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Supercritical Carbon Dioxide Applications for Energy Conversion Systems

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Abstract

In the present paper, the possibility of increasing the thermodynamic efficiency of an electric energy production plant, by using an advanced energy conversion system based on supercritical carbon dioxide (S-CO2) as working fluid, has been analyzed. Since the supercritical carbon dioxide cycles are being considered as a favorable candidate for the next generation of nuclear power plant energy conversion systems, a lead cooled fast reactor has been selected as reference in the present analyses. The main aim of the present study is to compare two different S-CO2 thermal cycles applied on the conversion system of a nuclear power plant. The reference Lead cooled Fast Reactor (LFR) used for the present analyses is the ALFRED reactor, which has a thermal power of 300 MW and it is considered the scaled down prototype of the industrial European Lead Fast Reactor (ELFR).

Thermodynamic cycles selected for the present study are a Recompression Cycle and a Brayton Cycle with Regeneration. Each of them has been analyzed under several design conditions regarding the maximum pressure and the regeneration coefficient. Among different design conditions, the solution allowing the maximization of the overall efficiency has been identified. Thermodynamic analyses have been carried out with GateCycle™ v. 6.1.1, which is a General Electric software able to predict design and off-design performance of power plants.

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Keywords: SC-CO2; GateCycle; Supercritical Fluids.

1. Introduction

Supercritical carbon dioxide (SCO2) is currently used for may industrial and research applications because of its special characteristics.

After preliminary studies on SCO2 applications, during last few years a growing interest on its applications was found. An original research papers on S-CO2 applications on power cycles for power production was proposed in late '60s by Angelino [1] [2]. A lower temperature cycle, despite the cycle efficiency is not higher than an equivalent steam cycle, the simplicity and the compactness of systems provide advantage for many applications. At higher temperature cycles, CO2 shows higher efficiency and simplicity than a steam cycle. Moreover, Feher [3] proposed a S-CO2 power cycle operating completely above the CO2 critical pressure. The proposed cycle is regenerative and, in order to minimize the

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pumping work, the compression is in the liquid phase. This cycle has been developed at the MIT; because of cooling technical issues (very cold water is continuously needed), CO2 condensation is eliminated and the pump is replaced with a compressor. In order to minimize the compression work, this is carried out close to the critical point, where isobars are in a close-range.

Many papers, available in literature, present possible industrial applications of S-CO2. Chen et al. [4] proposed a comparison between CO2 and other organic fluids with respect to the ability of the respective power cycles to convert energy from low-temperature heat sources. Kim et al. [5] analyzed the potential of the S-CO2 cycles using both low and high temperature heat sources. Song et al. [6] proposed a trans-critical CO2 power cycle driven by solar energy.

Because of the relatively unknown properties of S-CO2, many base studies have been performed for the evaluation of its thermo-physical properties as well as its heat transfer characteristics. Studies are especially focused on the trans-critical region, where thermo-physical properties suddenly change. Many studies on these topics are available in literature (e.g. [6], [7], [8], [9], [10]).

Other possibilities of S-CO2 industrial applications concern with electrical production from nuclear reactors (e.g. [11]). The present paper is aimed at investigating the possibility of using S-CO2 as the working fluid for thermodynamic cycle of a nuclear plant. In particular, a thermodynamic analysis of two cycles has been carried out for the ALFRED fission reactor.

ALFRED (Advanced Lead Fast Reactor European Demonstrator) is a fast spectrum nuclear reactor, cooled by liquid lead, characterized by a thermal power of 300 MW. The lead coolant operative temperatures are included between 400 °C and 480 °C. In the thermodynamic analysis, cycles taken into account are:

- S-CO2 recompression cycle;
- S-CO2 Brayton cycle.

