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Analysis of Allam Cycle Performance from Thermodynamic and Energy Point of View

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ABSTRACT

The Allam Cycle is based on combustion using pure oxygen instead of ambient air and the working fluid of this cycle is carbon dioxide. According to the results of the validation part of the initial simulation, the efficiency of the supercritical carbon dioxide cycle with three cooling stages in the compression part (in non-optimal and initial state) is 54%, which is approximately 4% of the cycle efficiency. By reducing the inlet fluid pressure to the pump from 75.38 to 73.43 bar, the cycle efficiency increases from 53.9 to 54. According to the second part of the results, which shows the effect of combustion chamber temperature (in the range of 800° C to 1300° C) on cycle performance, by increasing the combustion chamber temperature from 800° C to 1200 ° C, the cycle efficiency increases from 44.61 to 61.38. Also, the highest efficiency of the Brayton cycle is obtained in the pressure ratio of 20, which is approximately equal to 38% for the cycle with real specifications, while the highest efficiency is obtained in the Allam cycle with a pressure ratio of 10, which is about 55%. Therefore, in addition to being able to absorb 100% of carbon dioxide, the Allam cycle has a much higher efficiency than the Brayton cycle.

Keywords: Gas Turbine, the Allam Cycle, Brayton Cycle, Carbon Dioxide, Pressure Ratio

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1. INTRODUCTION

Zhang et al. (2006) proposed a new LNG power unit with exergy and net energy efficiencies above 65% and 50%, respectively. The total area of the required heat exchanger is about 460 square meters for each megawatt of electricity generated. In addition to the electricity and carbon dioxide consumed, the by-products of the unit are water, liquid nitrogen and argon [1]. Anderson et al. (2008) proposed a new system. Oxy-fuel units have a high amount of water, 200 ° C water vapor and carbon dioxide that can be used as cooling fluid inside the combustion chamber. For the first generation, a 170 MPa turbine without a compressor is installed to operate in an oxy-fuel combustion chamber with a pressure above 170 MPa. The inlet gas temperature of 700 ° C was selected to eliminate the need for turbine cooling [2]. Fiaschi et al.

(2009) in a study entitled " Performance of an oxy-fuel combustion CO2 power cycle including blade cooling " compared different systems for carbon dioxide capture from technical and economic perspectives [3]. Climate change is driven by the accumulation of greenhouse gases in the atmosphere. Human activities lead to the emission of greenhouse gases in various ways, including deforestation and the combustion of fossil fuels for energy. In the fight against climate change, work aimed at reducing emissions, stopping their effects and diminishing future consequences is known as mitigation. There is no single solution, but the development of carbon capture and sequestration technology could play an important role in addressing this issue.

