SBLOCA analysis of SMART with Trans-Critical CO₂ power conversion system for Maritime Propulsion

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1. Introduction

Northern Sea Route (NSR) located between the Arctic and Russian north coast could save about 40% of the sailing distance from Asia (Yokohama) to Europe (Rotterdam) compared to the conventional route via Suez Canal [1] as shown in Fig. 1.

Fig. 1. Comparison of Northern Sea Route and Conventional Route [2]

From these reasons, exploration of the NSR is receiving attentions for logistics and resource development but accessibility of NSR for ordinary merchant ships is limited due to difficult ice-condition depending on weather and geographical location. Additionally, since the icebreaking cost is abruptly increased after Russia government stopped granting subsidies for maintaining the icebreakers in 2003, the economic benefit of sailing through NSR is reduced for ordinary merchant ships. When icebreaking cost becomes negligible, the net profit through NSR is always higher than Suez Canal route. To realize reduction in icebreaking cost, a feasible option is designing a merchant ship equipped with nuclear power based icebreaking ability. In terms of economy of scale, ultra large container vessel (ULCV) is selected as a target vessel to apply a nuclear engine whose required engine power is estimated 100MWe to have icebreaking capability. Therefore, SMART reactor, which adopts inherent safety design and passive features, economic improvement features including system simplification, components modularization, and on-shop fabrication, is considered as a heat source [3]. For power conversion system of the nuclear engine, trans-critical CO_2 cycle (T-CO_2 cycle) is taken into account. T-CO_2 cycle is basically operated above the critical point (7.3773 MPa /30.98 °C) but it goes through phase change in the condenser so that the cycle is preferred to operate in low temperature environment. However, former passive residual heat removal system (PRHRS) of SMART, which forms water natural circulation through a steam generator and isolated feed water / main steam line, cannot be directly applied to SMART with T-CO_2 system so that the original PRHRS should be replaced with a CO_2 based PRHRS (CPRHRS).

In this paper, the CPRHRS are designed by satisfying NRC requirements and the transient performance of the designed system is validated with MARS-KS code.

2. Methods and Results

2.1 CO₂ PRHRS design for SMART with T-CO₂ cycle

Following the NRC recommendations, a new concept of passive residual heat removal system (PRHRS) for SMART is suggested to accomplish hot shutdown condition 200ºC within 36 hours and maintain the state for 72 hours [4]. The original SMART is equipped with four trains of water-steam operating PRHRS and it was designed to be capable of accomplishing hot shutdown state with only two trains out of four. Similarly, passive system of the targeted system is considered as the CO_2 natural circulation loop through IHX's CO_2 channels for removing residual heat passively. The difference is that the CO_2 cooling heat exchanger (CHEX) of CO_2 Passive Residual Heat Removal System (CPRHRS) should be passively cooled by ambient air for the fully passive operation for indefinite residual heat removal. This is because it is not guaranteed that passive systems for marine application can be replenished or aided from any external active system after 72 hours. Hence, the passive systems for the proposed nuclear powered icebreaking container ship is designed to equip with semi-permanent passive cooling ability. This design choice leads to abandoning the ECT concept. Similarly, passive system of the targeted system is considered as the CO_2 natural circulation loop through IHX's CO_2 channels for removing residual heat passively. The difference is that the CO_2 cooling heat exchanger (CHEX) of CO_2 Passive Residual Heat Removal System (CPRHRS) should be passively cooled by ambient air for the fully passive operation. Similar to meet design requirements of PRHRS, CPRHRS should have capability of removing 1.5% of reactor thermal power to cool down the reactor core to 200ºC. In terms of conservatism, the reactor core outlet temperature is set to be 185ºC after CPRHRS is engaged. From the existing works, mass flow rate of primary side was calculated 125 kg/sec after the reactor shutdown due to the natural circulation between reactor core and steam generator under Loss of

