the role of the compressor and the gas turbine is changed and firstly we have expansion before compression. Additionally, the working-fluid in the DBC with the use of oxy combustion and CO_2 capture contains a great amount of H_2O and CO_2, and the condensation process of steam (H_2O) overlaps in negative pressure conditions. The analysis has been done for variants values of the compression ratio, which determines the lowest pressure in the double Brayton cycle.

Keywords: Inverse Brayton cycle, Brayton cycle, gas-steam unit, oxy combustion, CCS, thermodynamic analysis, numerical analysis, CFM

Nomenclature

h	–	specific enthalpy, kJ/kg
l	–	specific work, kJ/kg

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N	–	power, kW
$\dot{m}$	–	mass flux rate, kg/s
p	–	pressure, Pa
$\dot{Q}_{chem}$	–	chemical energy flux, kW
t	–	temperature, °C
T	–	temperature, K
W_d	–	fuel calorific value, kJ/kg
x	–	vapor quality

Greek symbols

β	–	coefficient of energy consumption (specific work for air separation), kWh/kg
ΔT	–	temperature difference in the heat exchanger, K
η	–	efficiency, %
Π	–	compression/expansion ratio

Subscripts

a	–	point of end regeneration
amb	–	ambient
el	–	electrical
ex	–	exhaust
f	–	fuel
i	–	internal
ic	–	internal compresor
it	–	internal turbine
m	–	mechanical
o	–	oxygen
$1s, 2s, ...$	–	isentropic points of cycle
$1, 2, ...$	–	real points of cycle
IBC	–	inverted Brayton cycle
DBC	–	double Brayton cycle
BC	–	Brayton cycle
GT	–	temperature on the turbine outlet
TIT	–	turbine inlet temperature

Superscripts

in	–	point in inversed Brayton cycle

1 Introduction

Along with the civilization development and technical progress, the worlds requirement on the electrical energy grows up. According to it, many problems with electricity appear [7]. At an increasing output of the electrical power the care about the environment it is needed to be taken. All of the rules were determined by the EU Directive No. 2010/75/UE [10]. It ought to call attention to the fact that the alarming signals from the environment and meteorological effects have been noticed lately. However, the scientists do not live up to one theory about the causes of more often found climate disorders. One fact needs to be emphasized, the bigger and bigger combustion of the fossil fuels can affect the atmosphere, mainly due to ash dust and toxic oxides emissions. Economic growth of countries should be optimized with the sustainable energy policy to develop in environmental, economical and social order. And this is how we describe the sustainability, which main pillar is the even-tempered energy conversion [2,4].

The way to the clean and sustainable energy conversion is through the use of renewable sources of energy and also 'clean' carbon technology. However, it is worth to concentrate on the 'clean' gas technology, according to the large amount of shale gas in Poland. It would help to diversificate the energy sources [16,33]. It is worth to remind that the other sources of energy, such as geothermal source of energy, wind energy and nuclear energy, will not be able to have a big influence on energy market in Poland, which is the enhancement of the electrical energy output. In this situation, the main role may play the gas-steam power units, accommodated to the escape of carbon dioxide (CO_2) [29]. The technologies, which base on high-efficiency power units with usage of oxy combustion and capture of CO_2, may stabilize and support the electroenergetical system in reduction of gas emissions according to EU policies. Such a system can be based on the double Brayton cycle with oxycombustion in wet combustor chamber and with water condensation combined with CO_2 capture.

According to the fact that in this cycle working fluid is a mixture of steam and gas, it is an example of gas-steam turbine cycle which binds the advantages of both, gas and steam, systems. As it was mentioned, gas-steam turbine, operates at the higher temperature compared to steam turbines, which is about 1400 K (in some other cases, the temperature reaches the value of 1700 K) [1,12,17]. Inlet pressure above 4 MPa exceeds the levels of typical gas-turbines [17]. In the condenser the negative pressure is obtained [8]. In the USA the Clean Energy Systems and Siemens Corporation develope large scale oxy combustion power plant. This power plant combines the gas and steam turbine operating condition [1,12]. In the literature, this cycle, with oxy combustion and water injection is the so called water cycle [6,18,20], because of the 90% content of the steam. The rest 10% is CO_2 from methane combustion [6,11]. More sophisticated cycle, working on steam and allowing to reach higher efficiency, is the Graz cycle [14,22].

