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Design and Transient Analysis of a Trans-critical CO_2 Rankine Cycle for Nuclear Marine Application

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1. Introduction

The KAIST-MMR is a SMR (Small Modular Reactor) developed by KAIST research team to operate in a remote region where fully integrated electricity grid infrastructure cannot be found. It was originally designed with the S-CO_2 cooled direct Brayton cycle adopting an air cooling for minimizing the dependence on the cooling water in dry regions [1].

In this study, the KAIST-MMR is re-designed for the marine application by coupling with the trans-critical CO_2 Rankine cycle instead of the Brayton cycle. This is because the current system for the ocean application can utilize lower temperature heat sink since it is operating in the ocean environment. The cycle cooling can be carried out with the seawater which is usually below the critical point of CO_2 31.1 degree Celcius.

To model the CO_2 two-phase flow close to the critical point, a system analysis code adopting the HEM (Homogeneous Equilibrium Model) as a two-phase model is developed in this study. The code is called as KAIST-STA (System Transient Analysis) code. The reason why the HEM is chosen is because homogeneous flow conditions are good assumptions when the liquid and gas properties are similar. A typical example is the two-phase flow condition close to the critical pressure like the two-phase flow in an S-CO_2 power conversion system [2].

The designed trans-critical CO_2 Rankine cycle for the nuclear energy marine application is analyzed with the KAIST-STA code. Since evaluating the load following capability is the most important aspect of the designed system for marine application, the system behavior for load reduction operation is analyzed with the developed code.

2. Design of a trans-critical CO_2 Rankine cycle

2.1 Reactor Information

The KAIST-MMR adopts a drum-type control rod rotating around the active core and the reflector to reduce the reactor height. Since the KAIST-MMR is operating in the high temperature core outlet temperature 550℃, uranium carbide (UC) and Oxide Dispersion Strengthened (ODS) steel are adopted as the fuel and cladding materials, respectively, due to high melting temperature and thermal conductivity [3]. The core is designed to react with fast spectrum neutrons and have a strong negative reactivity feedback coefficient, so the reactor power is autonomously adjusted by its inherent feature. The thermal power of the core is about 36.2 MWth.

2.2 Power Conversion System Design

Fig. 1 shows the configuration of the trans-critical CO_2 Rankine cycle of the KAIST-MMR for ship application with the design points and the T-s diagram of the cycle. All the points of the cycle is in supercritical state except for the pump inlet which is at subcooled liquid state, 25.8℃ and 7.31MPa. Thus, the CO_2 phase change occurs in the pre-cooler from the supercritical state to liquid phase. The trans-critical cycle is designed with 36.9% thermal efficiency, 13.1MWe, 118.9kg/s mass flow rate at steady-state, whereas the Brayton cycle of the onshore KAIST-MMR is 34.1%, 12MWe, 179.9kg/s.