In 2013, Allam and colleagues introduced a new system. Using a power generation cycle, they sought to generate electricity from fossil fuels at a price competitive with existing power plants. They were also looking for carbon sequestration technologies that could eliminate the environmental pollution of the power plant without reducing the cycle performance compared to conventional power generation cycles [4]. Francesco et al. Reviewed and compared all published works on the subject, including different concepts of the cycle (independently and in combination with other cycles).Obviously, this large heterogeneity of the available data (especially the considered temperatures and pressures) makes it impossible to make a fair comparison between the configurations examined [5]. Martin et al. Reviewed the most advanced sCO2 power generation systems with a focus on technical and operational issues. Following a review of the historical background and thermodynamic aspects, emphasis was placed on the discussion of turbocharged engines, heat exchangers, materials, and control system design, with priority given to experimental samples [6]. Damiano et al. stated that since supercritical carbon dioxide cycles are considered a suitable candidate for the next generation of nuclear power plant energy conversion systems, a lead-cooled fast reactor will be used as a reference in the analysis. They chose themselves. The aim of their study was to compare two different thermal cycles in a nuclear power plant conversion system [7]. Luis et al. analyzed the characteristics and performance of a supercritical CO2 cycle with multiple heating sources in centralized solar power plants. The new solar field had a similar configuration to the solar tower, but the receiver and heliostat were divided into two parts, and each part had different requirements in terms of concentration, fluid temperature, and heat flux. Flexibility of the multi-heating structure to efficiently solve constraints Supercritical cycles were very useful. Multiple heating power plants had higher efficiencies than power plants with standard solar towers and supercritical cycles [8]. Yoonhan et al. Studied the benefits of the S-CO2 cycle. In this study, several heat sources, including nuclear fuel, fossil fuels, wasted heat, and renewable heat sources such as solar thermal cells were investigated [9]. Dhinesh et al. Performed multi-objective optimization to compare sCO2 cycles and provided performance prediction maps. In this study, a new sCO2 cycle is proposed that improves productivity by 1.4%. They show that when the pressure ratio is considered as a design variable to optimize the overall performance of the plant, the performance of the plant improves. In their study, a new sCO2 cycle configuration was proposed [10]. Chenchen et al. Performed thermodynamic analysis of operating parameters, including temperature difference, pressure, turbine inlet temperature, reheating steps and parameters, as well as compressor inlet pressure and temperature [11]. Charlotte et al. presented a study on oxygen separation and power generation and showed that adding oxygen storage to these power plants would save surplus renewable energy production. Preliminary findings showed that oxygen storage could be valuable for both factory operators and system operators. In this model, with a bypass heat source, 58.0% net efficiency was achieved [12]. Wen et al. Proposed a new scheme of the Allam cycle with reheating, in this study it is shown that the net efficiency of the Allam optimization cycle with reheating is up to 49.32%. The proposed cycle had a higher net power net and net specific work. The results showed that the minimum cycle temperature and the second combustion outlet temperature have a significant effect on the cycle performance, while the maximum cycle pressure has the least effect on the cycle performance. The highest exergy degradation in an optimized cycle results from two combustions [13]. Jing et al. Performed an experimental analysis for a coal Allam cycle. Most exergy destruction occurs inside the gas injection device and then combustion. The efficiency of the cycle using coal is 22% lower than that of natural gas. The highest rate of exergy destruction occurs within the gas injection device, followed by exergy destruction of the combustion chamber, air separation unit, and turbine, respectively. In addition, the results of the experimental analysis in this study are compared with the results of the Brayton cycle. This study showed that turbine inlet pressure, outlet pressure and isentropic efficiency have significant effects on overall efficiency [14]. Zaryab et al. Proposed a new system in which oxy combustion is recycled as a temperature regulator and excess CO2 produced can be absorbed and stored. To adjust the cycle load, different load control strategies were proposed. These control strategies vary in different load cycle conditions. This study showed that efficiency can only be achieved by optimally adjusting the compressor guide vanes and the minimum cycle pressure [15]. Zilong et al. Integrated the power generation cycle with CO2 capture. In their design, the efficiency was equal to 48.05% with a turbine input of 30 MPa and 900 ° C. In this design, zero CO2 emissions and maximum load were proposed and investigated, and also the effect of turbine parameters on cycle performance was investigated [16]. Ahmad et al. Studied the important research gaps related to supercritical carbon dioxide (sCO2) power cycles. This study was on the disadvantages of adding additional components, high operating temperature and direct use of oxy combustion [17].

One of the important points about the Allam cycle is the possibility of combining this system with other energy systems. For example, Abbaspour and Saraei in a study optimized the combined CCHP system with the Brayton system. In the present study, the aim is to simulate the new Allam cycle and compare it with the Brayton cycle, and then by examining the system parameters, the optimal state of expression is determined. [18]

