Design features of the passive decay heat removal system of KALIMER-600

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1. Introduction

KALIMER-600 [1] employs a pool-type primary heat transport system (PHTS), a two-loop intermediate heat transport system (IHTS), a steam generator system (SGS), and diverse decay heat removal (DHR) systems. The PDRC (Passive safety-grade Decay heat Removal Circuit) is the passive safety-grade decay heat removal system of KALIMER-600, and it utilizes a purely passive principle with a high reliability for a core decay heat removal. To satisfy the passive feature, several innovative or effective design considerations are implemented for its operation. This study provides the key design features regarding the cold pool cooling mode of the PDRC system with the preliminary evaluation results to confirm its feasibility.

2. Methods and Results

2.1 Description of the PDRC system

The PDRC is comprised of two independent loops, and each loop is equipped with a single sodium-to-sodium decay heat exchanger (DHX), single sodium-to-air heat exchanger (AHX), and the intermediate sodium loop connecting the DHX with the AHX.

During a normal plant operation, the DHX located inside the DHX support barrel is partially immersed into the cold pool sodium to prevent unexpected sodium solidification inside the PDRC loop [2]. This feature makes the {UA} value of the DHX larger, and thus the amount of heat transferred to the PDRC cooling flow through the DHX would increase. The immersed portion is 30~35% of the effective heat transfer tube length of the DHX, and the relevant design parameters are optimized to maintain a minimum loop sodium flow with a minimized heat loss [2].

Under an accident condition like a loss of normal heat sink [1], the level difference between hot and cold pool disappears because of the PHTS pump trip following the reactor shutdown as depicted in **Fig.1**. In this case, since the normal heat transport path is not available, the hot pool sodium is expanded due to the discrepancy between the core decay heat generation and its removal capability.

The hot pool sodium consequently overflows into the DHX support barrel and then it is mixed with the sodium inside the barrel. The coolant continuously flows into the shell-side DHX and then the cooled sodium flows into the cold pool region.

As the sodium flow rate through the shell-side DHX increases, the heat transfer rate through the DHX proportionally increases due to the enhancement of convection heat transfer. The heat transferred to the tube-side DHX contributes the formation of natural circulation flow of the PDRC loop sodium, and it is finally dissipated into atmosphere through the AHX by the density-driven air flow.

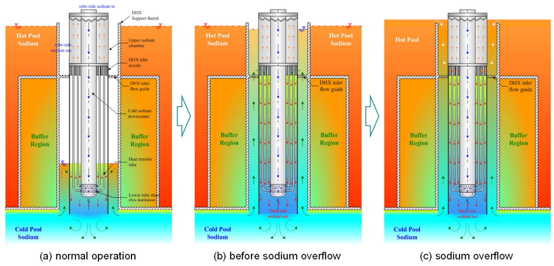

Fig.1 DHX configuration and DHR process

The system is totally self-regulating since the heat removal capacity of the PDRC is directly proportional to the pool sodium temperature variation. Thus, the effective decay heat removal function is accomplished by using the purely passive concept depending on a density-driven flow without either an operator's action or any active component actuation.

2.2 Key design feature of the PDRC system

For the PDRC operation mode, there are two distinct flow paths communicating the hot and cold pool. One is the normal flow path passing the IHX (Intermediate Heat eXchanger), and the other is the emergency cooling path via the DHX as depicted in **Fig.2**. These two paths become parallel only if the hot pool sodium overflows into the DHX support barrel during an accident condition. This feature provides an effective heat removal capability through the PDRC system.

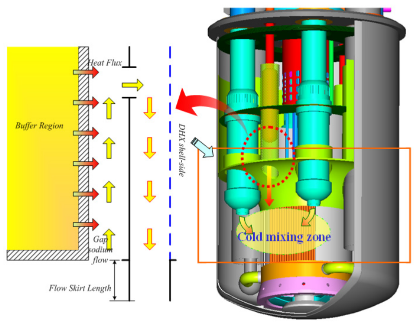

Fig.2 Concept of the PDRC parallel flow path

Although the DHR function of the PDRC system is mainly accomplished by the sodium overflow from the hot pool region, the PDRC heat removal is always working even without the overflow. The cold pool sodium level increases inside the DHX barrel when the primary pump shuts down [1], and then the full length of the DHX heat transfer tubes is immersed into the sodium pool. In this case, the sodium filled inside the annular space between the inner surface of the DHX support barrel and the outer surface of the DHX shroud is heated by the heat flux coming from the hot sodium pool via the buffer region [1][2].

