Influence of the initial parameters on the thermodynamic efficiency of carbon dioxide power cycles

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Abstract. This paper considers the main CO₂ power cycle configurations based on the Allam and JIHT cycles. In particular, the authors of the article have proposed new configurations of the power cycle. The efficiency of these cycles is studied as a function of the initial temperature and pressure of the working fluid. The thermodynamic efficiency can reach 65–66%. It is shown that the presence of regenerative heat transfer and the properties of supercritical carbon dioxide have a great influence on the thermal efficiency.

Introduction
At present, technologies decreasing the carbon footprint are becoming more and more relevant. The reason for this is the efforts of the world community to reduce anthropogenic greenhouse gas emissions in furtherance of sustainable development and global warming mitigation [1–3].

Therefore, nonconventional and renewable power sources that reduce the consumption of hydrocarbon fuels have been actively developed in power engineering. However, it is equally important to develop technical solutions in the field of using traditional fossil fuels that can reduce or completely eliminate the carbon footprint. These technical solutions include carbon dioxide based power cycles, in which the working fluid of the cycle is supercritical carbon dioxide. Currently, the best-known and widely described in the literature cycles are the JIHT cycle [4] and the Allam cycle [5], which use almost pure carbon dioxide as a working fluid, and differ from each other in that condensation of the working fluid occurs in the JIHT cycle and does not occur in the Allam cycle. In addition, there is the theoretical Graz cycle [6], which uses a mixture of carbon dioxide and water vapor as a working fluid. In all cases, CO₂ is utilized by liquefaction and disposal. Gas is used as a fuel, and oxygen as an oxidizer; therefore, the combustion products are only CO₂ and water vapor resulting from combustion of fuel hydrogen. After the expansion of the working fluid in the turbine, water condenses and pure carbon dioxide remains, which can be recycled in another process or disposed. Therefore, the study of carbon dioxide power cycles is an urgent task.

Research object and method
In this paper, the main carbon dioxide power cycle configurations are considered (see Figure 1).
Cycle 1 is a simplified variant of the JIHT cycle, and cycle 4 is a simplified variant of the Allam cycle. Cycle configurations 2 and 3 are proposed by the authors of the paper. These cycle configurations and features of their operation are described in more detail in [7].

Figure 1. Thermodynamic CO₂ cycles and schematic diagrams of power generation

The efficiency of these cycle configurations (Figure 1) was analyzed in [7]. The calculation showed that the thermal efficiency of all cycles exceeds that of the traditional single-stage cycles used today in the power industry. The efficiency of the presented cycle variants is 57–63% at the initial parameters (temperature of 1300 °C, pressure of 300 bar) similar to those declared in the Allam cycle [5]. The final pressures of the considered cycle variants differ from each other, Table 1. This is explained by the technological features of each cycle [7].

Table 1. Final pressure of the considered cycles

| Cycle number | 1   | 2   | 3   | 4   |
|--------------|-----|-----|-----|-----|
| Final pressure, bar | 57,2 | 75  | 30  | 30  |

It is also important that the thermal efficiency of the cycles proposed by the authors of the article is not only comparable to but in some cases even higher than that of the Allam and JIHT cycles widely described in the literature. However, these variants of cycles have not been reported in the literature, so it is advisable to study them further.

Here we analyze the thermodynamic efficiency of the cycles depending on the initial pressure over a wide temperature range. At this stage, the efficiency of possible equipment that can be used at a real power plant, costs for own needs (for example, for fuel supply) are not considered. Only costs of
compression (in isentropic process) of CO₂ removed from the cycle are taken into account. The calculation method used for this is based on the material and heat balance equations for the combustion chamber and the regenerative system described in [7] and thermodynamic tables and phase diagrams for CO₂ and water vapor. Methane is selected as fuel for calculation in all cycle configurations.

**Results and discussions**

The thermal efficiency of the cycles is calculated in the temperature range 1000–1500 °C for three initial pressures: 200, 300, and 400 bar. The calculation results are presented graphically in Figure 2. The numbers on the curves corresponds to the type of cycle in Figure 1.

![Figure 2](image)

**Figure 2.** Curves of the thermal efficiency of cycles versus initial temperature at different initial pressures of the working fluid. Legend: curves with squares correspond to an initial pressure of 400 bar, curves with triangles to 300 bar, and curves with circles to 200 bar. The number on the line indicates the type of cycle.

At an initial pressure of 200 and 300 bar over almost the entire temperature range, cycle 2, entirely located in the zone of supercritical parameters and proposed by the authors of the paper, has the greatest efficiency. Cycle 1 (simplified JIHT, with condensation) ranks second in efficiency, and cycle 4 (simplified Allam, without phase transition) ranks third. Cycle 3 shows the least efficiency. When the pressure rises to 400 bar, the cycle 1 (JIHT) has the greatest efficiency, cycle 2 (proposed by the authors) ranks the second.

