Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Innovative Intermediate Compact Heat Exchanger Design for Possible Application on VHTR System

YongWan Kim [a*], Injin Sah [a], and Eung Seon Kim [a]
[a]*Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, 305-353*
[*]*Corresponding author: ywkim@kaeri.re.kr*

1. Introduction

The outlet helium coolant temperature of VHTR (Very High Temperature Reactor) exceeds 950°C in order to produce hydrogen. It is difficult to use the conventional heat exchanger for VHTR heat transfer system due to very high coolant temperature. The printed circuit type compact heat exchanger is considered as an innovative solution for the elevated temperature application such as VHTR intermediate heat exchanger and the process heat exchanger of the hydrogen production system. However, rules for design and fabrication of PCHE (printed circuit heat exchanger) are basically specified only in ASME Section VIII [1] but not in ASME Section III [2] of nuclear components.

In this study, design procedure for compact heat exchanger is described according to ASME Section VIII. As an example, IHX of VHTR system is designed according to the explained procedure. Finite element analysis is done for the flow channel region and the secondary header. A lot of diffusion bonded heat transfer plates are designed to constitute a module. Then a number modules are installed inside a pressure vessel to generate the required heat transfer capacity of the VHTR system.

2. Design Procedure

2.1 Compact heat exchanger design procedure

Compact heat exchanger is to be designed as following sequences. The tentative flow channel radius is determined from the thermo-hydraulic judgement. Then the plate thickness, vertical pitch and horizontal pitch are determined by the strength criteria of ASME Section VIII mandatory appendix 13. The shape of effective heat transfer area and a module size are determined from thermo-hydraulic analysis. Then the header and connecting pipe size are determined by strength criteria of ASME Section VIII. As for the large power intermediate heat exchanger assembly, several modules are connected to produce overall heat capacity. The external pressure vessel and the insulation design are to be done in sequance. Finally, overall thermo-hydraulic performance analysis and stress analysis are to be done.

2.2 ASME Section VIII

The flow channel of PCHE is a semi-circular shape. Semi-circular flow channels are assumed to be a rectangular cross section. According to ASME section VIII mandatory appendix 13, the membrane stress across the thickness S_m should be less than allowable stress of ASME Section II Part D [3]. Also, total stress S_T should be less than 150% of allowable stress. It is specified in the ASME Section VIII mandatory appendix 42 that the joint efficiency of diffusion bonding is 0.7 along the diffusion bonded direction.

2.3 Effective heat transfer region

The effective heat transfer region of PCHE is defined by several key dimensions such as flow channel radius R, edge width t_1, wall thickness t_2, and ridge width t_3[4]. The radius of flow channel is mainly influenced by thermo-hydraulic performance and other parameters are dominated by the strength criteria and the manufacturability. Equation (1), (2), (3) are to be used to determine edge thickness and equations (5), (6), (7) are to be used to determine plate thickness of effective heat transfer region.

$$S_m = \frac{Ph}{2t_1}\left\{3 - \left[\frac{6+K(11-\alpha^2)}{3+5K}\right]\right\} \tag{1}$$

$$(S_T)_N = \frac{Ph}{2t_1}\left\{3 - \left[\frac{6+K(11-\alpha^2)}{3+5K}\right]\right\} + \frac{Pc}{24I_1}\left[-3H^2 + 2h^2\left(\frac{3+5\alpha^2 K}{3+5K}\right)\right] \tag{2}$$

$$(S_T)_Q = \frac{Ph}{2t_1}\left\{3 - \left[\frac{6+K(11-\alpha^2)}{3+5K}\right]\right\} + \frac{Ph^2 c}{12I_1}\left(\frac{3+5\alpha^2 K}{3+5K}\right) \tag{3}$$

$$S_m = \frac{PH}{2t_2} \tag{4}$$

$$(S_T)_M = \frac{PH}{2t_2} + \frac{Ph^2 c}{12I_2}\left[\frac{3+K(6-\alpha^2)}{3+5K}\right] \tag{5}$$

$$(S_T)_Q = \frac{PH}{2t_2} + \frac{Ph^2 c}{12I_2}\left(\frac{3+5\alpha^2 K}{3+5K}\right) \tag{6}$$

Where α, K, and I stand for aspect ratio, vessel parameter, and moment of inertia respectively.

2.4 Module header shape design

Secondary module header is welded to the stacked diffusion bonded effective heat transfer plates. The module header is subjected to high temperature and pressure. In order to reduce stress value and form loss, header is designed to a obround shape as shown in Fig. 1 generally. The stress distribution for a half cylindrical header and a circular ended module headers can be calculated from ASME Section VIII.

