Concepts of Passive Residual Heat Removal System for 130 MWth Nuclear Powered Ship

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1. Introduction

Many countries are facing global warming and they are preparing many measures for that. In the ocean industry, people also try to reduce the GHG and to change fossil-fuel-powered engine to nuclear powered engine for their ships. Compared to the nuclear reactor built on the ground, additional conditions such as slant, pitching, rolling and etc., should be considered for a nuclear reactor operating in marine environment. South Korea started to develop nuclear reactors for marine use. As a first step, South Korea launched a new project to build 130 MWth nuclear powered ship. Before the basic design stage, we classified element technologies to be proven and among them, the passive residual heat removal system (PRHRS) of the nuclear powered ship was decided to be improved above all. The reason was that after Fukushima nuclear accident, PRHRS is also recommended to enhance the safety of a nuclear powered ship. Up to now, there are many concepts for PRHRS in the world but they are not specified. And, also, their results produced by experimental way or numerical analysis are not quantitative. Therefore, to reach our goal, we planned our schedule to develop PRHRS of the ship. First, a variety of RPHRS concepts will be categorized and be examined by numerical analysis and then the design parameters of each concept will be quantified based on the results. Lastly, we will induce the concept of PRHRS of the ship and will optimize the system particularly in the point of the space and weight based on the results.

2. Methods and Results

Unlike a land based nuclear plant, a nuclear plant for a ship is installed in limited space. So the nuclear plant for a ship should be optimized based on space and weight at all design stages. In case of a containership, if a nuclear system installed in the containership occupies a large volume of ship's space, transportation efficiency goes down because the maximum container load decreases. Including space and weight, there are many factors restricting PRHRS design in a ship. In this work, variables affecting PRHRS design of a nuclear powered ship were examined and proposed concepts for PRHRS were investigated. Through the results, the optimum configurations of PRHRS for a nuclear powered ship will be suggested in this paper.

2.1 PRHRS Categorization

IAEA's report, 'Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants,' introduces a variety of PRHRS concepts and introduces their features. The report aims to enhance the safety of new generation reactors adopting PRHRS. The report defines the active and the passive residual heat removal system and classifies many passive systems into four categories based on the level of passivity as shown in Table I. Among the categories, the category 'D' PRHRS is investigated for the maritime condition [1]. To deduce the new PRHRS concept for 130MWth nuclear powered ship, we paid attention to the concepts, 'Passively cooled steam generator natural circulation', 'Passive residual heat removal heat exchangers', 'Containment pressure suppression pools', and 'Containment passive heat removal/pressure suppression systems' [1].

Table I: PRHRS Categorization

Category	Features
A	• no signal inputs of 'intelligence' • no external power sources or forces • no moving mechanical parts • no moving working fluid
B	• no signal inputs of 'intelligence' • no external power sources or forces • no moving mechanical parts • moving working fluids
C	• no signal inputs of 'intelligence' • no external power sources or forces • moving mechanical parts, whether or not moving working fluids are also present
D	• signal inputs of 'intelligence' to initiate the passive process • energy to initiate the process must be from stored sources such as batteries or elevated fluids • active components are limited to controls, instrumentation and valves to initiate the passive system • Manual initiation is excluded

2.2 Design Factors

2.2.1 Code and Standard

For the new concept of PRHRS for the nuclear powered ship, recent regulations and standards were considered. The concepts must follow 'General Design Criteria for Nuclear Power Plants', appendix A to part 50, 'Regulation of the Nuclear Safety and Security Commission', article 29, No. 24, ASME, and, KEPIC.

2.2.2 Basic Requirements

To provide new concept of PRHRS for the nuclear powered ship, several requirements were set as follows:

- The initial decay heat is about 7% of the full power and the decay heat for the long term cooling is set at around 1% of the full power.
- The target temperature of the RCS is about 215 ℃ right before water depletion of the PRHRS.
- After water depletion of the PRHRS, an air cooler performs the duty thoroughly and, at this moment, the average heat skink temperature (in the air) is 25 ℃.
- There is no operator intervention.
- PRHRS should be compact to be installed in a ship.
- The sea water should be considered as an ultimate heat sink.

2.2.3 Arrangement

Generally, PRHRS is much larger than other components so its structure and constitution is affected by reactor and other components arrangement. Moreover, a ship has very limited space to install components, such as, reactor, pressurizer, steam generator, and coolant pump of a nuclear power system. Therefore, PRHRS should be composed as an integrated feature. Also, the integrated feature ensures the pipe break prevention.

2.2.4 The Route of Residual Decay Heat Removal

The ultimate goal of PRHRS of a ship is to remove residual heat out of a containment or a ship. As presented in the figure 1, there are three routes to remove residual decay heat. The first route (Route A) is that the heat of the primary loop coolant is dumped outside of the containment by directly connecting PRHRS installed out of containment. The second route (Route B) is that the heat of the secondary loop coolant is eliminated by flowing the secondary coolant into the outside PRHRS. Lastly, the small portion of the decay heat is transferred into the inside of the containment that causes the pressure increase of the containment. Therefore, to mitigate the pressure rise, the heat of the containment should be removed (Route C). Among the routes, route A was excluded because there is possibility of radio material release into the air due to pipe failure.