Other cycles utilizing the oxy combustion in traditional combustion chamber, which also provide huge perspectives are: SCO-CC (semi-closed oxy-fuel combustion combined cycle) [25], Matian [21,26], COOPERATE cycle [26,28], COOLENERG cycle [23] In turn, in these cycles, mentioned above, CO_2 predominates as a medium.

It is ought to emphasize that there are some other cycles, which are also worth to be mentioned. These are such systems as:

- ZEITMOP (zero emission ion transport membrane oxygen power) system with Ion Transport Membrane [27],
- AZEP (advanced zero emission power plant) – system with a mixed conductive membrane reactor [18,30],
- CLCC (chemical looping combustion cycle) [18],
- system with natural gas reforming [30],
- system with fuel cells in hybrid cycle (SOFC-GT) [19].

The main aim of this paper is to investigate the thermodynamic parameters of the double Brayton cycle with oxy combustion and with the capture of the CO_2. This was carried by accessible numerical CFM codes type, by step-by-step modeling of separates apparatus.

2 Double Brayton cycle

The whole system consists of the first traditional Brayton cycle and the second inversed one. The 'inversed Brayton cycle' means that the order of the compressor and turbine is inversed, so that first there is the expansion of the working-fluid and than its compression [5]. Wet and hot exhaust gases at the atmospheric pressure (from the gas turbine or from the fuel cell) are able to generate extra turbine power, by expanding to the negative pressure (it is the expansion, which is very similar to the expansion in the steam turbine) [19]. The gas mixture, at that level, is still a high temperature fluid and it needs to be colled. It is all done by using a special regenerative heat exchanger (HE). After desuperheating, steam is envisaged to condensate (or just a part of it). The gases pressure is lower than the atmospheric one and that is why the exhaust needs to be compressed in the compressor (C). Compressed gases are directed to the second precooling heat exchanger and second condenser, which dries them. Additionally, the battery of devices realizing the cycle, consists of the turbine (GT), the heat exchanger (HE) and the compressor (C) (Fig. 1). The cycle described above is the inversed Brayton cycle (IBC) indeed. Temperature-entropy diagram of the double Brayton cycle is presented in Fig. 2, where the characteristic points (1, 2, 2s, ..., 5^{in}) are denoted.

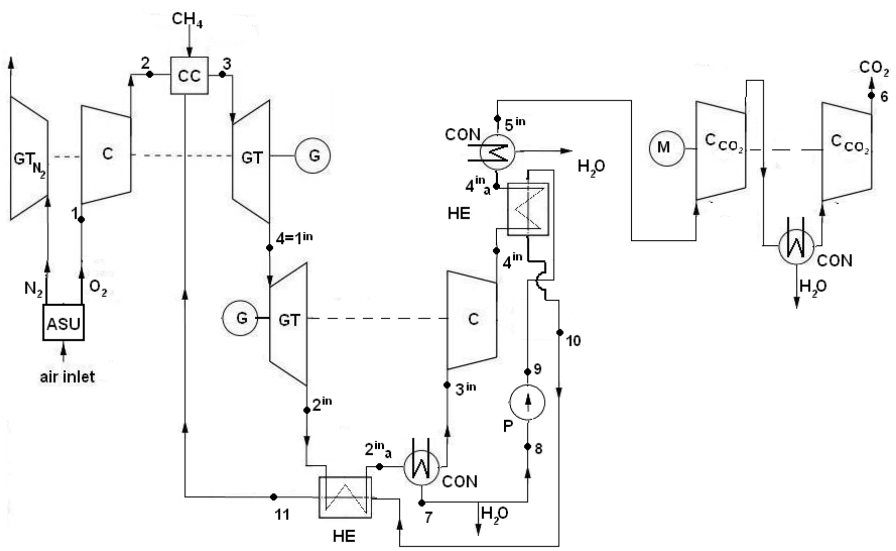

Figure 1. Schematic diagram of the double Brayton cycle with the use of oxy combustion and capture CO_2 (ASU – air separation unit, CC – combustion chamber, C – compressor, GT – gas turbine, HE – heat exchanger , G – electric generator, M – motor, CON – condenser, P – pump, GT_{N2} – additional gas turbine of N_2, C_{CO2} – compressor of CO_2).