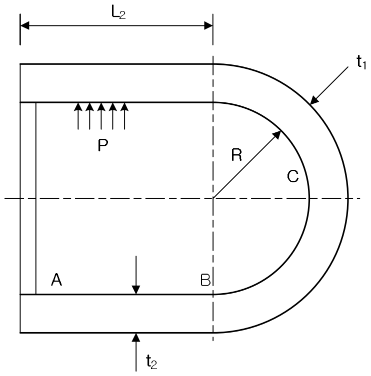

Fig. 1 Schematic drawing of secondary header

In order to compare membrane stress and total stress, each component can be calculated as follows. Membrane stresses at the spherical section are equation (7), (8) and cylindrical section is equation (9). Bending stresses for spherical section and cylindrical section are expressed as equation (10), (11) and (12), (13) respectively.

$$(S_m)_B = \frac{PR}{t_1} \qquad (7)$$

$$(S_m)_C = \frac{P}{2t_1}\left[2(R+L_2)-L_2\right] \qquad (8)$$

$$S_m = \frac{PR}{t_2} \qquad (9)$$

$$(S_b)_B = \frac{PL_2c}{2I_1A}\left[F(B-AL_2)-\frac{C_1}{3}+AL_2\right] \qquad (10)$$

$$(S_b)_C = \frac{PL_2c}{2I_1A}\left[F(B-AL_2-AR)+A(L_2+2R)-\frac{C_1}{3}\right] \qquad (11)$$

$$(S_b)_A = \frac{PL_2c}{2I_2A}\left(BF-\frac{C_1}{3}\right) \qquad (12)$$

$$(S_b)_B = \frac{PL_2c}{2I_2A}\left[F(B-AL_2)-\frac{C_1}{3}+AL_2\right] \qquad (13)$$

Detailed descriptions of each notation are explained in ASME Section VIII mandatory appendix.

3. Compact Heat Exchanger Design

3.1 Flow channel sizing

Intermediate heat exchanger for 350MWt VHTR has been designed by using of printed circuit type heat exchanger. From the thermo-hydraulic design, the heat transfer plate is designed to be a 1010mm x 470mm plate. A flow channel is divided into two flow channel in effective heat transfer area. Stress calculated based on ASME Section VIII is given in Table 1. Subscripts M, N, Q of stress components at Table 1 are shown in Fig. 2. The total stress component at 950^{o}C is larger than the allowable limit. Finite element analysis by using of ABAQUS [5] was done to confirm stress.

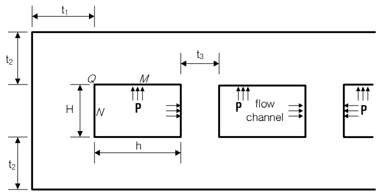

Fig. 2 Notations for stress component.

Table 1 Stress values at each location and allowable stress

Stress Category	Normal flow channel	Flow channel merging area	Allowable stress, Mpa
Short Side(S_m)	0.025	0.05	5.54
ShortSide$(S_T)_N$	0.026	0.055	8.31
ShortSide$(S_T)_Q$	0.026	0.055	8.31
LongSidePlate(S_m)	0.5	0.5	5.54
LongSidePlate$(S_T)_M$	2.5	8.5	8.31
LongSidePlate$(S_T)_Q$	2.5	8.5	8.31
Ridge(S_m)	2	4	5.54
Ridge(S_T)	2	4	8.31

Fig. 3 shows stress state at normal flow channels and Fig. 4 shows the stress state at flow channel merging area. As for the normal flow channels, the linearized ASME total stress values are 0.87Mpa and 0.79Mpa for vertical direction and horizontal direction respectively.

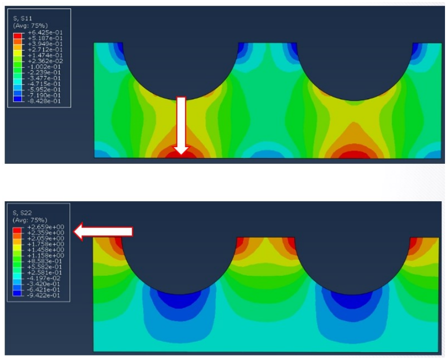

Fig. 3 Stress distribution at normal flow channel.

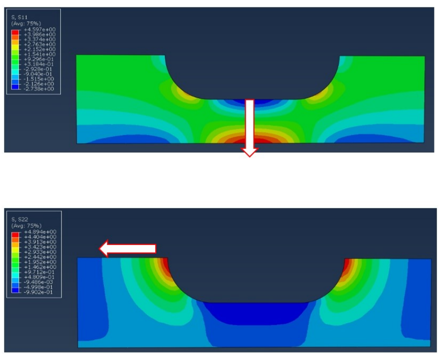

Fig. 4 Stress distribution at flow channel merging area.