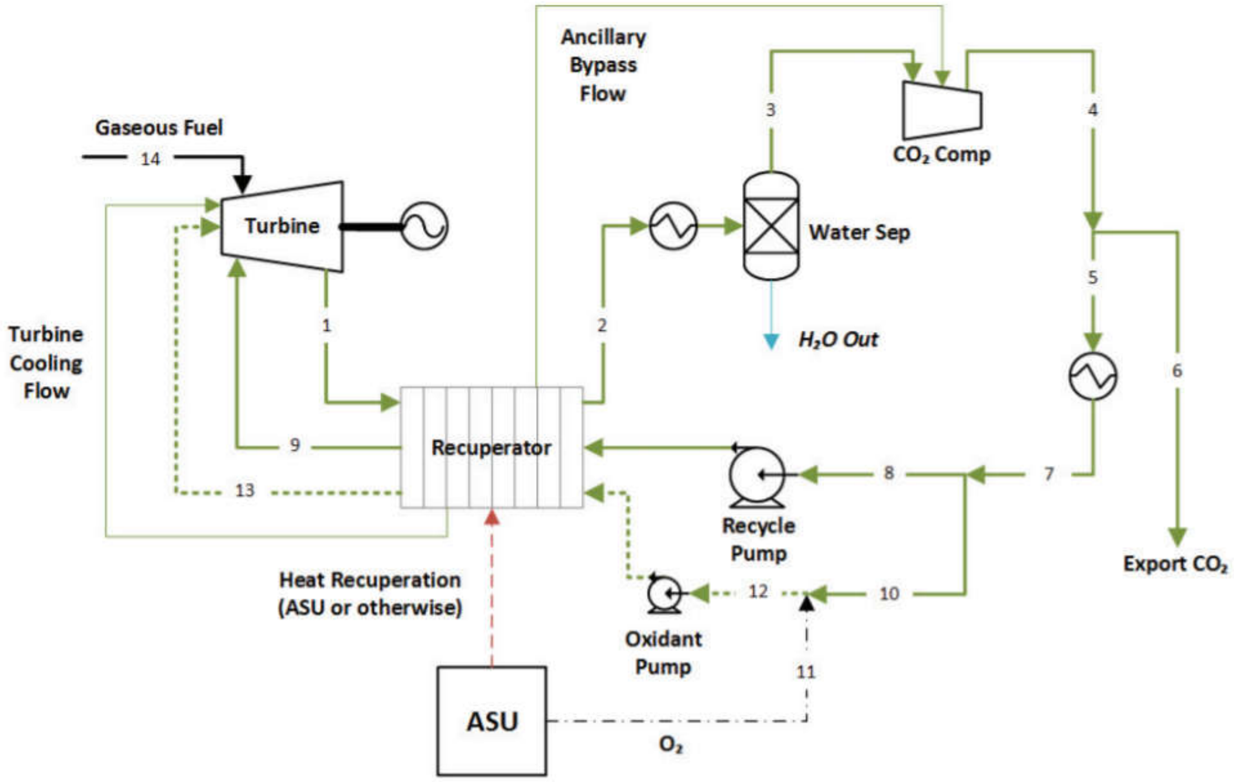

Figure (1): Schematic of power generation through the Allam cycle, adapted from Allam et al, [19].

2. SPECIFICATIONS OF CARBON DIOXIDE

Carbon dioxide has many advantages as a working fluid in power generation cycles, including its relatively low critical pressure. In fact, because of the low critical pressure, it is easier to liquefy carbon dioxide than other gases, such as helium. One of the most important factors that increase the efficiency of the gas turbine cycle is the gas expansion ratio in the turbine. In fact, the denser the gas entering the turbine, the higher the cycle efficiency. On the other hand, according to studies, the compaction work for carbon dioxide gas in the range of the critical point (30.98 ° C and 74 bar) and points above the critical point (pressure more than 74 bar) is significantly reduced. [20]

3. THE GOVERNING EQUATIONS

Using equations, changes in specific work and thermal efficiency can be shown as a function of pressure ratio and temperature ratio. By keeping the temperature ratio constant, the efficiency or performance can be calculated in terms of pressure ratio for different values of the isentropic efficiency of the compressor and turbine.

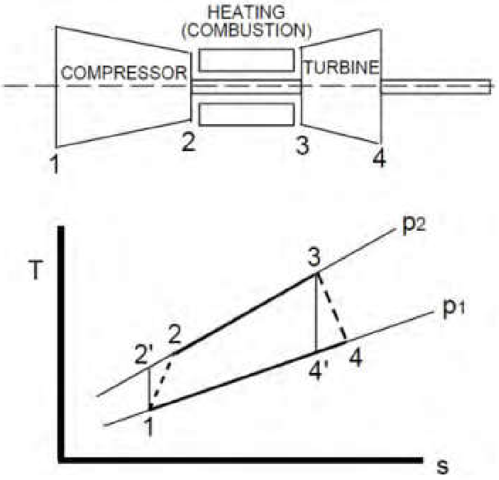

Figure (2): gas turbine cycle [21]

If the pressure ratio is equal to the following value, the maximum specific work is obtained.

$$r_{\mathrm{p}} = \left(\eta_c \eta_t \frac{T_3}{T_1}\right)^{\frac{\gamma}{\eta(\gamma-1)}} \tag{1}$$

For a two-stage compressor, it is assumed that P1, P2, and P3 are suction, discharge and intermediate pressures, respectively. Therefore, the total power consumption is equal to the sum of power consumption in two stages, which is as follows.

$$W_{\mathrm{ad}} = P_1 V_1 \frac{\gamma}{\gamma-1}\left[\left(\frac{P_i}{P_1}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] + P_i V_i \frac{\gamma}{\gamma-1}\left[\left(\frac{P_2}{P_i}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] \tag{2}$$

In compressor design, it is assumed that the intercooling equals the temperature of the inlet gas to the second stage equal to the temperature of the inlet gas to the first stage. In this case, the following relation is obtained:

$$P_1 V_1 = P_i V_i \tag{3}$$

In addition, power consumption is minimized when the following relationship is established:

$$\frac{\mathrm{dw}}{\mathrm{dp}_i} = 0 \tag{4}$$

$$\mathrm{r_{stg}} = \sqrt[N]{\frac{\mathrm{P}_2}{\mathrm{P}_1}} \tag{5}$$

In calculations, gases are assumed to be ideal.

