ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 55 (2013) 326 – 332
Procedia Engineering
www.elsevier.com/locate/procedia

6th International Conference on Creep, Fatigue and Creep-Fatigue Interaction [CF-6]

Evaluation of Creep-fatigue Damage for Heat Exchangers in the Stella Sodium Test Loop

Hyeong-YeonLee*,Yong-BumLee, Jong-Bum Kim

989-111Daeduk-daero, Yusong-gu, Daejeon 305-353, Korea Atomic Energy Research Institute, Republic of Korea

Abstract

Creep-fatigue damage evaluation of DHX (Decay Heat Exchanger) and AHX(Air Heat Exchanger) in the sodium test facility has been performed. The sodium test loop of the STELLA-1 is for component performance tests of the main components, heat exchangers and mechanical pumps which are to be installed in an integral sodium test loop (STELLA-2) for simulating thermal hydraulic decay heat removal behaviour of the Korean demonstration Sodium-cooled Fast Reactor. High temperature design and fabrication of the DHX and AHX have been conducted and the components were installed at KAERI site. Evaluation of creep-fatigue damage at critical locations of the two heat exchangers were conducted according to the elevated temperature design codes of the ASME-NH and RCC-MR and the evaluation results were compared.

Keywords: Decay heat exchanger; Air heat exchange; creep-fatigue; Mod.9Cr-1Mo steel; stainless steel 316

1. Introduction

The accidents at the Fukushima nuclear power plant (NPP) have given the lesson that the decay heat removal system at NPP should remain functional under any severe accidents in order to avoid nuclear disaster. That is the rationale why the decay heat removal systems in Korean Demonstration Sodium-cooled Fast Reactor (SFR)[1,2] are classified as safety grade. Since the design concept of the decay heat removal in Korean SFR[2] is different from the conventional design, it is required to conduct a validation and verification test on the performances of decay heat removal systems to get licence from regulatory body on the SFR design. KAERI (Korea Atomic Energy Research Institute) is developing a large-size sodium test loop facility, STELLA (Sodium integral effect test loop for safety simulation and assessment).

The STELLA project is composed of two stages. In phase I of the STELLA project (STELLA-1), verification of computer codes through performance and validation tests of the heat exchangers of DHX (Decay heat exchanger; sodium to sodium heat exchanger) and AHX (Air heat exchanger; air to sodium heat exchanger), and for performance tests of the PHTS (Primary heat transport system) mechanical sodium pump

*Corresponding author:
E-mal: hylee@kaeri.re.kr

doi:10.1016/j.proeng.2013.03.261

will be performed. In phase II of the STELLA project (STELLA-2), verification tests on the performance of passive decay heat removal circuits will be performed.

The material of the shell and tube in the DHX are Mod.9Cr-1Mo steel (ASME Grade 91, Gr.91) which has good mechanical and thermal material properties, yet there is concern of type IV cracking at the welded joint [3-5]. The material of the shell and tube for AHX is austenitic stainless steel type 316 [6].

In the present study, a high temperature design and evaluation of creep-fatigue damage for DHX and AHX were conducted based on a full 3D FE analysis. So far, the evaluations of structural integrity for heat exchangers with tube-to-tube sheet junctions were mostly conducted using simplified 2D FE analysis, which could lead to overly conservative results or mislead the real behaviour of the heat exchanger component [7,8].In this study, 3D FE analyses with full consideration of tubes, tubesheets, and shellswereconducted to evaluate the structural integrity through simulating the DHX and AHX component more realistically. Evaluation of creep-fatigue damage for the two heat exchangers was conducted according to the high temperature design codes, ASME Section III Subsection NH [9] and RCC-MR [10]. Code comparisons were made based on the evaluation results of creep-fatigue damage.

1. 2. Sodium test loop, the STELLA

2.1 Overview of the STELLA-1 sodium test loop

The reference reactor of the sodium test facility, STELLA-1 is Korean Demonstration SFR[2]. The height and length scale is 1/5, working fluid is sodium and maximum simulated core power is 7% of scaled nominal power. The schematic arrangement of the STELLA-1 test loop is shown in Figure 1. The main components to be tested in the STELLA-1 test loop are DHX, AHX and PHTS pump.

