

Evaluation of Steam Generator Thermal-Hydraulic Characteristics under Load-Following Conditions Using CFD

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1. Introduction

Load-following operation results in changes in reactor thermal power and consequently alters both primary coolant conditions and secondary-side feedwater states. Such operating changes alter heat transfer across steam generator (SG) tube bundles and may influence internal flow distribution, vapor generation, and buoyancy-driven circulation behavior. Since the SG serves as both a heat exchanger and a pressure boundary between the primary and secondary systems, evaluation of its thermal-hydraulic response under varying power conditions is of engineering importance.

Although one-dimensional system codes have been widely used for SG analysis, their governing equations rely on averaged formulations and empirical closure relations, which may limit the resolution of local three-dimensional flow structures [1]. To address this limitation, detailed computational fluid dynamics (CFD) approaches can be applied to SG analysis.

In a previous study, an integrated CFD model of a replacement steam generator (RSG) was developed and its validity was assessed under nominal operating conditions [2]. The CFD model developed in the previous study was applied to load-following scenarios corresponding to 80%, 100%, and 102% rated thermal power. The present study also aims to provide thermal-hydraulic information relevant to the assessment of steam generator tube wear. Accordingly, CFD analyses were conducted under both nominal and load-following operating conditions.

2. Materials and Methods

The integrated CFD model includes both primary and secondary flow domains, as illustrated in Fig. 1. The secondary side incorporates U-tube bundles, support structures, flow distribution plates, and moisture separation regions. Geometrically complex internal structures were modeled using porous media regions to represent distributed hydraulic resistance.

Steady-state RANS simulations were performed using the Realizable $k-\epsilon$ turbulence model, which was selected based on prior turbulence model sensitivity evaluation showing differences within 0.6% among

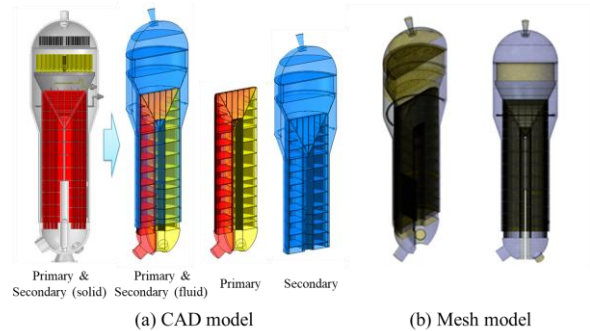


Fig. 1 Integrated CFD model of the steam generator.

Table I: Summary of operating conditions for load-following analysis

Parameter		80% Power	100% Power (Reference)	102% Power
Core Thermal Power		0.80	1.00	1.02
Primary Inlet	Flow Rate	1.00	1.00	1.00
	Temperature	0.99	1.00	1.00
Secondary Economizer FW	Flow Rate	0.75	1.00	1.02
	Temperature	0.98	1.00	1.00
Secondary Downcomer FW	Flow Rate	1.21	1.00	0.99
	Temperature	0.98	1.00	1.00
Circulation Ratio		1.30	1.00	0.98

major models. Buoyancy effects were included to represent density-driven flow behavior, and phase change in the secondary side was modeled using a homogeneous two-phase formulation.

Boundary conditions for load-following operation were defined for three power levels (80%, 100%, and 102% of rated thermal power). The 80% and 102% cases were selected based on plant-representative design data, while the 100% case was used as the nominal reference. Corresponding primary- and secondary-side thermal-hydraulic conditions were adjusted for each power level.

3. Results and Discussion

Fig. 2 presents the predicted velocity magnitude, vapor volume fraction, and temperature distributions under the three operating conditions. The 100% and 102% cases exhibit nearly identical spatial characteristics across all fields, indicating that a slight increase in thermal power does not significantly modify the internal thermal-hydraulic structure of the SG.

In contrast, more pronounced changes appear under the 80% power condition. Reduced feedwater flow and thermal input lead to decreased vapor generation and contraction of the phase-change region within the tube bundle, which is also reflected in the temperature field as an expanded low-temperature region and an upward shift of the phase-change region.

The reduction in flow intensity observed in Fig. 2 is quantitatively confirmed by the averaged velocity comparison shown in Fig. 3. Under the 80% condition, axial, cross-flow, and vertical velocity components decrease to approximately 78–80% of nominal values, whereas differences between the 100% and 102% cases remain marginal.

This asymmetric behavior is mainly attributed to nonlinear variations in vapor generation predicted by the CFD simulation. While sufficient vapor production is maintained under slightly increased power conditions, reduced-power operation weakens buoyancy-driven flow intensity and leads to redistribution of internal flow patterns.

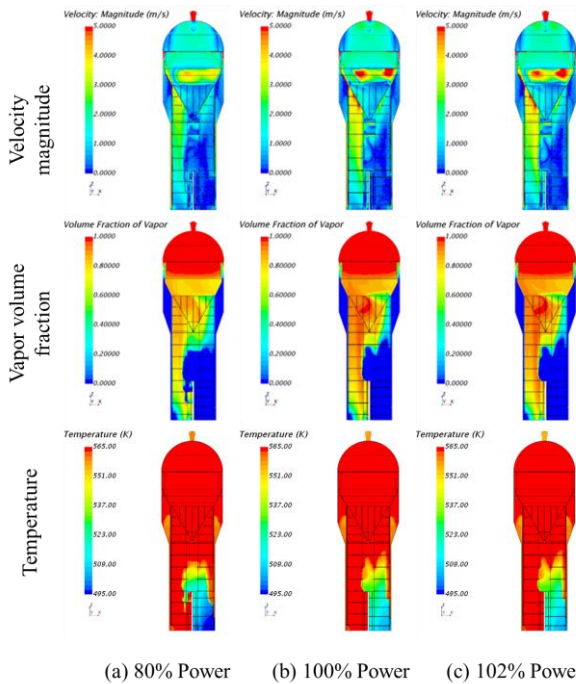


Fig. 2. Secondary-side velocity magnitude, vapor volume fraction, and temperature distributions at different power conditions.

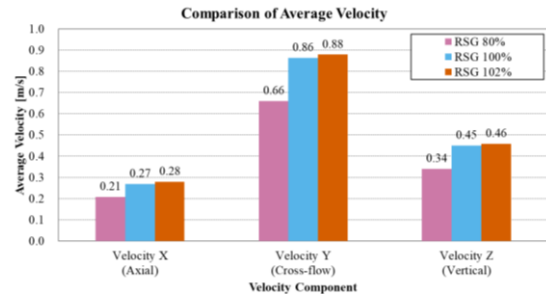


Fig. 3 Averaged velocity components in the horizontal tube region at different power conditions.

4. Conclusions

An integrated CFD model of a steam generator was applied to evaluate thermal-hydraulic responses under load-following operating conditions.

Results indicate that internal flow distribution and vapor generation characteristics remain nearly unchanged between 100% and 102% rated power conditions. However, reduced-power operation at 80% leads to decreased vapor generation and reduced secondary-side flow velocity predicted by the CFD model.

The results indicate that changes in reactor thermal power affect internal thermal-hydraulic behavior in the steam generator, leading to noticeable variations in flow velocity in the upper tube bundle region. The results of this study may be utilized as thermal-hydraulic data for steam generator tube wear assessment.

Acknowledgement

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