As it was mentioned, in the condenser (CON), working fluid is separated into water and CO_2. Next, the 'clean' CO_2 goes to the compressor (C), where it compresses and, after that, it is cooled and condensated. Liquid carbon may be sold or might be used as a fracturing fluid [33]. The main disadvantage of the whole system is the necessity of the air separating station (ASU), to supply combustion chamber in pure oxygen. Moreover, the 95%-oxy-combustion eliminates almost entirely the problem of the NO_x emission. Additionally, the nitrogen turbine (GT_{N2}) might be used and would be fueled from the oxygen and nitrogen separating station.

Technical realization of the IBC may cause such problems as the increase

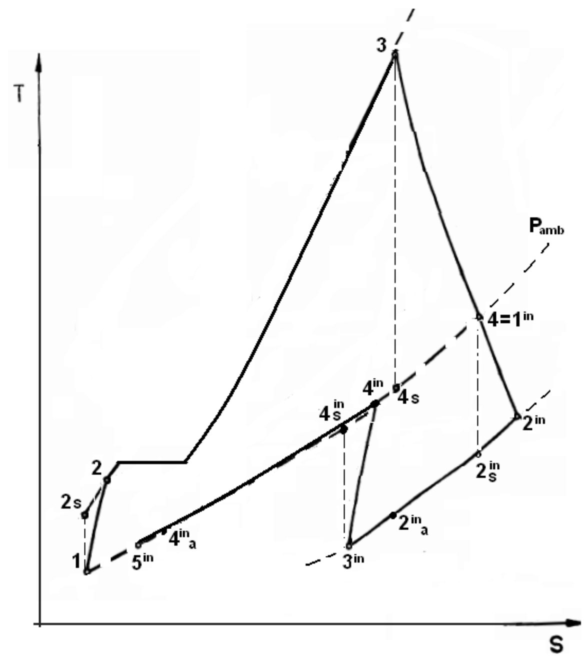

Figure 2. Temperature-entropy diagram of the double Brayton cycle.

of low pressure part size of gas turbine. The IBC turbine, in which the end of expansion runs in negative pressure conditions, what in turn causes that the end part needs to be as big as a low pressure steam turbine. The increase of the diameter is caused by the necessity of axial velocity reduction of the flowing gases through the blading system. Also, the nature of the exchanger operation needs more complex geometry to decrease the loss of movement [19].

3 Mathematical model in the CFM code

To analyse the double Brayton cycle with oxy combustion and capture of CO_2, the computational flow mechanics code (CFM) code was used [3,4,19,24]. Mathematical CFM models use mass, momentum and energy equation in the '0D' engineering form [3,24]. In this paragraph, computational procedures for each component of the turbo assembly are presented, namely: the compressor, combustion chamber, turbines, pumps and the heat exchangers. The output power and the efficiency calculations are also presented in the paper.

The CFM code, relying to the internal efficiency of the compressor, also determines the power consumption. The input data include the internal efficiency of the compressor, η_{ic}, the mechanical efficiency of the compressor, η_{mc}, compression ratio and also the mass flow rate, $\dot{m}$. Having known the compressor inlet thermodynamic parameters, such as the pressure p_1, the temperature T_1, the pressure p_2 can be calculated using the formula presented below [15,24]

$$p_2 = \Pi_{BC} p_1 \ . \tag{1}$$

For the inversed Brayton cycle there is [19]

$$p_{4^{in}} = \Pi_{IBC} p_{3^{in}} \ , \tag{2}$$

where Π_{IBC} is the compression ratio in inverse Brayton cycle and $p_{3^{in}}$, $p_{4^{in}}$ are the pressure at characteristic points (3^{in}), (4^{in}), respectively. Particular equations of CFM code, used in the inversed Brayton cycle, are similar to those in the traditional Brayton cycle. The total compression ratio is given as

$$\Pi = \Pi_{BC} \Pi_{IBC} \ . \tag{3}$$

Isentropic exponent, κ, of mixture has been predicted on the basis of thermodynamic tables for each medium and that is what makes the calculations shorter. The ideal compression process is described by the isentropic equation $s = idem$ [15,24]

$$T_{2,s} = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} \ . \tag{4}$$

This formula allows calculate the theoretical temperature of the end of the compressing process, T_{2s}. Having given the internal efficiency of the compressor, η_{ic}, it is possible to calculate the real temperature of the compressing process, T_2. The efficiency of the compressor is described by [15,24]

$$\eta_{ic} = \frac{l_{t1-2s}}{l_{t1-2}} = \frac{h_1 - h_{2s}}{h_1 - h_2} \ , \tag{5}$$

where l_{t1-2s} is the specific work of the compression process, l_{t1-2} is the real work of the compressor, and h_1, h_2, h_{2s} are the mixture enthalpy attributable to each point (1), (2), (2s), respectively. To calculate the compressor power and its enthalpy in characteristic points of the whole system, thermodynamic tables of H_2O and CO_2 need to be used.