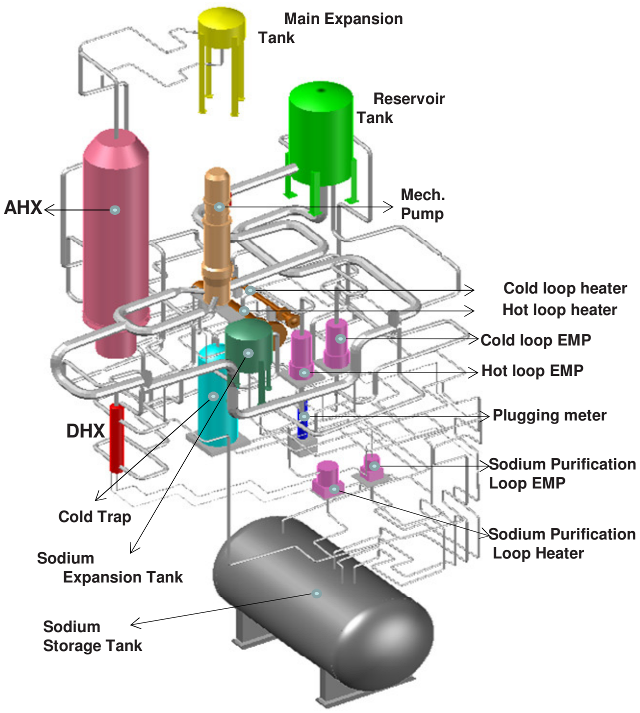


Fig. 1. General arrangement of the sodium test loop, STELLA-1.

The function of the sodium-sodium heat exchanger, DHX is to transmit the decay heat in the reactor core and PHTS to the decay heat loop which is connected to the air-sodium heat exchanger, AHX after reactor shutdown as shown in Figure 2. For the decay heat removal there is passive circuit (PDRC) and active circuit (ADRC) based on a diversity design concept of the SFR.

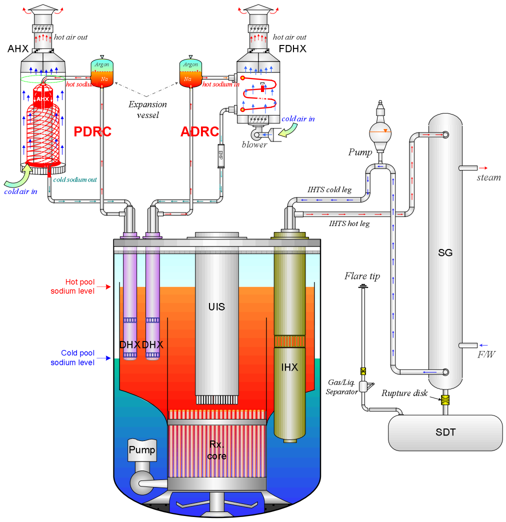
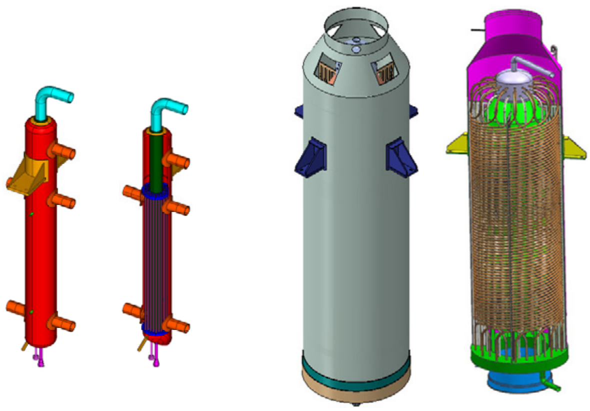


Fig. 2.Configuration of decay heat removal circuits in Korean demonstration SFR.

