Failure Assessment of Hypervapotron Mockup for Fusion Application with KAERI High Heat Flux Test Facilities

D. W. Lee[a*], H. G. Jin[a], E. H. Lee[a], J. S. Yoon[a], S. K. Kim[a], T. S. Kim[a], S. H. Jeong[a], S. Cho[b]
[a]*Korea Atomic Energy Research Institute, Republic of Korea*
[b]*National Fusion Research Institute, Republic of Korea*
[*]*Corresponding author: dwlee@kaeri.re.kr*

For developing the extreme cooling technology for Plasma Facing Component (PFC), hypervapotron mockup was fabricated and tested using Neutral Beam Injection (NBI) heating system at KAERI. During the test, especially with the JAEA ion source, which has a focused beam and a long pulse, some failures in the mockup with a hypervapotron were experienced. Using the existing correlation for a critical heat flux (CHF), the incident CHF was assessed, in which the modified Tong-75 CHF correlation for the one-sided heat flux was used. In addition, using the conventional CFD and FEM codes such as ANASYS-CFX and ANYS-mechanical, the thermal life times were evaluated according to the beam operation and water cooling conditions. The evaluated ICHF is 28.6 MW/m^2 and is much higher than the loaded peak heat of about 8.7 MW/m^2 at a 2.3 MW heat load. Therefore, it is difficult that the failure of the mockup was caused by CHF. The thermal lifetimes were evaluated to be about 100 cycles and 11 cycles for 1.56 MW and 2.3 MW heat load conditions, respectively. When the dump heat is reached in the mockup frequently, it can fail in the corner of the inlet region below 11 cycles when a 2.3 MW heat is loaded.

1. Introduction

For developing the extreme cooling technology for Plasma Facing Component (PFC), hypervapotron mockup was fabricated and tested using Neutral Beam Injection (NBI) heating system at KAERI. Among them, some failures in the hypervapotron mockup were occurred during the test of JAEA ion source which have the long pulse characteristics and a focused beam [1].

To investigate the cause of the failure, a Critical Heat Flux (CHF) assessment using the existing correlation and a thermal-fatigue analysis were performed with the conventional code such as ANSYS in the present study.

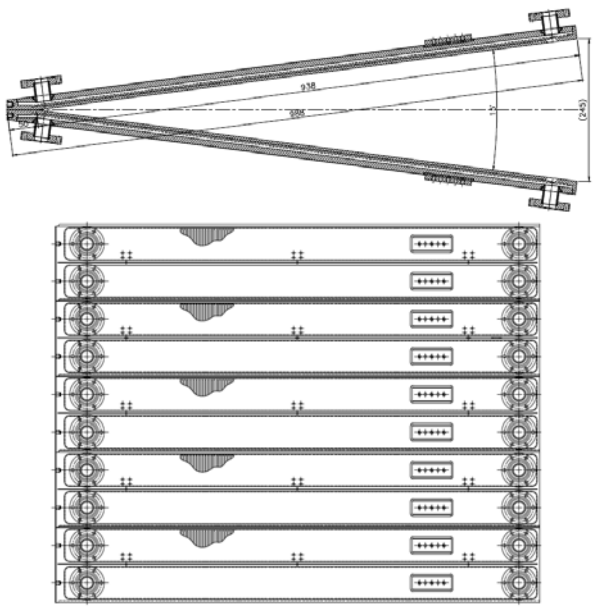

Fig. 1. Hypervapotron mockups in the KSTAR NB Test Stand.

2. RESULTS OF THE JEA ION SOURCES EXPERIMENT

Five pairs of hypervapotron mockups were used in KSTAR NB Test Stand as shown in Fig. 1 for testing the JAEA ion source and one of them was failed as shown in Fig. 2. The melted parts and holes were formed and the coolant leaked. In this test, inlet velocity of the mockups was 5.5 m/sec and the heat flux were 1.56 ~ 2.3 MW/m^2 with Gaussian distribution.