2. GateCycle™

In order to analyze advantages of each thermodynamic cycle and to carry out analyses under different operating conditions a specialized software has been used. In particular, the present analyses have been performed through the GateCycle™ computer program that is a General Electric software aimed at designing and assessing thermal power plants for both design and off-design conditions. The software combines a graphical interface with analytical thermodynamics models, heat transfer and fluid-mechanical processes.

The GateCycle™ computer program allows at simulating many thermodynamic cycles exploiting a user-friendly interface for the components selection and the cycle parameters definition [12]. Once the components are correctly connected to simulate the thermodynamic cycle, the GateCycle™ analysis module can be run. The software reads and analyzes connections and equipments and it identifies the cycle resolution order through the Flow sheet Decomposition procedure. Input values and cycle parameters consistency are checked to identify any errors. Each component/equipment is solved by means of specific models, following the order above identified.

The first step of the whole system simulation is completed when each components is resolved. The convergence of the whole system is checked by GateCycle™ at the end of each step. The convergence assessment foresees that each output variable has to match its value at the previous step within a user defined tolerance. Moreover, mass and energy balances have to be satisfied and each outlet parameter has to match with the same parameter passed as input to the downstream component within a user defined tolerance.

A typical GateCycle™ simulation converges within fifty system iterations. The computational time depends on the complexity of the model, the convergence tolerances selected, the number and complexity of macros and on the accuracy of the initial database values.

The following analyses have been carried out with GateCycle™ version 6.1.1.

3. Cycles Description

Currently, the most used thermodynamic power cycles for closed cycle engines are the Rankine cycle and the recuperated Brayton cycle. The main difference is that in the Rankine cycle the working fluid operates in its saturated region, while in the Brayton one, the working fluid is in its gas or supercritical phase.

In order to overcome typical limits related to the two abovementioned cycles, a S-CO2 recompression cycle has been proposed and analyzed. This is characterized by two regenerators, one at low temperature and the other at high temperature. These regenerators are characterized by two different flows to cope with the large variation of heat capacity of the cooler fluid flow.

According to the purpose of the present study, the primary heat source of the thermal cycle is the ALFRED nuclear reactor core. Because of this, the S-CO2 is heated into a dedicated heat exchanger, located within the reactor main vessel, which is in contact with the lead coolant.

In the paragraphs below, the reference cycles (i.e. S-CO2 recompression cycle and S-CO2 Brayton cycle) are presented. The present analysis has been performed with a constant regenerator efficiency equal to 0.9 and three different pressure levels: 18.25 MPa, 22.25 MPa and 25.25 MPa.

3.1. Model of the S-CO2 recompression cycle

In Fig. 1 the S-CO2 recompression cycle scheme and the GateCycle™ input are presented. A recompression cycle is characterized by the hot working fluid, coming from the heat source (RE), that reaches the gas turbine (T) where it expands. The S-CO2, which comes from turbine outlet, is cooled into two regenerators, the first at higher temperature (HT-R) and the second at lower temperature (LT-R), releasing heat to the cold leg high pressure stream. Downstream the LT-R, the S-CO2 is divided into two streams. The first stream is recompressed up to the high pressure into the auxiliary compressor (AC), while the second stream passes through a pre-cooler (P-C) and the main compressor (MC) before reaching the secondary side of the LT-R heat exchanger. The two streams are hence mixed before entering the HT-R, which precedes the heat source.

3.2. Model of the Brayton cycle

In Fig. 2 the S-CO2 Brayton cycle scheme and the GateCycle™ input are reported. In the Brayton cycle, the hot working fluid, which comes from the reactor (RE), expands in the turbine (T) where it produces energy. After expanding in the turbine, the S-CO2 is cooled into a regenerator (R). The flow passes through the cooler (P-C) and the main compressor (MC) before reaching the secondary side of the R heat exchanger.

