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Feasibility study on the design options to prevent the PDRC loop sodium freezing in KALIMER-600

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1. Introduction

The conceptual design of the sodium cooled fast reactor, KALIMER-600 (Korea Advanced LIquid MEtal Reactor) of which the electric output is 600MWe, has been developed. The main design features of the reactor are the pool type primary heat transport system (PHTS), the two-loop intermediate heat transport system (IHTS), the steam generator system (SGS) and the passive decay heat removal (DHR) system. In particular, the safety-grade passive decay heat removal circuit (PDRC) is provided to cope with an accident condition like a protected loss of normal heat sink event [1]. **Fig. 1** shows the configuration and DHR process of the PDRC system in KALIMER-600.

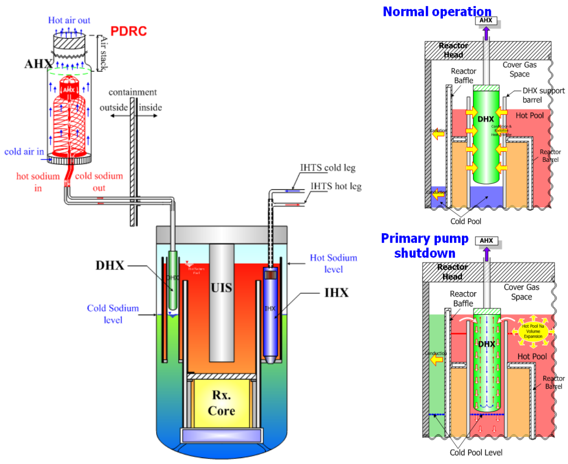

Figure 1. Overview of the PDRC System

The PDRC system utilizes the atmosphere as the ultimate heat sink and employs an intermediate heat removal loop (hereafter called a PDRC loop) that thermally connects the primary sodium pool to the heat sink part. Since the PDRC loop coolant directly exchanges heat with an ambient cooling air at the AHX (sodium-to-air heat exchanger), the working fluid inside the PDRC loop may freeze when the heat supply from the primary sodium system is not enough in a plant shutdown mode (i.e. refueling period) or when the ambient air temperature falls to -40°C during winter even in a plant normal operation mode.

This kind of undesirable PDRC loop sodium freezing phenomenon may cause a severe risk to plant safety due to a failure of a natural circulation in the PDRC loop. Hence sufficient design considerations to prevent a loop sodium freezing are required to enhance the operational reliance of the PDRC system.

This study provides three design options to essentially eliminate the possibility of a sodium freezing in the PDRC loop with the evaluation results of their feasibilities.

2. Methods and Results

For the current design of the PDRC system, the lowest sodium temperature at the PDRC cold-leg is 128°C during a plant normal operation, which is above the melting temperature of the working fluid of sodium (~98°C). However, the PDRC cold-leg sodium temperature can be close to the melting temperature or fall below it if the ambient air temperature becomes lowered during the winter season. Hence, there is a need to develop a method which can prevent the sodium freezing for the entire plant operation mode and various environmental conditions. The potential candidates for the design options to prevent the sodium freezing in the PDRC loop are summarized as follows.

i) the partially-dipped DHX concept
ii) the CACS-coupled PDRC concept
iii) the NaK-used PDRC concept

The first option, the partially-dipped DHX concept is to simply decrease the DHX (sodium-to-sodium decay heat exchanger) elevation while the other system parameters are kept the same as the reference design [2]. That is, it makes the thermal center of the DHX lower than the reference design so that a larger portion of the DHX heat transfer tubes is immersed in the pool sodium even in a normal operation mode.

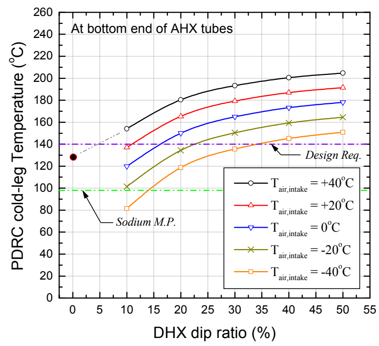

Figure 2. PDRC cold-leg temperature variations

In this case, the {UA} value of the DHX becomes larger as the dipped portion of the DHX heat transfer tube increases. However, the AHX heat transfer area should be reduced from an economic sense to keep the total value of the {UA} constant as possible when compared to the reference design. By using this approach, PDRC loop sodium temperature can be higher than the reference design, so the possibility of the PDRC loop sodium freezing can be drastically reduced as we can expect. **Fig. 2** shows the lowest PDRC cold-leg fluid temperature variations depending on the ambient air temperatures and dip ratios of the DHX heat transfer tubes. Though the sodium freezing issue can be resolved by using this concept, the criterion for a permissible heat loss regarding a plant thermal efficiency should be confirmed due to an undesirable heat transfer increase through the PDRC system during a normal plant operation.

