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Application of Bellows to Mitigate Thermal Expansion Stress in Pipes Penetrating the HCCP TBM-set

Seong Dae Park[a], Suk-Kwon Kim[a], Dong Won Lee[a], Jae-Sung Yoon[a], Hyoseong Gwon[b]
[b]*Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*
[b]*Korea Institute of Fusion Energy, Daejeon, Republic of Korea*
[*]*Corresponding author: sdpark@kaeri.re.kr*

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1. Introduction

ITER has introduced Test Blanket Modules (TBM) to test tritium breeding and heat removal concepts under reactor conditions [1-3]. Korea has been developing the HCCP TBM-set as a candidate design [4]. In this configuration, pipes penetrating through the TBM-set experience thermal stresses due to constrained axial expansion. Previous studies have highlighted stress issues in pipe bends and the potential use of bellows for mitigation [5,6].

2. Design Concept and Methodology

The penetrating pipe was modeled with a 90° bend, which is necessary to reduce direct neutron streaming. Two design cases were considered: welded connection and bellows connection. A thermo-structural analysis methodology was adopted, with thermal analysis results providing the temperature distribution under the tritium outgassing state (TOS), which was then used as thermal load input for structural analysis [7-9].

3. Structural Analysis

3.1 Analysis Model and Geometry

The analysis model consisted of simplified TBM-box, TBM-shield, attachments and process pipes. The HCCP TBM-set configuration and its bolted connection to the port plug were partially included to represent the real restraint conditions. Analysis model is shown in Fig. 1.

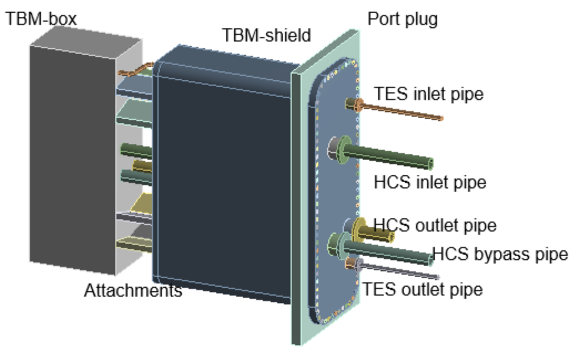


Fig. 1. Analysis model

3.2 Mesh and Boundary Conditions

The mesh was generated with 10-node tetrahedral solid elements, resulting in 321,205 nodes and 165,747 elements. The average mesh quality was 0.67. Refined meshes were applied in the bending and welded regions. The boundary conditions reflected the bolted connection of the TBM-set to the port plug, with the port plug fixed in the radial direction. Loads included the thermal distribution obtained from TOS thermal analysis and internal pressures of 8 MPa for the HCS pipes and 0.4 MPa for the TES pipes [10]

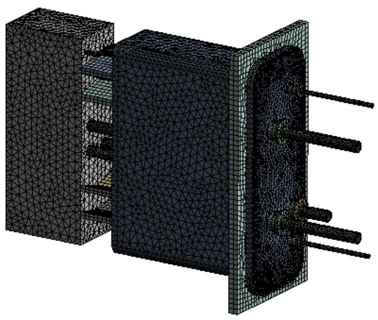


Fig. 2. Meshing model for analysis

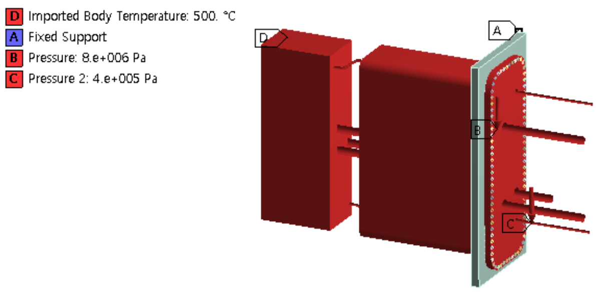


Fig. 3. Constraint & boundary conditions

3.3 Thermal Analysis

Under TOS, 500 °C helium was assumed to flow in the TBM-box, HCS, and TES pipes, while 240 °C water was assumed in the TBM-shield. The thermal analysis showed high temperatures in the pipes and TBM-box, with lower temperatures in the shield. The attachment region displayed a smooth temperature transition between the structures. The resulting temperature distribution was used as thermal load in the structural analysis [11].

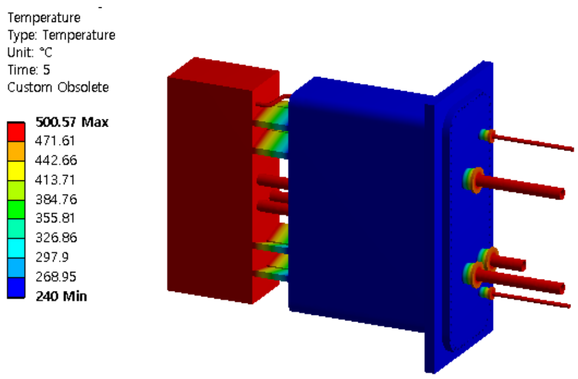


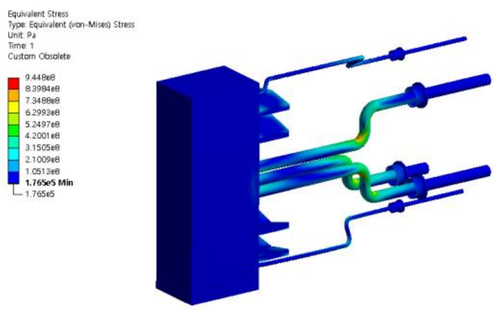
Fig. 4. Temperature distribution on TBM-set under TOS

3.4. Stress Analysis of Pipe Connections (Welded vs. Bellows)

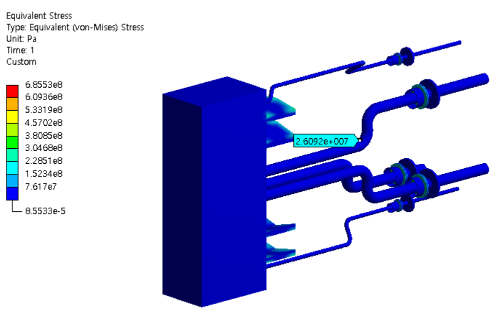
(1) Welded connection: Significant stress concentration occurred at the 90° bending section, particularly at the transition between the straight and curved regions. No remarkable stress concentration was observed at the shield rear welded interface.

(2) Bellows connection: With bellows, axial displacement was partially absorbed and stresses were reduced in both the bending section and the shield interface.

(3) Comparison: Welded connections are structurally simple but suffer from stress concentration at the bends, whereas bellows effectively mitigate thermal expansion stress.



(a) Welding joint condition



(b) bellows joint condition

Fig. 5. Stress distribution on TBM-set according to the

4. Conclusions

Thermo-structural analysis of the penetrating pipe in the HCCP TBM-set under TOS conditions was conducted. The temperature distribution from thermal analysis was used as input for structural analysis. Results showed that welded connections caused stress concentration at the 90° bending section, while bellows reduced stress levels overall. Bellows are thus confirmed as an effective option to mitigate axial thermal expansion stresses.

Acknowledgment

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