FY22 Progress on Computational Modeling of the Water-Based NSTF

Nuclear Science and Engineering Division
About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory’s main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov

DOCUMENT AVAILABILITY

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandra, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: orders@ntis.gov

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@osti.gov

Disclaimer
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.
FY22 Progress on Computational Modeling of the Water-Based NSTF

prepared by
Zhiee Jhia Ooi, Qiuping Lv, Rui Hu, Matthew Jasica, Darius Lisowski
Nuclear Science and Engineering Division, Argonne National Laboratory

September 2022
ABSTRACT

This report summarizes the system-level modeling effort by Argonne National Laboratory (Argonne) of the Natural convection Shutdown heat removal Test Facility (NSTF) in FY22. As an extension of the effort from FY21, this year’s work focuses primarily on the two-phase modeling of the NSTF using RELAP5-3D, particularly with the inclusion of the cavity model.

The results from simulations were used to compare against experimental data for benchmarking purposes of the RELAP5 deck. Additionally, RELAP5 was used as a predictive tool to guide planned test operations and identify expected system behaviors. In the first part of this report, details are provided of the cavity omitted model where heat flux is applied directly as a boundary condition to the risers. The general trend predicted by the RELAP5 model matches that from the experimental data when a single-phase natural circulation flow is first established, followed by an oscillatory two-phase period and finally a stable two-phase flow. However, the onset of oscillations is predicted early by the model due to the smaller thermal mixing region in the tank. However, by expanding the simulated thermal mixing region in the tank, the onset of oscillations predicted by the model is able to match that from the experiment. These oscillations were studied in depth and are deduced to be flashing-induced instability.

The model was then modified to simulate an accident scenario case where a representative heat load based on the full-scale Framatome’s 625 MW_t SC-HTGR was applied directly to the riser channels. The simulated initial and boundary conditions were identical to those performed experimentally, facilitating direct comparisons between the predicted and experimental results. It was determined that the results showed some discrepancies remain, likely due to the overprediction of vapor generation rate by the computer model.

In the second part of this report, the cavity model is re-introduced where it is observed that the RELAP5 prediction is now able to capture the major trends of the observed flow commonly observed during two-phase conditions. However, the onset of oscillations is once again predicted early by the model, possibly caused by the underprediction of heat loss from the heater and cavity. This is likely due to the omission of support structures in the cavity that can act as additional pathways for heat to escape to the environment. To overcome the underprediction of heat loss, part of the insulation surrounding the cavity side panels and the back of the heaters are removed to allow heat to escape directly to the environment, which then improves the RELAP5 prediction.

Parametric studies are also performed to investigate the effects of heater power, tank inventory
level, and tank gas space pressure on flow behaviors, also in direct comparison to conditions tested experimentally. User option-61 in the RELAP5-3D input deck, which changes the heat transfer coefficient correlations used for calculating the vapor generation, is also investigated where it is found that by enabling the option, the overall duration of oscillations is increased and matches that from the experiment better. The RELAP5 model is further benchmarked with a header inlet-throttling case where it is observed that the prediction from the model fails to capture some major features observed in the experiment. By using a modified loss coefficient curve for the valve, the accuracy of the prediction is improved where most of the major features observed in the experiment are predicted by the model. Lastly, the model is benchmarked with an inventory depletion scenario where it is observed that despite the modeling limitation of RELAP5, the prediction shows good agreement with the experimental data where major trends and features are captured by the model.

Future work will see continued development of the current RELAP5-3D input deck of the NSTF to both improve the accuracy of the model’s predictive capability and continuing serving the experimental program. The mutually beneficial relationship between analysis and experimental efforts has become integral to the parent NSTF program, and the greater objective to fully understand and accurately predict the heat removal performance of a full scale RCCS concept.
Contents