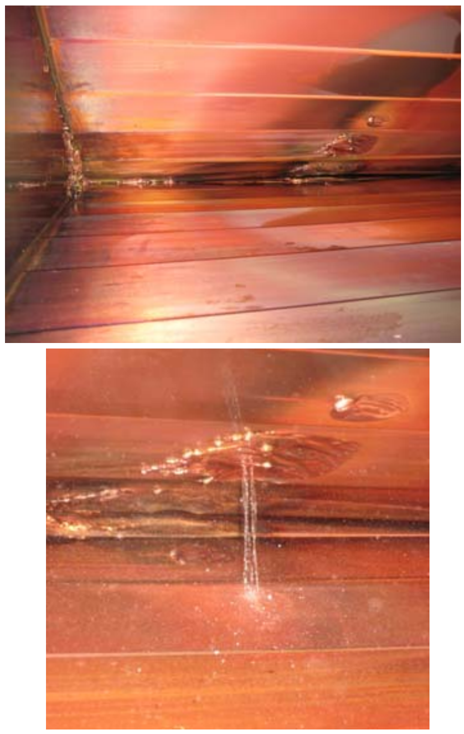

Fig. 2.Photo of the tested hypervapotron mockup; failure and water leakage.

3. CHF ANALYSIS

Using the existing correlation, which was used for the hypervapotron divertor in ITER by A.R. Raffray et al. (1999) (equations 1-2) [2], a CHF was evaluated; the CHF at wall is 34.32 MW/m^2 and an incident CHF was 28.6 MW/m^2, respectively. They are much higher than the experiment conditions, which were 8.5 MW/m^2 and 5.8 MW/m^2 of peak heat flux at 2.3 MW and 1.56 MW of the deposited heats, respectively as shown in Fig. 3.

$$CHF_w = 0.23\, fGH_{fg}\left(1+0.00216\left(\frac{P}{P_c}\right)^{1.8}\mathrm{Re}^{0.5}\,Ja\right)Cf$$

and

$$ICHF_w = \frac{CHF_w}{f_p}\,.$$

It means that the failure was not caused by CHF.

4. THERMAL-FATIGUE ANALYSIS

In this study, commercial ANSYS codes such as ANSYS-CFX for thermal-hydraulic analysis [3] and ANSYS-mechanical for the thermo-mechanical analysis [4] were used to find the cause of the failure by the assessment of the thermal-fatigue lifetime.

From the original mockup with five-pair of hypervapotron mockup, one-pair was modeled and simplified for the thermal-fatigue analysis as shown in Fig. 4. Detailed key and measurement holes were removed for simplification. And the inlet/outlet parts were simplified but the flow areas of them were preserved. Total 3,394,770 hexa meshes were produced by ICEM-CFD as shown in Fig. 5, in which the minimum and average qualities were 0.146 and 0.905, respectively.

Three cases were simulated according to the test conditions in order to define the cause of the failure; cases 01 and 02 were for the deposited heat of 1.56 MW but the inlet was different since we found the wrong connection of the inlet line after the test. Case 03 was for the deposited heat of 2.3 MW with the right inlet position.

Other fluid conditions were from experiments; operation pressure of 0.7 MPa, inlet water temperature of 25 ^{o}C, and inlet water velocity of 5.5 m/sec. The deposited heat was converted to the Gaussian-distribution of heat load as shown in Fig. 6.

