Conceptual design and modeling of passive decay heat removal system of nuclear reactor applicable to ships

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1. Introduction

A conceptual design of the passive decay heat removal systems (PDHRS) of a nuclear reactor applicable to ships is proposed, and a performance analysis on the proposed design is conducted. The PDHRSs are composed of two systems and those are a wall cooling PDHRS (WCPDHRS) and an upper cooling PDHRS (UCPDHRS), respectively. The wall cooling system located near containment inner wall removes heat of a coolant tank, where reactor coolants are discharged during accident. And the atmosphere cooling system located inside containment upper part removes heat of containment atmosphere, which is heated and pressurized by steams ejected from reactor due to a hypothetical accident.

Conceptual designs for each PDHRS are conducted, and the draft system layouts for each are proposed. The both systems are composed of heat exchangers heating and cooling coolant, operate based on passive buoyance driven force without pump, and remove decay heats during accident conditions.

A numerical investigation on the proposed PDHRS design is conducted using MARS code. The performance of passive operation and heat removal capacity is analyzed.

This work is conducted using draft design data of nuclear reactor plant. The size and specifications of the core, the accident sequences and conditions, and the initial condition of heat source are not defined yet. The purpose of this study is to propose a design layout and to see if it passively operates at an initial stage of the project without the specific design of the core and detail accident conditions. And further study will be performed based on more detail design data under way.

2. Conceptual design and modeling

2.1 System layout

Fig. 1 shows the layout of WCPDHRS. The WCPDHRS is composed of coolant pool where reactor coolants are discharged and three heat exchangers, those are a heating heat exchanger that absorbs heat of the coolant pool, a cooling heat exchanger that removes heat of main loop coolant heat using air cooled water, and a cooling heat exchanger that cools using sea water, respectively. The system coolant is water, circulating passively based on the buoyance force driven by temperature difference.

The heat source is reactor coolant, which flows from reactor into coolant pool that is located near the containment wall, heating the water in the pool. The heated water in the coolant pool flows into a shell side inlet of the heating heat exchanger and heats main loop coolant flowing through tube side of the heat exchanger. The main loop coolant heated in the pool flows into tube sides of two cooling shell and tube heat exchangers. The cooling heat exchangers are composed of a supplementary and a primary one. The supplementary cooling heat exchanger, located above the heating heat exchanger, uses air cooled water as a coolant and operates mainly to induce buoyance driven flow circulation, while cooling main loop coolant partially. The primary cooling heat exchanger, located below the heating heat exchanger, uses sea water as a coolant and operates mainly to cool main loop coolant.

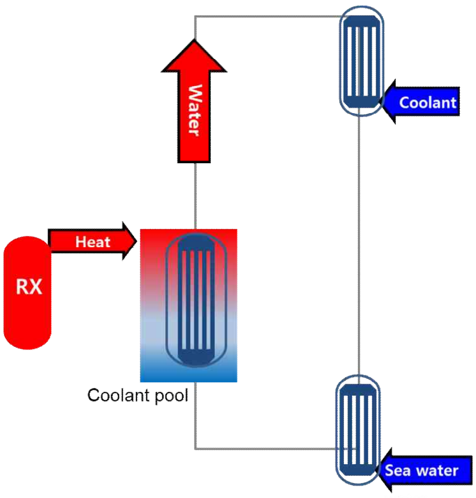


Fig. 1 Layout of WCPDHRS

Fig. 2 shows the layout of UCPDHRS. The UCPDHRS is located in containment above reactor, composed of two heat exchangers, and those are a heating heat exchanger that absorbs heat of steam in the containment, and a cooling heat exchanger that removes system coolant heat using air cooled water, respectively. The system coolant is water, circulating passively based on the buoyance force driven by temperature difference.

The heat source is reactor coolant steam, which is discharged from reactor and flows into the containment, increasing temperature and pressure of the atmosphere inside the containment. The steam in the containment flows into a shell side inlet of the heating heat exchanger and heats main loop coolant flowing through tube side of the heat exchanger, exiting as a condensed state. The main loop coolant heated by the reactor coolant flows into tube sides of the cooling heat exchanger. The cooling heat exchanger, located above the heating heat exchanger, uses air cooled water as a coolant and operates to cool main loop coolant temperature. And the buoyance driven force generated by the heating and cooling process induces natural flow circulation in the main loop. Inside the shell of the heating and cooling heat exchangers, the steam and the coolant are fed passively due to their cooling and heating process.

