Static Analysis of 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. The NPM's pressurized water reactor system, along with its natural circulation-based cooling system, sets it apart from conventional large-scale nuclear power plants, making it simpler, more flexible, and highly resilient. 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]. Flow instability occurs when the flow becomes erratic and reverses upstream due to violent boiling processes within the tubes. As a consequence, rapidly expanding bubbles and subsequent liquid flow disruptions can lead to flow oscillations within the SG.

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. NuScale Power, LLC [3] also reported on instability characteristics but provided only general theories and ideas.

In this study, we address the issue of flow instability in the NPM's SG. Specifically, we apply the static flow instability model proposed by Lee et al. [4] to determine whether it can ensure stable flow on the secondary side of the tubes at operational power levels, thus mitigating the possibility of reactor power oscillations.

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 that play a vital role in the heat transfer process. The SG follows a once-through design configuration and employs 690 helical coiled tubes. The tube used in the SG has an outer diameter of 15.88 mm and a thickness of 1.27 mm, ensuring optimal heat transfer efficiency while maintaining structural integrity. The total heat transfer area of the SG is 1665.5 m^2, and the length of the coiled tube is calculated at 24.2 m. Importantly, to account for potential tube plugging, each of the two independent SGs is equipped with a 10 percent tube plugging margin, ensuring continued performance and reliability over time.

In Table 1, we provide a comprehensive overview of the steam generator's full-load thermal-hydraulic operating conditions, allowing for a clear understanding of its capabilities and performance characteristics [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

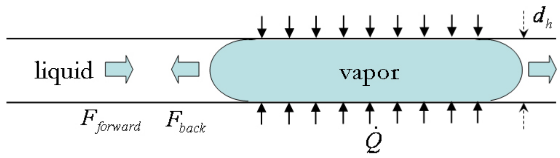

Fig. 1. Schematic of Static Flow Instability Model.

2.2 Static Flow Instability Model

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. The model accounts for evaporation momentum change, inertia, and surface tension effects. Figure 1 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.

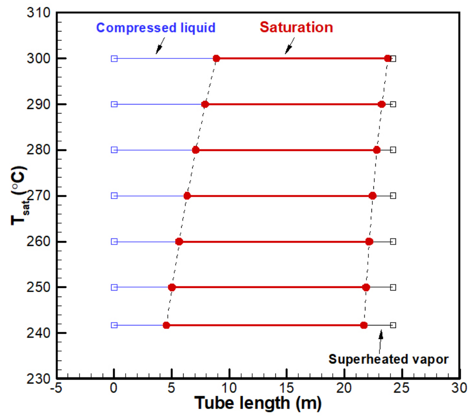

Fig. 2. Phase inside a tube with a variation of saturation temperature.

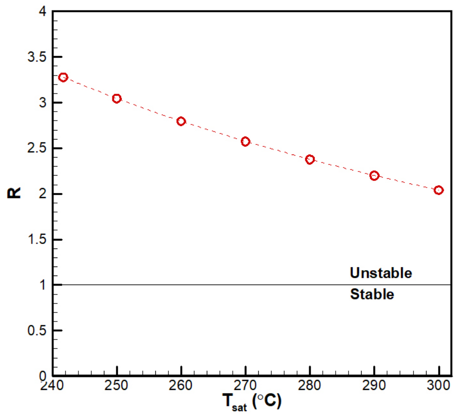

Fig. 3. Instability parameter with an increasing saturation temperature.

Finally, the ratio of the backflow force, F_{back}, and the forward flow inertia, $F_{forward}$,

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

can be expressed as the instability parameter, R

$$R = \sqrt{\frac{F_{\text{back}}}{F_{\text{forward}}}} = \frac{\dot{Q}}{2A i_{fg} G} \sqrt{\frac{\rho_f}{\rho_g}} \quad (2)$$

where $\dot{Q}$, A, i_{fg}, G, ρ_f, ρ_g 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, respectively. To ensure a stable flow on the secondary side of the tubes, it is imperative to maintain the instability parameter below unity. 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.

2.3 Stability Analysis

Before a static model of flow instability is applied to the operating condition given in Table 1, it is mainly assumed as the followings:

- No pressure drop in a tube
- Considering a tube without restriction orifice
- Uniform heat flux boundary condition
- Annular flow pattern inside a tube
- No contraction plenum in a train
- No fouling effect

Since SG outlet pressure is 3.45 MPa, resulting in a saturation temperature of 241.7°C. To understand the effects of varying saturation temperatures, we gradually increase it at 10°C intervals until reaching 300°C, where the outlet steam temperature is 306.9°C. Estimating the tube length occupied by the annular bubble is crucial for calculating the instability parameter. Figure 2 illustrates the phase along the tube with the variation of saturation temperature.

As the saturation temperature increases, the saturation region decreases, influencing the behavior of annular bubbles and potentially affecting flow stability. Figure 3 presents the relationship between the instability parameter and saturation temperature. Based on the operating condition in Table 1, our analysis predicts that the SG may experience flow instability, as the instability parameter exceeds 2. To address potential flow instability concerns, NuScale has integrated several design features, including an optimized tube bundle layout, specialized support structures, and flow control devices such as helical wire wraps and flow restrictors. For future work, we plan to update and refine the static flow instability model, incorporating the influence of design features employed by NuScale. to achieve stable flow on the secondary side of the tubes during operational power levels, contributing to the advancement of reliable small modular nuclear reactors.

3. Conclusions

We applied the static flow instability model [4] to analyze the full-load operating conditions of the NPM's SG. Our analysis indicates the possibility of flow instability in the SG. To address this concern, we will continue developing our model to ensure that it can effectively mitigate flow instability.

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