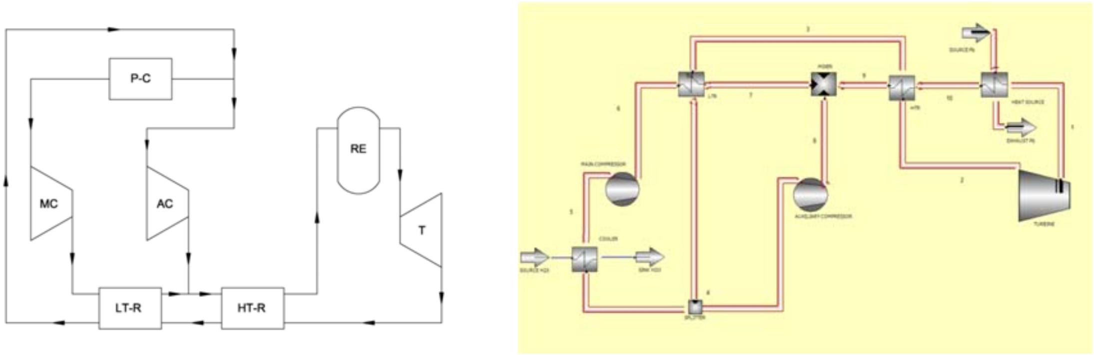

Fig. 1. a)S-CO2 recompression cycle scheme. b) GateCycle™ input.

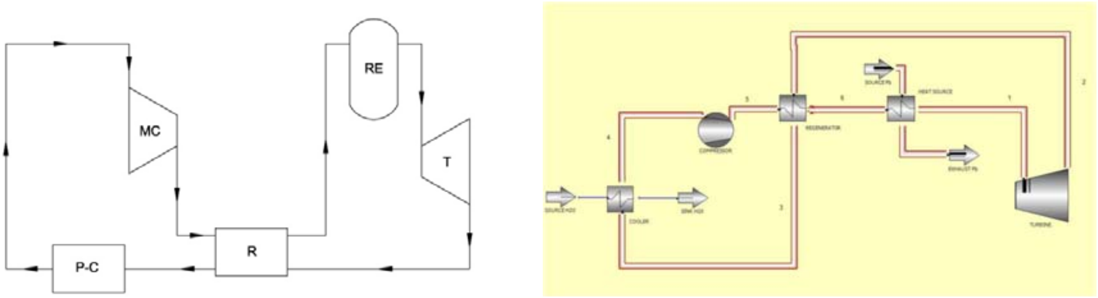

Fig. 2. a)S-CO2 Brayton cycle scheme. b) GateCycle™ input.

4. Results

As it is clearly visible, the S-CO2 recompression cycle presents higher efficiency, at all the analyzed pressures, compared to the S-CO2 Brayton cycle. This is especially due to the presence of two regenerators that operate at different temperature levels. Thanks to this solution, the LT-R allows at the recompression cycle highest efficiency because of its lower irreversibility if compared to the single regenerator of the Brayton cycle.

Concerning the present analysis and the dependence of the efficiency to the maximum operating pressure, it can be noted that the Brayton cycle is much more sensible to the maximum operating pressure. Increasing the maximum pressure from 18.25 MPa to 22.25 MPa the Brayton cycle efficiency improves of about 2.6%. A further increase in the maximum operative pressure, from 22.25 MPa to 25.25 MPa, generates a lower increase in the global efficiency: about 1.3% for the Brayton cycle.

The S-CO2 recompression cycle efficiency does not be strongly affected by the maximum operative pressure increasing. In this case, about 1.2% of global efficiency is gained passing from 18.25 MPa to 22.25 MPa and less than 0.5% passing from 22.25 MPa to 25.25 MPa.

In Fig. 3 the efficiency trends of S-CO2 recompressing and Brayton cycles, as function of the maximum pressure level, are shown. In Table 1 and Table 2 the main parameters are tabulated for the two analyzed cases.