The power, N_{C-BC}, required to drive the oxygen compressor, is given by the relation [15,24]

$$N_{C-BC} = \dot{m}_o \eta_{mc} (h_1 - h_2) \ , \tag{6}$$

where $\dot{m}_o$ is the oxygen mass flow rate, and η_{mc} is the compressor mechanical efficiency [19]. The power, N_{C-IBC}, required to drive the compresor of exhaust gases

$$N_{C-IBC} = \dot{m}_{3^{in}} \eta_{mc} (h_{3^{in}} - h_{4^{in}}) \ , \tag{7}$$

where $\dot{m}_{3^{in}}$ is the medium mass flow rate on the compressor inlet in the inversed Brayton cycle, and $h_{3^{in}}$, $h_{4^{in}}$ are the medium enthalpy determined at characteristic points (3^{in}), (4^{in}), respectively.

In CFM model of combustion chamber, an energetic balance including all energy fluxes, need to be taken in to account. The heat losses in the combustion chamber were determined using the efficiency of the combustion chamber, η_{CC}. The chemical energy contained in the fuel is defined as [15,24]

$$\dot{Q}_{chem} = \dot{m}_f W_d \ , \tag{8}$$

where $\dot{m}_f$ is the fuel mass flow rate, and W_d is the the low calorific value of the fuel.

The heat balance of the combustion chamber may be written as [15,24]

$$\eta_{CC} (\dot{Q}_{chem} + \dot{m}_o h_2 + \dot{m}_f h_f + \dot{m}_{11} h_{11}) = \dot{m}_{ex} h_3 \ , \tag{9}$$

where $\dot{m}_{ex}$ is the exhaust mass flow rate, $\dot{m}_{11}$ is the heated (regenerated) water injected mass flow rate, and h_f, h_3, h_{11}– fuel, exhaust and heated water enthalpy, respectively.

Moreover, the equations given above Eqs. (10) and (11) were fulfilled following with mass balances [15]

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_o + \dot{m}_{11} \ , \tag{10}$$

$$\dot{m}_{2^{in}} = \dot{m}_{3^{in}} + \dot{m}_7 \ , \tag{11}$$

where $\dot{m}_{2^{in}} = \dot{m}_{ex}$ is the medium mass flow rate out the turbine outlet in the inversed Brayton cycle, $\dot{m}_7$ is the condensates steam mass flow rate in the condenser. To simplify, fuel (gas) is assumed to undergo absolutely and entirely combustion. General the chemical reaction is shown below [24]

$$\mathrm{CH_4 + 2O_2 = CO_2 + 2H_2O} \ . \tag{12}$$

Oxygen, from a cryogenic air separation unit, is fed in a stechiometric ratio with the fuel in the combustor. Based on the composition of the resulting exhaust gases, its temperature $T_3 = T_{TIT}$ and enthalpy h_3 were computed from the energy balance. The expansion process in the gas turbine is defined as [15,24]

$$\eta_{it} = \frac{l_{t3-4}}{l_{t3-4s}} = \frac{h_3 - h_4}{h_3 - h_{4s}} , \tag{13}$$

where l_{t3-4s} is the unitary isotropic expansion work l_{t3-4} is the real expansion work, and h_3, h_4, h_{4s} are the enthalpy of the medium (CO_2 + H_2O) in points (3), (4), (4s), respectively; there is an analogy adopted for other points of the cycle.

The turbine power output of Brayton cycle [24]

$$N_{GT-BC} = \dot{m}_{ex}\eta_{mt}(h_3 - h_4) , \tag{14}$$

where η_{mt} is the turbine mechanical efficiency, and turbine power output, N_{GT-IBC}, of inverted Brayton cycle formula is [19]

$$N_{GT-IBC} = \dot{m}_{ex}\eta_{mt}(h_{1^{in}} - h_{2^{in}}) , \tag{15}$$

where $h_{1^{in}}$, $h_{2^{in}}$ are the medium enthalpy determined at characteristic points (1^{in}), (2^{in}), respectively.