4. MODELING

In this modeling, three stages of carbon dioxide compressor with intercooling are used. The following figure shows the cycle in Thermoflow software. The combustion section includes the fuel source, fuel compressor, combustion chamber and mixer of oxygen and carbon dioxide. After condensing, the fuel enters the combustion chamber and is then directed to the turbine.

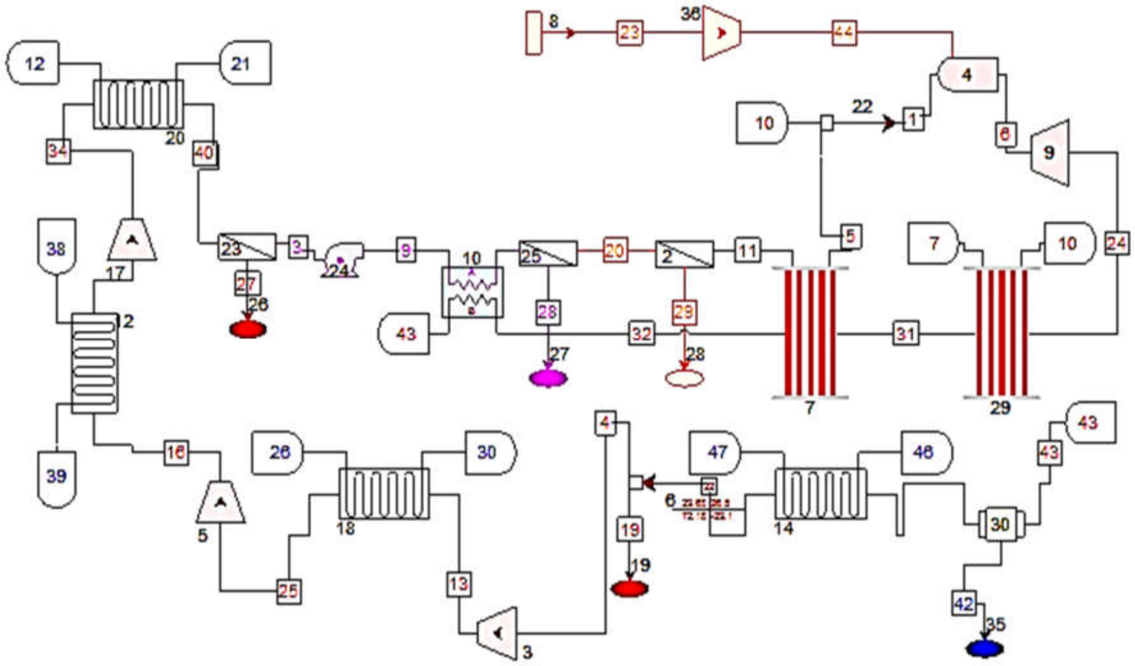

Figure (3): Modeling in Thermoflow software

In order to increase the efficiency in increasing the fluid pressure, the intercoolers of the compressor and the cooling of the inlet gas to the pump have been used. Cooling is designed so that the temperature of carbon dioxide cools to 20 ° C after each compression step.

5. RESULTS AND DISCUSSION

The results of the first simulation are related to the optimal state of the supercritical carbon dioxide cycle with two carbon dioxide compressors with two intercooling stages, which is the basis for the validation of the main cycle.

Table 1. Cycle simulation results in two modes, three and two compressor stages

Parameter	**Present work**	Yann Le Moullec, (2013) [22]
Gross Power	35027 kW	34081 kW
total power consumption of compressors	**3187 kW**	**3468 kW**
efficiency	**76.45 %**	**72.93%**
Fuel flow rate	0.983 kg/s	1.01 kg/s

In both cases considered in Table (1), the percentage of recurrent carbon dioxide in the mixer is equal to 93.7%. Also in these two cases, the output pressure from the last compressor of carbon dioxide (carbon dioxide pressure before the pump) is equal to 76.7 bar. As illustrated in the Table (1), the efficiency of the supercritical carbon dioxide cycle with three stages of cooling in the pressure section (in non-optimal and initial state) is 53.98%, which is 4% of Optimal cycle efficiency with two cooling steps is higher. In addition to indicating the correctness of the simulated cycle in the present work, it also indicates the importance of intercooling in this cycle. In fact, in this case, with the addition of intercooling from 2 to 3, due to a 0.4% increase in cycle efficiency, the amount of fuel consumed is reduced from 1.01 to 0.983 kg/s.
According to the results obtained in Table (1), the total power consumption of compressors, with the addition of intermediate cooling from 2 to 3, has decreased from 3468 kW to 3187 kW.

