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Steam Generator Model Design Parameter Sensitivity Study Using Advanced Optimization Tools

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Idaho National Laboratory

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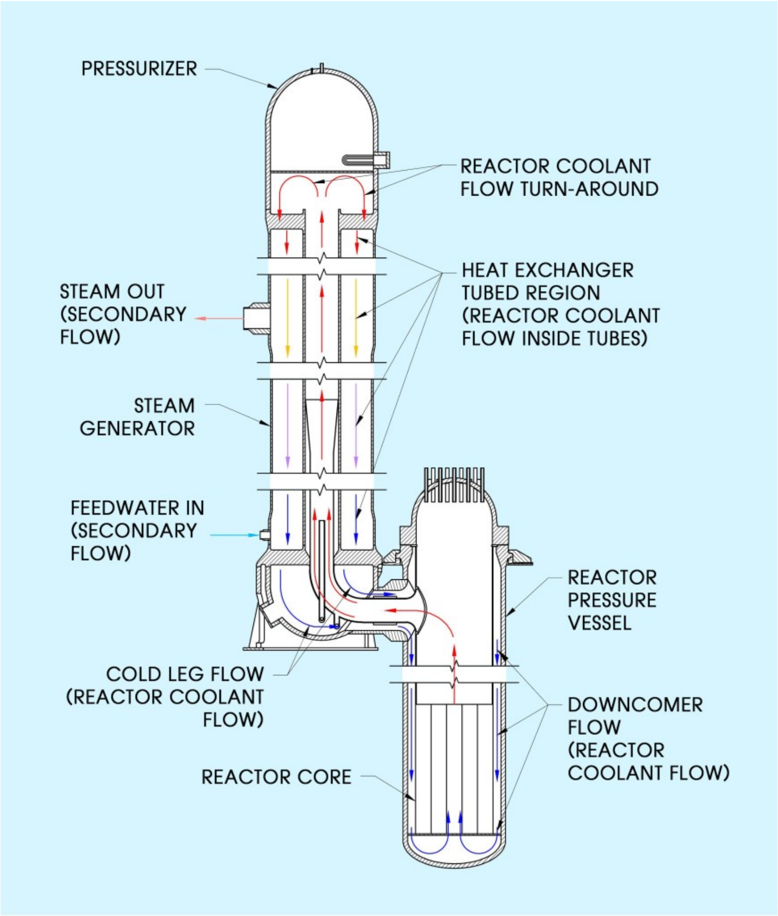

Figure 1: Steam generator for a SMR system.

Taken from: https://holtecinternational.com/2020/12/23/a-key-topical-report-on-smr-160-submitted-to-the-usnrc/

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Objectives

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- Perform parameter sensitivity studies pertaining to a steam generator (SG) model:
  - Using both Python and machine-learning tools for a small modular reactor (SMR) system [1][2].
- Design studies involve:
  - Changing the model's input design parameters (e.g., temperature, pressure, mass flow rate)
  - Observing the resulting effects on the output of the system (e.g., heat transfer coefficient [HTC], Nusselt number, heat transfer performance)
  - Supporting reactor system design, analysis, and licensing [3].
- Sensitivity studies analyze:
  - The degree to which system output and/or desired parameters (e.g., HTC or heat transfer performance) are sensitive to changes in the input parameters.
- INL developed the Risk Analysis Virtual Environment (RAVEN), which is used to perform the parametric, sensitivity, and optimization studies.