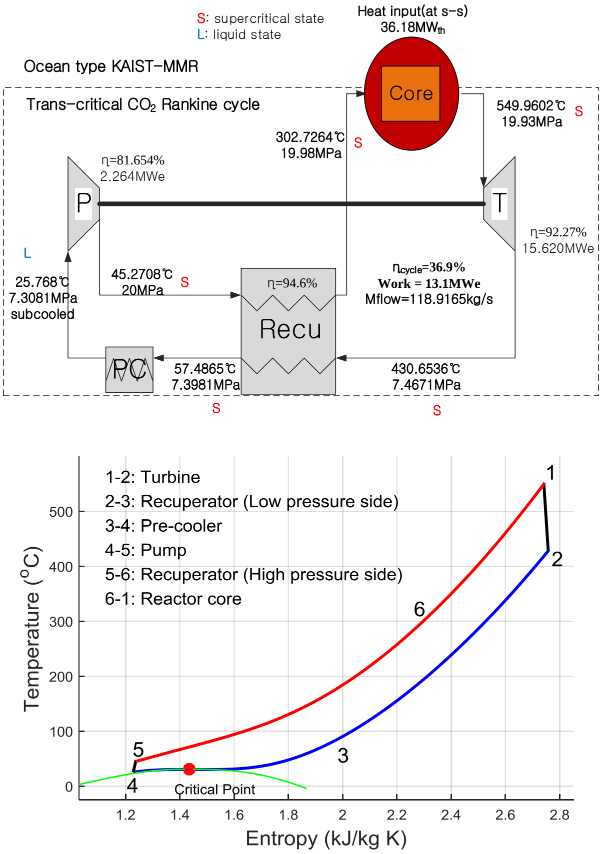

Fig. 1. Configuration and T-s diagram of the trans-critical CO_2 Rankine cycle.

2.3 Design of main components

On the basis of the cycle design, the main components of the power conversion system are designed such as turbomachinery, heat exchangers and pipes between the components. The performance maps of the radial type turbine and pump could be generated with the in-house code. Figs. 2-3 show the turbine and pump performance maps of pressure ratio.

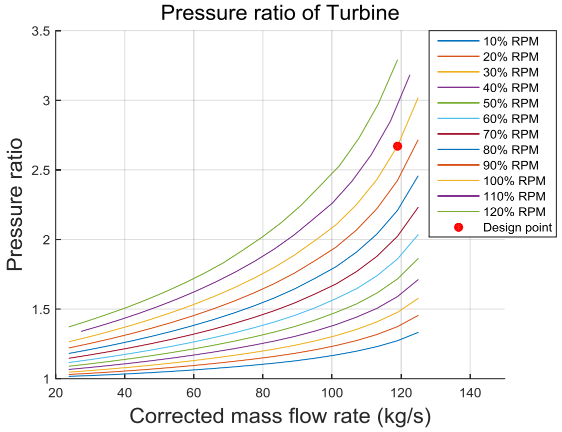

Fig. 2. Turbine pressure ratio performance map of the trans-critical CO_2 cycle.

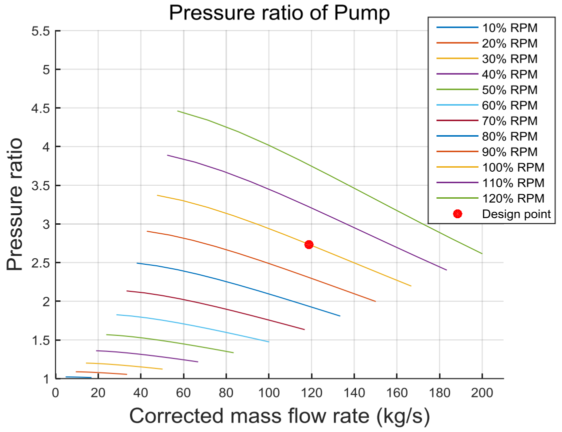

Fig. 3. Pump pressure ratio performance map of the trans-critical CO_2 cycle.

All the heat exchangers of the trans-critical CO_2 cycle is designed as a PCHE (Printed Circuit Heat Exchanger) type heat exchanger, the pre-cooler and recuperator. In this study, a preliminary pipe design is carried out with the method using the optimal flow velocity and ASME standard. After determining the average pipe diameter and the minimum thickness from the optimal velocity calculation, the proper pipe material is selected considering to the ASME standard [4-5].

3. Transient modeling and transient analysis

Using the KAIST-STA code, the KAIST-MMR system is modeled as shown in Fig. 4. The reactor core is modeled as two parts; the hot channel and the cold channel. The turbine and pump are connected on the same shaft and read the turbomachinery performance maps every time step for the analysis. The nodalization shows both the design point and code prediction together on the on-design condition of the trans-critical cycle. As shown in the result, the KAIST-STA code shows a good agreement compared to the design values at the steady-state within ± 1% temperature and pressure.

