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Recuperated versus single-recuperator re-compressed supercritical CO_2 Brayton power cycles for DEMO fusion reactor based on dual coolant lithium lead blanket

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ABSTRACT

The EUROfusion research program is currently exploring alternative solutions for a future fusion power plant with DEMO (DEMOnstration Power Plant) prototype. One of the most important issues arising from a dual coolant lithium lead blanket-based reactor is the correct integration of the four thermal sources in order to achieve the highest electricity production. This study analyses the technical feasibility of supercritical CO_2 Brayton power cycles. Starting with a classical re-compressed cycle, which is taken as the baseline case, two alternative proposals are investigated. On the one hand, a modified re-compressed layout with only one recuperator is studied, and is found to achieve the same electric efficiency as that of the baseline case (34.6%). On the other hand, an optimised recuperated layout is proposed, which achieves a 33.6% electric efficiency. A parametric study is conducted in order to optimise the heat exchanger size. When the re-compressed layout is optimised, a loss of efficiency (5%) is experienced. In the case of the recuperated layout optimisation the efficiency loss is reduced to 3%, achieving a reduction in heat exchanger size of 2/3.

1. Introduction

Fusion reactors offer a promising option for future electricity generation technologies due to their short-life nuclear waste, zero CO_2 emission, and long-term natural resources (sea water for producing deuterium and lithium for producing tritium). However, this emergent technology poses a large number of challenges, including the materials involved, tritium permeation, safety analysis and remote handling [1]. Although these challenges are based on physical issues, there are also certain important engineering aspects, such as the conversion of thermal energy into electricity [2]. The DEMOnstration Power Plant (DEMO) is a project of the European Fusion Development Agreement (EFDA) which aims to build a prototype power plant at an operating scale (500 MWe) once the scientific challenges of the reactor have been tested in the International Tokamak Experimental Reactor (ITER) [1].

There are three thermal sources in a fusion reactor, each with a different temperature range. The main thermal source is the breeding blanket, where the tritium is produced from lithium. Depending on the breeding blanket's cooling medium, four blanket types are established: water cooled lithium lead (WCLL), helium cooled lithium lead (HCLL), dual cooled lithium lead (DCLL) and self cooled lithium lead (SCLL). The DCLL blanket provides a long-term design option with moderate temperatures (500 °C). It makes use of two coolants: a eutectic of lithium-lead (LL) and helium, the former being responsible for removing the majority of the heat (approximately 60%). The advantage of the DCLL lies in the absence of water, which results in issues regarding its interaction with tritium, and the fact that the heat removed by helium is only 40% of the total heat released by the reactor. This entails to a lower pumping consumption compared to the HCLL blanket [3]. The following thermal source in order of importance is the divertor, which is designed to recover waste heat from the plasma. It has two operating temperature ranges: above 500 °C (cooled by helium) and below 250 °C

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(cooled by water). The last thermal source is the vacuum vessel, which releases heat to the power conversion system, although its exergy level is usually low [3].

The Brayton cycle is highly attractive as an energy conversion system due to its relative simplicity and compactness. Moreover, it does not use water as working fluid, which avoids the tritium issues mentioned above. However, in a classical Brayton cycle, the compressor consumes a significant amount of power produced by the turbine. This problem is usually overcome by achieving very high turbine inlet temperatures, as is the case in the very high temperature reactor (VHTR) fission reactors [4], where temperatures higher than 900 °C are expected. However, these high temperatures will not be reached in fusion reactors, even with the use of high temperature diverters [5]. One approach to reducing the high compressor consumption is changing the working fluid of the Brayton cycle. Helium and other light gases are postulated in VHTR, but it is possible to use CO_2 at supercritical pressure (S-CO_2). The closeness of the compressor suction to the critical point significantly increases the specific volume, which contributes to reducing the power consumption.

The first studies using S-CO_2 took place in 1980 by the Kobe University, Kawasaki Heavy Industries and Shinko Pfaudler Company [6]. S-CO_2 was applied to replace the steam Rankine cycle, aiming for turbine inlet temperatures higher than 650 °C. The use of S-CO_2 power cycles for coal power plants remains a research topic, either through analysing the integration with the carbon capture and storage facility [7] or studying the power plant alone [8]. Its application to combined cycles has been analysed by Akbari and Mahmoudi [9], using a topping S-CO_2 cycle and a bottoming organic Rankine cycle (ORC), as well as by Wang et al. [10], who proposed a bottoming transcritical CO_2 power cycle. Dostal compiled the cycle fundamentals and improved its performance [11,12]. A comprehensive analysis of S-CO_2 Brayton cycles was recently carried out by Ahn et al. [13], in which a comparison between this cycle and others (steam Rankine, organic Rankine and combined cycles) can be found. The most suitable application fields are presented in this paper and the advantages of the S-CO_2 are explained based on its fundamentals. This paper also reviews certain experimental facilities, paying particular attention to those developed at Korean Atomic Energy Research Institute (KAERI).