In the merging region, the linearized ASME total stress values are 1.08Mpa and 3.5Mpa for vertical direction and horizontal direction respectively. All of the stress components from finite element analysis satisfy allowable limit.

3.2 Header sizing

Secondary module header is designed by the equations (7) ~ (13). Finite element analysis was done to confirm the stress state of the header. Stress state of the header is shown in Fig. 5.

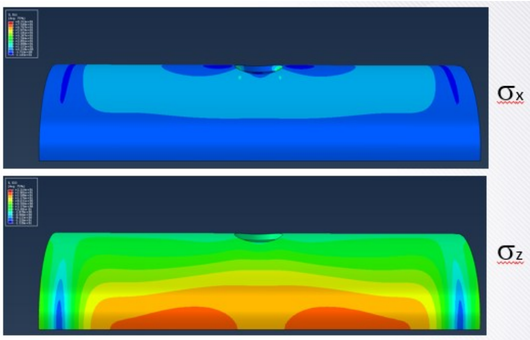

Fig. 5 Normal stress distribution at the header surface

Stress analysis for the secondary header cross section based on ASME is satisfied as follows:

$P_m \leq S_{mt}$
$11.6MPa < 32.5MPa\ (10^6 hr)$
$P_L+P_b \leq K\ S_m$
$17.1MPa < 103.8MPa$
$P_L+P_b/Kt \leq S_{mt}$
$16.0MPa < 32.5MPa\ (10^6 hr)$

3.3 Assembly of modules

It is composed of 56 PCHE modules. Arrangement of PCHE modules inside the pressure vessel.

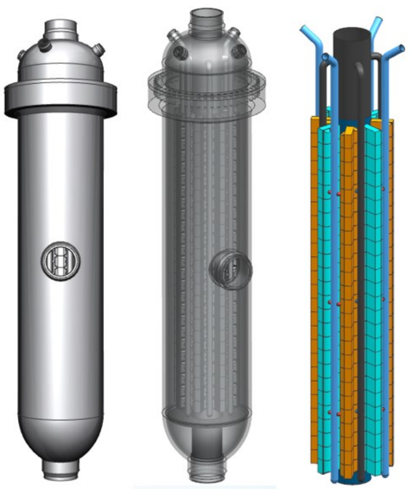

Fig. 6 Assembly of compact heat exchanger modules

Whole modules are divided into 8 sections and each section has several modules. Alloy 617 is used to design heat transfer modules, internal pipes to distribute and collect secondary helium. The pressure vessel is designed by the conventional PWR material SA508. As for the flow path, the primary helium is supplied to the bottom of the pressure vessel and then is distributed to each module in radial direction. Secondary cold helium is supplied through four nozzles attached at the head of the pressure vessel. The secondary helium heated at the effective heat transfer modules is collected to the header located at the top of the pressure vessel. The axial thermal expansion of the primary header is absorbed by the sliding joint located below the bottom of the effective heat transfer area. The secondary pipes located inside the vessel are hang from the pressure vessel head for axial free expansion.

4. Conclusions

Design procedure for the compact heat exchanger is explained and the intermediate heat exchanger of VHTR is designed as an example. Fundamental dimensions of a heat transfer module including thickness, horizontal pitch, and vertical pitch are determined by ASME section VIII criteria. Finite element analysis is used to confirm the stress state for the severely loaded area. In order to design the printed circuit type compact heat exchanger as an innovative nuclear component, design methodology for the diffusion bonded area at elevated temperature should be established according to ASME. Also, creep, fatigue & allowable stress data for the diffusion bonded area is prerequisite of high temperature application. The development of the inspection methodology of PCHE which is not discussed in this paper is an important issue for the practical nuclear application.

Acknowledgement

This study was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP).
(Grant code : 2017M2A8A1014758)
(Grant code : 2016M2A8A1952772)

REFERENCES

[1] ASME, ASME Boiler and Pressure Vessel Code Section VIII, Division 1, 2019.
[2] ASME, ASME Boiler and Pressure Vessel Code Section III, Division 1, 2019.
[3] ASME, ASME Boiler and Pressure Vessel Code Section II, Part D, 2019.
[4] Y.W. Kim, J.H. Kang, and E.S. Kim, "Mechanical Design for Key Dimensions of Printed Circuit Heat Exchanger," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 17-18, 2018.
[5] ABAQUS/CAE 6.13-4