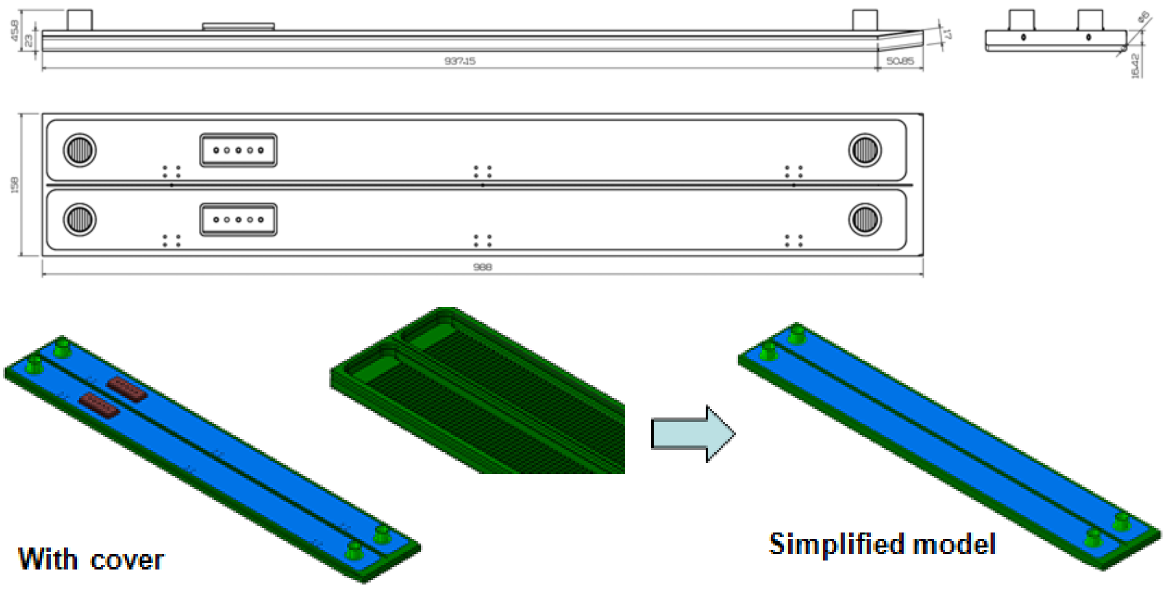

Fig. 4. Simplified model for analysis of one-pair mockup.

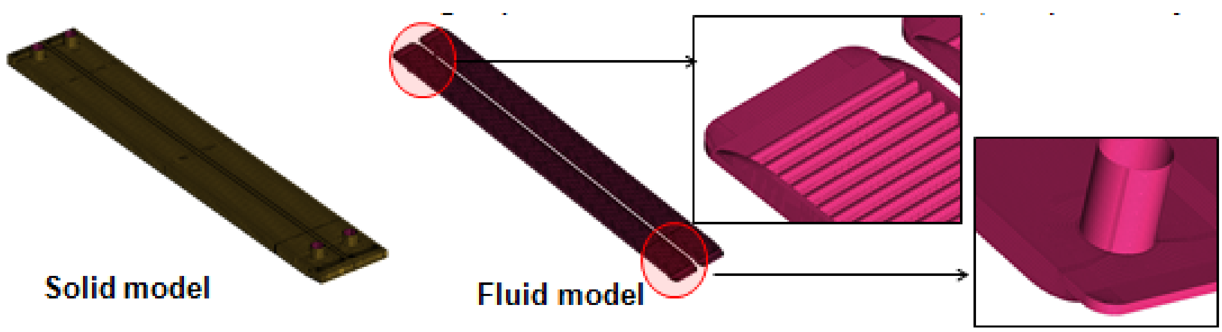

Fig. 5. Generated meshes for solid and fluid models.

