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Sizing Orifice for Sustaining Flow Instability of a Steam Generator in NuScale SMR

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1. Introduction

The NuScale Power Module (NPM) is a Small Modular Reactor (SMR) designed by NuScale Power, LLC. One crucial component of NuScale's SMR system is the Steam Generator (SG). However, during the design and testing phases of the NuScale SMR, concerns arose regarding potential flow instability in the SG [1]. While several studies have been conducted on flow instability in the NPM, the existing research has limitations. Reyes [2] conducted experiments to investigate the onset and evolution of density wave oscillations using the full-height TF-2 counterflow test facility, developing a density wave oscillation onset correlation. Lee and Bae [3] analyzed the possible occurrence of flow instability in the SG using a static flow instability model. At that moment, they did not consider several design features like flow restrictors to sustain flow instability. In this study, we analyzed the sizing of the diameter of a sharp-edged orifice to sustain flow instability in the NPM's SG.

2. Methods and Results

2.1 NuScale SMR

The NPM incorporates a distinctive self-contained, modular design philosophy, with each module capable of generating up to 160 MWt of thermal power. Within the NPM, there are two independent SGs as shown in Fig. 1. The SG follows a once-through design configuration and employs 690 helically coiled tubes. Among the coils, one-fourth are connected to a single core plenum in Fig. 1. The tube used in the SG has an outer diameter of 15.88 mm and a thickness of 1.27 mm. The total heat transfer area of the SG is 1665.5 m², and the length of the coiled tube is calculated at 24.2 m. In Table 1, we provide an overview of the SG's full-load thermal-hydraulic operating conditions [1].

Table 1: Steam Generator Full-Load Thermal-Hydraulic Operating Conditions

Parameter	Value
Total heat transfer (MW_t)	159.13
SG outlet pressure (MPa)	3.45
SG outlet temperature (°C)	306.9
SG inlet temperature (°C)	148.7
SG flow (kg/s)	67.07

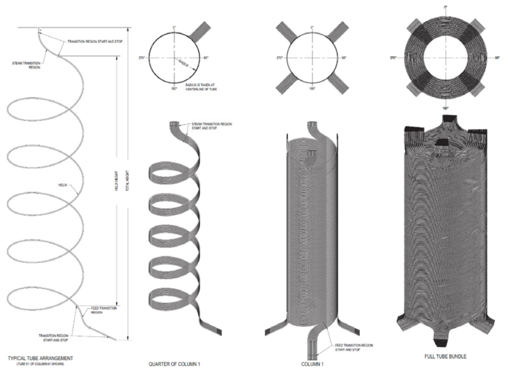

Fig. 1. Steam Generator Helical Tube Bundle [1].

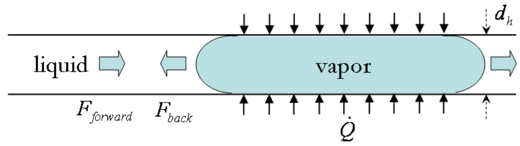

Fig. 2. Schematic of Static Flow Instability Model Steam Generator Helical Tube Bundle.

2.2 Instability Parameter with Inlet Orifice

A static model has been developed to analyze flow instability by considering force balances on a liquid-vapor interface during the growth of a bubble inside a tube. Figure 2 provides a schematic of the force balances acting on a squeezing bubble within the tube. The tube's confinement causes the growing bubble to be compressed towards both the upstream and downstream ends. During this stage, the volume generation rate of the bubble can be estimated based on the heat supply from the tube wall and the latent heat involved in the boiling process. This static model offers insights into the behavior of the squeezing bubble and its impact on flow dynamics within the tube. When an inlet orifice is installed in front of a straight microchannel, the backward evaporation momentum force of the expanding elongated bubble has to work against the forward force of the flow due to the large pressure drop at the inlet orifice. Finally, the ratio of the backflow force, F_{back}, and the forward flow inertia, $F_{forward}$ are

$$F_{\text{back}} = \rho_g \left(\frac{\dot{Q}}{\rho_g i_{fg}} \frac{1}{2A} \right)^2 A = \frac{1}{4\rho_g A} \left(\frac{\dot{Q}}{i_{fg}} \right)^2$$
$$F_{\text{forward}} = \rho_f \left(\frac{G}{\rho_f} \right)^2 A = \frac{G^2 A}{\rho_f} \quad (1)$$

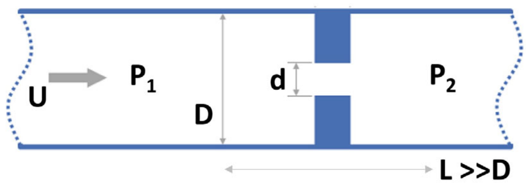

Fig. 3. Schematic of sharp-edged orifices.