2.2 Configurations of heat exchangers

The two heat exchangers installed in the STELLA-1 project are DHX and AHX as shown in Figure 3. The DHX of STELLA-1 test loop is a shell and tube type heat exchanger with 36 straight tubes. The Gr.91 tube has outer diameter of 21.7mm, thickness of 1.65mm and effective length of 1.73m.

The AHX in the STELLA has 36 helical tubes having the same sizes with those of the demonstration reactor. The size of the AHX is 1.59m in diameter and 6.5m in height. The materials of the shell and tube are austenitic stainless steel 316 and 304SS, respectively. The 316SS tube has outer diameter of 34mm, thickness of 1.65mm and effective length of 23.8m.



(a) DHX (b) AHX

Fig. 3. Configurations of the two heat exchangers.

3. Evaluation of creep-fatigue damage

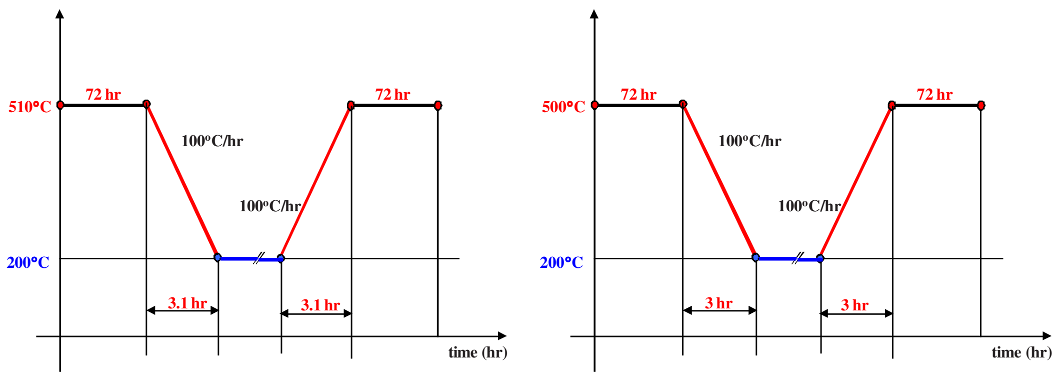
3.1. 3D Finite element modeling

A 3-D finite element models were generated for the DHX and AHX component based on the 3D computer-aided design models. The ABAQUS [11] FE model for DHX is composed of 225,511 3D linear solid elements and 290,790 nodes while that for AHX is composed of 523,752 3D linear solid elements and 803,199 nodes. Since all 36 helical coils were FE modeled, the number of nodes and elements in AHX was increased.

As boundary conditions for DHX, the supporting points of the left-hand side support structure were completely fixed while the supporting points of the right-hand slot-type side-support were set free in radial direction in order to absorb thermal expansion. The AHX component is supported by four support structures as shown in Figure 3(b). The vertical directions of the supports were fixed, while thermal expansions in the radial direction were allowed with the introduction of the slot type support structures.

3.2. Loading conditions

For DHX, the transients of the primary side are composed of (1)steady state at 510°C, (2)cool-down to 200°C with cool-down rate of 100°C/hr, (3)steady state at 200°C, (4)heat-up to 510°C and (5)finally reaching 510°C as shown in Figure 4(a). The heat transfer coefficient of this transient was assumed to be uniformly 50,000W/m^{2}K. The thermal loading transients for the secondary side are similar to those of the primary side as shown in Figure 4(b).



(a) Primary side of the DHX (b) Secondary side of the DHX

Fig. 4. Thermal loading conditions.

In AHX of the STELLA test loop, the temperature range of the sodium side is 500°C to 200°C and that of the air side is 350°C to 20°C, respectively. Materials of AHX are shown in Figure 5(a) and the flow paths of primary and secondary side are shown in Figure 5(b).

Nozzle loads at the end of the nozzles were applied at the end of the nozzles. The nozzle loads were determined from piping analyses for the connected piping systems subjected to thermal and mechanical loads.