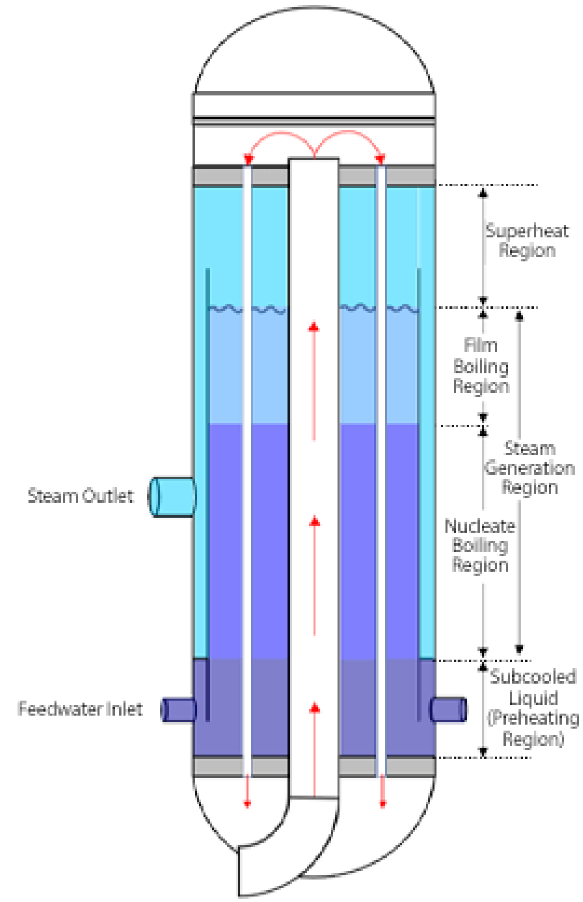

Figure 2: SMR once-through SG [4].

Introduction

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- The vertical, once-through SG, which is the primary subject of this study,
  - Comes from a reference SMR design [4].
- Reactor heat is fed into a hot fluid that enters the hot-leg (HL) through the riser section and is then carried through the various small SG tubes,
  - Referred to as the primary-side.
- The secondary-side consists of the shell encasing the SG tubes and provides a path along which the secondary fluid can flow,
  - Thus enabling heat transfer between the primary and secondary fluids to occur [5].
- As shown in Figure 2(a), the SG tubes are supported by
  - Baffles positioned within the shell where secondary fluid flows through.
  - The middle column, or "riser," experiences a change in cross-sectional area, becoming wider at the top.
  - The hot fluid becomes gathered up at this point prior to being sent directly back down through the SG tubes.

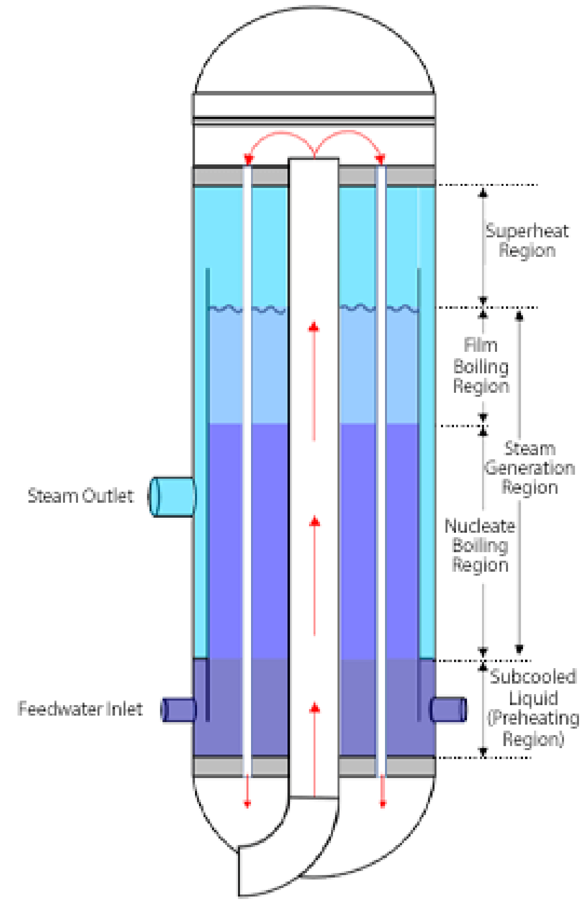

Figure 2 (a): SMR once-through SG [4].

Methodology

- The RAVEN code discretizes the length of the SG into thousands of intervals in which the fluid properties are assumed to be constant.
- The SG model is a mathematical representation (including fluid flow and heat transfer equations/models/correlations) of a steam-generating unit in a PWR-type SMR system.
- Starts with an initial guess for the HL outlet temperature to be 239.85°C – from this boundary, conditions for the next interval can be calculated.
- This calculation is repeated until the error between the HL inlet temperature and the guessed parameter is lower than 0.01.
- The code also accounts for a phase change in the secondary fluid of the SG (i.e., subcooled boiling, nucleate and film boiling).
- INL developed the RAVEN optimization tools and Python algorithm used in this study [6] to support design studies, including sensor placements [7] [8].

