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Preliminary Assessment on Feasibility of the Indefinite Passive Residual Heat Removal System for the ATOM-SCO_2

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1. Introduction

Small Modular Reactors (SMRs) have been consistently developed with global interest. In spite of this interest, generally, the cost competitiveness of SMR is lower than that of the commercial large reactor in terms of economies of scale [1]. Recently, to raise the competitiveness of the SMR, innovative features and designs have been applied like NuScale and CAREM. Following this trend, a new concept of SMR with innovative features such as supercritical carbon dioxide (SCO_2) cycle, passive safety systems and dry air cooling tower (DACT) has been investigated by a Korean research group, called Autonomous Transportable On-demand reactor Module (ATOM).

A major distinctive feature of the ATOM is the adoption of SCO_2 Brayton cycle as a power conversion system. In the SMR with the SCO_2 Brayton cycle, printed circuit heat exchanger (PCHE) replaces the conventional steam generator (SG). The PCHE has larger heat transfer area compared to the conventional shell and tube HX in a limited volume. In addition, the turbomachinery used in the SCO_2 Brayton cycle is quite smaller than that of steam Rankine cycle due to relatively low compression ratio of SCO_2. Thus, adopting SCO_2 Brayton cycle enables the SMR to have simple and compact configuration [2].

As there were no studies regarding the safety of the SMR with SCO_2 cycle, it is questionable to apply the same safety system used in steam Rankine cycle to the SCO_2 cycle. In the preceding study of our research team, the passive residual heat removal system (PRHRS) coupled with dry air cooling tower (DACT) for the ATOM with the steam Rankine cycle was presented [3]. In the presented system, called indefinite PRHRS, it was confirmed that it can indefinitely mitigate water consumption in the emergency cooldown tank (ECT) using the air-cooling mechanism. To reject the residual heat from the core using the indefinite PRHRS, the stable establishment of natural circulation in the secondary system is important. Since the SCO_2 replaced the water in a secondary system, the feasibility of the indefinite PRHRS in SCO_2 Brayton cycle should be newly assessed.

In this study, preliminarily assessment on the feasibility of the indefinite PRHRS for the ATOM-SCO_2 was carried out. The feasibility of the indefinite PRHRS was evaluated in terms of cooling capability and coolant sustainability. For the transient analysis, the MARS-KS, a thermal hydraulic system analysis code, was utilized.

2. Preliminary designs of SCO_2 cycle ATOM

The ATOM which generates 330 MW thermal power on normal operation was selected as reference reactor. It is pressurized water-cooled reactor (PWR) like SMART. The distinctive feature of the ATOM is adoption of SCO_2 Brayton cycle as a power conversion cycle. For the SCO_2 cycle, general steam generator (SG) was replaced with an intermediate heat exchanger (IHX) using printed circuit heat exchanger (PCHE) [4]. The major design parameters of operating condition were shown in Table I.

Table I. Design operation condition of ATOM-SCO_2

Design Parameters	Value
Primary system	
Thermal power (MWt)	330
Electric power (MWe)	100
Operating pressure (MPa)	15
Core inlet temperature (K)	556
Core outlet temperature (K)	596
Core mass flowrate (kg/s)	1471.2
Secondary system	
IHX pressure (MPa)	24.925
IHX inlet temperature (K)	437
IHX outlet temperature (K)	583

3. Design of Indefinite PRHRS with SCO_2 cycle

A design of indefinite PRHRS for the ATOM-SCO_2 was shown in fig. 1. During normal operation, the heat from the core is transferred to the SCO_2 at the IHX. The heated SCO_2 flows through a turbine for electrical power generation. Because of low compression ratio of SCO_2, the SCO_2 after passing through the turbine has a high temperature. Thus, a recuperator is installed to enhance thermal efficiency. Finally, at the pre-cooler, the SCO_2 is cooled down until near the critical point. The SCO_2 near the critical point is pressurized at the compressor. The compressed SCO_2 is heated in recuperator and flows to the inlet of the IHX. On the other hand, if the station blackout (SBO) accident occurs, the SCO_2 flows another path by the operation of the indefinite PRHRS. When the reactor is shutdown, the secondary systems including turbine, compressor, and pre-cooler are stopped and the PRHRS valve is opened. This valve diverts SCO_2 flow to the PRHRS loop. The SCO_2 heated by residual heat is cooled at the heat exchanger in the ECT (HX-ECT). Due to natural circulation flow established in the PRHRS loop, the residual heat is transferred to the ECT and removed by the latent heat of the water. Furthermore, to coupling DACT with the PRHRS, another closed loop is adopted called intermediate loop. Through this loop, the heat from the ECT is transferred to the DACT. Ultimately, naturally driven environmental air removes the heat in the DACT. Major design parameters of the indefinite PRHRS was presented in Table II.

