Evaluation of high-temperature piping system in a sodium test facility of the SELFA

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1. Introduction

For a safety-grade decay heat removal system, an FHX (Finned-tube sodium-to-air heat exchanger) has been introduced in an active decay heat removal system (ADHRS) of Prototype Generation IV Sodium-cooled Fast Reactor (hereafter 'PGSFR')[1]. The Sodium thermal-hydraulic Experiment Loop for Finned-tube sodium-to-Air heat exchanger (SELFA) is a sodium test facility to validate the computer codes for design and safety assessment and to provide experimental data of the FHX in the PGSFR [1].

The SELFA test facility, which draft design had been evaluated in the paper [2], has been built in 2016. This paper mainly deals with pipe analysis of the SELFA test facility. Evaluation refers to the two design-by-rule (DBR) codes of ASME B31.1 [3] and RCC-MRx RD-3600 [4]. B31.1 is an industry design code for power pipes and RD-3600 is a class 3 nuclear grade code. The safety from the analysis results according to the two design codes is compared.

2. The SELFA test facility

2.1 Configuration of the SELFA

The SELFA consists of test section including FHX, expansion tank, and other supplementary systems. The whole system is shown in the left hand side of Fig. 1, and installed components such as air duct, expansion tank, part of cold leg and sodium storage tank are shown in the right hand side of Fig. 1. A hot leg and a cold leg pipings are shown in Fig. 2.

The material of the piping system is austenitic stainless steel 304L, and the size of the pipes in the branches is 2"SCH20S. Since the SELFA piping system operates at relatively low temperature and austenitic stainless steel of 304, which is an actual structural material for FHX, is not readily available, the material of 304L SS has been selected instead as a piping material for the sake of procurement.

Fig. 1. The SELFA test facility (left:3D model, right:photos)

The design temperature of the hot leg piping system is 480 °C, while design temperature for the cold leg is 360°C. Table 1 summaries design parameters of the piping system.

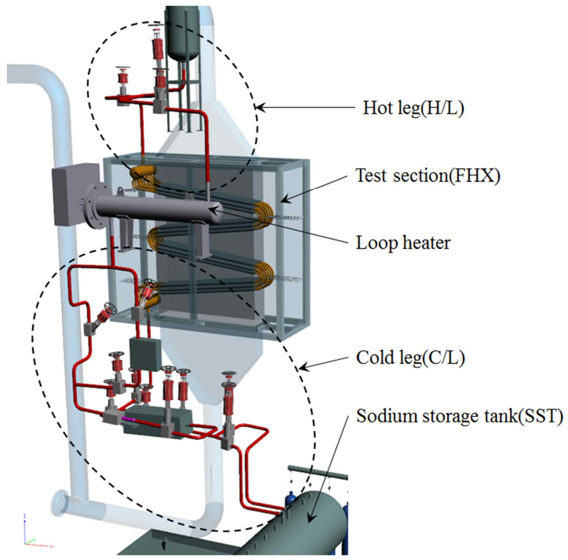


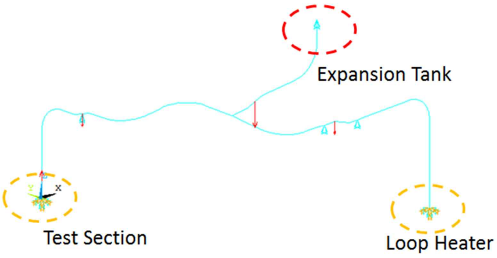
Fig. 2. Piping system of the SELFA test loop

Table 1: Design data of the piping system

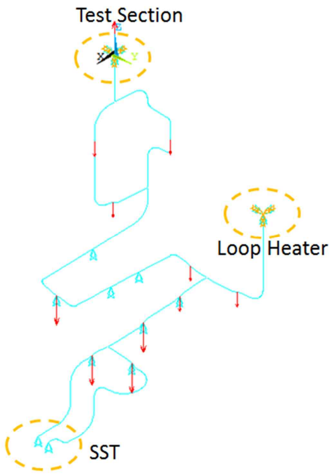
Parameter	Unit	value	Remarks
Pipe OD / thickness	mm	60.5	2''SCH20.
Pipe thickness	mm	3.5	
Design pressure	MPa	0.5	
Design temperature (H/L)	°C	480	
Design temperature (C/L)	°C	360	

2.2 Finite Element Modeling

Two separate Finite Element (FE) models are used, with 1-D pipe element in ANSYS mechanical APDL[5] as shown in Fig. 3. For the hot leg, two fixed boundary conditions on test section and loop heater at each pipe end are applied. The pipe exit to the expansion tank is constrained vertically, because the motion of the pipe attached to the tank can be considered to be greater than the tank. Three pipe supports near the valve locations (fixed in vertical) and three concentrated loads due to valve weights are placed.