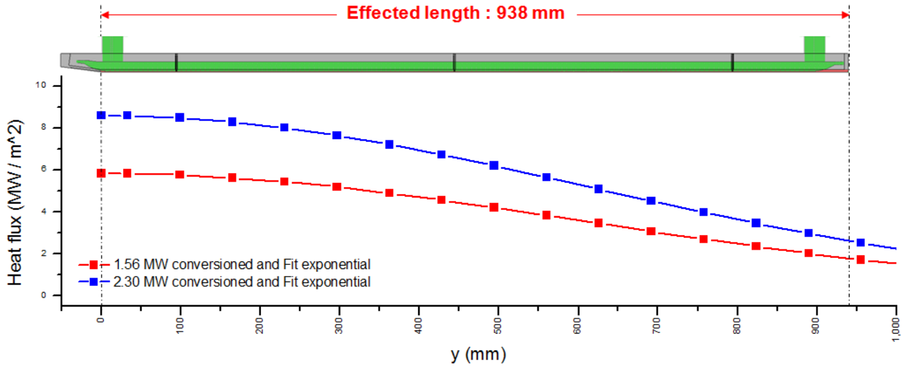

Fig. 6. Converted heat flux from the deposited heat with Gaussian distribution.

Table 1 Summary of the thermal-fatigue analysis results

	Case 01	Case 02	Case 03
Deposited heat [MW]	1.56	1.56	2.3
Max. temperature [^{o}C]	316.4	296.1	452.9
Max. Stress by Elastic analysis [MPa]	632.4	648.9	632.4
Max. strain by Elastic-Plastic analysis [%]	1.0285	1.0775	3.0091
No. of cycle to failure	131	117	11
Deformation [mm]	2.747	3.086	4.584

Figure 7 shows the temperature distribution of the heating surface of the hypervapotron mockup for the cases 01 to 03 from the thermal-hydraulic analysis with the ANSYS-CFX code. The maximum temperatures were around 300 ^{o}C at 1.56 MW heat load and 450 ^{o}C at 2.3 MW heat load, respectively.

The temperature distribution, as well as the node and element information from the thermal-hydraulic analysis, was transferred to the thermo-mechanical analysis, and the stress and strain results were obtained from the structural analysis with the ANSYS-mechanical code. In the elastic analysis, the maximum von Mises stresses of the case 01 and 02 were 632.4 MPa and 648.9 MPa, respectively, which were over twice the yield strength (313 MPa at 300 ^{o}C) of CuCrZr alloy [5]. In the same way, maximum von Mises stress of the case 03 was 914.6 MPa and which was over twice the yield strength (275 MPa at 400 ^{o}C). Since the ASME code [6] recommends that if the general thermal stress associated with a distortion in the structure exceeds twice the yield strength of the material, the elastic analysis might be invalid and elastic-plastic analysis was required.

The elastic-plastic analysis was performed, and the von Mises stress and strain distribution were obtained as shown in Fig. 8. The results show that the maximum stress is 392.3 MPa, which is higher than the yield strength, and the maximum strain is 1.0285%, occurred at the corner of the mockup. According to the maximum strain in the CuCrZr alloy, the thermal fatigue life was only 131 cycles under this design and operational conditions. It can be concluded that the current design cannot meet the design requirements since the maximum stress in the elastic analysis was higher than twice the yield strength, and it can easily fail before 131 cycles under this operating condition. In the same way, elastic-plastic analyses were performed for the case 02 and 03 and the results were summarized in Table 1.