However, a plain S-CO_2 cycle faces difficulties in obtaining an optimum heat exchange between the gas streams on both sides of the recuperator. The heat recovery is complex due to the fact that the specific heat of CO_2 is substantially higher at high pressure than at low pressure in the range of 70–150 °C. This issue is resolved in the so-called re-compression cycle employing two recuperators: one for the high-temperature range (HTR), with the same mass flow rate in both streams, and another for the low-temperature range (LTR), where the mass flow rate is lower on the high-pressure side. The technical and economic aspects of this subject can be found in Ref. [11]. One of the most significant advantages of S-CO_2 cycles compared to Rankine cycles is high compactness. However, S-CO_2 cycles are not exempt from certain issues regarding the heat release process [14] as a result of the sharp variation in the specific heat of CO_2 when it is close to the critical point.

Most studies on S-CO_2 Brayton cycles have dealt with Generation IV fission plants, particularly those with sodium fast reactors (SFRs). The high-temperature thermal sources of SFRs are comparable to those of the DEMO blanket (although the average inlet temperature in SFR is somewhat higher than that in DEMO). For example, in the CP-ESFR project, the inlet/outlet temperatures of the secondary loop Na/CO_2 heat exchanger are 340/525 °C [15]. In Ref. [12], different supercritical CO_2 Brayton cycle arrangements are analysed. The studies conclude that basic Brayton configurations should attain very high pressures in order to achieve substantial efficiencies (approximately 40%); however, when testing outlet compressor pressures of 250 bar, although attractive efficiencies are achieved, pinch-point drawbacks are faced in the heat exchangers. Other options differing from the basic arrangement have also been explored. It was found that pre-compression may yield high efficiencies (42%), given that the high pressure is higher than or equal to approximately 100 bar. Likewise, re-compression was found to exhibit the potential to achieve high efficiencies (greater than 46%), but pressure should be over 200 bar for a significant result. This re-compression architecture was also modelled using two-stage expansion and, although similar behaviour was demonstrated, the efficiency was lower. Furthermore, partial cooling resulted in a significant improvement and, at 100–150 bar, efficiencies similar to those of a 200 bar re-compression cycle were achieved, but this demanded an additional compressor. The effects of inter-cooling and re-heating on the S-CO_2 cycle's efficiency have been explored by several researchers. According to [16], inter-cooling and re-heating options would not produce increased efficiency in similar conditions to those found in the DEMO blanket. Pham et al. [17] analysed the application of a S-CO_2 power cycle to both an SFR reactor with a turbine inlet temperature of 515 °C, and a small modular reactor (SMR) with a turbine inlet temperature of 275 °C. In the high temperature (SFR) case, the authors analysed the limitation of the highly efficient heat power recovery imposed by the stream returning to the source, an issue already present in fusion reactors. Power cycles with partial cooling are proposed in order to address this concern.

S-CO_2 cycles usually employ printed circuit heat exchangers (PCHEs) for recuperators, and eventually for heat source and heat sink heat exchangers. There are three major reasons for this: PCHE exhibits effective behaviour at high pressure differences; the thermal effectiveness can achieve values close to 99%; and their compactness is very high. The previous statements have been supported by various authors. Halimi et al. [18] achieved an increase in thermal effectiveness from 92% to 98.7%; the Sandia National Laboratory (SNL) [19] recommends its use for all the types of heat exchanger types, focusing on its high compactness; Mito et al. [20] highlighted the reduced pressure drop and Gezelius [21] postulated a volumetric density 10 times higher using PCHE than with shell and tube heat exchangers in similar conditions.

The closeness of the main compressor suction to the critical point is a key issue in the S-CO_2 cycle. The numerous authors who have proposed this cycle as promising for use in fission nuclear reactors (especially SFR in Generation IV), fusion and concentrating solar power plants have considered this concept. The stability of the compressor with suction close to the critical point has been tested in comprehensive experimental work by SNL (in collaboration with Barber Nichols Inc.) [22], and these tests concluded that no stability problems appear.

A later study carried out by Noall et al. [23], also at the SNL in collaboration with Barber Nichols found that the low-density ratio of liquid/vapor in the vicinity of the critical point prevents instability problems. These experimental measurements could overcome the concerns reported by certain authors [24] who noticed condensation inside the compressor due to acceleration effects, based on numerical analysis.

All power cycles in a fusion power plant tackle an important challenge, namely operation in pulsed mode. Concentrated solar plants (CSPs) provide an effective reference for analysing the performance of S-CO_2 cycles in such conditions. In Ref. [25], a thorough description can be found, which proposes molten solar salt as a thermal energy storage (TES) system. An advantage of CO_2 systems with respect to Rankine cycles is their faster reaction to transients, due to the smaller thermal inertia resulting from a lower mass amount in the circuit. This fact becomes more relevant given that