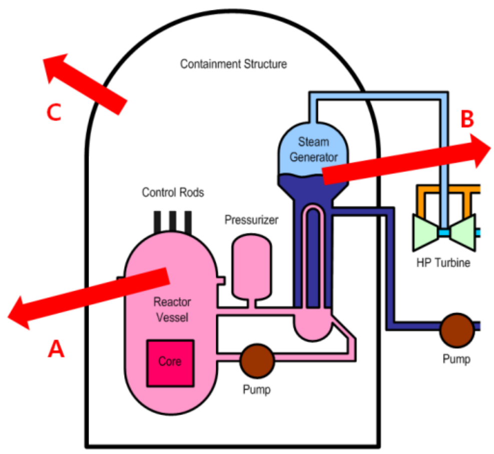

Fig. 1. Three routes to get rid of the residual decay heat.

2.3 New PRHRS Concepts

2.3.1 SG-PRHRS

According to SECY, it is allowed to operator action to relieve an accident consequence at least 72 hours later after PRHRS initiates [2]. That means operators could supply external electricity and water inventory on the land. However, in case of a ship floating in the middle of the ocean, it is very limited to provide external electricity and water. Therefore, the air cooling for the long term cooling was included to our consideration. Also, to prevent thermal stratification and dead zone in water inventory, and to reduce the size and the volume of PRHRS, we combined the water cooling and the air cooling method as illustrated in figure 2. This hybrid heat exchanger is composed of the water tank, the heat exchangers, the boiling pot, and the steam chamber. After an accident occurs, the residual decay heat is removed by two coolers, the water heat exchanger and the air heat exchanger in combination. While hot steam or water coming from the steam generator is going through the air cooler and boiling pot, a certain amount of the heat is removed by the air cooler and the rest of the heat is transferred to the water in the boiling pot which is connected to the top of the water tank by pipe. The steam generated in the boiling pot flows immediately to the top of the water tank so that the heat is sufficiently eliminated. After the water in the tank was depleted, the residual decay heat is continuously eliminated by the air cooler. The steam chamber makes dynamic pressure when the steam exhausts to the air through the holes. At the initial stage, the air cooler shares the decay heat load so that the water inventory could be reduced. On top of that, the combined feature could takes up a smaller space than the feature that each cooler is installed separately due to the maintenance space.

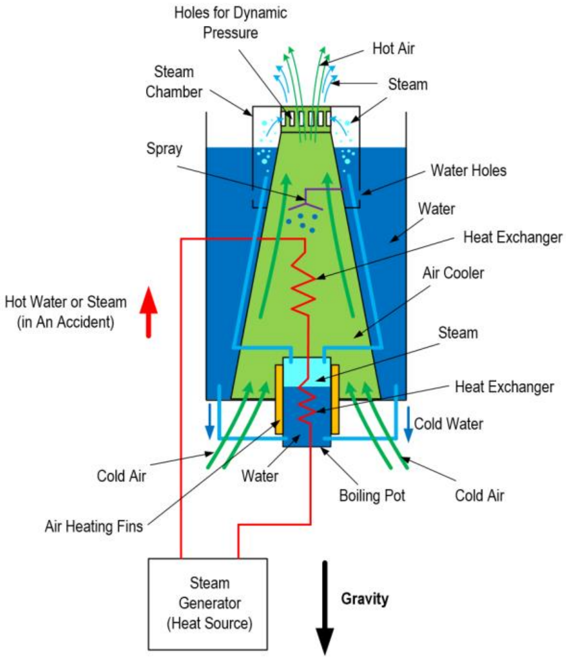

Fig. 2. The concept of the hybrid SG-PRHRS.

2.3.2 PRHRS Using the Sea Water

To achieve the natural circulation, in other word, to obtain sufficient driving force by gravity, a water tank is placed above a heat source (steam generator) with a certain length of height. Larger inventory of the water ensures sufficient residual heat removal. But, if the large water tank is installed at higher position, it could lead to structural weakness. To deal with this problem, the way to use the sea water was took into consideration as an ultimate heat sink, and, as a result, the sea water heat exchanger was additionally introduced into the loop. To make a driving force to supply hot water or steam to the sea water heat exchanger, PRHRS exchanges a minimum amount of heat. And, a large amount of the residual heat could be removed through the sea water heat exchanger. Figure 3 presents our important concept regarding PRHRS optimization. The cooling tank could be replaced with the air cooler. Our numerical results presented that the size of PRHRS could be reduced to 10~20% compared to the PRHRS without the sea water heat exchanger. And, the sea water heat exchanger could be placed at 3 m (10%) ~ 4 m (20%) below the center of the heat source.