(a) Hot leg



(b) Cold leg

Fig. 3. Finite element models of the SELFA piping system

In the cold leg, both upper end parts connected to loop heater and test section are completely fixed for the vertically assembled EM(Electro-Magnetic) flow-meter, EM pump, sodium storage tank and valves (Fig. 3). Ten concentrated loads (specified as red arrows in the figure) are applied to consider the valve weights.

Table 2 shows the material properties as a function of temperature for the stainless steel 304L. The loading conditions of steady state assuming the same sodium pressure and temperature in Table 1 were applied. Piping stress analysis results on the as-built piping layouts are discussed in the following section.

Table 2: Material properties of stainless steel 304L

Temperature (°C)	100	200	300	400	500	600
Elastic modulus (GPa)	190	183	176	168	158	149
Coefficient of thermal expansion (10^{-6}/°C)	16.8	17.3	17.7	18.1	18.5	18.7
Poisson's ratio	0.3	0.3	0.3	0.3	0.3	0.3
Density (kg/m^3)	7710	7680	7650	7610	7580	7540
Thermal conductivity (W/m-°C)	16.23	17.91	19.35	20.76	22.18	22.48
Specific heat (J/kg-°C)	501	522	538	556	578	601

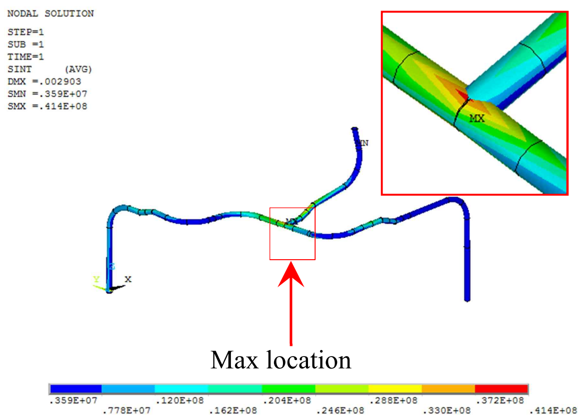
3. Analysis and Evaluation results

Results on deflections and stresses are summarized in Table 3 for both hot leg and cold leg. Maximum stress occurred near the tee or on the support, but the stress levels are relatively low compared with the allowable values.

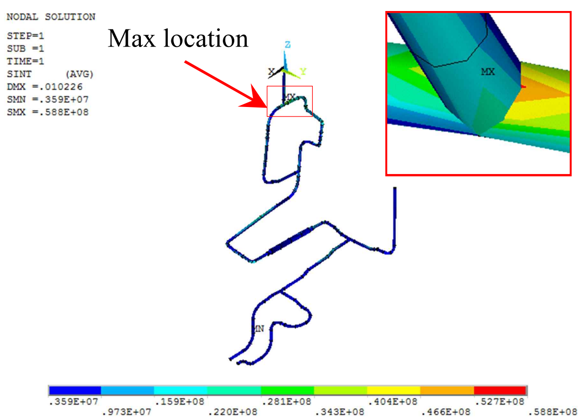
The stress intensity (SI) results for sustained loads and thermal expansion loads of the piping system are shown in Fig. 4 and Fig. 5, respectively. It is observed that high stresses (41.4 MPa at the hot leg and 58.8 MPa at the cold leg) under sustained loads occurred at the tee pipe part of both legs which is the location of geometric discontinuity in a piping system. Under thermal expansion loads, maximum stress intensity of 131 MPa occurred near the vertical valve support in hot leg, while 159 MPa occurred at tee part in the cold leg.