In the following discussion, the effect of inlet pressure to the pump, combustion chamber temperature and turbine pressure ratio on the cycle efficiency is investigated.

5-1- Fluid pressure effect

In this section, the effect of inlet fluid pressure to the pump or outlet pressure of the last compressor on the cycle performance is investigated. By increasing the number of cooling steps in the compression part of the cycle, the carbon dioxide output temperature from the last stage of the compressors decreases from 65.41 ° C to 51.02 ° C. Therefore, in order to increase the cycle performance, the output pressure of the final stage compressor can be reduced more than before. By applying this task in the present simulation and implementing the cycle in the 5 modes shown in the diagram below, the cycle performance is investigated. According to Figure (4), which shows the effect of inlet pressure to the pump on the performance of the cycle, by reducing the inlet pressure to the pump from 75.38 to 73.43 bar, the efficiency of the cycle increases from 53.93 to 53.98.

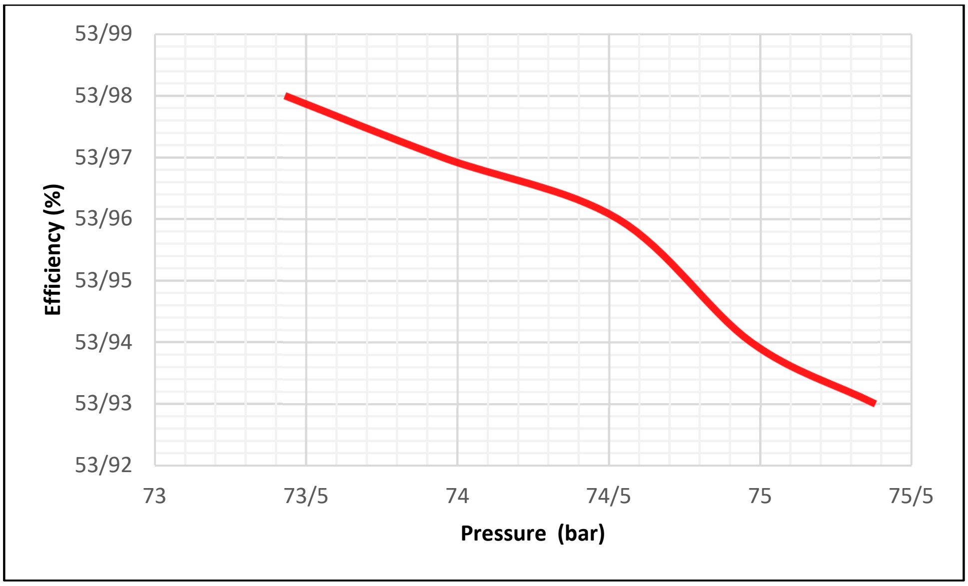

Figure (4): The effect of pressure on the efficiency of the Allam cycle

5-2- The effect of combustion chamber temperature

In this section, the aim is to investigate the effect of combustion chamber temperature in the range of 800 to 1300 on the cycle efficiency. For this purpose, the cycle performance in 6 different modes is investigated according to the following diagram. In all these cases, the pressure ratio is 9.8, the output pressure of the third compressor is 74 bar and the percentage of carbon dioxide returned in the mixer is 94.8%.

According to Figure 5, which shows the effect of combustion chamber temperature on cycle performance, by increasing the combustion chamber temperature from 800° C to 1200 ° C, the efficiency of the cycle increases from 44.61 to 61.38.

