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Study of the cooling systems with S-CO_2 for the DEMO fusion power reactor

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HIGHLIGHTS

- The S-CO_2 thermodynamic cycles are very perspective technology suitable for fusion power.
- The high net efficiency of the S-CO_2 cycles for the DEMO fusion power plant is demonstrated and found higher than the net efficiency of the Rankine steam cycles.
- The S-CO_2 power conversion cycle technology is also significantly more compact, flexible and cheaper than the steam technology.
- The focus is centered on finding the optimal S-CO_2 cycle layout for the case including all available heat sources of the fusion reactor.

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ABSTRACT

The power conversion system is one of the key parts of the fusion power plant. The DEMO fusion power reactor features multiple heat sources, like the first wall, blanket, divertor and vacuum vessel, on different temperatures and power levels. The heat addition into a thermodynamic cycle from different heat sources is disadvantageous in terms of efficiency of steam Rankine or helium cycles. However, it is advantageous for the S-CO_2 cycles as it resolves the real S-CO_2 property issues. S-CO_2 is thus an option for conversion of heat into electricity and might have overall better performance than the steam Rankine or helium Brayton cycles. Therefore, it should be considered as an option for the DEMO fusion power reactor. The paper focuses on the application of S-CO_2 for the European DEMO fusion power plant. The higher net efficiency of the S-CO_2 cycles for the DEMO fusion power plant in comparison with the Rankine steam cycles is presented.

1. Introduction

The main goal of the fusion power plant DEMO is to demonstrate the electricity production by nuclear fusion. Electricity generation will be performed by a thermodynamic conversion cycle, like steam Rankine or gas Brayton cycles.

Generally, DEMO has three main heat sources: the first wall and blanket, divertor and vacuum vessel with different output temperatures and thermal powers. In the reference European DEMO concept, the blanket and the first wall are helium cooled. In some other concepts, the blanket, and the first wall are water cooled or cooled by LiPb eutectic alloy [1]. The divertor will most likely be cooled by water; helium cooling is also developed [2]. The conversion cycle considered for the European DEMO is the conventional Rankine steam cycle [3].

The use of the Rankine steam cycle in the case of multiple heat sources has an effect on the cycle efficiency. The heat addition into a thermal cycle from different heat sources with low temperatures can decrease the efficiency of the Rankine steam cycle. A supercritical carbon dioxide (S-CO_2) cycle is proposed as an alternative to the Rankine cycle. The reason is that the S-CO_2 cycle achieves high efficiency at low operating temperatures. The S-CO_2 cycles are more compact than the water and helium cycles, and compressor and turbine are significantly smaller due to the high operating pressures [5]; the size of heat exchangers can be optimized by operation parameters and type selection.

The S-CO_2 cycles have technical challenges. The existence of the so-called "pinch point" in heat exchangers significantly affecting their design is the most important and well-known feature.

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Table 1
Heat sources parameters.

First wall and blanket	
Thermal power	2176 MW
Cooling medium	Helium
Pressure	8 MPa
Input temperature	300 °C
Output temperature	500 °C
Divertor	
Thermal power	259 MW
Cooling medium	Water
Inlet pressure	5 MPa
Input temperature	150 °C
Output temperature	161.5 °C
Vacuum vessel	
Thermal power	65 MW
Cooling medium	Water
Inlet pressure	3.15 MPa
Input temperature	190 °C
Output temperature	200 °C

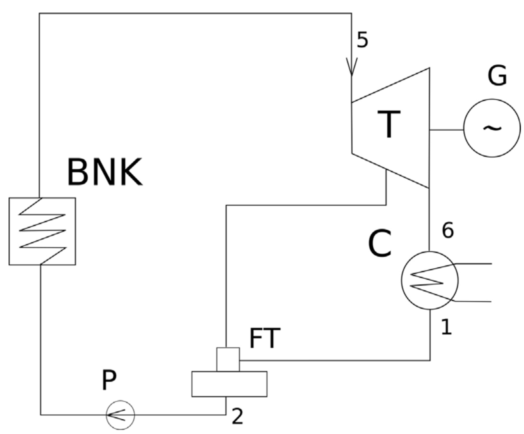

Fig. 1. Cycle layouts of the Rankine cycle with one heat source (blanket).