It can be seen that as the initial pressure increases from 200 to 400 bar in the investigated temperature range 1000–1500 °C, the efficiency of cycles 1, 2, and 4 increases, and the thermal efficiency of cycle 3 decreases. This is due to the fact that cycle 3 involves only compression of carbon dioxide in the compressor to the operating pressure of the cycle. This variant is much more energy intensive and leads to the fact that the increase in the heat drop due to an increase in the initial pressure is slower than the increase in the cost of compressing the working fluid in the compressor. As the pressure increases from 200 to 400 bar, the available heat drop increases by a factor of 1.33, and the compression power consumption increases by a factor of 1.54.
In cycles 1, 2, and 4, the pressure rises in two stages: first in the compressor to 75 bar and then in the pump to the operating pressure. Therefore, in these cycle configurations, there is no sharp increase in power consumption for compression as the initial pressure increases.

At the same time, cycles 1, 2, and 4 are characterized by an inflection of the efficiency curves. This is due to the influence of the heat regenerator and the properties of carbon dioxide. This happens as follows. An increase in the initial temperature of the working fluid leads to the need to burn more fuel, which results in an increase in combustion products and an increase in the fraction $\delta$ of CO$_2$ introduced into the cycle from fuel combustion. Then exactly this amount of carbon dioxide is removed from the cycle and disposed of after expansion in the turbine and passage through the regenerative heat exchanger. The CO$_2$ flow reduced by the value of $\delta$ returns to the combustion chamber and is supplemented with combustion products, and the cycle repeats. However, before entering the combustion chamber, this flow is heated in the regenerative heat exchanger by the carbon dioxide flow coming out of the turbine, which exceeds the heated flow by the value of $\delta$ and the mass of water vapor formed from the oxidation of fuel hydrogen. At the same time, the heated CO$_2$ stream is under the operating pressure of the cycle (about 10 times higher than the turbine exhaust pressure) and has a higher heat capacity due to the properties of CO$_2$. Usually, the difference in heat capacity allows the heated flow to receive all heat of the larger heating flow of CO$_2$ and water vapor. However, at a certain moment, the quantity $\delta$ reaches such a value that the heated CO$_2$ stream is no longer able to accept the entire amount of heat of the regenerator, and part of the heat is forced into the atmosphere and does not remain in the cycle, which leads to a decrease in the overall thermodynamic efficiency and the appearance of an inflection in the curve.

As the initial pressure of the cycle increases, the heat capacity of carbon dioxide also increases. This leads to the need to burn even more fuel to achieve a high temperature. Because of this, the value of $\delta$ increases over the entire range of initial temperatures, which leads to the fact that even at lower initial temperatures of CO$_2$, a situation arises where not all the heat of the working fluid coming out of the turbine is used by the regenerator. The inflection of the curve is shifted to the left.

For the same reason, the cycle efficiency curves for different initial pressures stick together as the initial temperature increases.

Conclusions
The main configurations of single-stage carbon dioxide power cycles were considered, and their thermodynamic efficiency was determined at various initial pressures (200, 300, 400 bar) in a wide range of initial temperatures (1000–1500°C). The thermodynamic efficiency can reach 65–66%, which is consistent with literature data on the well-known similar cycles (Allam cycle and JIHT cycle). It is shown that the presence of regenerative heat transfer and the properties of supercritical carbon dioxide have a great influence on the dependence of the thermal efficiency on the initial parameters, which requires a more detailed study when considering more complex cycle configurations.

References
[1] Meng-Tian Huang, Pan-Mao Zhai 2021 *Advances in Climate Change Research* **12**(2) 281-286
[2] D.M. Smith, A.A. Scaife, E. Hawkins et al. 2018 *Geophysical Research Letters*, **45**(21) 11895-11903
[3] Leung D Y C., Caramanna G, Maroto-Valer M M 2014 *Renew. Sustain. Energy Rev* **36** 426-443
[4] Kosoi A S, Zeigarnik Yu A, Popel’ O S, Sinkevich M V, Shterenberg V Ya 2018 *Thermal Engineering* **65**(9) 597-605
[5] Allam R, Martin S and others 2017 *Energy Procedia* **114** 5948-5966
[6] Wolfgang Sanz Graz Cycle. – A Zero Emission Power Plant for CCS (Carbon Capture and Storage) http://www.graz-cycle.tugraz.at/
[7] Shchinnikov P, Borush O, Frantseva A, Sadkin I 2021 *E3S Web of Conferences* **289** 02001