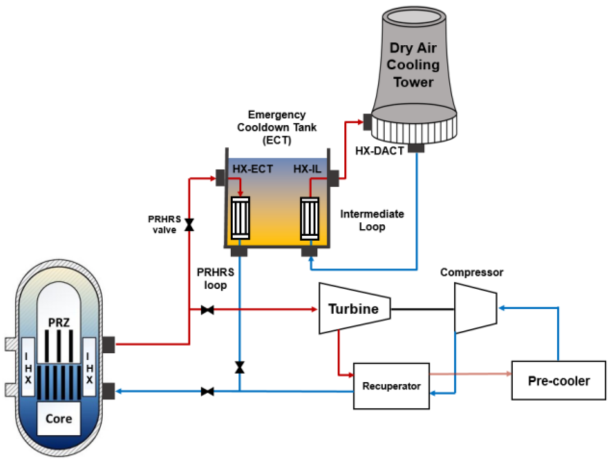


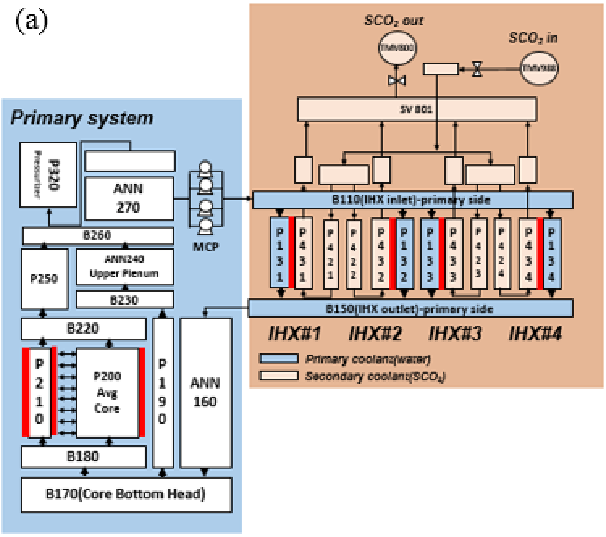
Fig. 1. Schematic diagram of indefinite PRHRS at ATOM

Table II. design parameter of indefinite PRHRS

Parameters	Value
ECT area (m^2)	20
ECT height (m)	5
ECT volume (m^3)	100×2
Length of HX-ECT (m)	2.5
Length of HX-IL (m)	2.5
Heat transfer area of HX-ECT (m^2)	56.5×4
Heat transfer area of HX-IL (m^2)	56.5×2
DACT height (m)	27.5
Height of HX-DACT (m)	2.5
Inner tube diameter (mm)	13.5
Outer tube diameter (mm)	18.0
Number of tubes	800
Heat transfer area with fin effect (m^2)	1131.0×2

4. MARS-KS modeling of ATOM with indefinite PRHRS

To assess the feasibility of the indefinite PRHRS of the ATOM, the transient simulation was imperative. For the transient simulations, the MARS-KS, thermal hydraulics system code, was utilized. The developed MARS input model of the ATOM with indefinite PRHRS was shown in Fig. 2. As MARS-KS input model was developed for transient simulation under the accident condition, the systems for power generation were not included. Figure 2(a). shows primary and secondary system of the ATOM. The pipe component 200 represents the reactor core of the ATOM. The primary coolant flowing through the IHXs are modelled as pipes 131, 132, 133, and 134. The SCO_2 flowing though the other side of the IHXs are also modelled as pipe 431, 432, 433, and 434. The heat transfer between two fluids is simulated by heat structures connecting both pipes. Figure 2(b) shows the indefinite PRHRS of the ATOM. The ECT is modelled by two pipes connected with multi-junction for simulating lateral flow inside the ECT. Pipes 950 and 955 simulates the inside the DACT which naturally driven air flows.