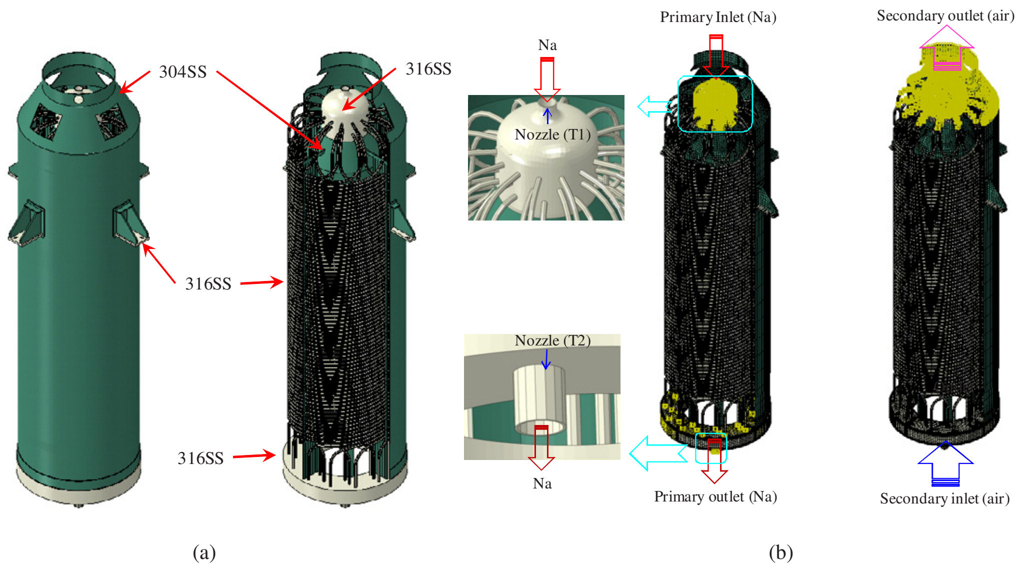
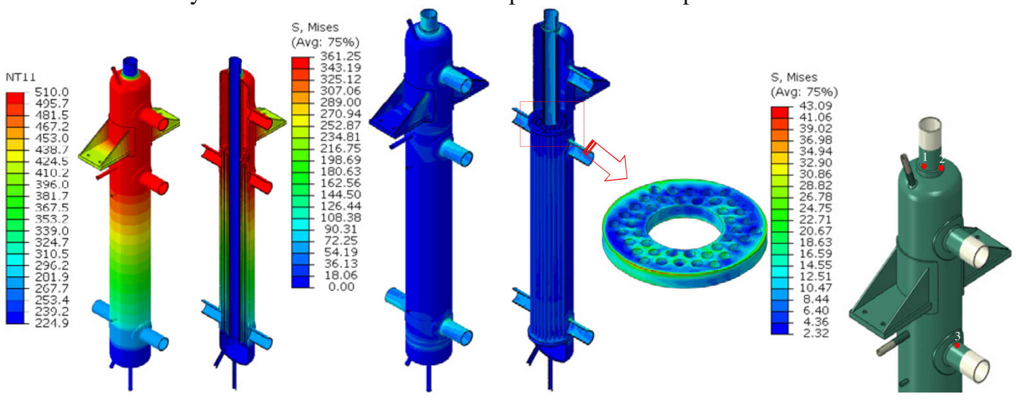


Fig. 5. Materials of AHX and flow paths.

3.3. Thermal stress analysis

In heat transfer analysis for DHX, the temperatures of the bulk sodium near the inlet side up to tubesheet were assumed to be uniform and the bottom part down to bottom tube sheet was also assumed to be uniform as shown for the primary sodium side. The temperatures of sodium in between inlet and outlet nozzles were interpolated linearly, and heat transfer analyses by using heat transfer coefficient of 50,000W/m^{2}K were conducted. Analysis were conducted with ABAQUS[11]. The temperature distributions of DHX at cool-down and heat-up are shown in Figure6, which shows gradual change in temperature distributions along the axial direction of the DHX. Stress analysis results are shown in Figure 6 and it is shown the stress level of top tube sheet is quite low with maximum 43.09MPa as shown in Figure 6(c).

