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Design and Transient Analysis of Turbocharger-aided PRHRS for the sCO_2 Cycle coupled integral PWR

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1. Introduction

With the recent increase in interest in small modular reactors (SMRs), the supercritical CO_2 (sCO_2) based cycle has gained attention as a power conversion system due to its high efficiency and small volume. Oh et al. previously designed a 100 MW_e trans-critical CO_2 (T-CO_2) cycle coupled to a pressurized water reactor (PWR) type SMR for a nuclear icebreaker to be operated on the Northern Sea Route [1-2]. As well as the power conversion system, the air-cooled CO_2 passive residual heat removal system (PRHRS) was designed while considering the low ambient temperature. It is designed as a 6 m high CO_2 natural circulation loop that passively transfers reactor residual heat to the ultimate heat sink in the event of an accident.

The authors have previously proposed a preliminary concept of a sCO_2 passive turbocharger [3]. It was confirmed that it could potentially improve the residual heat removal performance of a PRHRS by increasing the mass flow rate of the natural circulation loop in the early stages of the accident. The improvement in initial cooling performance implies that the level of reactor residual heat that would have to rely entirely on natural circulation cooling can be reduced. Ultimately, there is the potential to lower the height of the natural circulation loop. In this study, based on the CO_2 PRHRS designed by Oh et al., a turbocharger-aided PRHRS (TC-PRHRS) with a smaller volume is newly designed in consideration of a passive turbocharger, and compared with the original PRHRS through an accident analysis using the system analysis code, MARS.

2. Methods and Results

2.1 Design of TC-PRHRS

The height of the natural circulation loop of TC-PRHRS is roughly estimated. From the design procedure for CO_2 PRHRS by Oh et al., the mass flow rate of a natural circulation loop is proportional to the 1/3rd power of the thermal center difference (TCD), if all other design variables except height are the same. The air-cooled heat exchangers in the original PRHRS were designed based on 6% of the reactor nominal power. The accident analysis results showed that the reactor residual heat dropped to 6% in about 30 seconds and to 2% after about 1,500 seconds. Therefore, if the passive turbocharger can operate for about 25 minutes or more to help remove the high levels of residual heat at the beginning of the accident, the reactor residual heat removal based on the natural circulation loop design can be reduced from 6% to 2%. If the design basis residual heat is reduced by 1/3, the CO_2 mass flow rate required for natural circulation cooling is also reduced by 1/3, leading to a dramatic reduction in the TCD of the natural circulation loop to 1/27. To verify this, MARS code simulations of the same accident scenario have been performed by reducing the height of the natural circulation loop in the modeling of the existing system, and the analysis results are shown in Table I. It can be observed that the rough estimate is in reasonable agreement with the simulation results, and therefore the target of this study is to reduce the height of the natural circulation loop to 1/27 of the original design value by applying a turbocharger.

Table I. Estimated and simulated mass flow rate

Thermal center difference	Estimated CO_2 mass flow rate (single train) [kg/s]	Simulated CO_2 mass flow rate (single train) [kg/sec]	Error [%]
100 % (6 m)	93.6	98.7	5.4
80 %	91.625	90.3767	-1.4
60 %	83.25	80.7	-3.1
40 %	72.72	69.34	-4.65
20 %	57.72	54.55	-5.5
1/27 (0.22 m)	32.9	32.82	-0.23

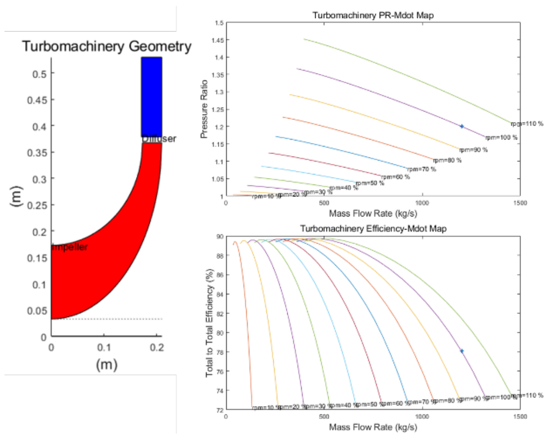

Fig. 1. Conceptual design of the compressor.

The compressor and the turbine comprising the turbocharger are conceptually designed using the

KAIST-TMD code, an sCO_2 turbomachinery design code [4]. Fig. 1 and Fig. 2 show the design results of each turbomachinery. Geometry and performance maps are implemented into the system code modeling.

Geometry information and performance maps for each turbomachinery have been added to the system analysis code modeling.

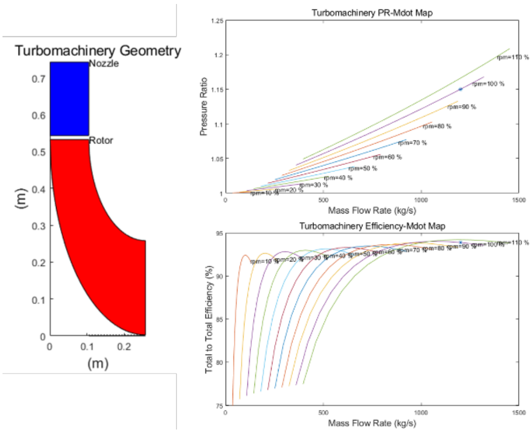

Fig. 2. Conceptual design of the turbine.

