Evaluation of the Structure Design Concept of a Combined Heat Exchanger for Decay Heat Removal System in a Sodium-cooled Fast Reactor

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1. Introduction

The conceptual design of a 600MWe demonstration sodium-cooled fast reactor (DSFR-600[1]) was completed by the Korea Atomic Energy Research Institute (KAERI). In order to enhance plant safety, reliable decay heat removal (DHR) systems with natural circula-tieon flow have been employed to provide ultimate heat sink means to the environment. To achieve reliable DHR performance, KAERI has developed an innovative design concept called the PDRC [1,2], which is similar to a conventional DRACS [3] but its detailed flow path inside the reactor vessel is very creative.

In the DSFR-600 design, the internal flow path from the hot pool to the cold pool is somewhat ambiguous owing to the split flow ratio formed in a parallel path between the IHXs and DHXs. This ambiguity results in a large uncertainty in the DHX shell-side flowrate and corresponding heat transfer performance. To improve this weak point, we proposed a new design concept with a simplified flow path from the hot pool to the cold pool via a serial path passing the DHX and IHX. Hence, we developed a creative design concept of the combined IHX-DHX unit (hereafter called the CHX) and its thermal sizing and structural analysis with 3D modeling works have been carried out.

This paper logically addresses the assessment results of a high temperature design and structural integrity evaluation for the CHX unit in DSFR-600[1,2]. The design procedures for ensuring structural integrity regarding creep-fatigue damage conditions are briefly discussed as well.

2. Methods and Results

2.1 Combined IHX-DHX unit (CHX)

The CHX is a shell-and-tube type counter-current flow heat exchanger with a helically-coiled tube arrangement. Figure 1 shows the CHX configuration with the IHX coaxial pipe arrangement inside the reactor vessel. Total 4-row heat transfer tube bundle of the DHX surrounds the coaxial part of the IHX unit, and its lower end is vertically placed above the IHX inlet window nozzle. The annular-type sodium downcomer chamber surrounds the IHX coaxial pipe, and an annular-type hot sodium riser chamber also surrounds it. As a result, the quadruple sodium chambers constitute the segregated sodium flow paths of the DHX and IHX units in the proposed CHX configuration.

The vertical cylinder welded on the separation plate (hereafter, called a flow guide barrel [2]) is installed to surround the DHX tube bundle. Therefore, the flow guide barrel provides a unified single flow path from the hot sodium pool to the cold pool via the CHX shell path, which is composed of a serial flow path of the DHX tube bundle and IHX shell region. The top end of the flow guide barrel is vertically positioned sufficiently below the sodium free surface to avoid unexpected gas entrainment [1]. This feature makes a transient sodium flow path very simple and improves the DHR capability.

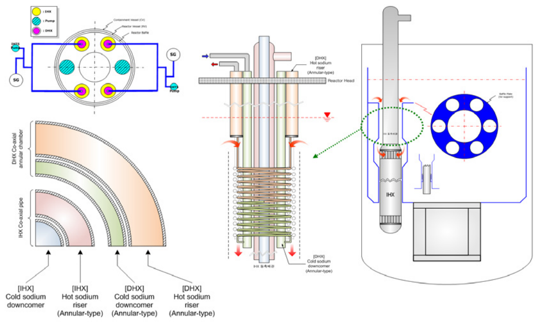


Fig.1 Configuration of the CHX unit

2.2 Modeling for 3D Finite element analysis

A three-dimensional finite element mesh was generated based on the 3D computer-aided design model of the CHX. Since the helical tubes of the unit do not allow symmetric modeling due to its asymmetric configuration, a full 3D model has been implemented in the present structural analysis. The ABAQUS [4] FE model shown in Figure 2 is composed of 725,794 3D elements and 1,017,972 nodes.

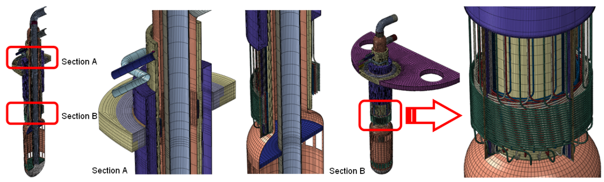


Fig.2 Configuration and FE model of the CHX unit

Total 42 helical tubes are sequently installed in a radial direction arrays with 4-row configuration. Each helical coil array has a different radius from the center of the inner shell and has been installed with alternating directions for every other tube row. Since the maximum coolant temperature in the CHX is 510°C in shell-side sodium path, the stress and strain states of the CHX unit are greatly influenced by the boundary conditions. The 42 helical tubes are supported by four plate strips in axial directions. The strips, functioning as spacers and support of the helical tubes, are installed at every 90-degree angle along the azimuthal direction. The plate strips have holes into which helical tubes pass through.

In the present finite element analysis, frictionless contact was assumed between the tubes and plate strips.