Load (LOL) conditions [5]. Equally, when the CPRHRS is designed, the natural circulation mass flow rate of primary side is decided to be 125 kg/sec for SMART and T-CO_2 coupled system. In short, boundary conditions of IHX's primary side are prescribed, which are target core outlet temperature 185°C, primary natural circulation mass flow rate 125 kg/sec and decay heat for 0.5% of rated reactor power (single train of CPRHRS has three IHXs and 1.5% of rated reactor power should be removed through three IHXs). Since IHX's geometry is already fixed, the required mass flow rates of IHX's CO_2 side can be calculated by changing inlet temperature of IHX's CO_2 side as shown in Fig. 2. After the required mass flow rate and inlet / outlet temperature of IHX's CO_2 side are obtained, the CHEX can be also deigned, while satisfying the 1.5% rated reactor power heat removal requirement.
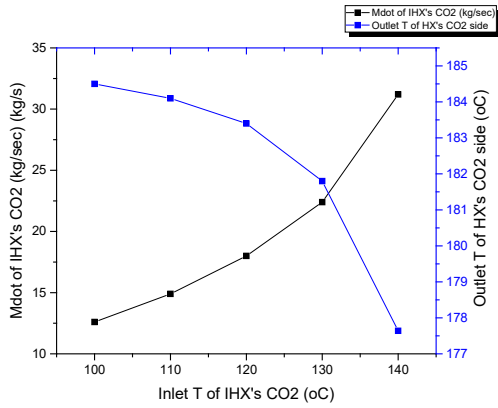

Fig. 2. Required mass flow rate of IHX's CO_2 side to remove generated residual heat and the outlet temperature of IHX's CO_2 side

A U-shape heat exchanger is taken into account for the configuration of CHEX as shown in Fig. 3 because pressure drop of air should be extremely low since active air circulators or fans are not used in the passive system.
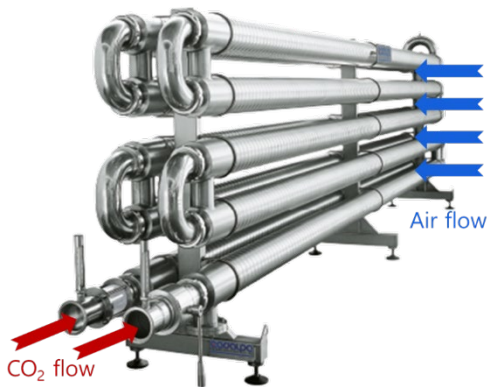

Fig. 3. U-shape type air cooled CHEX

The correlation for designing CHEX's tube inside is chosen as Dittus-Boelter for heat transfer coefficient and Blasius for friction factor. Robinson and Briggs correlations for the tube outside are selected for both heat transfer and friction factor coefficient as Yan adopted for dry cooling system design [6].

$$Nu = 0.092\,\mathrm{Re}^{0.723}\,\mathrm{Pr}^{1/3}$$
$$f = 37.86\,\mathrm{Re}^{-0.316}(S_t / D_r)^{-0.927}(S_t / S_d)^{0.515} \tag{1}$$

Here, S_t and S_d are the transversal pitch and diagonal pitch, respectively. The boundary conditions of air is referred from the Arctic region statistics [7, 8]. The average wind velocity and ambient temperature was selected for 5 m/s and 15°C, considering conservatism from the statistics. With the air boundary conditions, the CHEX can be designed by using prescribed conditions in inlet / outlet temperature and required mass flow rate for IHX's CO_2 side to remove decay heat in the core. The design criteria of CHEX are set to be lower than 50kPa for CO_2 pressure drop and 4kPa for the air side.

After all geometries of main components of CPRHRS are determined, the required natural circulation loop can be obtained from changing the thermal height between IHX and CHEX. The conventional method to calculate natural circulation mass flow rate is using a closed integral method by combining steady state continuity, momentum and energy conservative equations for given geometry, and condensation temperature and power of heat source [9]. The closed supercritical natural circulation loop has to consider the dramatic property changes near the critical point and pseudo critical point so that the Boussinesq approximation is not be applicable to calculate the closed supercritical natural circulation loop because the approximation is assuming that the thermal properties between two temperatures are nearly constant. Instead, the reduced pressure and enthalpy are used to correlate the governing equations as shown in Eq.(2).

$$\rho^* = \rho / \rho_{pc} \quad / \quad i^* = \beta_{pc}\left(i - i_{pc}\right)$$
$$Where,\ \beta = \frac{\beta_T}{C_p}\ (\text{Enthalpy volume expansion}) \tag{2}$$