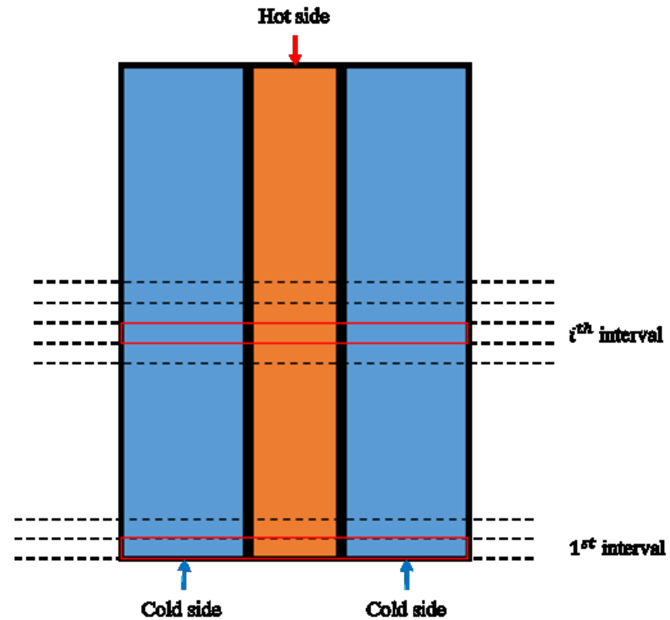

Figure 2 (b): Python code computational grid schematic.

Constitutive Models and Correlations

Parameter	Model/Correlation	Applicable Range	Reference
Single-phase frictional factor		0 < Re < 2300	White [9]
			Petukhov et al. [10]
Two-phase fictional pressure drop			Lockhart and Martinelli [11]
Two-phase acceleration pressure drop			Todreas and Kazimi [12]
Two-phase gravitational pressure drop			Todreas and Kazimi [12]
Single-phase Nusselt Number			Incropera et al. [13]
			Gnielinski [14]
Sub-cooled boiling heat transfer rate			Chen [15]
Nucleate boiling heat transfer rate			Chen [15]