The pressure drop of the inlet orifice comes from:

$$F_{\mathrm{orf}} = \frac{1}{2\rho_{\mathrm{f}}}\left(\frac{GA_1}{A_{\mathrm{orf}}}\right)^2 K_{\mathrm{orf}} A_1 \tag{2}$$

After the orificing force, F_{orf}, is added to the forwarding flow inertia, the instability parameter, R, becomes

$$R = \sqrt{\frac{F_{\mathrm{back}}}{F_{\mathrm{forward}} + F_{\mathrm{orf}}}} \tag{3}$$

where $\dot{Q}$, A, i_{fg}, G, ρ_f, ρ_g, and K are total heat amount (W), area (m^2), latent heat (J/kg), mass flux ($kg/m^2/s$), liquid density (kg/m^3), vapor density, minor loss coefficient, respectively. To ensure a stable flow on the secondary side of the tubes, it is imperative to maintain the instability parameter below unity [4]. It is noted that this model's application is specifically tailored for scenarios involving long elongated bubbles resulting from violent boiling processes inside a tube. The minor loss coefficient is adopted from the reference [5].

2.3 Stability Analysis

Before applying the static flow instability model to the operating conditions given in Table 1, it is assumed that there is no pressure drop in the tube, a uniform heat flux boundary condition exists, an annular flow pattern is present inside the tube, and there is no fouling effect. Since the SG outlet pressure is 3.45 MPa, resulting in a saturation temperature of 241.7°C, estimating the tube length occupied by the annular bubble is crucial for calculating the instability parameter. Figure 4 illustrates the phase along the tube with the variation of saturation temperature. Lee and Bae [3] reported the possible occurrence of flow instability in the SG without any flow restrictors to sustain flow instability at this operating condition because the instability parameter is 3.45. Figure 5 presents the relationship between the instability parameter and the ratio of an orifice to plenum diameter (d/D). When the ratio of orifice diameter is less than 0.18, it is expected that the flow instability may be sustained in the NPM's SG because R is less than unity.

3. Conclusions

We applied the static flow instability model [4], which includes an inlet orifice to sustain flow instability, to analyze the full-load operating conditions of the

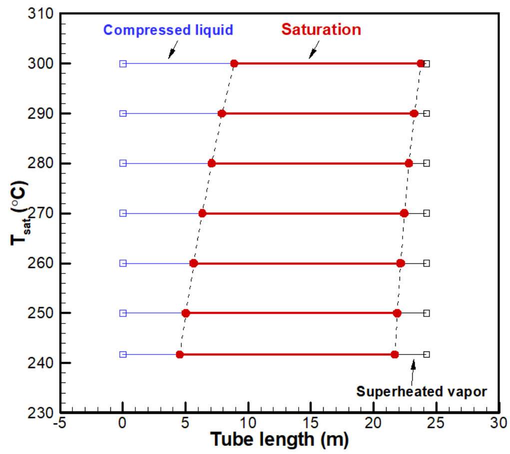

Fig. 4. Phase inside a tube with a variation of saturation temperature.

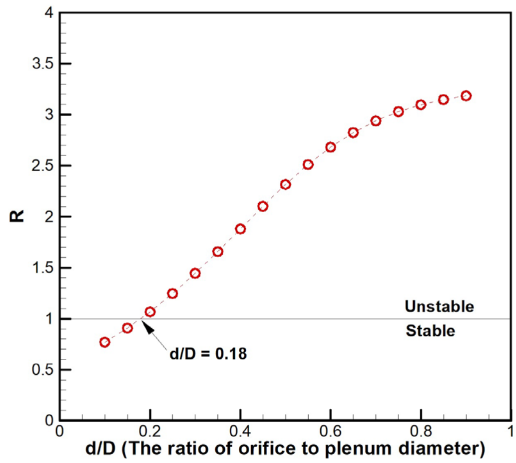

Fig. 5. The instability parameter vs. the ratio of an orifice to plenum diameter.

NPM's SG. Our analysis indicates that flow instability is sustained when the ratio of an orifice to plenum diameter less than 0.18 is installed in front of the train of the helical coil bundles.

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