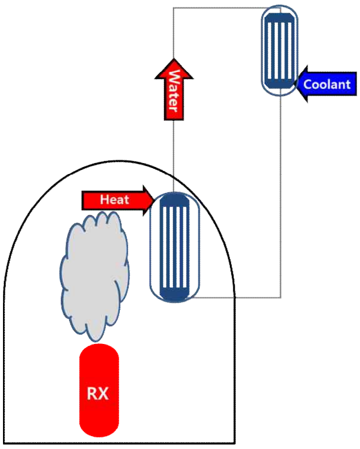


Fig. 2 Layout of UCPDHRS

2.2 Conceptual design and modeling

Fig. 3 shows the modeling design of WCPDHRS. The conditions of the heat source reactor coolant are set to 120 ^{O}C, 20kg/s, respectively. Temperatures of coolants for supplementary cooling HX and primary cooling HX are set to 77 and 17 ^{O}C, respectively. The total elevation of the system is designed to 29m as a reference value. The heat and cooling source conditions are tentative ones. Those are tentatively set to propose a design layout and to see if it passively operates at an initial stage of the project without the specific design of the core and detail accident conditions. The thermodynamic conditions of the heat source and dimension of the coolant pool will be updated according to the core and main system design progress.

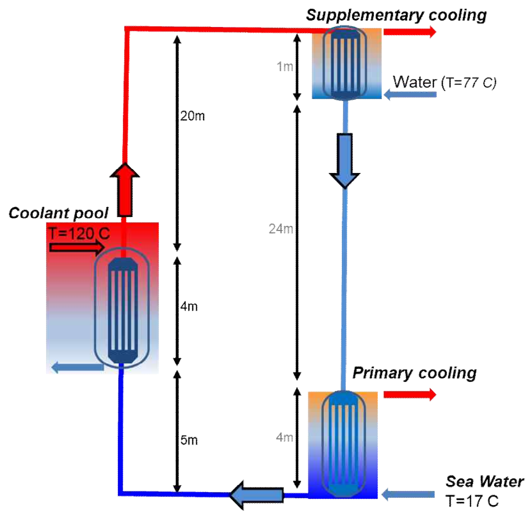


Fig. 3 Modeling design of WCPDHRS

Table 1 shows design parameters of the three heat exchangers. The total amount of decay heat from reactor is assumed to 7% of 75MWt, and the heat exchanger size and pipe size are designed based on it. The value of the decay heat is an arbitrary one and will be revised following the system design progress,

The proposed systems are aimed to remove decay heat, not entire heat, generated during a severe accident, and to be applied to the cooling water pool and the containment atmosphere, not to a place where heat and pressure are substantially high, exceeding decay heat level. The above heat source condition is draft one and will be revised when more specific core design and accident conditions are determined.

Table 1. Heat exchanger design parameters

	Heating	Supplementary cooling	Primary cooling
Tube id/od, mm	25 / 27	25 / 27	25 / 27
Tube no.	100	10	100
Tube length, m	4	1	4
Tube flow rate, kg/s	7.2	7.2	7.2
Tube flow area, m^2	0.05	0.005	0.05
Shell flow rate, kg/s	20	3.5	6.9
Shell flow area, m^2	0.074	0.007	0.074
Shell Dh, m	0.037	0.037	0.037
P/D	1.5	1.5	1.5

Fig. 4 shows the modeling design of UCPDHRS. The conditions of the heat source reactor coolant are set to 300 ^{O}C, 2 bar, x=1.0, 2kg/s, respectively. The design data are draft ones. Temperatures of coolants for cooling HX is set to 1, very low value set to help form natural circulation. The total elevation of the system is designed to 29m as a reference value.

The thermodynamic conditions of heat source and dimension of the coolant pool will be updated.

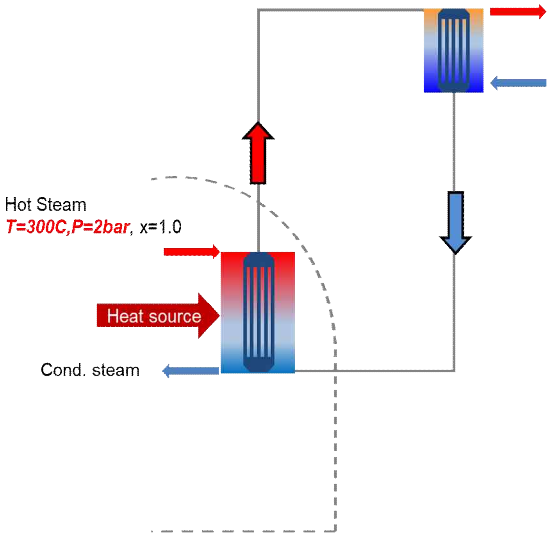
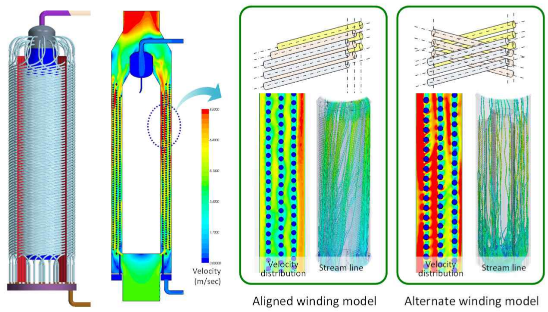