Here, subscript 'pc' means the properties at the pseudo critical point. According to Swapnalee et al., the reduced pressures with respect to reduced enthalpies are overlapped on a single line, regardless of fluids and the thermal state [10], and the line can be linearized by separating into three regions as shown in Fig. 4.
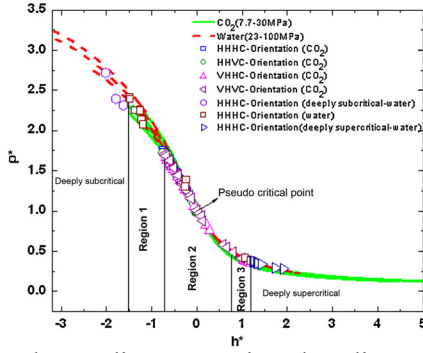
Fig. 4. The non-linear curve into three linear line by separating regions

The linearization formula between reduced density and enthalpy can be expressed as shown in Eq.(3).

$$\rho^* = C_1 - C_2 i^*$$
$$(i^* < -0.7): C_1 = 1.298 / C_2 = 0.6405$$
$$(-0.7 \leq i^* < 0.76): C_1 = 1.068 / C_2 = 0.9306 \quad (3)$$
$$(i^* > 0.76): C_1 = 0.4046 / C_2 = 0.0633$$

The integration of momentum equation for supercritical fluid can be expressed in terms of reduced pressure and enthalpy and the natural circulation mass flow rate can be expressed as shown in Eq.(5).

$$\frac{w^2}{A^2 \rho_{pc}} \oint dv^* + \frac{Rw^2}{2\rho_{pc}\rho^*} + \\ \oint dP + g\rho_{pc}C_1 \oint ds - g\rho_{pc}C_2 \oint i^* ds = 0 \quad (4)$$

$$w = \left[\frac{2C_2 \overline{\rho}^* \rho_{pc}^2 \beta_{pc} gHQ_h}{R} \right]^{1/3} \quad (5)$$

To verify the calculated mass flow rate for the closed supercritical natural circulation loop, the CFD analysis of CO_2 based natural circulation loop was compared to the developed in-house code. Yadav et al. selected a simple natural circulation loop as shown in Fig. 5.
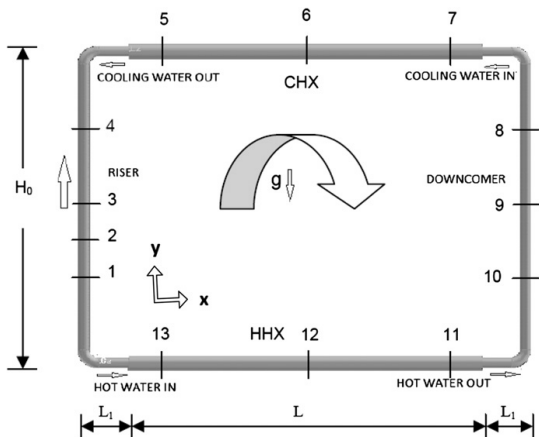

Fig. 5. The CO_2 natural circulation loop for verification

The comparison results of mass flow rate between CFD and the in-house code that adopts Swapnalee's method showed large deviation near the pseudo critical pressure as shown in Fig. 6.
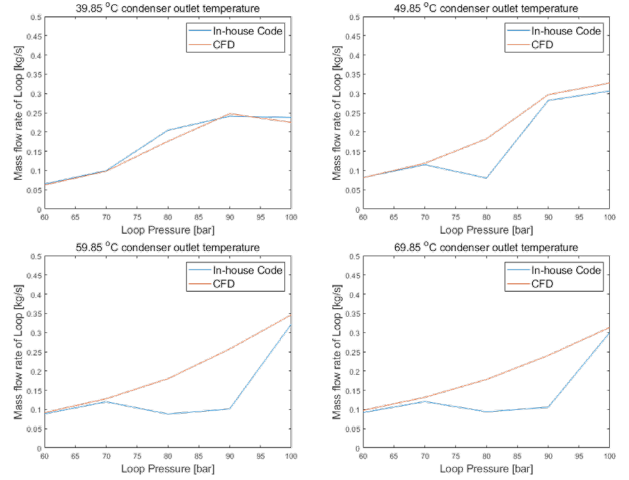

