Preliminary Structural Assessment of Printed Circuit Steam Generator Heat Exchanger for Sodium-Cooled Fast Reactor

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1. Introduction

Heat exchanger is one of important components in a nuclear reactor. High temperature operating environment makes heat exchanger plays a very critical role. The success of the next generation of nuclear reactor will depend in part upon the correct selection of high effectiveness and high integrity of heat exchanger [1].

To reach the high mechanical integrity of printed circuit heat exchanger, a tight standard will be strongly needed. In this paper, ASME Boiler and Pressure Vessel Code (BPVC) section VIII will be the standard for micro channel mechanical construction. In the other hand, ASME BPVC section III division 5 will be handed as the criteria code to evaluate the compliance of proposed geometry.

2. Methods and Results

Two methods are used to calculate the stress distribution at PCSG. Equations which are proposed by ASME Standard was used to calculate the primary membrane and bending stress. Finite Element Analysis (FEA) resulted by COMSOL multiphysics will describe the stress distribution and intensity. Proposed PCSG was designed by using austenitic stainless steel UNS S31600. The candidate materials are therefore selected from those high temperature materials that are approved by ASME VIII [2].

2.1 Finite Element Analysis

Finite element analysis (FEA) method was done to obtain the stress distribution at the surface area. Table I contains the applicable boundary conditions of this study.

Table I: Boundary condition

Parameter	Value
Water Channel temperature (°C)	240
Sodium Channel temperature (°C)	528
Water Channel Pressure (MPa)	18
Sodium Channel Pressure (MPa)	0.5

COMSOL Multiphysics is a simulation software that can be used to simulate the solid mechanics phenomena. In case of printed circuit heat exchanger, a simulation of temperature distribution and pressure losses were resulted close to the expected response were done [3].

A grid sensitivity analysis was performed on the number of elements in order to determine the convergence of the mesh. The convergence study was focused on the stress distribution along an observed line. The result indicates that the convergence value obtained when the number of elements 28,142.

Based on simulation result that is shown in fig. 1, high intensity can be found in the tip edge of both sodium and water channel. Highest value is shown at the tip edge of water channel. Simple stress-load relationship is determining this phenomenon. A very tiny pressurized surface can give a very high intensity of stress occurred.

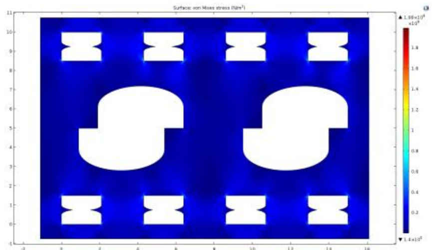

Fig. 1. Stress distribution at the surface

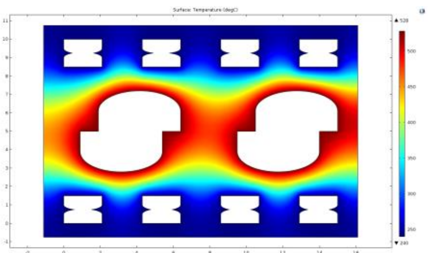

Fig. 2. Temperature distribution

2.2 Calculation based on ASME Section VIII

The mechanical design of printed circuit heat exchanger is normally of ASME VIII Division 1 [4]. In section VIII division 1 mandatory appendix 13, some simplified non-circular cross section designs were mentioned. In this preliminary study, an unreinforced vessel of rectangular cross section is used as model. The chosen modelling design which is shown in fig 3. Stress intensity based on ASME simplified modelling will include membrane stress, bending stress, and total stress. Membrane stress and bending stress will be needed for maximum allowable stress intensity and lifetime service period. Membrane and bending stress intensity can be determined by using equations those are stated in ASME BPV code section VIII division 1 mandatory appendix 13.

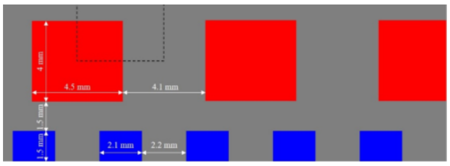

Fig. 3. Proposed simplified model

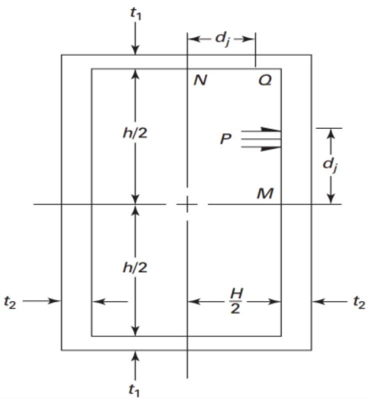

Fig. 4. Simplified model based on ASME

$$P_m \leq S_o \quad (1)$$

$$P_L + P_b \leq 1.5S_o \quad (2)$$

Where S_o is the maximum allowable stress intensity for design condition. P_m and P_L are the average primary stress component. The calculation results are shown in table II

Based on allowable design limits in ASME BPVC section III, stress intensity (S_o) of material SS316 at 525ºC shall not be more than 101 MPa. By considering of equation (1) and (2), Stress intensity of both channels can comply the stress design limit as well.

Table II: Calculation result

Variable		Water Channel	Sodium Channel	Unit
short side plate	S_m	8.263	0.273	MPa
Long side plate	S_m	9.000	0.667	MPa
Stay plate	S_m	23.193	0.595	MPa
Bending at short plate	$[S_b]_N$	0.673	-0.061	MPa
Bending at short plate	$[S_b]_Q$	6.949	0.296	MPa
Bending at long plate	$[S_b]_M$	18.986	2.269	MPa
Bending at long plate	$[S_b]_Q$	14.947	2.212	MPa
Total Stress at short side plate	$[S_T]_N$	8.936	0.212	MPa
Total Stress at short side plate	$[S_T]_Q$	15.212	0.569	MPa
Total Stress at long side plate	$[S_T]_M$	27.986	2.936	MPa
Total Stress at long side plate	$[S_T]_Q$	23.947	2.879	MPa
Total Stress at Stay plate		23.193	0.595	MPa

2.3 Lifetime Service Prediction

Service limit can be used to predict the lifetime operating service. Service limit should be determined for Level A and B service limit those are shown in below equations:

$$P_m \leq S_{mt} \quad (3)$$

$$P_L + P_b \leq KS_m \quad (4)$$

$$P_L + P_b / K_t \leq S_t \quad (5)$$

$$K_t = (K+1)/2 \quad (6)$$

ASME Section III describes the Service loading limit as shown at equation (3) to (6). S_{mt} value of SS316 is time dependent allowable stress intensity value as adopted from ASME BPVC sec III Div.5. In this case, S_{mt} value of SS316 is considered at 105 MPa for 300000 hours of service life time. Based on calculation of equation (3), P_m is less than S_{mt} (105 MPa) at water channel, sodium channel, and stay plate. Hence, 34 years of service life time is predicted on this heat exchanger usage.

3. Conclusions

Preliminary study of structural integrity steam generator heat exchanger has been conducted. Calculation result shows that proposed geometry can comply with ASME BPV code section III division 5. Allowable stress intensity (S_{mt}) can predict 3 x 10^5 hours of lifetime operating service.

FEA simulation using COMSOL Multiphysics indicate some "key-area" that should be highly considered for further study and design. Tip edge area of water channels are the highest area. Hence, it will be needed to give a strong concern in this area.

ACKNOWLEDGEMENT

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