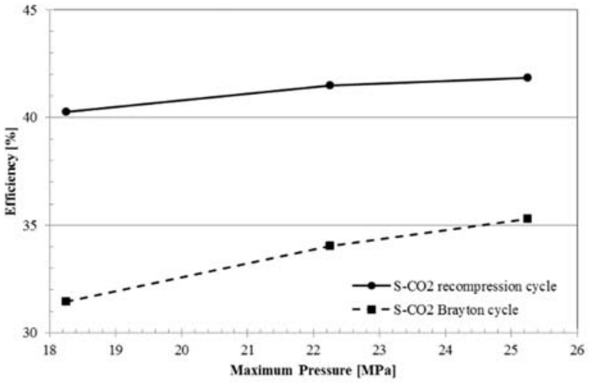

Fig. 3. S-CO2 Brayton cycle and S-CO2 recompression cycle efficiencies at different pressures.

Table 1. S-CO2 recompression cycle parameters at different pressure levels

		MAX pressure: 18.25 MPa			MAX pressure: 22.25 MPa			MAX pressure: 25.25 MPa		
From	to	T [K]	p [MPa]	h [kJ/kg]	T [K]	p [MPa]	h [kJ/kg]	T [K]	p [MPa]	h [kJ/kg]
RE	T	728.15	18.0	422.27	728.15	22.0	418.34	728.15	25.0	415.58
T	HT-R	626.74	7.6	316.17	603.94	7.6	290.11	589.52	7.6	273.69
HT-R	LT-R	455.66	7.5	122.22	473.81	7.5	142.91	485.13	7.5	155.77
LT-R	Splitter	351.60	7.5	-6.65	359.42	7.5	4.60	364.59	7.5	11.75
P-C	MC	304.15	7.4	-187.22	304.15	7.4	-187.22	304.15	7.4	-187.22
MC	LT-R	334.65	18.3	-169.11	342.22	22.3	-163.04	347.23	25.3	-158.63
LT-R	Mixer	438.72	18.2	53.67	456.61	22.2	65.39	467.78	25.2	72.83
AC	Mixer	434.60	18.2	47.38	463.89	22.2	76.35	483.34	25.2	96.06
Mixer	HT-R	436.98	18.2	51.02	459.46	22.2	69.71	473.59	25.2	81.61
HT-R	RE	583.39	18.2	244.97	567.20	22.2	216.90	558.28	25.2	199.54

Table 2. S-CO2 Brayton cycle parameters at different pressure levels

		maximum pressure: 18.25 MPa			maximum pressure: 22.25 MPa			maximum pressure: 25.25 MPa		
From	to	T [K]	p [MPa]	h [kJ/kg]	T [K]	p [MPa]	h [kJ/kg]	T [K]	p [MPa]	h [kJ/kg]
RE	T	728.15	18.1	422.22	728.15	22.1	418.30	728.15	25.1	415.54
T	R	625.69	7.5	315.06	602.97	7.5	289.10	588.59	7.5	272.73
R	P-C	357.03	7.5	1.22	363.23	7.5	9.89	367.20	7.5	15.30
P-C	MC	304.15	7.4	-187.22	304.15	7.4	-187.35	304.15	7.4	-187.22
MC	R	334.65	18.3	-169.11	342.16	22.3	-163.18	347.16	25.3	-158.77
R	RE	504.19	18.2	144.73	491.43	22.2	116.02	485.12	25.2	98.67

5. Conclusions

The S-CO2 recompression cycle efficiencies, at different pressures, are considerably higher than those obtained from the Brayton one. S-CO2 recompression cycle efficiency is always above the 40%, while the efficiencies of the Brayton cycle are lower. This is especially due to the reduction of losses in the LTR regenerator because of the mass flow rate split.

Increasing the maximum operative pressure, from 18.25 MPa up to 25.25 MPa, with a constant efficiency value of the regenerator equal to 0.9, greater efficiency values can be obtained. In particular, this is more evident for the Brayton cycle than in the recompressed one.

Acknowledgements

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