2.2 SBLOCA analysis

Fig. 3 shows the MARS code input nodalization of total system with the turbocharger. For accident analyses, power conversion system is treated as boundary conditions. In the original PRHRS, a turbine-compressor set is added to the connection with the intermediate heat exchangers (IHXs). In the early stages of the accident, the high enthalpy CO_2 flow, which received heat from the primary side, drives the turbine, which in turn rotates the compressor to provide sufficient mass flow to the PRHRS loop without relying entirely on natural circulation. As the cooling progresses, the rotational speed changes passively due to the work balance of the shaft and the rotational moment of inertia, and after the turbocharger stops, it enters the natural circulation cooling mode.

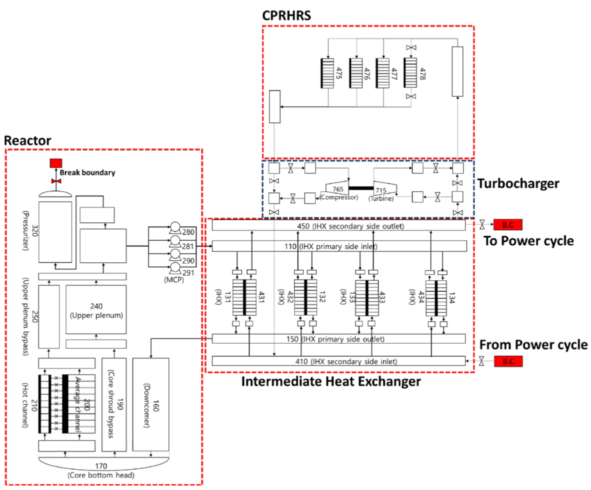

Fig. 3. MARS code input nodalization with TC-PRHRS.

Hypothetical accident scenarios and trip conditions are the same as in the reference study. For both the original PRHRS, and TC-PRHRS, SBLOCA simulations are performed that assumed a 44 mm diameter fracture at the top of the pressurizer and assumed all failures of the safety injection system and a single train failure of the four trains of the PRHRS. Fig. 4 compares the long-term transient behavior of the original PRHRS and TC-PRHRS. In the case of the TC-PRHRS, the turbocharger operates for about two hours, providing enough mass flow to remove residual heat. After the turbocharger stops, it switches to natural circulation cooling mode, and due to the low loop height, it has a lower CO_2 mass flow rate than the original loop causing a slight temperature increase. However, at this point, the reactor residual heat has already decreased to 1.27% of the nominal power, which is lower than the 2% assumed value when designing the TC-PRHRS. Thus, long term stable cooling is demonstrated. As a result, turbochargers can improve cooling performance in the early stages of an accident, when reactor residual heat levels are high, while significantly reducing the volume of passive safety systems that would typically require substantial space.

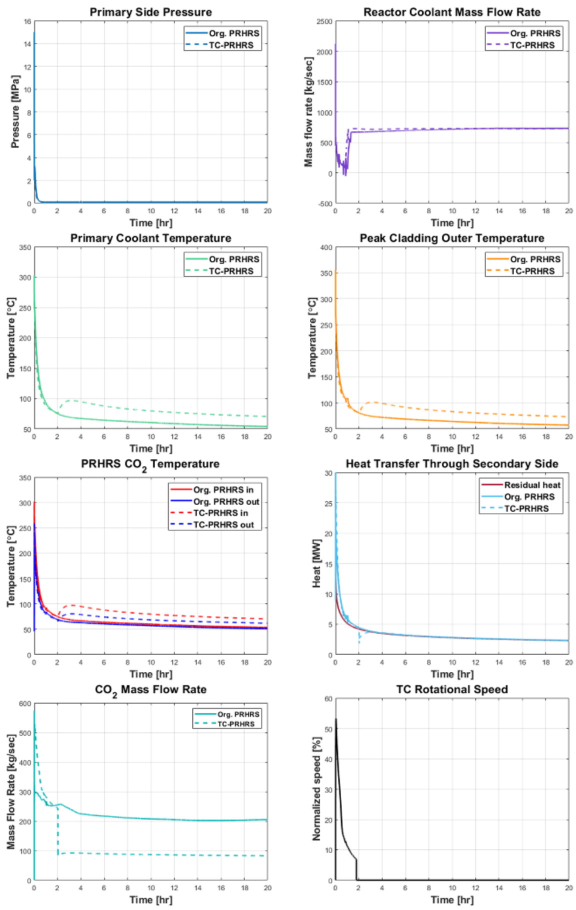

Fig. 4. Comparison between the original PRHRS and TC-PRHRS.

3. Summary and Conclusions

In this study, a TC-PRHRS with a passive turbocharger applied to a previously developed CO_2 PRHRS is newly designed, and the cooling performance is quantitatively evaluated with accident analysis. With the turbocharger, the natural circulation loop can be reduced to 1/27 of its original height, resulting in similar passive safety performance to the original PRHRS without turbocharger. Consequently, the application of turbocharger to a CO_2 PRHRS allows safety requirements to be met with a much smaller volume, leading to improvements in the safety performance as well as economics of SMRs.

ACKNOWLEDGEMENT

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