Table 3: Piping system analysis results

Parameters		Max deflection (mm)	Max S.I (MPa)	Max location
Sustained loads	H/L	2.90	41.4	On Tee
	C/L	10.2	58.8	On Tee
Thermal expansion loads	H/L	42.5	131	On support
	C/L	37.6	159	On Tee

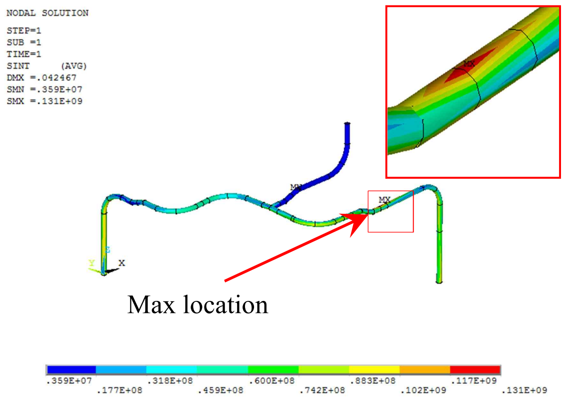


(a) Hot leg

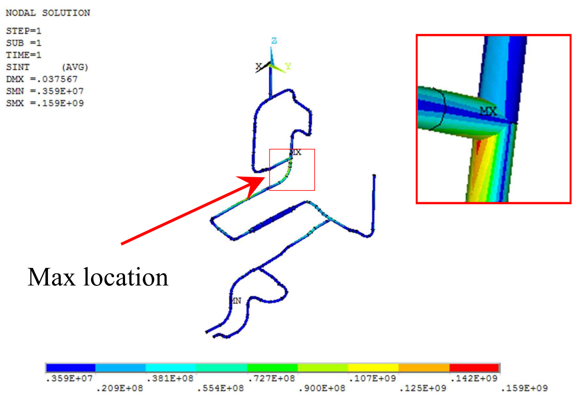


(b) Cold leg

Fig. 4. SI profile under sustained loads



(a) Hot leg



(b) Cold leg

Fig. 5. SI Profile of under thermal expansion loads

Except geometrical parameters and design pressure condition, the two design-by-rule formula requires reactive moment values. The term of occasional load M_b can be ignored because a negligible thrust load is expected [3-4] due to a very low value of maximum flow velocity, that is 1~2m/s, in a pipe.

Each evaluation code has different forms of mathematical formulae but the basic concepts of the equations with the terms on design pressure, bending and thermal expansion loads are the same [3, 4]. The results for the purpose of comparison between two codes are shown as Tables 4 and 5, respectively.

Table 4: Evaluation results of hot leg by design code

Parameters		Sustained loads	Thermal expansion loads
Critical point		On tee	On Tee
ASME B31.1	Allowable limit (MPa)	67.1	187.9
	Ratio	0.592	0.496
RCC-MRx RD-3600	Allowable limit (MPa)	74.4	*SE*:159.9
	Ratio	0.534	*SE*:0.583

Table 5: Evaluation results of cold leg by design code

Parameters		Sustained loads	Thermal expansion loads
Critical point		On tee	On tee
ASME B31.1	Allowable limit (MPa)	77.7	225
	Ratio	0.208	0.818
RCC-MRx RD-3600	Allowable limit (MPa)	84	*SE*: 162.3 *STE*: 246.3
	Ratio	0.192	*SE*:1.133 *STE*:0.812

In Table 5, the *SE* term is the only evaluation for thermal expansion loads, while the *STE(Thermal Expansion Stress)* term is the other evaluation when *SE (Expansion Stress)* exceeded allowable limit (mathematical formulae are the sum of sustained loads and thermal expansion loads).

Major difference on two design codes is the allowable limit. For B31.1, the allowable limit (67.1 MPa and 77.7 MPa) due to sustained loads is a lower value than RD-3600 (74.4 MPa and 84 MPa). So the evaluation results for sustained loads show that B31.1 (0.592 and 0.208) is more conservative than that of RD-3600 (0.534 and 0.192).

On the contrary, the comparison results due to the thermal expansion loads show a different trend. Ratios of B31.1 (0.496 and 0.818) show lower values than that of RD-3600 (*SE,* 0.583 and 1.133). This means RD-3600 is turned out to be more conservative than B31.1.

4. Conclusions

In this study, an as-built design of the SELFA piping system has been evaluated according to the ASME B31.1 and RCC-MRx RD-3600. Two sets of evaluation results for a hot and a cold leg pipings are summarized and contrasted.

It was shown that B31.1 was more conservative for the sustained loads while less conservative for thermal expansion loads than results based on RD-3600. Generally, industry codes such as ASME Section VIII are known to be more conservative than nuclear codes such as ASME Section III. In the present analysis when comparing B31.1 and RD-3600, B31.1 was shown to be more conservative for sustained loads but less conservative for thermal expansion loads (*SE*). Both analysis results according to the two codes show that the SELFA piping system satisfy structural integrity requirements within the design allowable limits.

ACKNOWLEDGEMENT

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