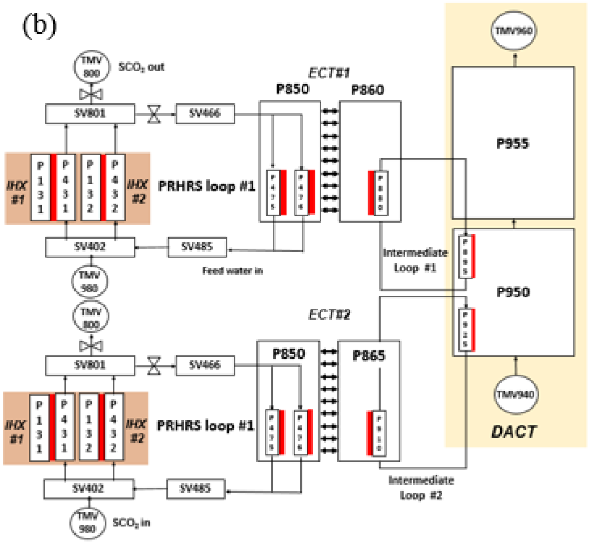


Fig 2. MARS-KS modeling (a) Primary and Secondary system of ATOM, (b) Indefinite PRHRS

5. Results and Discussions

To assess the feasibility of the indefinite PRHRS adopted to the ATOM, the transient simulations were conducted using MARS-KS. Since the assessment of cooling sustainability of the indefinite PRHRS was important, the simulations were carried out for 72 hours. To confirm the passive cooling performance of the indefinite PRHRS, the SBO accident was selected as reference accident. For the conservative assessment, it was assumed that the other safety systems except indefinite PRHRS were malfunctioned. At 1000 second, the reactor was shutdown by the halt of the main coolant pumps. Simultaneously, the PRHRS valves were opened and the indefinite PRHRS was operated.

As the indefinite PRHRS can be operated by natural circulation flow, the establishment of the natural circulation flow can greatly affect the operation of the indefinite PRHRS. Figure 3 shows natural circulation flows established in primary system, PRHRS loop, and intermediate loop respectively. In all systems, stable natural circulation flows were established.

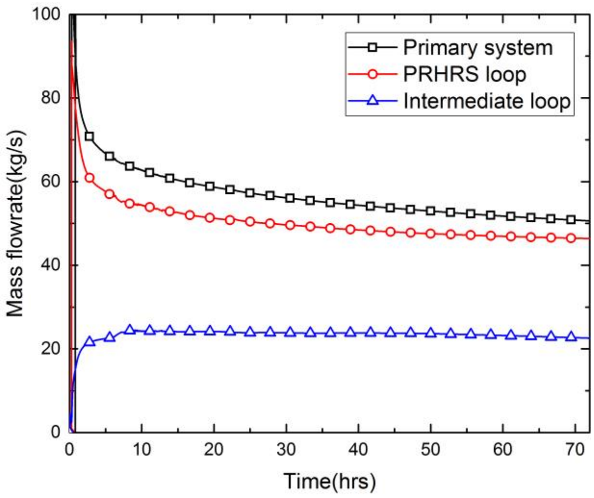


Fig 3. Mass flowrates in primary system, PRHRS loop, and intermediate loop.

The amounts of heat transferred at respective systems were shown in Fig. 4. The residual heat generated after reactor shutdown was exponentially reduced over time. The heat transfer rate of ECT means that the heat transfer rate between SCO_2 and water at the HX-ECT. The heat transfer rate of ECT was equal to the residual heat for 72 hours. It showed that the residual heat was successfully transferred to the ECT. On the other hand, the heat transfer rate of DACT was steadily increased until 7 hours after reactor shutdown. The increment of the heat transfer rate of DACT was due to the rise of water temperature in the ECT. During that period, the residual heat was consumed by the sensible heat of water in the ECT. After 7 hours, the water temperature reached at the saturation temperature and DACT started to remove almost constant heat. After 2 days, as the residual heat was reduced, the DACT removed most of the residual heat. It means that boiling loss of the water in the ECT is prevented.

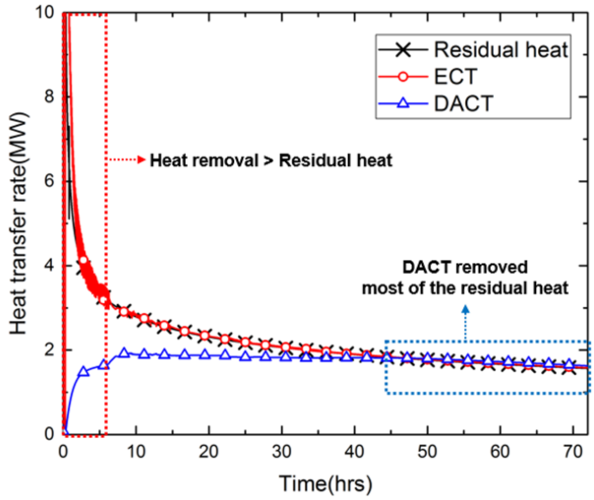


Fig 4. The change of residaul heat and heat transfer rate of ECT and DACT.