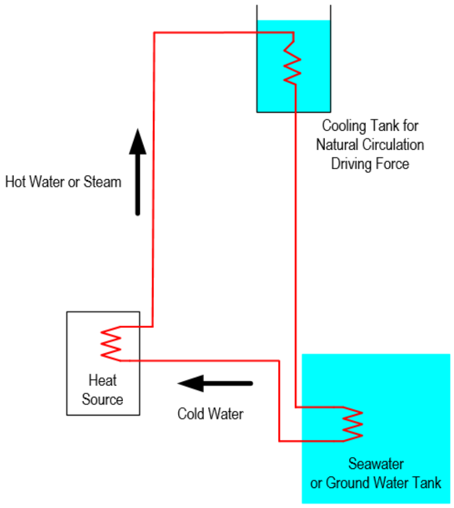

Fig. 3. PRHRS with the sea water cooling.

2.3.3 PCCS for Containment Pressure Rise Prevention

First of all, due to the space limitation of the ship, it is very hard to reserve the free volume inside of the containment so that the containment should be another pressure vessel. In this paper, the containment is regarded as an outer pressure vessel. As previously mentioned, a certain amount of the residual heat is transferred to the inside of the containment and that leads to pressure rise. To prevent pressure rise of the containment, we established two strategies. One strategy is that the heat in the containment is removed by natural convection using the upper side heat exchanger which is connected to PRHRS. In shown in figure 4, for example, when an accident occurs, the valve of the upper water tank becomes fail-open and the water is passively provided to the spray. The passive spray moderates the pressure rise and it provides water to the bottom plenum of the containment. The heat of the reactor is transferred to the water at the bottom plenum and the heat generates the steam. The steam is condensed by the upper heat exchanger. Finally, the condensed water drops into the water tank. The water tank has the minimum volume to make natural convention and it retains water to supply water to the passive spray and the bottom plenum. The gap of the bottom plenum between the reactor wall and the containment wall should be narrow enough to have the reactor merged. The other strategy is that the heat in the containment is removed by the containment wall conduction. To remove heat sufficiently, the cylindrical water tank is placed around the containment. The heat of the water at the bottom plenum is transferred to the outer water tank through the containment wall conduction. And, the heated water in the outer water tank is ultimately cooled by PRHRS as illustrated in figure 5. In addition, in many nuclear power plants, ADS is adopted to mitigate the sudden pressure increase in the reactor, but this way may causes the sudden pressure rise in the containment because the free volume of the ship's containment is extremely small. So the ADS pipe line is extended to the outer tank.

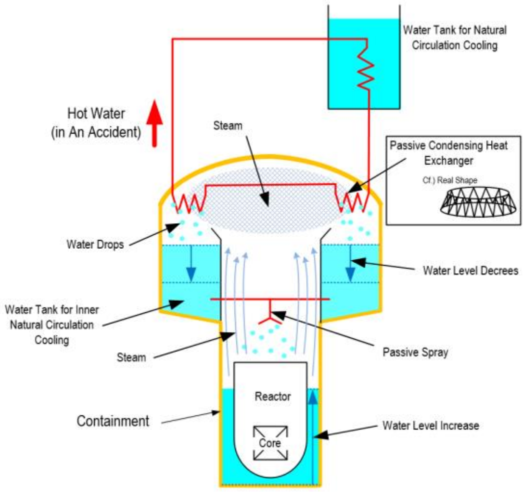

Fig. 4. Containment pressure rise prevention using the natural convection.

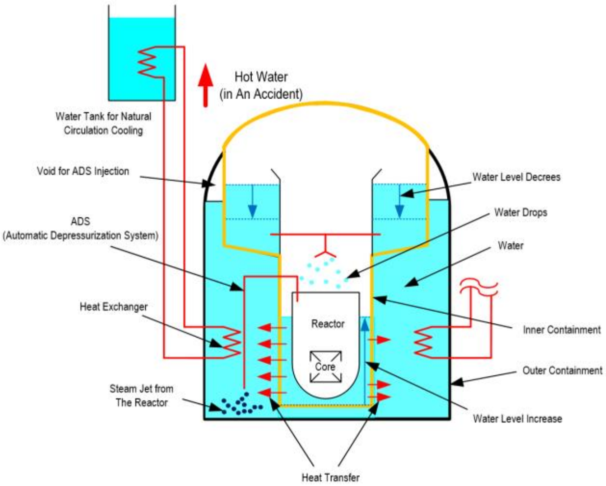

Fig. 5. Containment pressure rise prevention using the containment wall conduction.

3. Conclusions

A variety of PRHRS under development or in operation worldwide were examined and the relevant regulations and the design codes were reviewed. Also, the mechanism to remove the residual decay heat was investigated. As a result, the new concepts of PRHRS for 130 MWth nuclear powered ship were suggested. In the next step, our work aims to evaluate the performance of each concept and, finally, to find the best configuration to introduce to the nuclear powered ship.

ACKNOWLEDGEMENT

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[2] SECYs 93-083, 93-087, 94-084, 94-302, 95-132, 95-172, 96-128, and 97-044, USNRS.