Therefore the effective lengths of the DHX heat transfer tube and the equivalent DHX support barrel height provide the driving force of the density-driven sodium flow in the annular flow channel.

Consequently the local circulation flow path composed of "cold pool – the annular gap space – shell-side DHX – cold pool" is newly formed, and this gap flow rate becomes the key parameter to determine the PDRC heat removal capability during the cold pool cooling mode. The mathematical form of the local convection process in the gap flow channel is considered as represented in the following equations.

$$\frac{\partial \dot{m}}{\partial t}\sum_i \frac{\Delta S_i}{A_i} = \oint \rho g ds - \frac{\dot{m}^2}{2}\sum \frac{1}{\bar{\rho}_i A_i^2}\left(K_i + f_i \frac{\Delta S_i}{d_i}\right) \qquad (1)$$

$$\frac{\partial}{\partial t}\left(A \Delta x \rho C_p T\right)_{Na,i} = \dot{m}_{Na}\bar{C}_p\left(T_{in} - T_{ex}\right)_{Na} + Q_w \qquad (2)$$

Eq.(1) represents the balance between the developed static head difference and the pressure loss of the gap sodium channel (*which is composed of the annular space and the DHX cooling path*), and Eq. (2) is for the energy balance at a node in a numerical calculation mesh configuration. The term, Q_w is the convective heat transfer rate from the inner surface of the DHX support barrel to the gap sodium flow. From the understanding of the mathematical relations for the gap sodium flow, it was found that the gap flow rate passing the local circulation flow path would increase as the length of the gap flow channel increases.

From this finding, the lower end of the DHX shroud is extended to the cold pool region inside the DHX support barrel, and the structure is named as the DHX baffle cut [2]. This design feature has two advantages, which are i) providing a sufficient density difference and a resultant gap flow rate increase and ii) avoiding a flow interference between the rising flow toward the annular gap space and the downward flow discharged from the DHX cooling path.

2.3 Design verification by CFD analysis

Since the mechanism of the cold pool cooling mode is based on a multi-dimensional effect, CFD analysis was made by using CFX 5.7.1 [3] to verify the design concept of the mode. **Fig.3** shows the 3-D temperature and velocity fields for all the fluid domains of the gap flow channel surrounding the DHX.

As shown in the figure, multi-dimensional effect on the gap sodium flow with a local convection heat transfer to the DHX unit could be observed, and it was found that the gap flowrate is well developed without definite flow interference near the bottom part of the DHX support barrel.

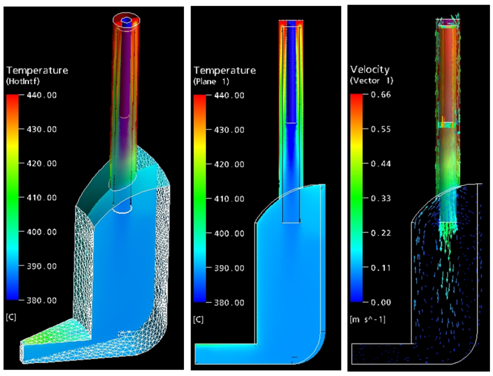

Fig.3 Temperature & velocity field near the DHX

Fig.4 shows the effect of the baffle cut length change on the variation of the gap flowrate and corresponding PDRC heat removal rate during the cold pool cooling mode. As shown in the figure, it was also found that the gap flowrate increases as the total length of the baffle cut increases. The design consideration regarding the baffle cut support was also made to determine its optimized length by considering with the DHX configuration inside the reactor pool.

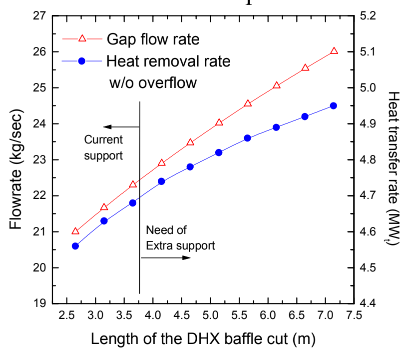

Fig.4 Effect of the DHX baffle cut length change

3. Conclusions

The key design features of the passive DHR system of KALIMER-600 were discussed with its heat removal mechanism by the operation modes, and the feasibility of the cold pool cooling mode was preliminarily evaluated by using the CFD analysis. From the analysis results, some design guides for the DHX configuration and its support were proposed as well.

ACKNOWLEDGEMENT

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