Fig. 6. Adopting three regions of reduced properties by Swapnalee

This is because the three divided regions were not an enough number to reflect the rapid property changes of CO_2 near the pseudo critical point. Hence, the regions are further divided into sixty sections to model the abrupt change of properties and the results of the modified in-house code shows better agreement with the CFD results as shown in Fig. 7.
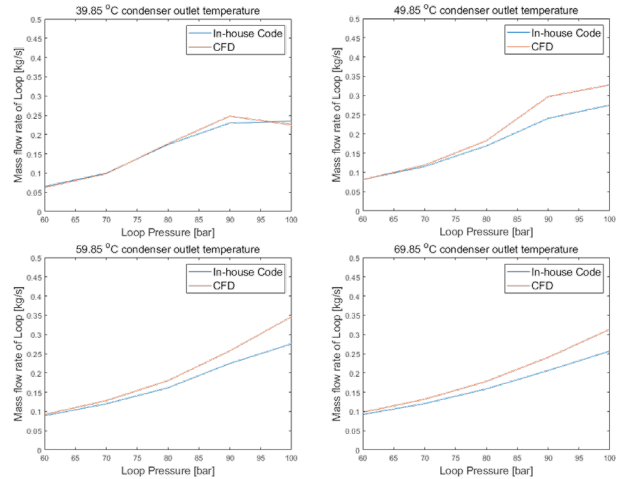

Fig. 7. Adopting finely divided regions of reduced properties

After the natural circulation mass flow rate is obtained, the required loop heights for prescribed cooler outlet temperature are needed to be calculated. However, before arriving to this stage, the optimal loop pressure should be first evaluated to confirm which loop pressure can generate the required mass flow rate as well. By changing the loop pressure and cooler outlet

temperature, it is found that the natural circulation mass flow will increase as the loop pressure becomes higher as shown in Fig. 8 so that the turbine inlet pressure (14.72MPa) was selected for the loop pressure.
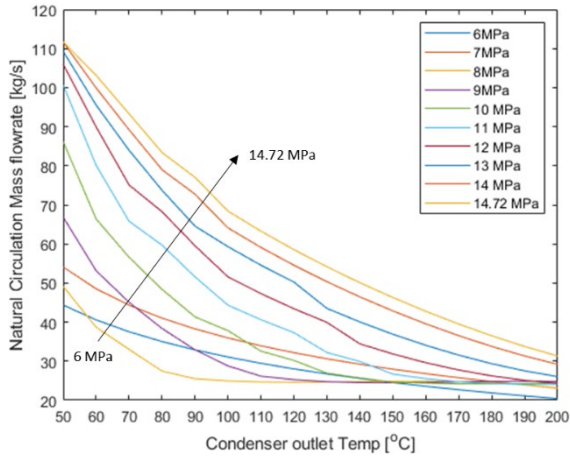

Fig. 8. Mass flow rates of closed natural circulation loop with respect to cooler outlet temperature and loop pressure

After all the conditions such as geometries, required mass flow rate and cooler outlet / inlet temperature are fixed, the required loop height is obtained. The designed loop is shown in Table I.

Table I. Design results of CO_2 PRHRS

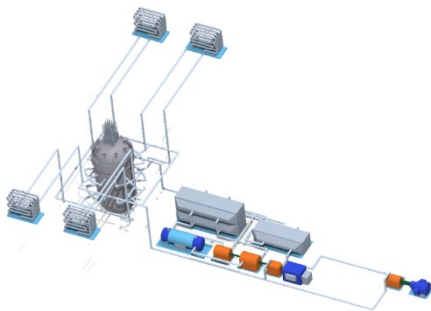|		
CHEX	$\dot{m}$ [kg/s]	93.6
	L_{tube} [m]	4.12
	Horizontal layer	3
	Vertical layer	28
	$A_{cross\_section}$ [m^2]	4.18 X 4.12
	Inner Diameter [mm]	52
	dP_{CO2} / dP_{air} [kPa]	45 / 2.87
Loop (3 IHX / 1 CHEX)	Pipe D_{cold} / D_{hot} [m]	0.451 / 0.49
	Height [m]	5.95

Fig. 9. Conceptual diagram of SMART coupled with T-CO_2 cycle and CPRHRS.