Fig. 4 Modeling design of UCPDHRS

Table 2 shows design parameters of the heating heat exchanger. The heat exchanger is designed through the law of similarity based on the helical type sodium to air heat exchanger [SFR-513-DF-302-001]. And Fig. 5 shows the referenced heat exchanger design layout.

Table 2. Steam heat exchanger design parameters

	Design values
Tube id/od, mm	3.0 / 4.0
Tube no.	24
Tube length, m	19.8
Tube flow rate, kg/s	1.1
Tube flow area, m^2	0.00173
Shell flow rate, kg/s	0.6
Shell flow area, m^2	0.00892
Shell Dh, m	0.01327
P/D	1.5



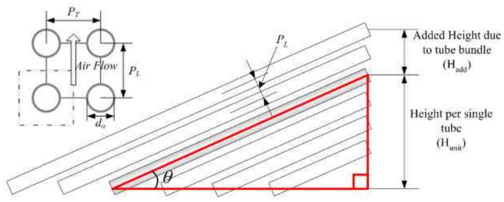


Fig. 5 Reference heat exchanger design layout

3. MARS code modeling results

Performance of the WCPDHRS design is calculated using MARS code. Fig. 6 shows performance analysis results. The heat removal amounts vary from 3.06 to 5.6 MW proportionally to the system elevation varying from 19 to 30m. Flow rate of the main loop coolant also changing proportionally to the elevation varies from 5.4 to 12.5 kg/s. Main loop coolant temperature at the heating, the supplementary and the primary cooling heat exchangers outlets are 145, 118 and 37 ^{O}C, respectively for the reference condition where the system elevation is set to 29m. The flow rate of main loop is 8.64 kg/s. Flow rate of supplementary and primary coolants are 10.4 and 11.7 kg/s, respectively.

Performance of the UCPDHRS design is calculated using MARS code. The heat removal amount is calculated to 1.4 MW. Main loop coolant temperature at the heating and the cooling heat exchangers outlets are 297 and 2 ^{O}C, respectively for the reference condition where the system elevation is set to 29m. The flow rate of main loop is 1.08 kg/s. And flow rate of the heat source steam and the coolant are 0.6 and 5.0 kg/s, respectively.

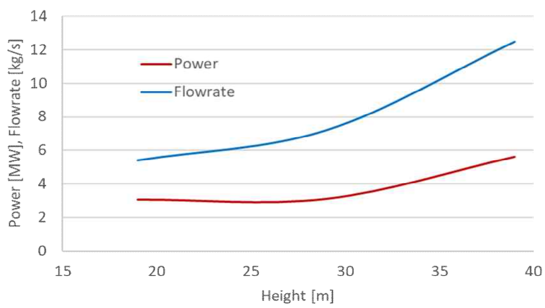


Fig. 6 Performance analysis results for WCPDHRS

Fig. 7 shows the calculation results of containment pressure. The containment pressure decreases due to heat removal from the heating heat exchanger, and the rate of pressure decrease is 0.118 MPa/h. The amount of pressure decrease is found marginal during short period, indicating that the UCPDHRS is applicable to a long term cooling system.

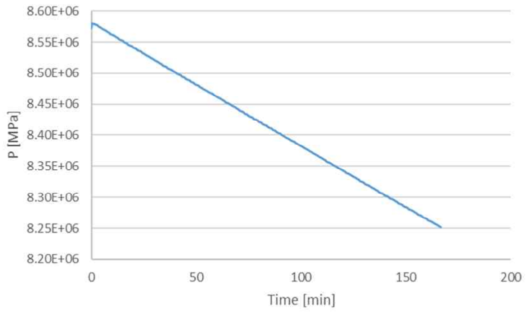


Fig. 7 Calculation results of containment pressure of UCPDHRS

5. Conclusion

Conceptual designs for two PDHRSs are conducted and the draft system layouts for each are established. A numerical investigation on the designed PDHRSs are conducted using MARS code. The performances of the proposed PDHRSs are analyzed.

REFERENCES

[1] D.H. KIM et al., “AHX size calculation,” KAERI report, SFR-513-DF-302-001, (2017).