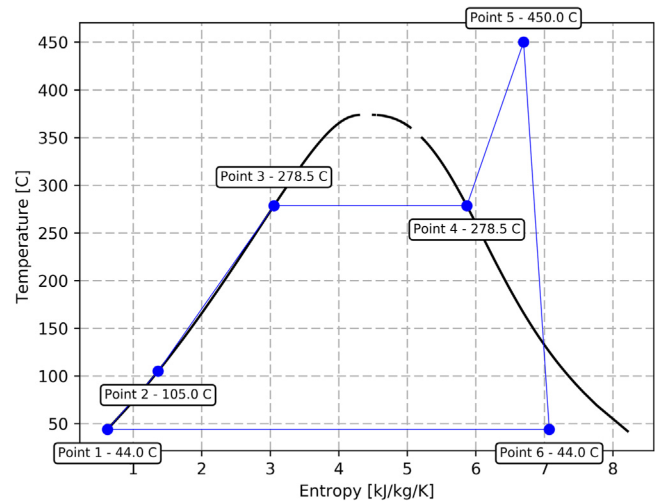

Fig. 2. T-S diagram of the Rankine cycle with one heat source.

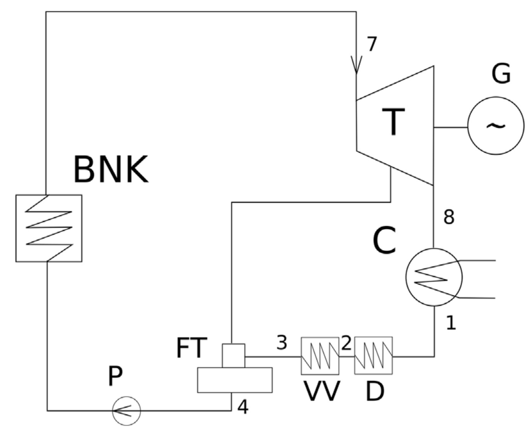

Fig. 3. Cycle layouts of the Rankine cycle with three heat sources (blanket and first wall, divertor, and vacuum vessel).

This paper focuses on the comparison of the Rankine cycle and the S-CO_2 cycle for the fusion power plant DEMO. The investigated layouts include cycles with one heat source only (blanket) and cycles with three heat sources (blanket, divertor and vacuum vessel).

2. Heat sources

The used basic thermodynamic parameters of the DEMO heat sources, including the first wall and blanket (BNK), divertor (D), and vacuum vessel (VV), are based on the European DEMO reference model issued in 2015 with the fusion power of 2037 MW and thermal power of 2500 MW [1–4]. The main parameters of the heat sources are summarized in Table 1.

3. Power cycles

The comparison of the power cycles was carried out for two Rankine cycles and two S-CO_2 cycles. The first cycles are used only the first wall and blanket with a thermal power of 2176 MW according to Table 1. The second cycles are used all the heat sources: the first wall, blanket, divertor and vacuum vessel with the total thermal power of 2500 MW.

4. Rankine cycle

The first layout of the Rankine cycle is a basic layout of the steam-water power cycle. The layout of the cycle is showed in Fig. 1, and the T-S diagram in Fig. 2.

The second layout of the Rankine cycle uses a low-pressure regenerative heating by the divertor and vacuum vessel heat sources. The layout improving the cycle efficiency and net power is showed in Fig. 3, and the corresponding T-S diagram is presented in Fig. 4.

The both types of the Rankine cycle consist of the turbine (T), condenser (C), pump (P), feedwater tank (FT) and heat source blanket (BNK). In the case of the second Rankine cycle, the divertor (D) and vacuum vessel (VV) heat sources are incorporated. For the reason of this study, the turbine inlet pressure was considered 6.27 MPa [7] and condenser outlet temperature of 44 °C. The pump efficiency of 75% and turbine efficiency of 87% were used for both the cycle layouts [8,9].

5. S-CO_2 cycle

The recompression S-CO_2 cycle according to nuclear and fusion power plant designs [5,6] is considered for the cycle layout with BNK heat source. The recompression cycle is shown in Fig. 5, Fig. 6 shows the T-S diagram. The recompression cycle consists of the turbine (T), two compressors (Com 1 and Com 2), two recu-

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