Structural Integrity Evaluation of PCHE Based on ASME code

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1. Introduction

Next-generation nuclear reactor operate at high temperatures, and high-performance heat exchangers are essential for efficient thermal energy transfer. A printed circuit heat exchanger (PCHE) is a compact heat exchanger consisting of numerous small flow channels and offers advantages in terms of heat transfer performance and compactness. However, the structural integrity of a PCHE must be carefully evaluated because it is subjected to high-temperature and pressure conditions for extended periods, together with variations in temperature and pressure during operation.

In this study, the structural integrity of an PCHE was evaluated using finite element analysis (FEA) and the linear elastic stress evaluation procedures specified in ASME Section III Division 5. Operating Cycle Transients (OCTs) were also considered to account for representative operating histories. In addition, an automated evaluation procedure was developed to efficiently process OCT data and calculate the parameters required for the ASME code assessment.

2. Analysis Method

2.1 Finite Element Model

Because a PCHE consists of a large number of periodically arranged micro-channels, modeling the entire geometry can result in excessive computational cost. Therefore, a representative volume element (RVE) corresponding to a representative channel region was selected for the structural analysis. Symmetry conditions were applied where appropriate to improve computational efficiency, and Stress Classification Lines (SCLs) were defined for the ASME stress evaluation.

TP316H was selected as the structural material. Temperature-dependent material properties, including Young's modulus, Poisson's ratio, and the coefficient of thermal expansion, were defined based on the high-temperature material properties specified in ASME Section II, Part D. The analysis temperature range was approximately 588~650°C. A locally refined mesh was applied to regions where stress concentrations were expected, particularly around the channel–solid junction.

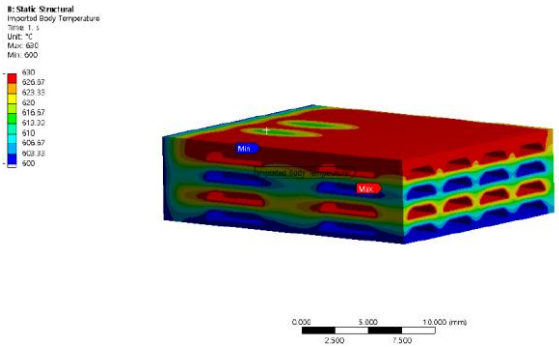


Fig. 1 Temperature distribution for PCHE

2.2 Loading Conditions and Stress Evaluation

The design pressure conditions of the PCHE were applied to the structural model. Pressures of 0.54 MPa and 0.586 MPa were applied to the hot and cold sides, respectively. Displacement constraints were imposed to prevent rigid-body motion, and bonded contact conditions were applied between the internal channels and solid walls.

A linear elastic static structural analysis was performed using ANSYS Mechanical in accordance with the stress classification procedure of ASME Section III Division 5. Stress Classification Lines were defined at representative locations, and the primary membrane stress (P_m), bending stress (P_b), and local primary membrane stress (P_L) were obtained through stress linearization.

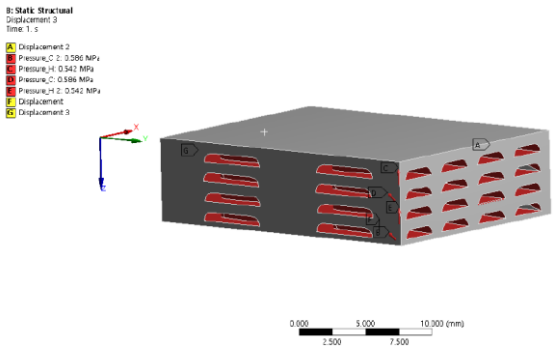


Fig. 2 Stress evaluation results for PCHE

2.3 OCT-Based ASME Code Evaluation

Operating Cycle Transients (OCTs) were used to account for the time-dependent temperature and pressure histories of the PCHE. OCT-1, OCT-2, and OCT-3 were considered, with maximum metal temperatures ranging from 588°C to 650°C.

To improve the efficiency of the repeated code assessment process, a Python-based automation program was developed. The program automatically extracts the operating time and temperature history of each OCT, identifies stress extreme points, and calculates the allowable stress and allowable time parameters required for the ASME Division 5 evaluation.

