Model Calibration-based Design Methodologies for Structural Design of Supercritical CO_2 Compact Heat Exchangers under Sustained Cyclic Temperature and Pressure Gradients

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ABSTRACT: Our *goal* is to develop a design method for rapid structural assessment of diffusion-bonded Hybrid Compact Heat Exchangers (H-CHX), for use as secondary heat exchangers in coupling Sodium Fast Reactors (SFRs) with supercritical CO_2 (sCO_2) Brayton power cycles. The use of H-CHX in nuclear power production can significantly reduce cost and increase efficiency, thus enabling a *broader societal benefit* by advancing carbon-free energy and energy diversification. However, a critical *technological issue* is the lack of a technical basis for a H-CHX specific ASME code case. Such a code case is needed to enable uniformity in design rule usage for structural design of H-CHX that are used in the above application. The deeper *technical issue* is the need for a method, based on recently developed EPP pressure vessel design techniques that accounts for the unique aspects of H-CHX while assessing cyclic creep induced failure under the elevated cyclic temperature and pressure gradients that the H-CHX is subjected to. The key *technical challenges* and our *approach* to resolving them are:

(1) Conventional cyclic Elastic-Perfectly-Plastic Finite-Element-Analysis (EPP-FEA), used for cyclic creep assessment in pressure vessels, is too time consuming for H-CHX design. This is because the multiple small features and complex flow pathways in the H-CHX require very small mesh sizes to be used. H-CHX also contain multiple diffusion-bonded joints that affect the structure's response to thermal and pressure loads. Conventional EPP-FEA does not typically account for the behavior of the joint, resulting in over-prediction of stresses at the corners of the flow channels. We will develop and validate a computationally rapid *Equivalent-Solid Cohesive-Zone* (EQS-CZM) method, based on EPP analysis, to account for the effect of (a) multiple complex micrometer-sized features and flow pathways; (b) temperature and pressure gradients; and (c) joints at the corners of the flow channels, on the stress-strain response of the H-CHX. Computational efforts will be complemented with experimental diffusion-bonding and thermal-pressure testing of test H-CHX articles.

(2) Conventional limit load interaction diagrams (2D Bree diagrams) for cyclic loading, built using conventional EPP-FEA, account for cyclic thermal and pressure loads but not for the significant spatial temperature gradients that can occur along the length of the flow channel. This can result in unconservative designs. We propose *Bree surfaces,* which extend 2D Bree diagrams by including another axis to represent flow channel length. We will develop methods for (a) efficient construction of the Bree surfaces, by leveraging the EQS-CZM method and existing EPP techniques; (b) exploration of Bree surfaces to enable design of feasible structural design pathways for the H-CHX.

The project *deliverables* will be method-specific procedures and mathematical formulations necessary for the design engineer to (1) use EQS-CZM method for estimation of compliance with EPP method imposed strain limits for creep induced failure; (2) construct and use the proposed Bree surfaces to arrive at feasible structural design pathways that consider cyclic creep-induced failure. The *outcome* of this project will be the creation and validation of methods which form a technical basis for the development of an ASME code case for H-CHX, or other compact heat exchangers, that are exposed to elevated cyclic temperature and pressure gradients during their operation.