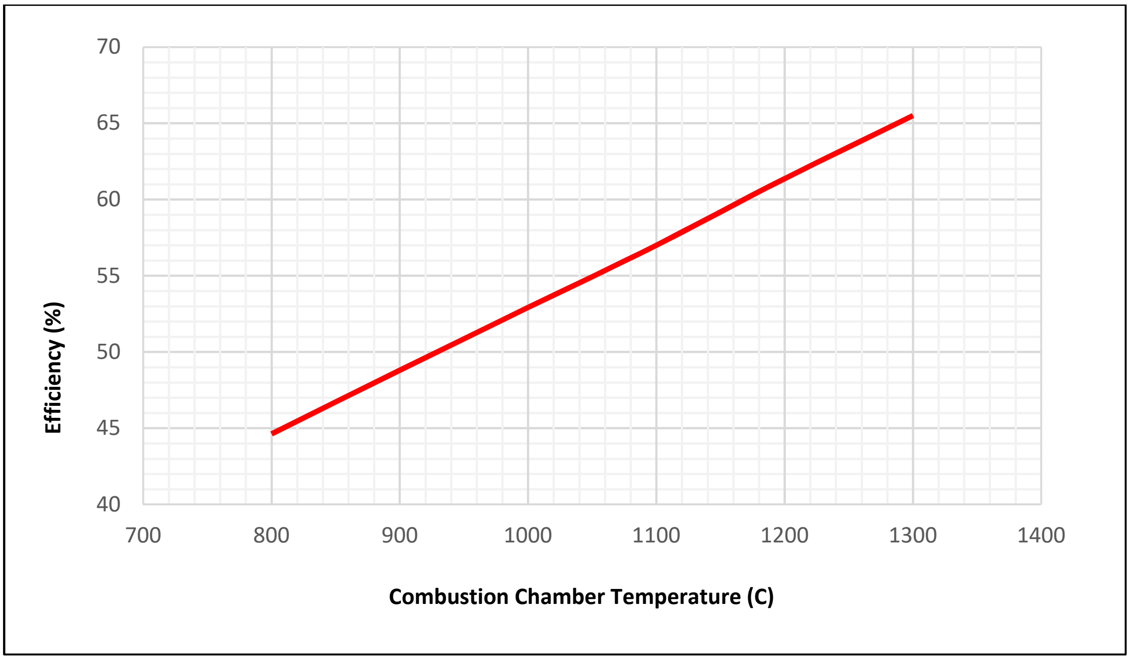

Figure (5): The effect of combustion chamber temperature on the efficiency of the cycle

5-3- The effect of pressure ratio

In this section, the effect of turbine pressure ratio in three different modes is investigated. These three states are related to the chamber temperature of 900^0 C , 1000^0 C and 1100 ^{0} C. In all these cases, the output pressure of the third compressor is 73.43 bar and the percentage of carbon dioxide returning to the mixer is 94.8%.

The results obtained in relation to the cycle efficiency in these three cases are shown in the following diagram. As can be seen, by increasing the pressure ratio from 2 to 9.8, the cycle efficiency in the first, second and third modes increases to 32.9, 32.97 and 32.55%, respectively. These values are almost equal. In fact, according to these results, as the pressure ratio increases, the efficiency change is independent of the combustion chamber temperature. Also, the maximum efficiency is related to the pressure ratio of 9.8, and for a ratio of pressures higher than this value, the efficiency is fixed, and further increase of the pressure ratio will even reduce the cycle efficiency. (Series1: 900^0 C, Series2: 1000^0 C and Series3: 1100 ^{0} C)

Figure 7 shows the thermal efficiency of the Brayton cycle in terms of pressure ratio.

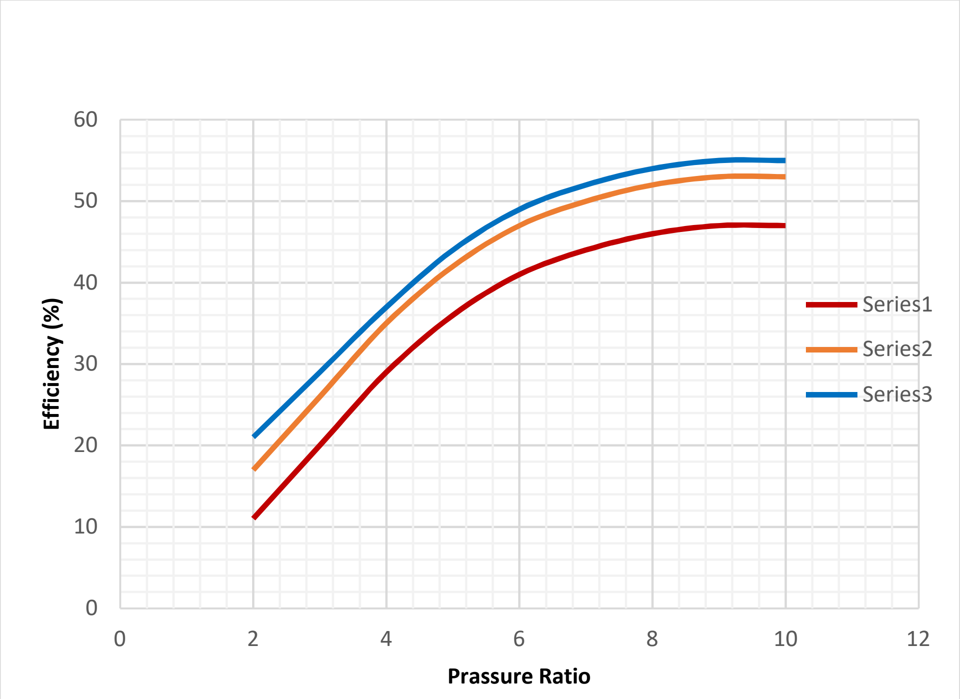

Figure (6): The effect of combustion chamber temperature on the overall efficiency of the cycle for three modes (Series1: 900^0 C, Series2: 1000^0 C and Series3: 1100 ^{0} C)