2.2 SBLOCA analysis

The original SMART does not have LBLOCA for the design basis accident by placing main components in a single pressure vessel and assembling main components nozzle to nozzle welding. Therefore, in this paper SBLOCA is analyzed with the new CPRHRS, which is generally regarded as the most severe initial event of decrease in primary side inventory category [11]. Choked flow and abrupt depressurization of pressurized water system is well developed and demonstrated in MARS-KS code that is a multi-dimensional and multi-purpose realistic thermal-hydraulic system analysis code for the light water reactor transients modeling. Therefore, SBLOCA of SMART system coupled to T-CO_2 cycle is analyzed with MARS-KS code. When SBLOCA is modeled, it is assumed that rupture location occurs at the top of pressurizer. Then, a single failure of PRHRS is assumed for conservatism, and all failure of injection systems is assumed to focus on the performance of CO_2 PRHRS during the accident. The sequence of SBLOCA is listed in TABLE II and the early transient behaviors of SMART and CO_2 PRHRS under SBLOCA are shown in Fig. 12. Due to low pressure signal in primary system, reactor trip signal is generated and reactor trip is actuated after 1.15 seconds delay. Then, main coolant pump (MCP) is also tripped with reactor trip signal and MCP coastdown begins. Main CO_2 line is perfectly isolated, and CO_2 PRHRS lines are fully opened after 10 seconds of reactor trip signal. In Fig. 12, reactor core power is abruptly decreased and heat transfer rate through IHX is also decreased but the reactor core power is slightly higher than the heat transfer through IHX so that temperatures of primary side and CO_2 side are increased again and then monotonically decreases. Fig. 13 shows the long-term transient behaviors of SMART and CO_2 PRHRS. The heat from reactor core becomes equal to the heat removal through IHX and pressure and temperature of primary side are steady due to heat removal of PRHRS. Remarkably, natural circulation flow of primary side shows large quantity because length of IHX is substantially reduced from the original helical steam generator for the steam Rankine cycle so that thermal center difference between hot side and cold side is larger than the original SMART design. Hence, it can be concluded that CO_2 PRHRS can remove residual heat from a reactor core so that SMART with T-CO_2 recompression cycle can be safely shutdown for various design basis accidents.

TABLE II. Sequence of SBLOCA

Time	Events	Set Point
0.0	Pipe rupture	44 mm
4.4	Low Pressure of Primary Side Trip	12 MPa

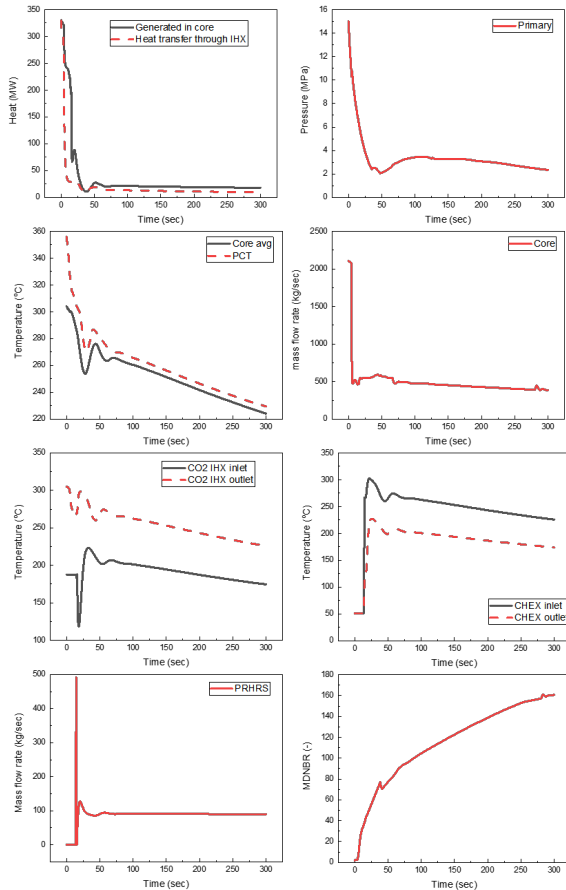| 5.55	Reactor Trip	1.15s delay
6.0	MCP trip	-
8.53	Turbine Trip	
15.6	PRHRS open / Feed line isolation	10.0s delay from Trip