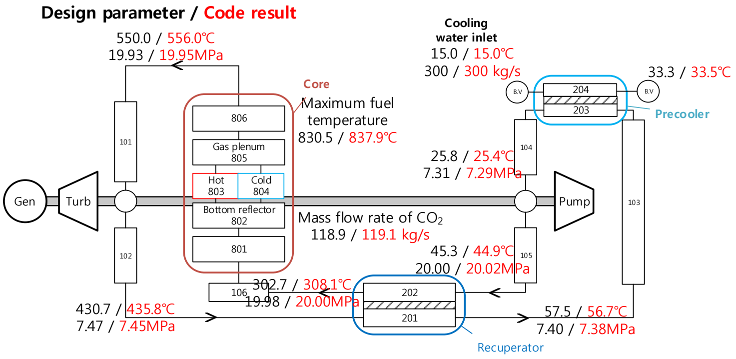

Fig. 4. Nodalization diagram of the marine KAIST-MMR with the comparison between design parameters and the code results.

In this study, the load follow operation of the KAIST-MMR is simulated with the inventory control according to the previously obtained optimal total mass of CO_2 in the KAIST-MMR for different grid demand and the core bypass control for adjusting the rotational speed of turbomachinery. Thus, the inventory control is used to retain high efficiency under different load and without a surge in a compressor. The core bypass control is used to maintain turbomachinery rotational speed at the nominal speed for the generator, which must be synchronized to the electricity grid. All control logics are based on PID (Proportional-Integral-Derivative) controller.

The change of grid demand is reflected as an analysis input data as shown in Fig. 5 with the work variations of the turbine and pump. The grid demand is reduced 10% for every 50 seconds and then the system stays in the condition for 50 seconds.

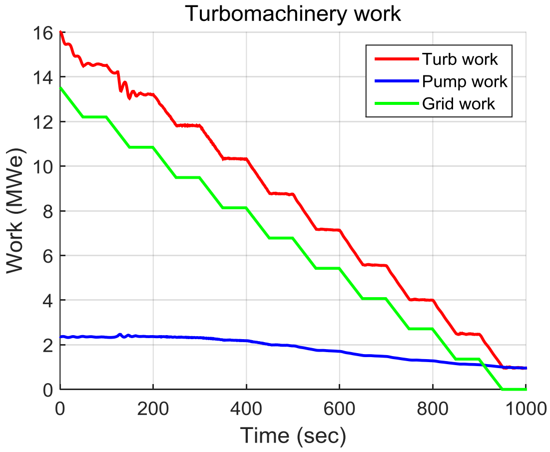

Fig. 5. Variations of grid and turbomachinery works during the part load operation.

Fig. 6 shows the open fraction of the control valves versus time. As a result of the valve open fraction control, CO_2 mass flow rate at the pump inlet, turbine inlet and core bypass line responded as shown in Fig. 7. Some portion of mass flow rate to the turbine is bypassed for decreasing grid demand to maintain the rotational speed of turbomachinery, so the mass flow rate to the turbine is reduced and the value to the pump is increasing relatively. Thus, the open fractions of valves are automatically adjusted by PID controllers, as shown in Fig. 8, the response of turbomachinery rotational speed is retained at the nominal speed for the generator while reducing 10% of grid demand.

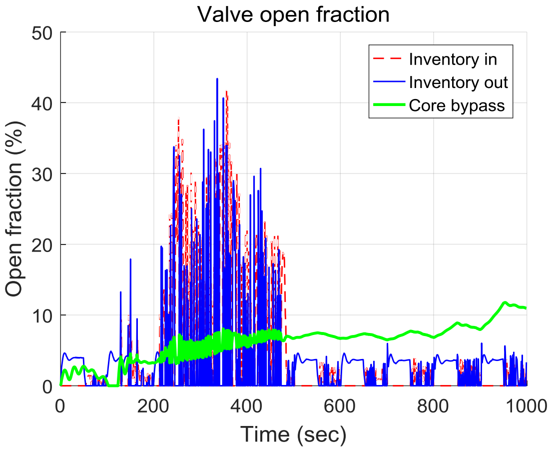

Fig. 6. Open fraction variations of control valves during the part load operation.