ABSTRACT ii

Contents v

List of Figures viii

List of Tables viii

1 Introduction 1

2 Experiment Approach 2

3 Modeling Approach 3

3.1 Primary Loop Model ........................................ 3

3.2 Cavity Model .................................................. 4

4 Results and Discussions 7

4.1 Simulation results without cavity model ......................... 7

4.1.1 Base model .................................................. 7

4.1.2 Modified tank model ...................................... 9

4.1.3 Effects of vapor generation rate ............................. 12

4.1.4 Boiling boundary ............................................ 13

4.1.5 Phase portraits of pressure drop in the chimney .......... 15

4.1.6 Framatome Accident Scenario .............................. 16

4.2 Simulation results with cavity model .......................... 22

4.2.1 Base model .................................................. 22

4.3 Parametric study ............................................... 28

4.3.1 Heater power ............................................... 28

4.3.2 Initial inventory level ...................................... 30

4.3.3 Tank gas space pressure ................................... 32

4.4 User-option study ............................................. 36

4.5 Heat loss modeling .............................................. 39

4.5.1 Exposed-cavity model ..................................... 40
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5.2</td>
<td>Exposed-heater model</td>
<td>42</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Combined exposed heater and cavity model</td>
<td>43</td>
</tr>
<tr>
<td>4.6</td>
<td>Throttling of riser inlet</td>
<td>45</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Default loss-coefficient curve</td>
<td>45</td>
</tr>
<tr>
<td>4.6.2</td>
<td>Modified loss-coefficient curve</td>
<td>49</td>
</tr>
<tr>
<td>4.7</td>
<td>Depleted inventory scenario</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>Conclusions</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>60</td>
</tr>
</tbody>
</table>
List of Figures