Reference Heat Exchanger Model using Python code

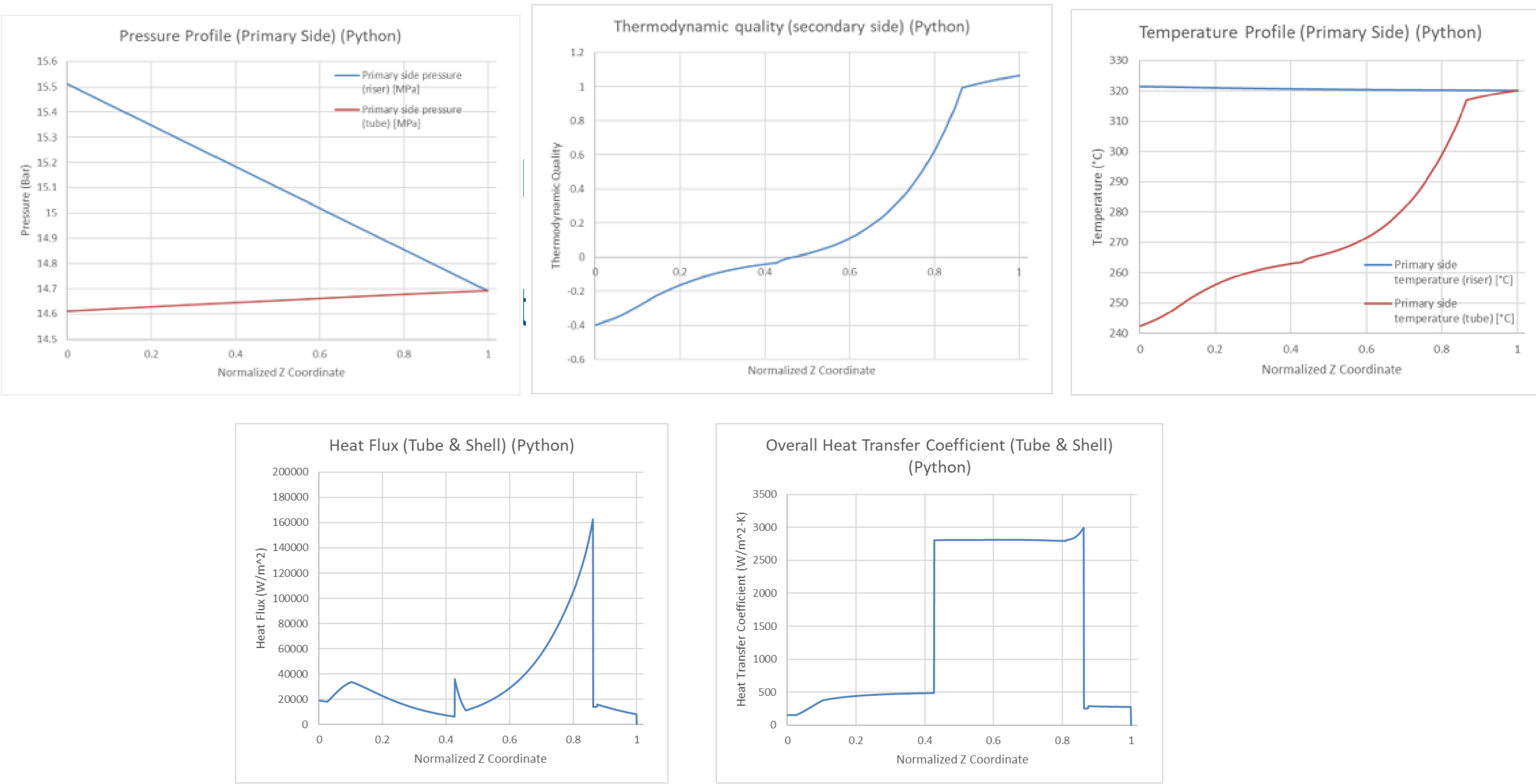

Figure 3: Sample plots output with the Python-based code.

Input/Output Parameters and their Ranges

- The code works on many specific correlations that work under certain ranges, so it is important to define the ranges for each input the code does not break down:
  - HL pressure input: ±5% from the baseline
  - HL temperature input: 0.2% below or 1% above the baseline
  - HL MFR input: 2% below or 5% above the baseline
  - CL pressure input: ±1% from the baseline
  - CL temperature input: 5% below or 1% above the baseline
  - CL MFR input: 3% below or 2% above baseline.
- Baseline inputs for parametric study (values removed as they are proprietary information).

Baseline Inputs	Parameters
Primary side	Pressure (MPa), inlet temperature (K), and MFR (kg/s)
Secondary side	

One-at-a-Time (OAT) Process

- **Input parameters:** HL/CL inlet: (a) pressure, (b) temperature, and (c) MFR.
- **Output parameters:** (a) tube/riser HTC, (b) primary side pressure and temperature profile (riser and tube), and (c) secondary side pressure and temperature profile.
- Baseline: Original 2 MW (scaled facility to prototype of 1:2) data.
- Range: All six inputs are increased from the baseline by 0.1% until 0.5%.
- The code is run five times, each time incrementing the input by 0.1%.
- The output parameter values are saved for each run to be graphed and analyzed later.

Results

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Influence of Input Changes on the HTC

This data shows that when all parameters are increased, the HTC begins to fluctuate at different locations along the SG, as indicated in Figure 4.

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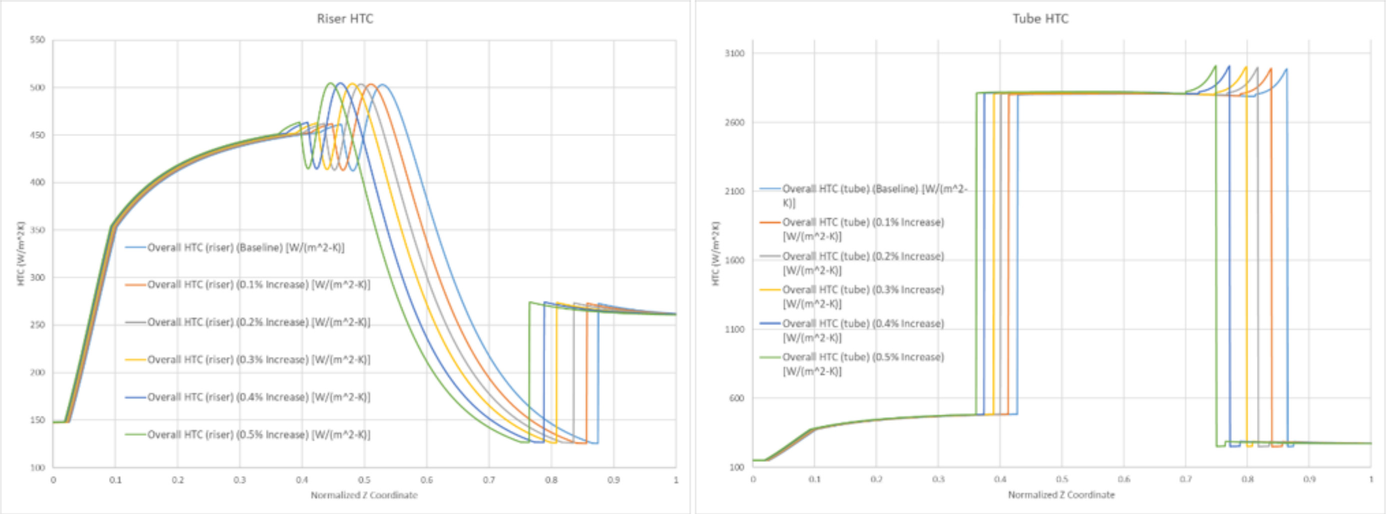