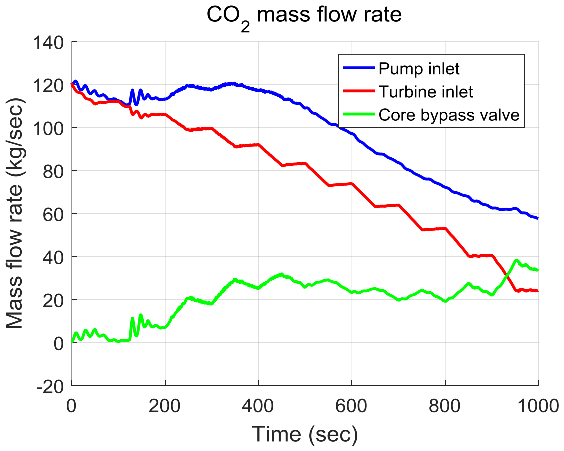

Fig. 7. Variations of CO_2 mass flow rate during the part load operation.

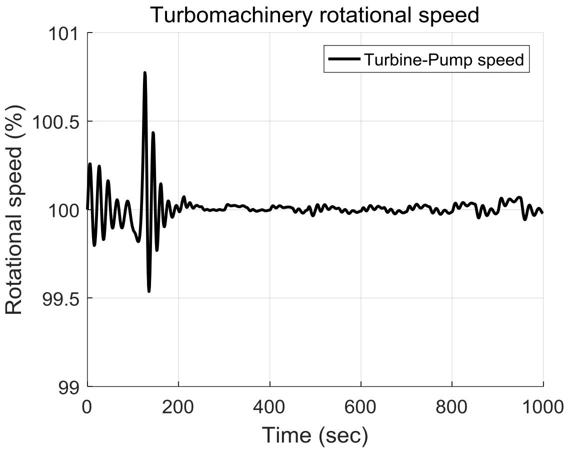

Fig. 8. Variation of turbomachinery rotational speed during the part load operation.

As a result of the inventory control, the total amount of CO_2 in the system is adjusted as shown in Fig. 9, and the difference of the cycle high (at the turbine inlet) and low temperature (at the pump inlet) is retained as much as possible as shown in Fig. 10 for the optimal cycle efficiency during the part load operation. The cycle efficiency variation during the load follow operation is represented in Fig. 11. Fig. 12 shows the change of reactor core power. It shows that the core power is controlled by the reactivity of the core during the transient situation.

The KAIST-STA code shows the ability to analyze the transient behavior of CO_2 cycle going through the two-phase region near the critical point of CO_2. The variation of CO_2 quality in the pre-cooler during the part load operation is shown in Fig. 13.

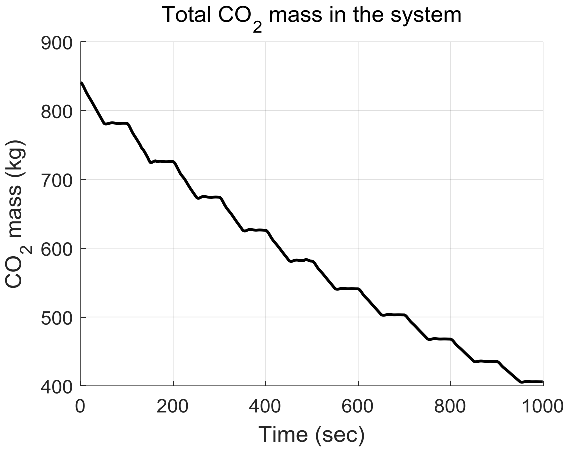

Fig. 9. Variation of the total amount of CO_2 in the system during the part load operation.