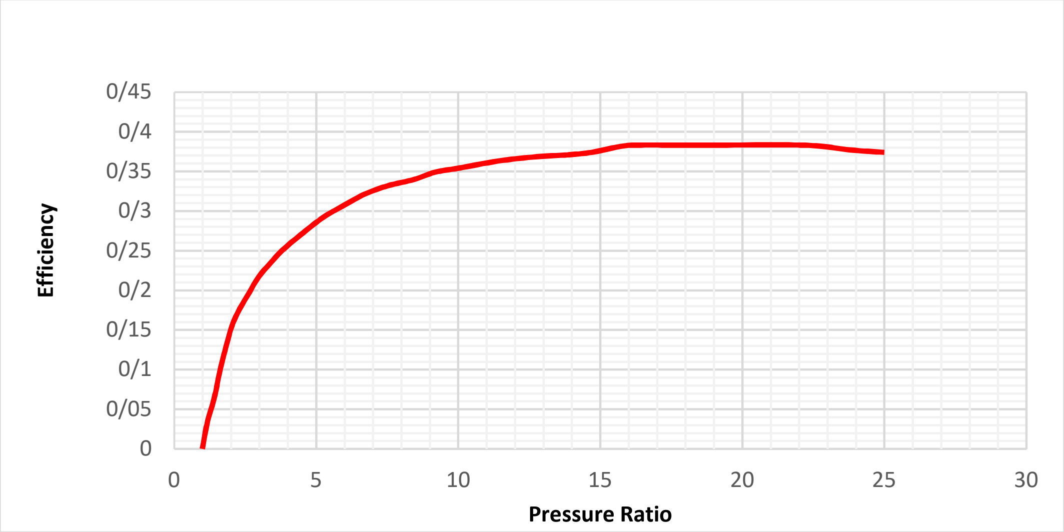

Figure 7. Efficiency in terms of pressure ratio in the Brayton gas turbine cycle

Figure (8) shows the dimensionless work in terms of pressure ratio in the Brayton cycle. As can be seen, the higher the temperature ratio, the higher the compression ratio at which the most work is produced. Therefore, if the temperature of the combustion chamber is higher, a higher quality turbine will be needed to provide the optimal pressure ratio. Figure 9 also shows the thermal efficiency and pressure ratio.

Special work is related to the size of the gas turbine. If the gas turbine is specially designed for low work, it must be made larger for a certain amount of actual output power to receive more air.

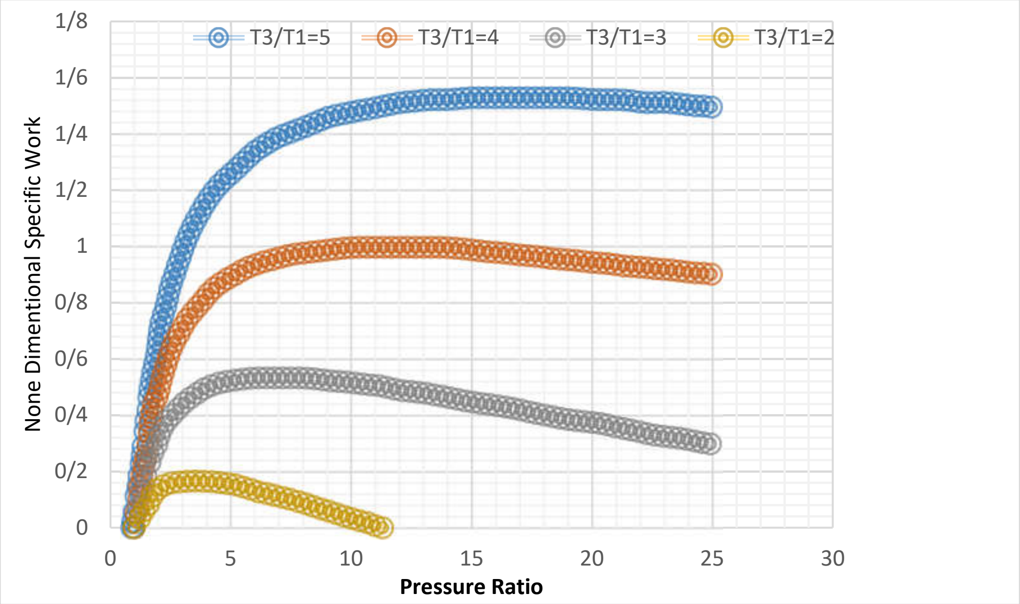

Figure (8): Specific dimensionless operation in terms of pressure ratio in the Brayton gas turbine cycle