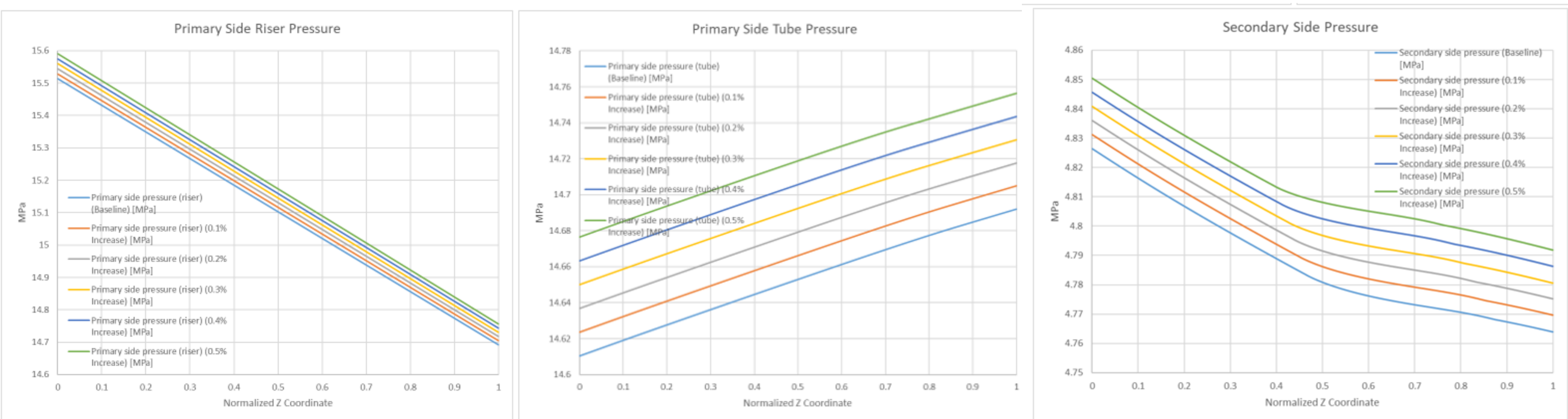
(a) (b)

Figure 4: SG HTC under varied inputs.

Results (cont'd)

Influence of Input Changes on the SG Pressure Profile

The primary- and secondary-side pressures are also significantly affected by changes to the inputs, as observed in Figure 5.



(a) (b) (c)

Figure 5: SG pressure profile under various inputs.

Sensitivity Study

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- Sensitivity analyses differ from parametric analyses in that they focus on how one specific input parameter affects the output as a whole, and each input is not varied a certain amount for each run. This analysis is conducted in two ways:
  - First, by manually varying the input parameters to obtain the sensitivity data with each input being assigned two different values within the given range to obtain the effect on the resulting output.
  - Second, by using RAVEN and its built-in techniques—paired with the Python code—AI-generated sensitivity data based on additional input perturbations are obtained, thus making the data more reliable.