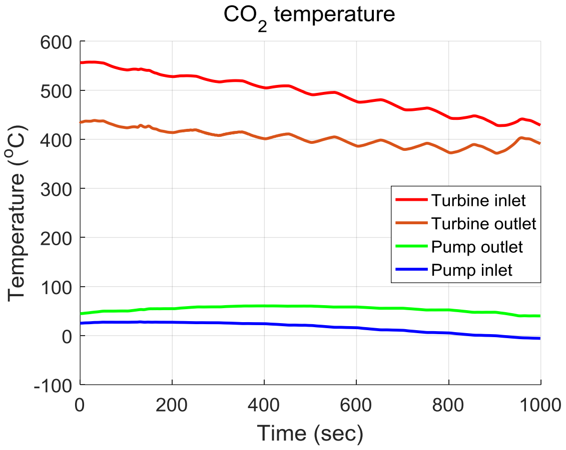

Fig. 10. Variations of system temperature during the part load operation.

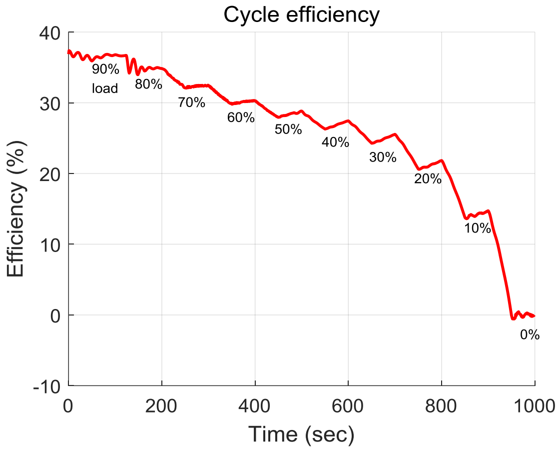

Fig. 11. Variation of cycle efficiency during the part load operation.

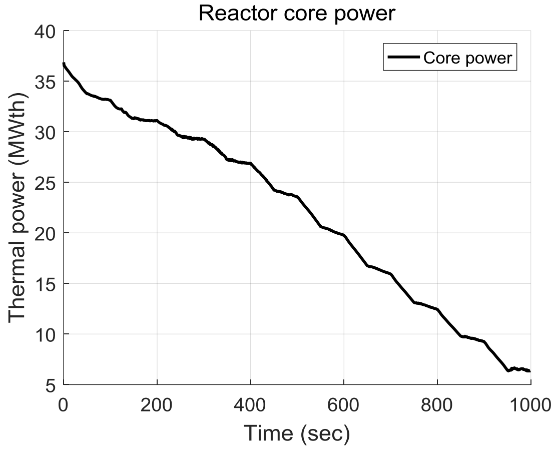

Fig. 12. Variation of reactor core power during the part load operation.

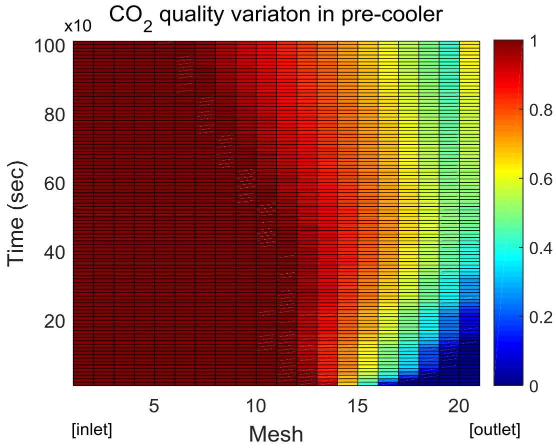

Fig. 13. Variations of CO$_2$ quality in the pre-cooler during the part load operation.

3. Conclusions

A concept of SMR (Small Modular Reactor) with a CO$_2$ power conversion system was designed and analyzed for the nuclear energy marine application in this study. The marine KAIST-MMR was modeled with the KAIST-STA code on the basis of the trans-critical CO$_2$ Rankine cycle design and a load reduction analyses were performed; from 100% to 0% load change (step load change).

The results show that the system can be autonomously controlled over the range of power demand without any control drum action due to the core characteristics. As a result, the marine KAIST-MMR can be controlled to operate under the operation limits during the part load operations.

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