The power of the pump was calculated using formula

$$N_P = \dot{m}_8\eta_{mp}(h_8 - h_9) , \tag{16}$$

where $\dot{m}_8$ is the water injected mass flow rate, η_{mp} is the pump mechanical efficiency, and h_8, h_9 are water enthalpy at characteristic points (8), (9).

Further, heat flux, exchange in the regenerative exchanger, with the assumed heat exchanger efficiency η_{he}, is expressed to be

$$\dot{m}_{ex}\eta_{he}(h_{2^{in}} - h_{2^{in}_a}) + \dot{m}_{4^{in}}\eta_{he}(h_{4^{in}} - h_{4^{in}_a}) = \dot{m}_9(h_{11} - h_9) , \tag{17}$$

where $\dot{m}_{4^{in}} = \dot{m}_{3^{in}}$ is the medium mass flow rate out the compressor outlet in the inversed Brayton cycle; $h_{2^{in}}$, $h_{4^{in}}$, $h_{2^{in}_a}$, $h_{4^{in}_a}$ are the medium enthalpy determined at characteristic points (2^{in}), (4^{in}), (2^{in}_a), (4^{in}_a); $\dot{m}_9 = \dot{m}_8$ is the water injected mass flow rate; h_9, h_{11} are the water enthalpy at characteristic points (9), (11).

Electric power of the generator terminals is defined upon the mechanical power of the individual components of the thermodynamic cycle, i.e., the gas turbine, N_{GT}, compressor, N_C, the water pump, N_P, and the generator efficiency, η_g. Electrical power of the Brayton cycle, N_{el-BC}, is the difference between the devices generating and consuming the power [15]

$$N_{el-BC} = \eta_g (N_{GT-BC} - N_{C-BC} - N_P) \; . \tag{18}$$

The electrical power of the inverse Brayton cycle, N_{el-IBC}, is given [19]

$$N_{el-IBC} = \eta_g (N_{GT-IBC} - N_{C-IBC}) \; . \tag{19}$$

The electrical power of the double Brayton cycle N_{el-DBC} is determined by

$$N_{el-DBC} = N_{el-BC} + N_{el-IBC} \; . \tag{20}$$

The electrical power, N_{el}, of the whole system, including the requirement of the ASU station, N_{el-ASU}, and the electric power needed to drive the CO_2 capture system, N_{el-CO2}, is described by

$$N_{el} = N_{el-DBC} - N_{el-ASU} - N_{el-CO2} \; . \tag{21}$$

The electrical efficiency of the whole system, $\eta_{el-netto}$, is defined as a quotient of the electrical power generated by the block and chemical energy flux contained in the fuel [15,24]

$$\eta_{el-netto} = \frac{N_{el}}{\dot{Q}_{chem}} = \frac{N_{el}}{\dot{m}_f W_d} \; . \tag{22}$$

The efficiency of the Brayton cycle η_{el-BC} may also be given as a quotient of the electrical power N_{el-BC} and the chemical energy flux contained in the fuel $\dot{Q}_{chem}$

$$\eta_{el-BC} = \frac{N_{el-BC}}{\dot{m}_f W_d} \; . \tag{23}$$

However, the double Brayton cycle efficiency is defined as a quotient of the electrical power N_{el-DBC} generated by the double Brayton cycle and fuel chemical energy flux $\dot{Q}_{chem}$ contained in the fuel

$$\eta_{el-DBC} = \frac{N_{el-DBC}}{\dot{m}_f W_d} \; . \tag{24}$$

The efficiency of the inversed Brayton cycle η_{el-IBC} is described as a difference of the η_{el-DBC} and η_{el-BC} as

$$\eta_{el-IBC} = \eta_{el-DBC} - \eta_{el-BC} \; . \tag{25}$$

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In turn, defining the specific work for air separation was corrected using the coefficient of energy consumption

$$\beta = \frac{N_{el-ASU}}{\dot{m}_o} \; . \tag{26}$$

The oxygen separating station was projected as a cryogenic station with double Linde column, which usage provides receiving oxygen, the purity of which varies in range 95–99.8% [9]. Moreover, the efficiencies of the elements system were all set up as

turbine: internal $\eta_{it} = 88\%$, mechanical $\eta_{mt} = 99\%$,
compressor: internal $\eta_{ic} = 87\%$, mechanical $\eta_{mc} = 99\%$,
pump: internal $\eta_{iP} = 75\%$, mechanical $\eta_{mP} = 98\%$,
generator $\eta_g = 97\%$,
combustion chamber $\eta_{CC} = 99\%$,
heat exchanger $\eta_{he} = 98\%$.