The sensitivity coefficient can be calculated mathematically via many methods but the simplest is to divide the change in output by the change in input, as given in Equation (1):

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To find the sensitivity coefficient of the given inputs:

To find the sensitivity of the SG HTC to the HL temperature:

Results

- Manual perturbation of HL and CL inputs are performed independently to observe:
  - The **axial distribution of HTC** in the primary-side tube and secondary-side shell regions.
  - Both the HL and CL input perturbations, which considered changes on pressure, temperature, and MFR input.
  - The results of the HTC based on the HL inputs (i.e., pressure, temperature, and MFR) and the changes/perturbations, which have a similar trend as Figure 5 for the varied SG HTC inputs.
- **The preliminary sensitivity results (e.g., Figure 6, Figure 7) were used to identify:**
  - The exhibited entrance/exit effects on the riser top plenum region.
- An **independent boundary case used for the top plenum region is needed:**
  - **To improve the SG design sensitivity and parametric studies**
  - **Keep consistency in the sensitivity results without any sudden spikes.**

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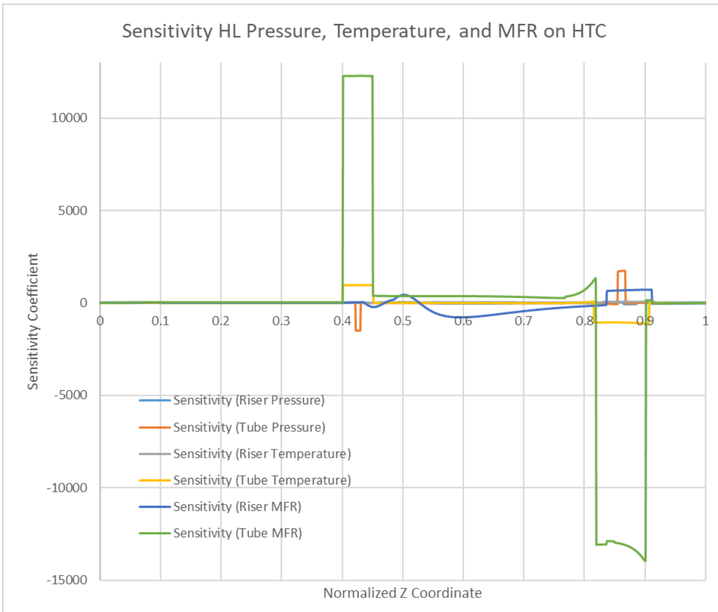
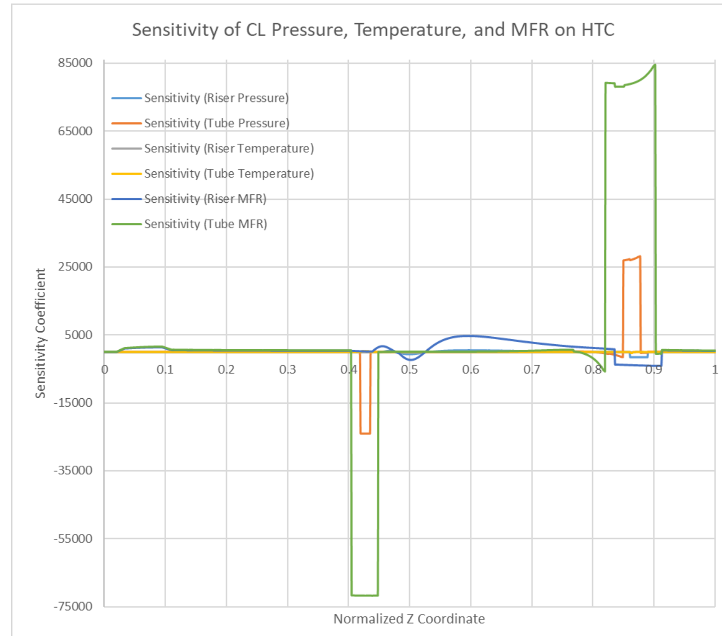
Results (cont'd)



(a)



(b)

Figure 6: Preliminary sensitivity results on HTC along the SG length for the: (a) HL input changes, and (b) CL input changes. (Note: Here, x-axis is the normalized z coordinate).