2.1 The schematics of (a) the water-based NSTF and the (b) riser coolant panel. 3
3.1 Nodalization diagram of the RELAP5 model for the water-based NSTF. 5
3.2 The (a) top view of the cavity and the (b) natural convection flow path in the cavity. 6
3.3 Side view of the NSTF cavity and the layout of the heater panel. 7
4.1 Heat input from the test Run057 applied directly to the wall of the riser tubes in the RELAP5 model. 8
4.2 Comparison of the system mass flow rate from Run057 and RELAP5-3D simulation. 10
4.3 Schematics of the (a) original and (b) modified tank model. 10
4.4 Comparison of the system mass flow rate from Run057 and RELAP5-3D simulation with the modified water tank model. 11
4.5 Comparison of the water temperature in the tank between the original and modified tank models. 11
4.6 Comparison of the system mass flow rate at different levels of heat flux in the two-phase region. 12
4.7 The expansion of the boiling boundary in the chimney section. 14
4.8 The partitioning of flow oscillations. 16
4.9 Comparison of the pressure drop with respect to the system mass flow rate from (a) volume-1 to 20, (b) volume-17 to 20, and (c) volume-19 to 20 in the chimney. 16
4.10 Comparison of the oscillation patterns of pressure drop and system mass flow rate from (a) volume-1 to 20, (b) volume-17 to 20, and (c) volume-19 to 20 in the chimney. 17
4.11 Heat load curve applied to the riser tubes in the accident scenario simulation. 18
4.12 Comparison of the experimental (Run074) and predicted mass flow rates for the accident scenario case. 18
4.13 Predicted void fraction of various volumes of the tank. 20
4.14 Predicted void fraction at the chimney inlet. 21
4.15 Comparison of the predicted bulk and saturation temperatures at the chimney midpoint. 21
4.16 Comparison of the experimental (Run074) and predicted void fractions at the chimney outlet. 22
4.17 Comparison of the mass flow rate between the experimental data and the RELAP5 simulation for Run057. 24
4.18 Comparison of the inlet and outlet temperatures of the riser between the experimental data and the RELAP5 simulation for Run057. 25
4.19 Comparison of the inlet and outlet temperatures of the chimney between the experimental data and the RELAP5 simulation for Run057. 25
4.20 Comparison of the chimney outlet void fraction between the experimental data and the RELAP5 simulation for Run057. 26
4.21 Comparison of the tank gas space pressure between the experimental data and the RELAP5 simulation for Run057. 27
4.22 System inventory level in the RELAP5 simulation. 28
4.23 Comparison of the system mass flow rates at different heater power levels with respect to the experimental data from Run057. 29
4.24 Comparison of the void fractions at the chimney outlet at different heater power levels with respect to the experimental data from Run057. 29
4.25 Comparison of the tank gas space pressures at different heater power levels with respect to the experimental data from Run057. 30
4.26 Comparison of the system mass flow rates for different initial tank levels with respect to the experimental data from Run057. .......................................................... 31
4.27 Comparison of the chimney outlet pressure for different initial tank levels. ........ 31
4.28 Comparison of the chimney outlet vapor generation rate for different initial tank levels. 32
4.29 Comparison of the chimney outlet void fraction for different initial tank levels with respect to the experimental data from Run057. ................................. 32
4.30 Comparison of system inventories for different initial tank levels. .................. 33
4.31 Comparison of tank gas space pressures at different tank discharge line loss coefficients with respect to the experimental data from Run057. ......................... 34
4.32 Comparison of the steam discharge rate at different tank discharge line loss coefficients. 34
4.33 Comparison of the system mass flow rates at different tank discharge line loss coefficients with respect to the experimental data from Run057. ......................... 35
4.34 Comparison of chimney outlet vapor generation rate at different tank discharge line loss coefficients. .......................................................... 35
4.35 Comparison of chimney outlet void fraction at different tank discharge line loss coefficients with respect to the experimental data from Run057. ......................... 36
4.36 Comparison of the system mass flow rates predicted by the model with the default option and Option-61 with respect to the experimental data from Run057. .... 37
4.37 Comparison of the chimney outlet vapor generation rates predicted by the model with the default option and Option-61. .......................................................... 38
4.38 Comparison of the chimney outlet void fractions predicted by the model with the default option and Option-61. .......................................................... 38
4.39 Breakdown of heat leaving the heater. ....................................................... 40
4.40 Breakdown of heat transfer from the heater to the cavity. ......................... 40
4.41 Breakdown of heat leaving the cavity predicted by the model in comparison with the heat entering the risers in Run057. .......................................................... 41
4.42 Comparison of the system mass flow rates predicted by the default model and the exposed-cavity model with respect to the experimental data from Run057. .... 42
4.43 Breakdown of heat leaving the cavity predicted by the exposed-cavity model in comparison with the heat entering the risers in Run057. ......................... 42
4.44 Mean heat transfer coefficients. .............................................................. 43
4.45 Comparison of the system mass flow rates predicted by the default model and the exposed-heater model with respect to the experimental data from Run057. .... 44
4.46 Breakdown of heat transfer from the heater predicted by the exposed-heater model. 44
4.47 Comparison of the system mass flow rates predicted by the combined exposed-heater-cavity model with respect to the experimental data from Run057. .......... 45
4.48 Breakdown of heat transfer from the cavity predicted by the combined exposed-heater-cavity model in comparison with the heat entering the risers in Run057. . 46
4.49 $C_v$ of ball valve with respect to the valve position and area (Lv et al. (2021a)). ... 47
4.50 Mass flow rate predicted by the RELAP5 model with a refilling system to maintain the inventory level in the tank. .......................................................... 48
4.51 The effects of riser inlet throttling on system mass flow rate and comparison with the experimental data from Run071. .......................................................... 49
4.52 The effects of riser inlet throttling on chimney outlet void fraction and comparison with the experimental data from Run071. .......................................................... 50
4.53 Comparison of the experimental $C_v$ curve and the reference $C_v$ curve by VAL-MATIC. 51
4.54 Comparison of system mass flow rates between the experiment (Run071) and the RELAP5 simulation with the reference $C_v$ curve in (a) full view and (b) enlarged view. 52
4.55 Riser outlet void fraction predicted by the RELAP5 model with the reference $C_v$ curve. .................................................... 53
4.56 Comparison of the predicted individual riser flow rates (enlarged). .................. 53
4.57 Comparison of chimney outlet void fraction between the experiment (Run071) and the RELAP5 simulation with the reference $C_v$ curve. .................................................... 54
4.58 Comparison of the experimental and predicted system mass flow rates for the depleted inventory scenario of Run069. ................................................. 55
4.59 Void fraction of different tank components predicted by RELAP5 for the depleted inventory scenario. ................................................................. 57
4.60 Total system inventory level predicted by RELAP5 for the depleted inventory scenario. 57