2.3 Loading conditions

In the CHX design of DSFR-600, the temperature ranges of the shell- and tube-side at the PDRC steady-state condition are from 510°C to 200°C and 498°C to 200°C, respectively [2]. The potential design transients of the shell-side unit are composed of (1) a duration at 510°C, (2) a cool-down to 200°C with a cool-down rate of 25°C/hr, (3) a duration at 200°C, (4) a heat-up to 510°C, and (5) finally maintaining 510°C. The transients of the tube-side are also composed of (1) a duration at 498°C, (2) a cool-down to 200°C with a cool-down rate of 25°C/hr, (3) a duration at 200°C, (4) a heat-up to 498°C, and (5) finally maintaining 498°C.

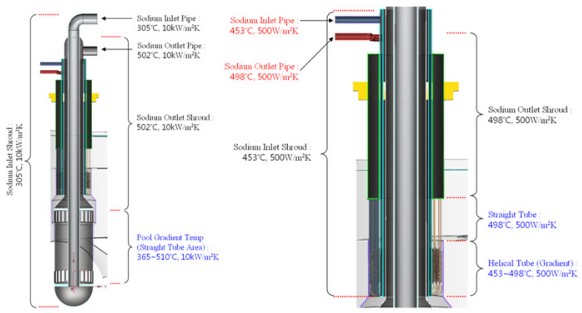
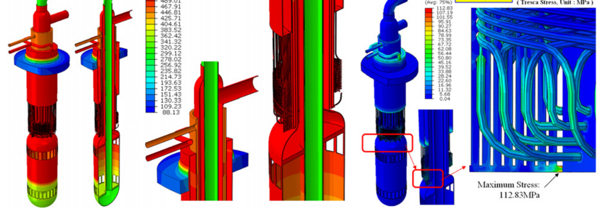


Fig.3 Boundary conditions of heat transfer for the unit

Nozzle loads at the end of the top header nozzle and bottom header nozzle were suitably applied for the stress analysis, which were determined from the piping analyses for the connected PDRC loop system subjected to thermal and mechanical loads.

2.4 Heat transfer and thermal stress analysis

Heat transfer analysis for the 3D FE model in a steady-state was made with the loading conditions mentioned in Section 2.3. For an evaluation of creep-fatigue damage, heat transfer and thermal stress analyses were firstly made by using ABAQUS [4]. For a simplified heat transfer analysis, it was assumed that the structures above the upper tubesheet and below the lower tubesheet of the helical bundle have uniform temperature distributions, while there were temperature gradients in the tube bundle region shown in Figure 3.

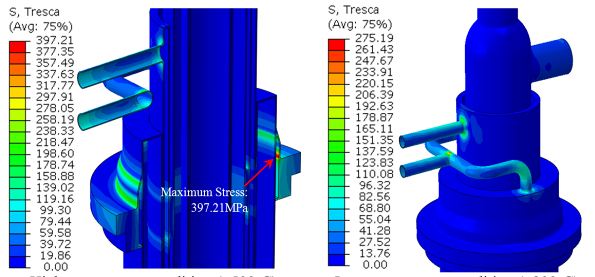


(a) Heat Transfer (b) S.I. for primary load

Fig.4 Heat transfer and Stress Analysis Results

The temperature distributions in a steady-state of the CHX show a gradual change along the axial direction as shown in Figure 4(a). The temperature distributions will be applied for the analysis of creep-fatigue damage in further works. Stress intensity (S.I) distribution under the primary loads was estimated to be within allowable design limit, and the maximum Tresca stress of 112.83MPa was observed at the bottom part of the tubesheet as shown in Figure 4(b).

The stress intensity distribution of the CHX unit under secondary loads in a steady-state is shown in Figure 5. It shows that the maximum S.I was estimated to be 397.21MPa at the supporting skirt structure interfaced with the reactor head plate and the surface temperature was 224°C, which is the sub-creep regime for Mod.9Cr-1Mo steel. Although this calculated maximum secondary S.I for the CHX unit is slightly below the $3S_m$ values for Mod.9Cr-1Mo steel, it should be within allowable design limits with enough safety factor by optimizing structural design concept of the CHX unit and its support. For this reason, the design change has been made and reasonable creep-fatigue damage analysis for the unit will be made as a further works.



< High temperature condition (~500°C) > < Low temperature condition (~200°C) >

Fig.5 Stress analysis results under secondary loads

3. Conclusions

A high temperature design and structural integrity evaluation of the combined IHX-DHX unit (CHX) in DSFR-600 was performed in this study. A full 3D finite element model was implemented, and reasonable heat transfer and thermal stress analyses were made by using ABAQUS [4]. The present design of the CHX unit was estimated to be structurally reasonable for a steady-state condition, but it was also found that some design improvement should be considered to reduce maximum stress intensity at the critical point. The results obtained from this study will be used for reasonable creep-fatigue damage analysis for the CHX unit.

Acknowledgement

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