In simplified heat transfer analysis for AHX, it was assumed that the top header area and tube sheet area were of uniform temperatures, while there were temperature gradients at the area in between the header and bottom tube sheet. The temperature distributions of AHX at the end of the heat-up are shown in Figure7, which shows a gradual change in temperature distributions along the axial direction. Stress analysis results show that the maximum stress intensity of 279.9 MPa occurred at top header nozzle part.



(a) Temperature (b) Stress Intensity (c) top tubesheet (d) critical location

Fig. 6. Distributions of temperature and stress intensity at the end of heat-up

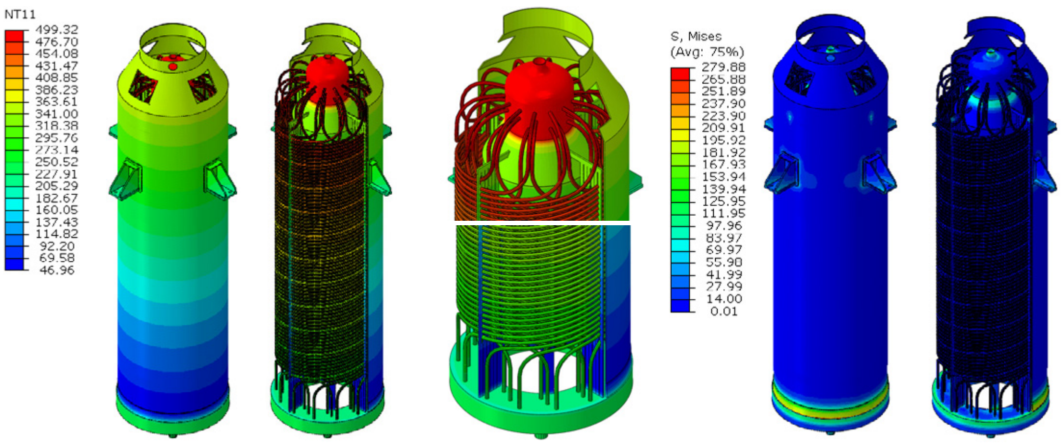


Fig. 7. Temperature distributions and stress profiles at the end of heat-up (400⇒500°C).

3.4. Damage evaluation

Creep-fatigue damage was evaluated for the critical several points of the DHX and AHX according to the high temperature design codes of the ASME-NH and French RCC-MR code, which evaluates damage based on strain based simplified inelastic analysis.

The evaluation procedure of creep-fatigue damage in ASME-NH is based on simplified inelastic analysis. Both design codes are 2010 editions.

Creep-fatigue damage for DHX at location '3' of Figure 6(d) according to ASME-NH was obtained as in Eq. (1).

$$\frac{n}{10,753,904} + \frac{\Delta t}{1,463} \leq D \tag{1}$$

where n is number of applied repetition of cycle, Δt is duration of the time interval in one load cycle, and D is total damage.

Creep-fatigue damage equation according to the RCC-MRa the same location, was also calculated as in Eq. (2). The RCC-MR provides fatigue life cycles up-to 1×10^7 cycles which is one-order lower than that of the ASME-NH for Gr.91. It should be noted that the intersection point in creep-fatigue envelope is (0.3, 0.3) for RCC-MR while (0.1, 0.01) for the ASME-NH, which means that the allowable value of creep damage in ASME-NH is 1/30 of RCC-MR.

$$\frac{n}{>10^7} + \frac{\Delta t}{130,539} \leq D \tag{2}$$

When comparing creep rupture time of Eq. (1) of ASME-NH and Eq. (2) of RCC-MR, it is shown that the creep rupture time of the ASME-NH is far lower than that of RCC-MR, which makes larger difference when considering 1/30 factor in creep-fatigue damage envelope.