List of Tables

4.1 Summary of stages for restricted inlet throttle (Lv et al. (2021a)). ................. 47
1 Introduction

The high-temperature gas-cooled reactor (HTGR) is one of the candidates for the Gen-IV reactor designs that are currently under development. The HTGRs appeal to the nuclear industry due to their inherent safety features, high thermal-to-electric conversion efficiency, and the ability to provide high-temperature process heat (Wang et al. (2021)). Many HTGR designs rely on the Reactor Cavity Cooling System (RCCS) for passive decay heat removal and safe reactor shutdown during accident scenarios due to its relatively simple design, the reliance on natural forces, and the potential for high levels of performance (Lisowski et al. (2016)). The RCCS is designed to ensure that the vessel wall and the fuel peak temperature are maintained at safe limits during normal operation and accident scenarios, to maintain the reactor cavity concrete and support structures at safe limits, to sustain the intended function and performance across the 40-year life span of a reactor installation, and to accomplish the above functions without human intervention or active systems (Lisowski et al. (2016)).

In the effort to assist the design and development of the RCCS, the Natural Convection Shutdown Heat Removal Test Facility (NSTF) is constructed at Argonne National Laboratory (Argonne) under the support of the Department of Energy (DOE) Office of Advanced Reactor Technologies (ART) (Lisowski et al. (2016)). The NSTF is a test facility built specifically to study the performance of passive systems for advanced nuclear reactors. It is a large-scale thermal hydraulics test facility designed to perform highly instrumented experiments of RCCS concepts for reactor decay heat removal that rely on natural convection cooling with either air or water-based systems.

Along with the experimental effort, computational modeling effort is also carried out simultaneously to benchmark the NSTF tests, and it has been demonstrated to significantly strengthen the experimental program. The NSTF analyses are important because they can evaluate the limitations in typical approaches for modeling natural circulation RCCS concepts. Furthermore, these analyses also help to validate and benchmark analysis methods as well as computer codes that may be used for licensing. On the other hand, the NSTF analyses are beneficial to the experiment campaign by aiding in the design optimization of the RCCS and supporting experiment activities that include helping assure that the experimental procedures, setup, and measurements follow best practices to produce high-quality and traceable data. This mutually beneficial relationship between the analysis and experimental efforts has become integral to the overall program objective of examining the heat removal performance of the RCCS concept.
In FY21, the system-level modeling effort focuses primarily on single-phase natural circulation in the NSTF with some preliminary work on two-phase natural circulation. As a continuation of that effort, the focus in FY22 is on the in-depth analyses of two-phase natural circulation, as well as on the refinement of the existing model to improve its prediction under two-phase conditions.

This report documents the recent progress and achievements made in the computational analyses of the water-based NSTF, focusing on the fundamental understanding of the system-level modeling of the facility under two-phase oscillatory conditions. For the remainder of this report, the experimental and the system-level modeling approaches are first discussed, followed by the discussions on the simulation results, and finally the conclusions to summarize the progress of the work.

2 Experiment Approach

The design of the test facility is briefly discussed here. A schematic of the water-based NSTF is shown in Figure 2.1(a). In its current configuration, the water-based NSTF has a total height of 18.1 m with an eight-riser coolant panel test section extending 9.2 m in total length. The riser tubes are made of 1.5” Schedule-160 316L stainless-steel pipe where they are spaced apart from each other by a pitch-distance of 0.15 m and are welded together by a 5/16” thick 1018 carbon steel fins at the tube centerline, as shown in Figure 2.1(b). The primary loop of the facility is a single path network that joins the heat source and heat sink of the test facility, thus creating a closed loop for natural circulation. Downstream of the test section is the chimney made of 4.0” Schedule-40 316L stainless steel pipe, after which is the water storage tank with a 1,000-gallon capacity and a height-to-diameter ratio of two. The outlet of the tank is connected to the downcomer section made of the same pipes as the chimney, and the other end is connected to the inlet of the test section. The secondary loop consists primarily of the heat removal network that maintains a constant temperature of system inventory during single-phase steady-state tests and serves as the heat sink for steam condensation during two-phase operations. The heat removal network includes components such as a chiller, plate type heat exchanger, multiple water pumps, shut-off and diverter valves. In single-phase mode, cold water is returned to the water tank through a sparger, whereas in two-phase mode, condensate liquid is removed and stored within a condensation reservoir. Lastly, the facility is equipped with a wide variety of instrumentation including thermocouples for temperature measurement, pressure transmitters for absolute and pressure-drop measurements, magnetic flow
meters for flow rate measurements, as well as optical probes and Gamma-ray densometer for void fraction measurements. Details of the facility and instrumentation can be found in the work by Lisowski et al. (2020).

