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Finite Element Based External Limit Pressure Solution for Helical Tube Steam Generator Depending on the Geometric Parameter

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1. Introduction

The small modular reactor (SMR) has emerged as a next-generation nuclear technology, offering enhanced safety, economic efficiency, and flexibility. Conventional large-scale plants use U-tube steam generators. In contrast, the innovative SMR (i-SMR) applies a helical steam generator.

In the case of U-tube steam generators, burst failure due to internal pressure is considered the primary failure mechanism, whereas for helical steam generators, plastic collapse under external pressure becomes a major concern. This shift in failure mechanisms resulting from the design change necessitates new design strategies and technical considerations.

Previous studies [1-3] have numerically investigated the effects of geometric parameters, material properties, and work hardening on the collapse pressure of helical steam generators, analyzing various geometrical configurations. However, these studies primarily focused on mechanical loading without considering thermal effects.

In this study, both mechanical and thermal loads are comprehensively considered to evaluate the collapse pressure behavior of the helical steam generator. Furthermore, a predictive equation for collapse pressure under combined loading conditions is proposed.

2. Allowable external pressure solution in ASME BPVC Section III NB

ASME Sec. III NB-3133.3 [4] specifies the maximum allowable external pressure (P_a) for cylindrical shell structures. Depending on the mean outer diameter to thickness ratio (d/t), Eq. (1), (2) applies for d/t ≥ 10, whereas Eq. (3), (4) applies for d/t < 10. Use the smaller of P_{a1} and P_{a2} as the allowable external pressure, and compare it with the design pressure. If P_a is less than the design pressure, revise the assumed wall thickness and repeat the calculation until the design pressure is satisfied. Parameters A and B required to determine the allowable pressure are obtained from ASME BPVC Sec. II, Part D, Subpart 3. [5]

$$P_a = \frac{4B}{3\left(D_o/t\right)} \tag{1}$$

$$P_a = \frac{2AE}{3\left(D_o/t\right)} \tag{2}$$

$$P_{a1} = \left[\frac{2.167}{\left(D_o/t\right)} - 0.0833\right]B \tag{3}$$

$$P_{a2} = \frac{2S}{\left(D_o/t\right)}\left[1 - \frac{1}{\left(D_o/t\right)}\right] \tag{4}$$

3. Geometric parameters definition for numerical simulation of a helical steam generator

The geoetric parameters required for collapse pressure analysis of a helical steam generator was determined with reference to previous studies [1-3] The geometry is classified into four main parameters: helical bending radius (R), mean radius of the steam generator tube (r_m), wall thickness (t) and pitch (p) according to the number of bending, as shown in Fig. 1.

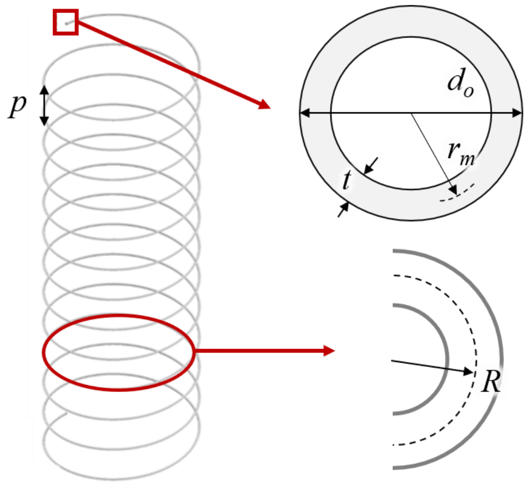

Fig. 1. Schematic of helical steam generator

Based on these parameters, the geometric information required for the numerical analysis was defined, and the selected values are summarized in Table 1. The material properties of Alloy 690 at 350 °C, as specified in ASME Section II [2], were adopted for the analysis, and an elastic–perfectly plastic (EPP) analysis was conducted. An elastic modulus (E) of 191 GPa, a Poisson's ratio (v) of 0.31, and a yield strength (σ_y) of 190 MPa were applied. These parameters serve as the fundamental input data, enabling a systematic evaluation of the collapse pressure characteristics of the helical steam generator in the subsequent structural analysis.