Creep-fatigue damage for AHX has been evaluated in similar way to DHX. The evaluation results for ASME-NH is

$$\frac{n}{2993} + \frac{\Delta t}{>3\times10^5} \le D \tag{3}$$

Creep-fatigue damage according to RCC-MR was also conducted. The creep-fatigue damage equation for T1 nozzle (header top nozzle) according to RCC-MRx, was then determined as in Eq. (4).

$$\frac{n}{92,593} + \frac{\Delta t}{>3\times10^5} \le D \tag{4}$$

When comparing the creep rupture time of Eq. (3) of ASME-NH and Eq. (4) of RCC-MR, it is shown that the fatigue cycles of ASME-NH is far lower than that of RCC-MR, which means that ASME-NH is more conservative.

5. Conclusions

High temperature design and evaluation on the DHX and AHX in the STELLA test loop was conducted. The DHX is a shell and tube type heat exchanger with 36 straight tubes. The materials of the shell and tube in the DHX are Mod.9Cr-1Mo steel. Full D-DFE analyses were conducted for DHX component and evaluations of creep-fatigue damage at critical locations were conducted according to the ASME-NH and RCC-MR.

In addition 3-D finite element analyses were conducted for the AHX, and evaluations of creep-fatigue damage at several locations were conducted according to ASME-NH and RCC-MRx.Creep-fatigue damage for AHX under the specified thermal transient conditions were calculated to be very low.

When comparing creep-fatigue damage in DHX and AHX according to the two design codes, ASME-NH was shown to be more conservative than the RCC-MR code.

Acknowledgements

This research was supported by the International Research & Development Program Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology.

References

[1] T.H.Lee, et. al., 2011, Design report of STELLA-1, KAERI/TR-4295/2011 (2011).

[2] J.H.Eoh, et. al., Test Requirements for the integral effect test to simulate a sodium-cooled Fast Reactor, KAERI/TR-4424/2011 (2011).

[3] H.Y.Lee, S.H.Lee, J.B.Kim, J.H.Lee, "Creep-fatigue damage for a structure with dissimilar metal welds of Mod 9Cr-1Mo and 316L stainless steel," *International Journal of Fatigue*, 29(2007)p.1868.

[4] H.Y.Lee, J.B.Kim, W.G.Kim, J.H.Lee,"Creep-fatigue Crack Behavior of a Mod 9Cr-1Mo steel structure with weldments," *The Transactions of the Indian Institute of Metals,*Vol.63, issues 1&2 (2010)p.245.

[5] H.Y.Lee, J.B.Kim, H.Y.Park, "High temperature design and damage evaluation of Mod.9Cr-1Mo steel heat exchanger," *Journal of Pressure Vessel Technology,* Transactions of ASME,(2011 Dec.) in press.

[6] H.Y.Lee, J.B.Kim, H.Y.Park,"Creep-Fatigue Damage Evaluation of Sodium to Air Heat Exchanger in Sodium Test Loop Facility," *Nuclear engineering and Design*, (2011 August) submitted.

[7] P.Chellapandi, R.Srinivasan, et. al.,"Structural design of the IHX for PFBR," SMIRT-10, Anaheim, CA, USA, (1989) August 14-18.

[8] S.Jalaldeen, R.Srinivasan, P.Selvaraj, P.Chellapandi, "Comparison of life of two types of decay heat exchangers used in prototype fast breeder reactor,"*Transactions of the Indian Institute of Metals*, Volume 63, No. 2-3,(2010), p.647.

[9] ASME Boiler and Pressure Vessel Code, Section III, Div. 1, Subsection NH, Class 1 Components in Elevated Temperature Service, ASME; (2010).

[10] RCC-MR, Section I Subsection B, Design and Construction Rules for Mechanical Components of Nuclear Installations, 2010 Edition (draft), AFCEN; (2010).

[11] ABAQUS Users manual, Version 6.10, Simulia, USA; (2007).