![Image of the water-based NSTF and the riser coolant panel.](image)

Figure 2.1: The schematics of (a) the water-based NSTF and the (b) riser coolant panel.

### 3 Modeling Approach

#### 3.1 Primary Loop Model

The system-level modeling of the NSTF is performed with RELAP5-3D version 4.3.4 (RELAP5 (2015)). In this work, the model of the NSTF can be broken down into the primary loop and the cavity. The primary loop consists of the riser channels, water tank, and the piping network while the cavity is defined as the enclosure surrounded by the heater panel, the riser panel, and the unheated panels. A reference RELAP5 model for the primary loop NSTF has previously been developed by Lv et al. (2017). The nodalization diagram of the model for the primary loop of
the facility is shown in Figure 3.1. The inlet and outlet headers of the riser tube assembly in the water-based NSTF are fabricated from a set of tees, which are modeled as branches in the present model, namely, B790 - B720 and B590 - B520. A total of eight risers are modeled, each consisting of an upstream non-heated region (P691 - P698), a heated region (P671 - P678), and a downstream non-heated region (P651 - P658). The riser tube assembly is connected back to the water tank through pipes of P450 - P490 while the outlet of the tank is connected to the inlet of the riser assembly via the downcomer modeled as P840 - P890. All the piping is made of 4.0” Schedule 40 pipes, with an ID of 4.067”.

The water tank is modeled as four different volumes, namely a branch (B969) and three pipes (P950, P971, P980). The branch-component represents the thermal-mixing water region, while the pipes represent the bottom half of the tank, the non-thermal-mixing water region, and the air/stream region, respectively. All the piping/tank walls are modeled as heat structures, with convective boundary condition for the inner surface. To model the heat loss, 2-inch-thick K-FLEX thermal insulation is modeled as part of the heat structures, and a natural convective heat loss boundary condition is applied to the outer surface. In the current work, the details of the heat removal network are not modeled. Instead, two time-dependent junctions (TDJ429, TDJ439) and two time-dependent volumes (TD997, TD998) are utilized to simulate hot water being drawn from the tank and cold water returning to the tank, as shown in insert of Figure 3.1. Note that the active-cooling component is only included for the single-phase model to keep the riser header inlet temperature at approximately 30°C throughout the simulation. For two-phase analysis, the active-cooling component is removed where water is allowed to boil off and steam is discharged from the system to the environment.

3.2 Cavity Model

The cavity of the NSTF consists of the eight riser tubes with the fins, the two side walls, the heated plate, the top and bottom walls, and the insulation plates sealing the edges of the riser tube assembly. The model of the cavity has previously been developed in the work Lv et al. (2021c) and is adopted in this work. The two main heat transfer mechanisms in the cavity are natural convection and radiative heat transfer. Hence, it is important to ensure that the modeling of both components are performed accurately. For radiation heat transfer, the riser assembly, heated plate, and the side walls are each axially divided into eight vertical layers, resulting in a total of 98 surfaces that are modeled within one radiation enclosure. The required inputs of view factors are calculated from
Figure 3.1: Nodalization diagram of the RELAP5 model for the water-based NSTF.

the CFD simulations. On the other hand, for the internal natural convection, results from CFD analysis shows that the flow is predominantly confined to regions next to the panels. Hence, the flow of natural convection in the cavity is modeled with flow channels with the flow area determined by the CFD analysis, as shown in Figure 3.2(a). Note that in Figure 3.2(b), the flow path of natural convection in the cavity is modeled with components 100 to 105. Components 103 and 104 represent the flows at the top and bottom panels of the cavity, components 101 and 102 represent the flows at the side panels, component 100 represents the flow at the heated panel, and component 105 represents the flow at the riser panels.
Figure 3.2: The (a) top view of the cavity and the (b) natural convection flow path in the cavity.