To confirm the effect on enhanced cooling sustainability by the adoption of indefinite PRHRS, comparison simulations were conducted in the case of PRHRS only (without DACT) and indefinite PRHRS (with DACT). Figure 5(a) shows the change of primary coolant temperature in both cases. The variation of primary coolant temperatures can be explained by the change of water level of the ECT as shown in Fig. 5(b). The primary coolant temperatures in both cases was gradually reduced until 28 hours after reactor shutdown. However, after 28 hours, the primary coolant in the case of PRHRS only started to increase. This point is when the water level of the ECT was reduced below the height of HX-ECT. As the HX was exposed to air, which means deterioration of heat transfer coefficient, the primary coolant temperature was elevated. The water level of the ECT in the case of PRHRS only was completely depleted at 62 hours. Concurrently, the primary coolant temperature was increased dramatically by the failure of the PRHRS. On the other hand, in the case of the indefinite PRHRS, the primary coolant temperature was steadily decreased over 72 hours without any increment as found in case of PRHRS only. The water level of the ECT maintained constantly as 4.4 m which is sufficient water level to cover the HX-ECT. According the comparison simulations, the effect of the indefinite PRHRS on enhanced cooling sustainability was confirmed.

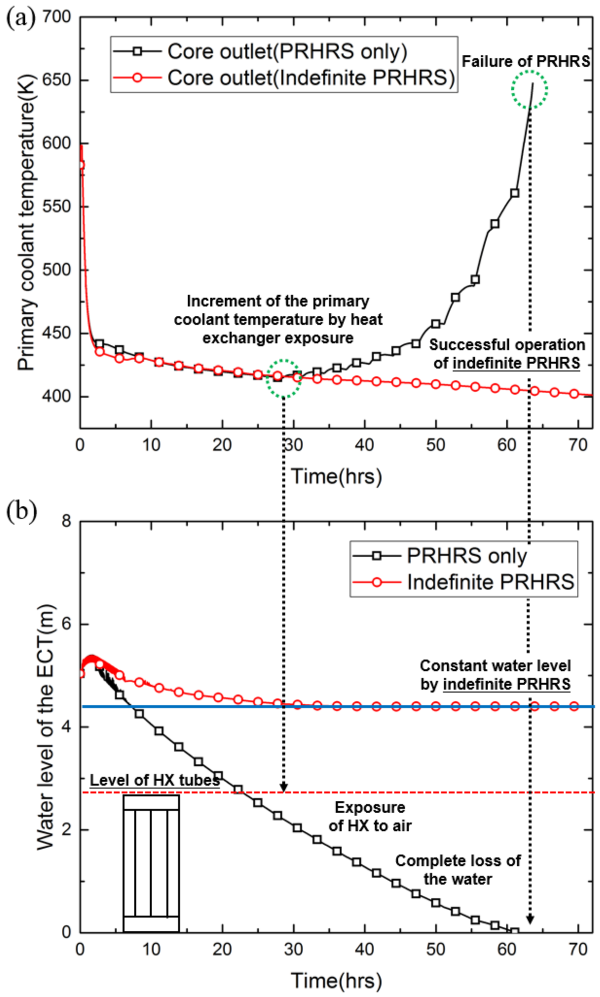


Fig 5. Comparison simulations for the cases with PRHRS only and indefitnie PRHRS. (a) Change of primary coolant temperature, (b) Change of water level.

6. Conclusions

The advanced concept of PRHRS was presented as the safety system of ATOM, called Indefinite PRHRS. The feasibility of indefinite PRHRS on the SCO_2 Brayton cycle was confirmed using MARS-KS code. The enhanced cooling sustainability was also assessed by comparison simulations in case of PRHRS only and indefinite PRHRS. The major conclusions are summarized as follows.

(1) The natural circulation of SCO_2 was stably established in the PRHRS loop driven by density difference. The applicability of the PRHRS on SCO_2 Brayton cycle was confirmed.
(2) All residual heat was successfully removed by the ECT. The DACT extracted most of the heat from the ECT using environmental air after two days.
(3) The cooling sustainability of the PRHRS without DACT was assessed as 62 hours. By adoption of DACT, the cooling sustainability of the indefinite PRHRS with same volume of ECT was extended indefinitely.

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