3. Results and Discussion

3.1 Stress Evaluation

The stress linearization results obtained along three SCLs showed primary membrane stresses of 1.0284, 1.1601, and 1.294 MPa, respectively. The maximum primary membrane stress was therefore 1.294 MPa at SCL 3. The calculated bending stresses were on the order of 10^{-5} MPa, resulting in a maximum local primary membrane stress of 1.294 MPa.

For the ASME Division 5 assessment based on the OCT conditions, the maximum temperatures ranged from 588°C to 650°C, and the corresponding allowable stress values ranged from approximately 50.3 to 70.0 MPa. The maximum calculated primary membrane stress of 1.294 MPa was significantly lower than the allowable limits for all evaluated conditions.

The combined local primary membrane and bending stress also satisfied the corresponding ASME Division 5 criteria for all operating conditions. These results indicate that the PCHE maintains sufficient structural stability with respect to primary stress under the mechanical loading conditions considered in this study.

3.2 User Fraction Evaluation

The User Fraction was calculated to evaluate the effect of the operating history under high-temperature conditions. The individual User Fraction values were as high as approximately 0.034, while the total User Fraction Sum was calculated to be 0.07. This value satisfies the ASME Division 5 criterion of UFS $\leq$ 1.0. Therefore, the evaluated OCT histories satisfy the allowable service-time requirements and demonstrate adequate structural integrity from the perspective of the primary stress and time-dependent allowable criteria.

4. Conclusions

The structural integrity of an PCHE was evaluated using ANSYS-based finite element analysis and the linear elastic stress evaluation procedures of ASME Section III Division 5. Based on the given OCT, the stress values calculated from the analysis results are combined and calculated according to the evaluation process of load controlled stress limits and stain and deformation limits of the ASME Section III, division 5, HBB-3221-1 as following Fig. 3.

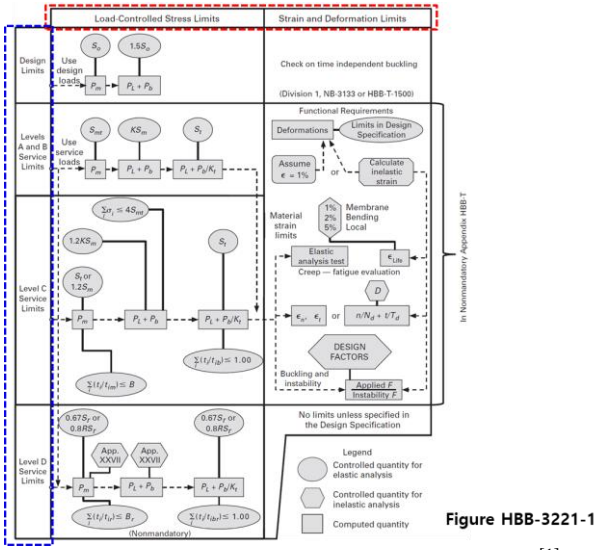


Fig. 3 ASME Section III, division 5, HBB-3221-1[1]

Under the considered operating temperature range of approximately 588~650°C and the design pressure conditions, the maximum primary membrane stress was calculated to be 1.294 MPa. The calculated stress values satisfied the ASME Division 5 allowable criteria for all evaluated OCT conditions.

The total User Fraction Sum was calculated to be 0.07, which is significantly lower than the allowable limit of 1.0. These results demonstrate that the PCHE satisfies the primary stress criteria under the mechanical loading and operating conditions considered in this study.

In addition, a Python-based automation program was developed to extract the key parameters required for ASME code evaluation from OCT operating histories. The developed procedure is expected to improve the efficiency and consistency of repeated structural integrity assessments during design modifications.

However, the present evaluation primarily focused on primary stresses induced by mechanical loading. Further investigations are required to evaluate secondary stresses caused by thermal expansion, strain limits, ratcheting, and creep-fatigue damage under high-temperature operating conditions.

Acknowledgement

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REFERENCES

[1] ASME, ASME Boiler and Pressure Vessel Code, Section III, Division 5, American Society of Mechanical Engineers.

[2] ASME, ASME Boiler and Pressure Vessel Code, Section II, Part D – Materials Properties, American Society of Mechanical Engineers.