As shown in Figure 3.3, the heater panel consists of a stainless-steel plate, ceramic heaters, multiple layers of insulation, and an air gap between the heated plate and the heaters. To maintain the accuracy of the model, all of these components are included. Additionally, heat losses due to air flow in the gap between the heated plate and the ceramic heaters as well as the radiative heat transfer between these two surfaces are also modeled, represented by component 106 in Figure 3.2(b). Lastly, the heat loss due to natural convection on the outer surface of the cavity walls is also considered in the model by specifying the heat sink temperature and temperature-dependent
heat transfer coefficients.

Figure 3.3: Side view of the NSTF cavity and the layout of the heater panel.

4 Results and Discussions

4.1 Simulation results without cavity model

4.1.1 Base model

System-level analysis is performed with RELAP5-3D to model a transient two-phase condition in the NSTF. Note that the primary objective of this work is to investigate the accuracy of RELAP5 model in simulating a two-phase condition with flow oscillations. Thus, one of the two-phase test cases performed by Lisowski et al. (2020), Run057, is used to benchmark the RELAP5 model. In order to reduce the uncertainties of the model, the cavity is not included in this analysis. Instead, heat flux obtained from Run057 is applied directly to the surface of the riser tubes to heat up the liquid. For the single-phase region, the experimental heat input can be applied directly to the riser tube wall. On the other hand, in the two-phase region, the mean values of the heat input over a small time window are obtained and applied to the riser tube wall to capture the effects of oscillations, as shown in Figure 4.1.

The system mass flow rates from Run057 and the RELAP5 simulation are compared in Figure 4.2 where the black line represents the experiment value and the red line represents the simulated result. The experiment is conducted for only about 20 hours while the simulation is performed
for about 28 hours. In the first 1.5 hours, the system mass flow rate is at zero as the heaters are not turned on. Once the heaters are turned on, the density difference of the water creates a thermal head that drives the flow of water in the facility. As the power increases, the mass flow rate increases accordingly due to stronger thermal driving head. It is observed that the experimental and simulated mass flow rates have an excellent agreement with each other in the single-phase region.

As the water temperature continues to rise and continues to flow upward in the chimney, the water temperature eventually becomes greater than the local saturation temperature, at which point flashing occurs and vapor is generated. In both the experiment and the simulation, the inception of flashing is followed closely by severe flow oscillations where the mass flow rate is observed to fluctuate by a magnitude of up to roughly 4 kg/s in the experiment and the simulation. Flow oscillations are widely observed at flashing inception and are caused by a sequence of events. When flashing occurs, the generation of vapor causes the hydrostatic pressure in the chimney to decrease, which in turn increases the flow rate and pushes subcooled liquid into the chimney, drives the vapor out, and returns the flow to single phase. The hydrostatic pressure then increases to the pre-flashing level which causes the saturation temperature to rise above the local fluid temperature and causes flashing to stop. The process is repeated until the liquid temperature is high enough for the
two-phase region to grow sufficiently in the chimney to sustain flashing, after which the oscillations diminish and the system mass flow rate remains relatively constant. Additionally, the decrease of inventory level further reduces the local pressure and saturation temperature, and enhances flashing in the upper chimney. The simulated flow rate remains at roughly 5 kg/s from roughly hour-18 onward. Unlike in the experiment where the flow rate decreases sharply at around hour-20, the simulated flow rate remains relatively constant for the remainder of the simulation as the ramping down of heater power is not included in the RELAP5 model. Additionally, at this time of the experiment, steam by-pass to the environment is opened, which causes a drop of the tank pressure and flow rate.

Figure 4.2 shows that the RELAP5 model predicts an earlier inception of flashing than the experiment, at roughly hour-11 and hour-14, respectively. Given that flashing is dictated primarily by the local saturation temperature, the earlier prediction of flashing inception by RELAP5 is possibly due to the inaccuracy of the components in the chimney and water tank. As discussed in the previous section, the water tank is modeled with four volumes in the RELAP5 model where thermal mixing is confined to only one volume. It is likely that the volume of the thermal mixing region is not modeled accurately where the thermal mixing region of the tank in the model is smaller than that in the experiment, thus the total amount of inventory that needs to be heated to roughly saturation is smaller, which then leads to an earlier flashing incipience. In the next section, the model of the water tank is modified to investigate its impact on the RELAP5 prediction.