Results (cont'd)

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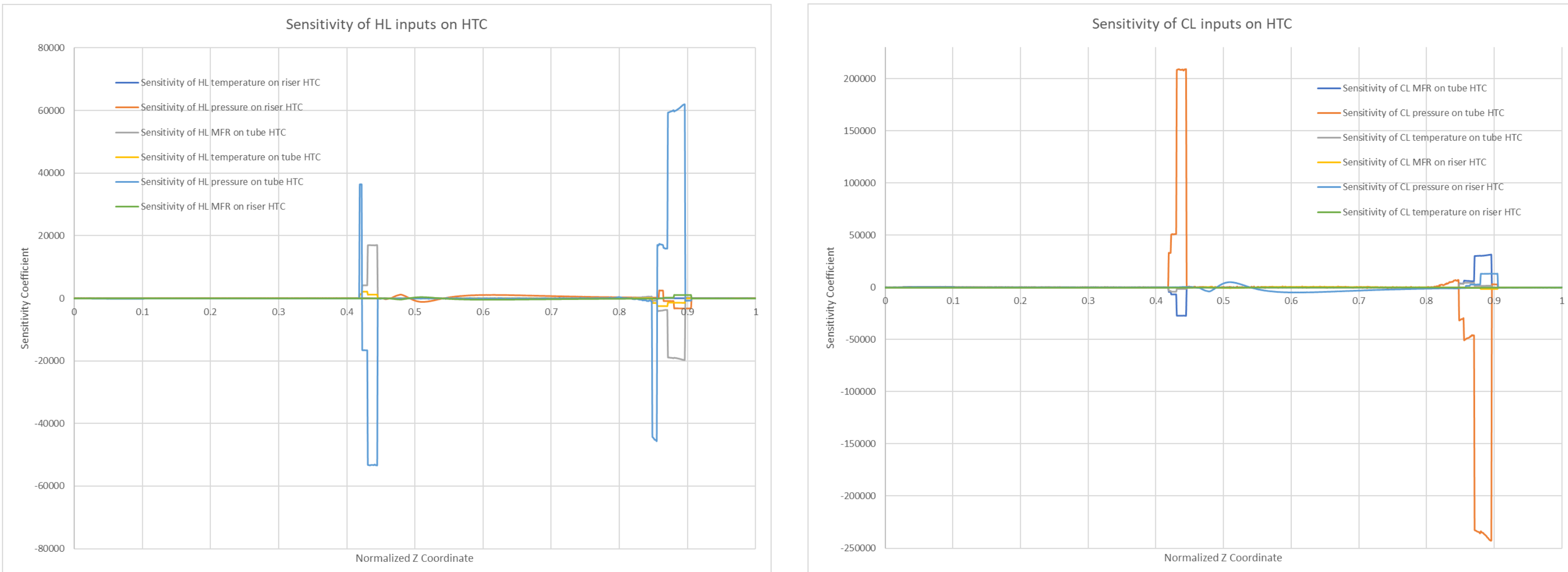

(a) (b)

Figure 7: Preliminary RAVEN-based sensitivity results on HTC along the SG length for the: (a) HL input changes, and (b) CL input changes. (Note: Here, x-axis is the normalized z coordinate).

Results (cont'd)