Fig. 12. Early transient behavior of SMART with CO_2 PRHRS under SBLOCA (0-300 seconds)
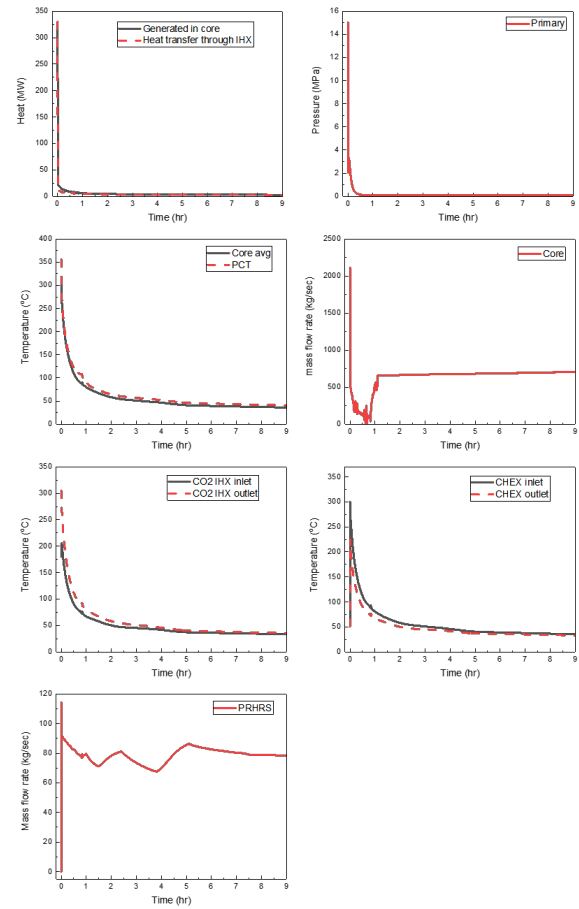

Fig. 13. Long-term transient behavior of SMART with CO_2 PRHRS under SBLOCA (0-9 hrs)

3. Summary and Conclusions

Due to reduced sailing distance of NSR compared to the conventional sea route connecting Asia and Europe, the NSR has large potential in terms of logistics but thick ice on the route is a challenge to overcome in order to make the sea route more economical. Thus, additional icebreaking cost is added when typical merchant ships navigates through the route in the past. To resolve this limitation, a merchant ship with icebreaking capability is suggested. To equip icebreaking capability, $100MW_e$ is estimated for the net power of the vessel so that SMART reactor is chosen for the energy source of the system and T-CO_2 recompression cycle is selected as a power conversion system because T-CO_2 cycle is regarded as the most appropriate cycle in low temperature heat sink and heat source conditions. Nonetheless, former PRHRS of SMART cannot be applicable to SMART with T-CO_2 system so that the original PRHRS should be replaced with a CO_2 based PRHRS (CPRHRS). However, Boussinesq approximation is not applicable to design a supercritical CO_2 natural circulation loop due to abrupt properties' change near pseudo critical point. By adopting reduced density and enthalpy concepts, mass

flow rate of the supercritical CO_2 natural circulation loop can be estimated. Especially, the non-linear relation between reduced density and enthalpy can be expressed as linear relation by separating the curve into several sections. After parameters of CPRHRS are determined including CHEX and loop height, transient performance of CPRHRS under SBLOCA condition is analyzed with the system TH code MARS-KS. The result shows the designed CPRHRS satisfies safety limit to mitigate SBLOCA of SMART coupled with T-CO_2 cycle. Thus, utilizing the proposed system to a ship navigating under the NSR conditions seems plausible in terms of safety and further detail evaluation will reveal its full potential.

Acknowledgement

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