4.1.2 Modified tank model

The tank in the RELAP5 model is modified to study its impact on the prediction. As discussed in the previous section, the early prediction of the onset of flashing is likely due to the inaccuracy in the modeling of the thermal mixing region in the tank. In the modified model, the thermal mixing region in the tank is expanded by removing volume P971 and expanding volume B969. This allows the water exiting the chimney to mix with a larger volume of water in the tank, which causes the bulk temperature in the tank to rise at a slower rate and delays the onset of flashing. Note that the new volume of component B969 in the modified model is equal to the combined volume of components B969 and P971 in the original model. The schematics of the original and the modified tank models are shown in Figure 4.3.

The comparison of the experimental system mass flow rate and the prediction with the modified tank model is shown in Figure 4.4. It is observed that by expanding the thermal mixing region in
Figure 4.2: Comparison of the system mass flow rate from Run057 and RELAP5-3D simulation.

![Graph showing comparison of mass flow rate](image)

Figure 4.3: Schematics of the (a) original and (b) modified tank model.

![Schematics of tank models](image)

the tank, the RELAP5 model is able to predict the onset of flashing closer to the experiment. This indicates that the expansion of the thermal mixing region in the tank allows the water temperature in the tank to rise at a slower rate to the saturation temperature, as shown in Figure 4.5, which
delays the onset of flashing. Given that the onset of flashing is predicted more accurately with the modified tank model, it is adopted for the analyses presented in remainder of this report.

![Figure 4.4: Comparison of the system mass flow rate from Run057 and RELAP5-3D simulation with the modified water tank model.](image)

![Figure 4.5: Comparison of the water temperature in the tank between the original and modified tank models.](image)
4.1.3 Effects of vapor generation rate

Using the model with the modified tank, the effects of vapor generation rate are investigated. This is accomplished by varying the heat flux applied to the wall of the riser tubes in the two-phase region. Note that the heat flux in the single-phase region is not modified to ensure that the onset of oscillations is roughly the same.

By varying the heat input to the system, the temperature of the water entering the chimney can be changed, which then changes the vapor generation rate predicted by RELAP5. For this study, the heat flux is lowered to 60% and 80% of the nominal heat flux value. The predicted mass flow rates at different heat fluxes are shown in Figure 4.6. It is observed that by decreasing the heat flux in the two-phase region, the onset of oscillations is delayed. The mass flow rate also decreases due to lower thermal head to drive the flow in the system. Furthermore, the overall length of oscillations increases as heat flux decreases, as shown by the 60% case, where the oscillations last for almost 10 hours compared to the roughly five hours exhibited by the cases with the nominal and 80% heat flux cases.

Figure 4.6: Comparison of the system mass flow rate at different levels of heat flux in the two-phase region.

Similar oscillations have been observed by Lisowski et al. (2014) with a facility similar to the NSTF. Lisowski et al. (2014) suggest that the instability could be Natural Circulation Oscillation (NCO) induced by Hydrostatic Head Fluctuations (HHF). NCO occurs due to fluctuations in the
hydrostatic head in the chimney caused by the insufficient flow momentum to fully flush vapor from a chimney network with horizontal portions, which allows vapor to accumulate in the chimney network. However, the lack of bends and long horizontal sections in the chimney of the NSTF suggests otherwise. Thus, it is likely that the oscillations predicted by the model are due to flashing-induced instability. At some point in the flow, the bulk temperature at the upper section of the chimney becomes higher than the local saturation temperature in the same region. This leads to flashing in the upper chimney where the vaporization of bulk fluid induces a drop in hydrostatic pressure. The decrease in hydrostatic pressure causes the natural circulation flow rate to increase and drives the void out of the chimney. Furthermore, the increased flow rate reduces the residence time of fluid in the riser channels, thus reducing the amount of heat entering the fluid. As a consequence, the bulk fluid temperature exiting the risers is lower and the fluid remains subcooled in the upper section of the chimney. This in turn causes flashing to stop and returns the hydrostatic pressure to the higher initial level. As the hydrostatic pressure increases, the natural circulation flow rate subsequently decreases and once again increases the residence time of fluid in the risers. This allows more heat to be transferred to the fluid. The bulk temperature of fluid exiting the risers increases once more and leads to flashing in the upper section as the local saturation drops below the bulk fluid temperature. The cycles is repeated until the boiling boundary in the chimney has grown sufficiently large to sustain stable flashing.