4 Results of analysis

Calculations of the heat cycle had been done for the constant mass flow rate of: oxygen 51.8 kg/s, water 117.7 kg/s and fuel 12.83 kg/s on the combustion chamber inlet. Total exhaust mass flow rate is about 182.3 kg/s. The combustion chamber pressure was fixed to 4 MPa. Moreover, the temperature difference in the heat exchanger was also assumed to be 20 K. Additionally, the condensation temperature was assumed to be equal $t_{3in} = 30\,^{\circ}\mathrm{C}$. During the thermodynamic analysis few efficiencies relations based on expansion/compression ratio parameter Π were evaluated $\eta_{el-netto}$ including η_{el-BC}, η_{el-IBC}, η_{el-DBC}. The analysis results were presented in Fig. 3. The temperatures, on the turbine outlet, t_{GT}, and temperature inlet turbine, t_{TIT}, were also analyzed in inversed Brayton cycle (Fig. 4). The thermodynamic parameters of components of the medium in the characteristic points of the cycle were presented in Tab. 1.

As it was shown in the analysis, instead of the initial efficiency decrease in Brayton cycle, total efficiency of the block raised, as it was presented in Fig. 3. The Brayton cycle efficiency firstly decreased because of the temperature decrease and that is why the regeneration level was falling too in the heat exchanger. However, the efficiency of the inversed Brayton cycle has been rising until it has reached the value of $\eta_{el-IBC} = 15.3\%$ for the expansion ratio equal $\Pi = 560$. It corresponds to the condensation pressure at

Table 1. Thermodynamic parameters of components of the medium in the characteristic points for the condenser pressure at the level of $p_{3^{in}} = 7.8$ kPa.

Point	t	p	x	$\dot{m}$	Mole fraction				
					O_2	H_2O	N_2	CO_2	NO_x
	[°C]	[kPa]	[–]	[kg/s]	[–]				
1	21	103.4	1.00	51.8	0.989	0.000	0.011	0.000	0.000
2	822	4050.0	1.00	51.8	0.989	0.000	0.011	0.000	0.000
3	1338	4000.0	1.00	182.3	0.000	0.908	0.002	0.089	0.000
4	641	101.3	1.00	182.3	0.000	0.908	0.002	0.089	0.000
2^{in}	302	7.8	1.00	182.3	0.000	0.908	0.002	0.089	0.000
2^{in}_a	150	7.8	1.00	182.3	0.000	0.908	0.002	0.089	0.000
3^{in}	30	7.8	0.93	50.8	0.001	0.504	0.011	0.484	0.000
4^{in}	226	101.3	1.00	50.8	0.001	0.504	0.011	0.484	0.000
4^{in}_a	60	101.3	0.60	50.8	0.001	0.504	0.011	0.484	0.000
5^{in}	30	101.3	0.99	36.4	0.003	0.042	0.021	0.934	0.000
6	155	8000.0	1.00	35.8	0.003	0.002	0.022	0.973	0.000
7	30	7.8	0.00	131.5	0.000	1.000	0.000	0.000	0.000
8	30	7.8	0.00	117.7	0.000	1.000	0.000	0.000	0.000
9	34	4000.0	0.00	117.7	0.000	1.000	0.000	0.000	0.000
10	129	4000.0	0.00	117.7	0.000	1.000	0.000	0.000	0.000
11	214	4000.0	0.00	117.7	0.000	1.000	0.000	0.000	0.000

the level of $p^{3^{in}} = 7$ kPa. In turn, the optimal value of the efficiency of the whole cycle reached at the expansion ratio equal $\Pi = 520$, which conforms to the condenser pressure at the level of $p^{3^{in}} = 7.8$ kPa. Additionally, the whole system efficiency zooms down for about 8.66% because of the oxygen production (6.38%) and CO_2 escapement (2.28%).

In the Fig. 4 the correlation of the temperature in the combustion chamber and on the turbines outlet was presented, for inversed Brayton cycle. As it is shown in the picture presented below, the temperature in the combustion chamber correlates to the regeneration level.