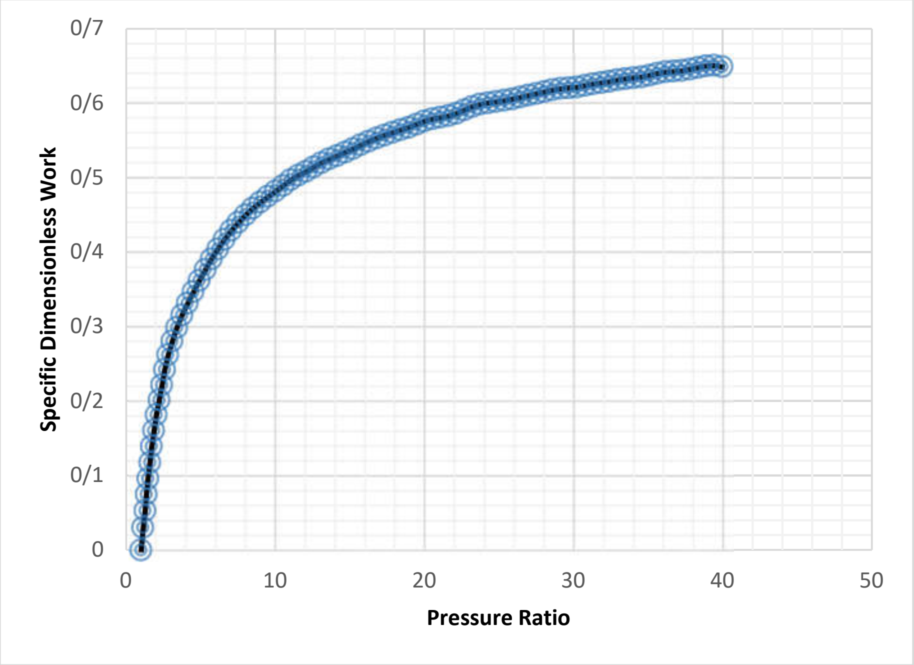

Figure (9): specific dimensionless work in terms of pressure ratio in the Brayton gas turbine cycle

6- CONCLUSION

In this study, the main parts of the Allam cycle were simulated with Thermoflow software and compared with the Brayton cycle. This cycle, which operates on the basis of the type of combustion using pure oxygen instead of ambient air, is a cycle with a carbon dioxide working fluid. According to the results of the validation part of the initial simulation, the efficiency of the supercritical carbon dioxide cycle with three cooling stages in the compression part (in non-optimal and initial state) is 53.98%, which is approximately 4% of the cycle efficiency. Optimal with two cooling steps, more. In the continuation of this research, the effect of three parameters of carbon dioxide pressure coming out of the third compressor, turbine pressure ratio, outlet fluid temperature of the combustion chamber on the cycle performance is investigated.

According to the first part of the results, which shows the effect of inlet fluid pressure to the pump on cycle performance, by reducing the inlet fluid pressure to the pump from 75.38 to 73.43 bar, the cycle efficiency increases from 53.93 to 53.98. According to the second part of the results, which shows the effect of combustion chamber temperature (in the range of 800° C to 1300° C) on cycle performance, by increasing the combustion chamber temperature from 800° C to 1200 ° C, the cycle efficiency increases from 44.61 to 61.38. Up to 1100 ° C, the complete cycle is implemented, but for 1100 ° C and below, the first heater, which is concerned with oxygen heating, is removed from the cycle. According to the third part of the results, which shows the effect of pressure ratio (at three different temperatures for combustion chamber outlets 900° C, 1000° C and 1100° C) on cycle performance, by increasing the pressure ratio from 2 to 9.8, the cycle efficiency in the first cases second and third increase to 32.9%, 32.97% and 32.55%, respectively. Also, the maximum efficiency is related to the pressure ratio of 9.9, and for a ratio of pressures higher than this value, the efficiency is constant, and further increase of the pressure ratio will even reduce the cycle efficiency. According to the results, the highest efficiency of the Brayton cycle is obtained in the pressure ratio of 20, which is approximately equal to 38% for the cycle with real specifications, while the highest efficiency in the Allam cycle is obtained with the pressure ratio of 10, which is about 55%. Therefore, in addition to being able to absorb 100% of carbon dioxide, the Allam cycle has a much higher efficiency than the Brayton cycle.

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