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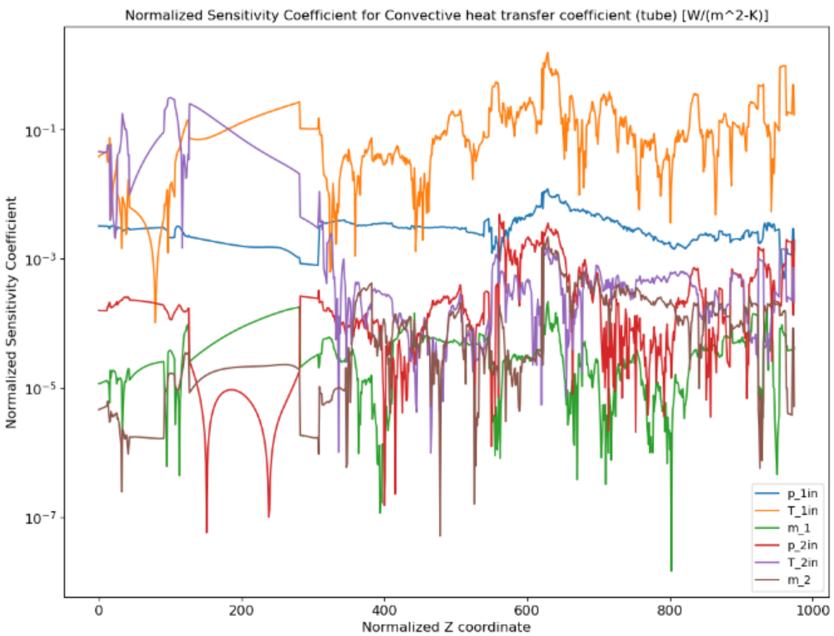
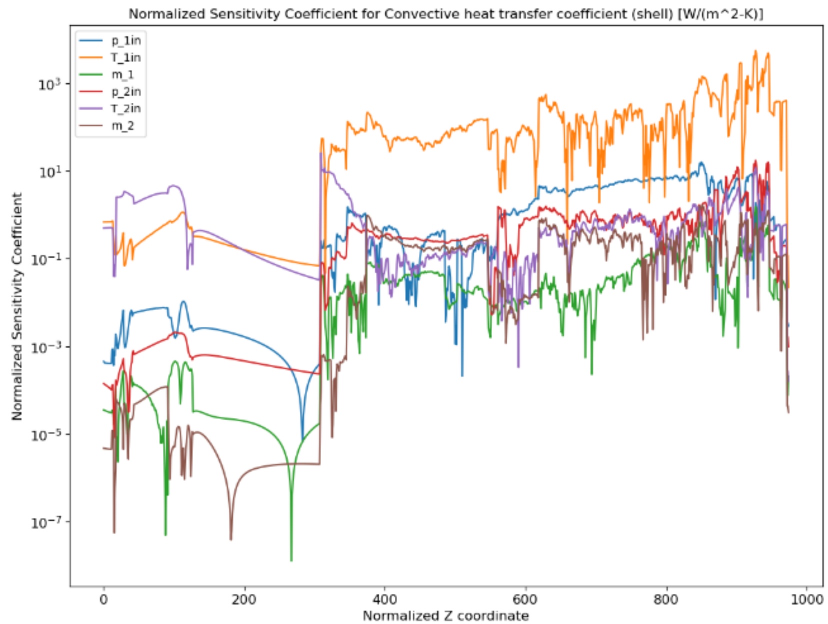
- **The preliminary sensitivity results (e.g., Figure 6, Figure 7) exhibited:**
  - Inconsistency on the riser top plenum region due to the entrance/exit effects, as indicated by the pulse (sudden spike) in the sensitivity results.
- An **independent boundary case used for the top plenum region is needed to improve the SG design sensitivity and parametric studies:**
  - **Riser section outlet (to planum) boundary conditions: temperature, pressure and mass flux is set as the tube inlet (from planum) boundary conditions.**
- The revised sensitivity study (with modified plenum region boundary conditions) results for 600 random samples:
  - **Using the Monte Carlo sampling method with RAVEN tools.**
  - **Sensitivity results exhibited no inconsistencies (or sudden spike)** as presented in Figure 8.
- The samples are generated using uniform distributions (±1% relative changes) for the following input parameters:
  - HL pressure input, HL temperature input, HL MFR input, CL pressure input, CL temperature input, and CL MFR input.

Note: HL for hot leg, CL for cold leg, MFR for mass flow rate.

Results (cont'd)



(a)



(b)

Figure 8: RAVEN-based sensitivity results for the: (a) tube side and (b) shell side. (Note: Here, x-axis is the index for the normalized z coordinate).

Summary findings and conclusion

- Successful nuclear reactor system design and analysis requires:
  - Various levels of qualifications for each system, structure, and component, and interaction among them, for obtaining regulatory approvals.
  - SG design parametric and sensitivity study is pivotal as the SG in a PWR-type SMR interfaces between the primary and secondary coolant loops.
- Therefore, the key findings, observations, and recommendations are as follows:
  - HL and CL temperature, pressure, and MFR have varied effects on the SG HTC:
    - The impact of the MFR on the HTC is greatest, followed by temperature and pressure.
    - However, the RAVEN-based results show that pressure and temperature also have a significant impact on the HTC—even more than the MFR.
  - The preliminary parametric and sensitivity study exhibited the entrance and exit effect in the top plenum of the riser section required modification:
    - Independent boundary cases were considered for the riser top plenum region, which provided improved design data.
  - The preliminary sensitivity study shows the maximum sensitivity for all parameters falls within the 0.4–0.9 normalized z-coordinate bounds, with certain parameters (e.g., CL temperature, MFR) having a more global impact on the HTC than others.
  - The revised SG model shows the sensitivity ranges between 10-7 and 5×10-1 for the HTC, which provides greatly improved data than the preliminary design case.

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Thank you for your attention!

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