It ought to be added that CFM type numerical tool gives a possibility to model combined gas-steam turbine cycles, what has recently been demonstrated in articles [15,31,32].

It should be emphasized that the carbon dioxide capture from the exhaust containing steam and CO_2 is rather simple comparing to other pre- and post-combustion methods, being in use. The energy consumption amounts to $\beta = 0.248$ kW/kgO_2. Obtained value of the energy consumption corresponds to values $\beta = 0.247$ and 0.250 given in [13,11].

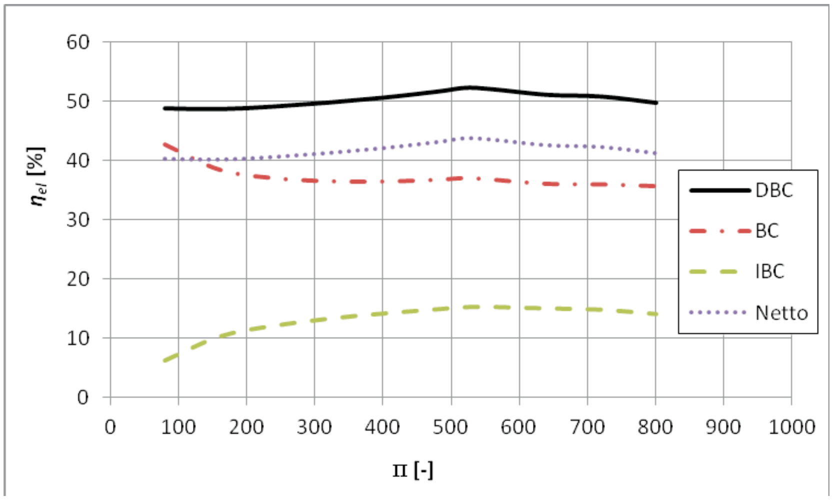

Figure 3. Dependency of electrical efficiency of the whole system $\eta_{el-netto}$, Brayton cycle efficiency η_{el-BC}; inversed Brayton cycle efficiency η_{el-IBC} and double Brayton cycle efficiency η_{el-DBC} against expansion ratio Π.

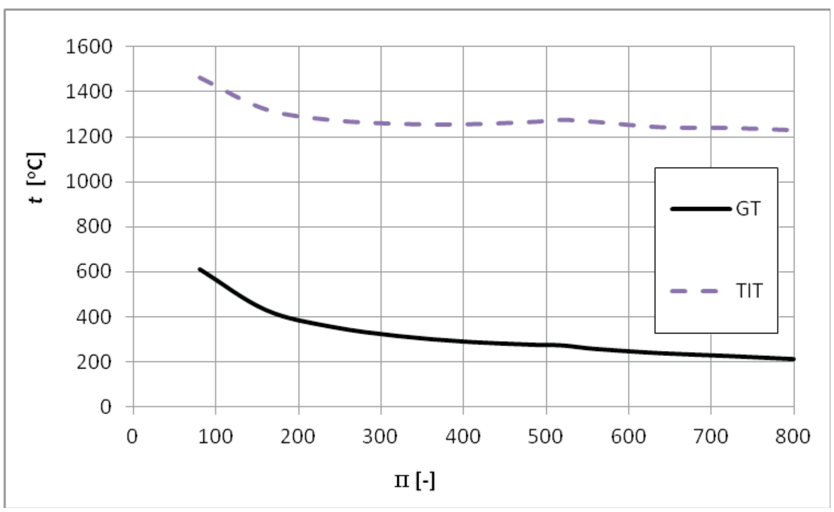

Figure 4. Dependency of outlet temperature of gas-steam turbine $t_{GT} = t_{2in}$ and temperature inlet turbine $t_{TIT} = t_3$ against expansion ratio Π.

5 Conclusion

The numerical analysis has shown that total energy output notably grows as the inversed Brayton cycle is being used. The highest netto efficiency of double Brayton cycle with oxy combustion and capture CO_2, at the level of $\eta_{el-netto} = 43.67\%$, was reached at the condenser pressure equal to $p_{3in} = 7.8$ kPa. However, the efficiency of the double Brayton cycle is equal to $\eta_{el-DBC} = 52.3\%$. The decrease of the efficiency is caused by the oxygen producing (6.38%) and capture the CO_2 (2.28%).The indubitable advantage of the double Brayton cycle with oxy combustion and CO_2 capture is the lack of pollution emissions such as NO_x and CO_2.

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