The second option for a sodium freezing prevention is the CACS-coupled PDRC concept, which utilizes the heated air exhausted from the cavity air cooling system (CACS) [3]. As shown in **Fig. 3**, the AHX intake air temperature can be regularly increased by coupling the CACS air flow path with the AHX intake air path.

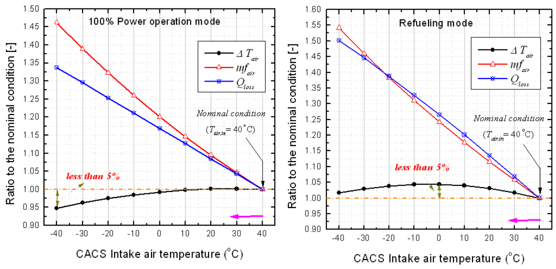

Figure 3. CACS-coupled PDRC concept

Since the CACS provides the capability to increase the air temperature of about 80°C during a normal operation condition, the AHX intake air temperature can be regularly maintained at least +20°C even in the design-basis temperature of -40°C. Hence the possibility of the sodium freezing in the PDRC loop becomes very low during a normal plant operation and a refueling period. However, a larger heat transfer area of the DHX and/or AHX needs to be guaranteed to achieve the same heat removal capability during a long-term cooling process. For this reason, the transient performance of the CACS-coupled PDRC system was tentatively investigated by employing the AHX intake air temperature of +120°C, and it was confirmed the design limit of the peak temperature during the long-term cooling process was satisfied even though the long-term temperature transients are generally much higher than in the case of the reference design.

The last option to resolve the sodium freezing issue is to use NaK eutectic coolant instead of sodium in the PDRC loop. This alternative is very practical because the melting point of NaK eutectic is -10°C [4] and thus the fluid freezing issue can be fundamentally eliminated. However, most thermo-fluidic properties of NaK eutectic are inferior to those of sodium from the view point of a heat transfer. In particular, thermal conductivity of NaK eutectic is no more than 40% that of sodium. Therefore we need a much larger heat transfer area in the DHX and AHX to assure a similar heat removal capability to the reference design employing sodium coolant as the working fluid in the PDRC loop. **Table 1** shows the comparison of the major PDRC design parameters depending on the working fluid. Based on the sizing results, to ensure a similar heat transfer capability corresponding to that of sodium, it was confirmed the required heat transfer areas of the DHX and AHX should be increased by up to about 180% if we use NaK eutectic as the working fluid in the PDRC loop.

Table 1. Design parameters for working fluid change

PDRC Loop	Unit	working fluid		Ratio*
		Sodium	**NaK**	
Mass flowrate	kg/sec	42.82	44.19	1.032
Total Flow Resistance	Pa-s^2/kg^2	3.7433	5.0805	1.357
Net developing head	kPa	6.8636	9.9196	1.445
DHX tube surface area	m^2	9.41	15.83	1.682
DHX U_{Avg}	W/m^2-K	5644.76	4412.25	0.782
AHX tube surface area	m^2	428.49	778.07	1.816
AHX U_{Avg}	W/m^2-K	108.78	71.39	0.656
Total {UA}	kW/°C	97.613	100.351	1.028

$^*Ratio \equiv \frac{\phi_{NaK}}{\phi_{Sodium}}$

3. Conclusions

The design options to prevent a sodium freezing in the PDRC loop were proposed, and their feasibilities were tentatively investigated for an entire plant operation mode. As a result, it was found that the partially-dipped DHX concept is very effective but, to cope with various environmental conditions, it is better to use it jointly with the CACS-coupled PDRC concept. Though the NaK-used PDRC concept could be an alternative as well, it was found that its high chemical reactivity and inferior thermo-fluidic properties prevent its wide use as the PDRC loop working fluid.

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