Table I: Summary of geometric information

Geometric parameter	Values
R/r_m	50, 100, 150, 200
r_m/t	2, 4, 6, 8, 10
p/d_o	1.2, 50, 150, 300

4. Prediction of collapse pressure through finite element analysis

4.1. Modeling for finite element analysis

Fig. 3. shows the finite element model for collapse pressure prediction, which was developed using the commercial software ABAQUS ver. 2024. [5] The entire geometry was modeled with 3D solid elements, and three-dimensional 20-node reduced integration elements (C3D20R) were employed. In the thickness direction, four elements were assigned, while 32 elements were applied in the radial direction. Along the axial direction, an element size of 6 mm was used. The end surfaces were constrained to the reference point through kinematic coupling, restricting all displacements and rotations except for displacement in the thickness direction.

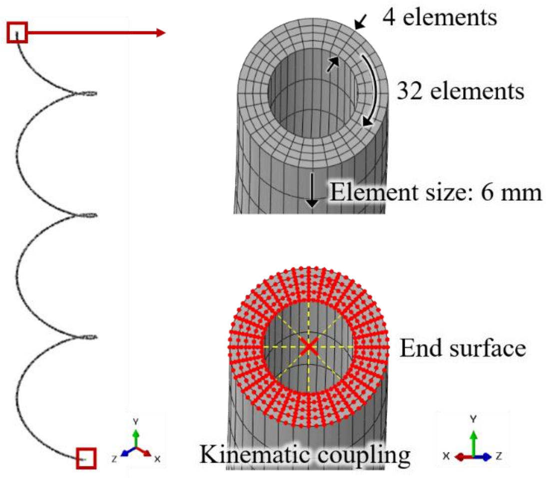

Fig. 2. FE mesh of helical tube steam generator for finite element analysis

4.2. Finite element analysis for predict collapse pressure

The external pressure was applied to the entire outer surface of the steam generator tube using the DSLOAD option with surface definition. An initial pressure of 1 MPa was specified, and nonlinear behavior (NLGEOM) was considered. A static analysis was performed, and the Riks option was employed to predict the collapse pressure.

The collapse pressure was predicted based on geometric effects, and the principal analysis results with respect to geometry were examined. Fig. 3. presents the collapse pressure as a function of helical pitch. As the pitch increased, the collapse pressure tended to decrease, and a sharp drop was observed at $p/d_o = 150$. Accordingly, pitch was identified as the dominant factor influencing collapse pressure.

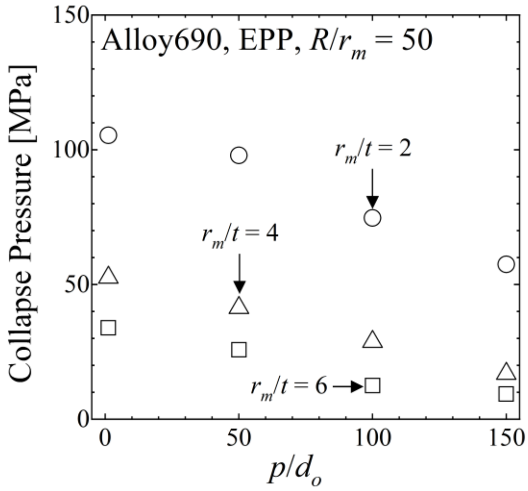

Fig. 3. Analysis results of collapse pressure with respect to pitch (p/d_o) in a helical tube steam generator.

5. Conclusion

In this study, the effects of geometrical parameters on the external pressure collapse of helical tubes newly applied in the innovative SMR steam generator were investigated. Based on the analysis results, a prediction formula for external pressure collapse was derived. In addition, a coupled analysis incorporating thermo-hydraulic conditions was performed. Through this approach, collapse pressure behavior under realistic operating environments was evaluated, and design strategies for the new geometry were considered.

ACKNOWLEDGEMENT

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[4] ASME, ASME Boiler and Pressure Vessel Code, Division I, Section III, Subsection NB, 2015.
[5] ASME, ASME Boiler and Pressure Vessel Code, Division I, Section II, 2015