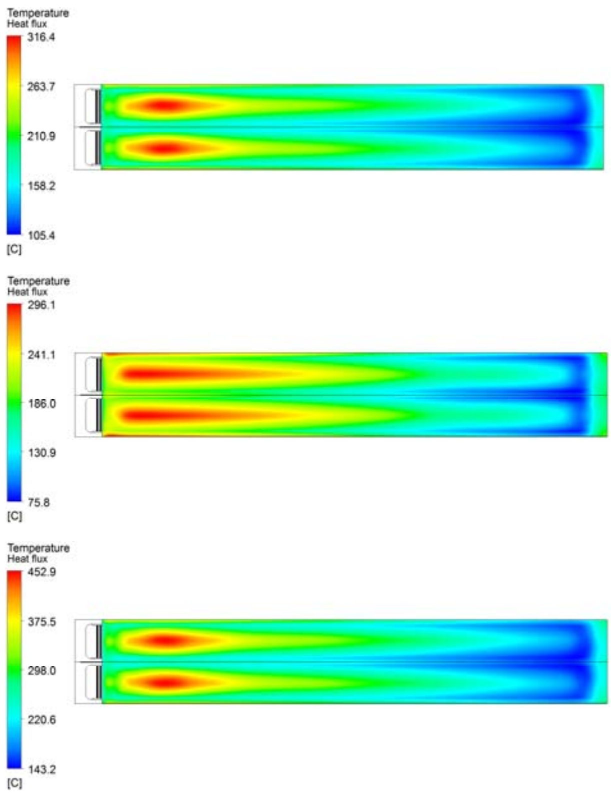

Fig. 7. Temperature distributions of the cases 01 to 03.

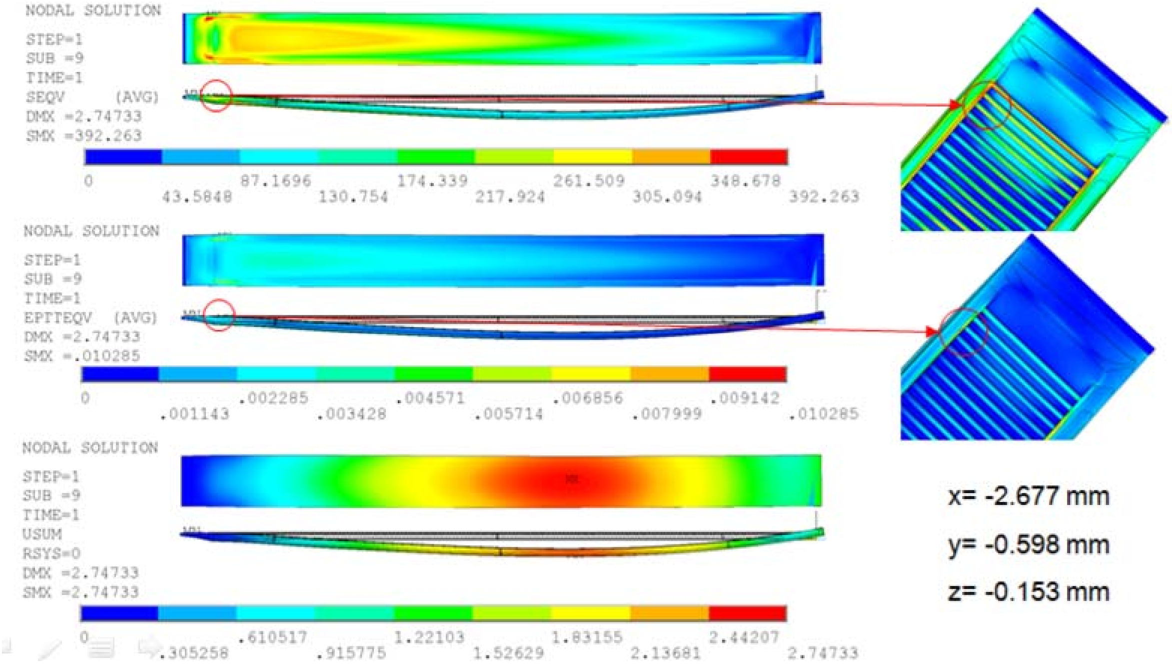

Fig. 8. Temperature, von Mises strain, and deformation distribution of the case 01.

5. Conclusion

We assessed the hypervapotron mockup which was failed during the JAEA ion source test with KSTAR NB Test Stand at KAERI. The following results were obtained;

(1) From the CHF analysis, the expected ICHF value is much higher than the experimental condition. The CHF seems not to be a cause of the failure.

(2) From the thermal-fatigue analysis, numbers of cycle to failure for heat load and inlet water conditions are 131, 117, and 11 cycles at each condition. When the dump heat is reached in the mockup frequently, it can fail in the corner of the inlet region below 11 cycles when a 2.3 MW heat is loaded.

The cause of failure cannot be defined clearly, however, the frequent heat load may cause the failure by the thermal-fatigue.

Acknowledgment

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