At low heat flux, the boiling boundary in the chimney takes longer to develop, which means that stable flashing cannot be sustained to stop the oscillations. Moreover, the result suggests that the vapor generation rate in flashing flow might not be predicted accurately by RELAP5 as the duration of oscillations is observed to increase with decreasing heat flux. In RELAP5, the vapor generation rate is defined as a function of the superheat, $\Delta T$ and the interfacial heat transfer coefficient, $h$. It is possible that the interfacial heat transfer coefficient in flashing flows is overpredicted by RELAP5, which in turn overpredicts the overall vapor generation rate, thus leading to a faster development of the boiling boundary in the chimney compared to the experiment. Similar inaccuracies in the prediction of vapor generation rate by RELAP5 have also been reported in the literature (Fullmer et al. (2016); Ooi et al. (2020)).

### 4.1.4 Boiling boundary

The oscillation of the two-phase region is investigated in this section. As highlighted previously, the oscillations are observed to stop once the two-phase region in the chimney section grows suffi-
ciently large to sustain stable flashing. As temperature continues to increase and the liquid in the water tanks continues to be boiled off, the hydrostatic pressure in the chimney further decreases, which causes the two-phase region to expand and the boiling boundary to shift to a lower location in the chimney. This then increases the system mass flow rate and provides sufficient momentum to fully flush vapor out of the chimney section, which in turn causes the fluctuations in the hydrostatic pressure to diminish and the flow to stabilize.

Figure 4.7 shows the system mass flow rate and the superheat of four volumes in the upper section of the chimney (P470) where each volume has a height of 0.31 m. The expansion of the two-phase flashing region is indicated by a positive superheat. It is observed that when flashing only happens in volume-19 and 20, the flow oscillations remain significant. However, as the boiling boundary shifts downward to volume-18, indicated by a positive superheat, the flow oscillations start to diminish and eventually stops. The observation further confirms that the flow oscillations are caused by the fluctuation in the hydrostatic pressure due to insufficient momentum to fully flush out the vapor accumulated in the chimney.

Figure 4.7: The expansion of the boiling boundary in the chimney section.
4.1.5 Phase portraits of pressure drop in the chimney

In this section, the relationship between the pressure drop in the chimney with respect to the system mass flow rate is investigated. Due to the difference in amplitude, the oscillations are partitioned into two regions as shown in Figure 4.8. For the analysis in this section, only the oscillations in Region A are studied. Figure 4.9 compares the pressure drop with respect to the mass flow rate at three different sections of the chimney while Figure 4.10 shows the patterns of oscillations for total pressure drop (frictional and hydrostatic pressure drop) and mass flow rate. Note that in Figures 4.9 and 4.10, each plot represents different section of the chimney. The first covers the entire length of the chimney, the second covers the section from volume-17 to 20, and the third covers the section from volume-19 to 20.

For the entire chimney, pressure drop is observed to increase with respect to the mass flow rate due to increasing frictional pressure drop. The pressure drop also appears to be in-phase with the mass flow rate. Furthermore, the periodic nature of the oscillations outlines a discrete path that bounds both the pressure drop and mass flow rate. The operating region is observed to shrink when the amplitude of the oscillations is smaller.

For volume-17 to 20, the pressure drop is observed to increase with the mass flow rate at lower values but decreases when the mass flow rate increases, thus creating a curve profile. This is because the pressure drop is partially out-of-phase with respect to the mass flow rate. For volume-19 to 20, pressure drop appears to decrease with increase mass flow rate as they become completely out-of-phase with each other. When the entire chimney is considered, the total pressure drop is dominated by frictional pressure drop primarily in the single-phase region and is in-phase with the mass flow rate. However, from volume-17 to 20, as the length of the section reduces, the single-phase region shrinks accordingly, and the frictional and hydrostatic pressure drops are now comparable. This is indicated by the pressure drop that is partially out-of-phase with respect to the mass flow rate. In volume-19 to 20 where the hydrostatic pressure drop is dominant, the pressure drop is completely out-of-phase with respect to the mass flow rate. This is because the mass flow rate is driven by the pressure drop in the chimney, hence mass flow rate always lags behind the pressure drop by half a cycle.
FY22 Progress on Computational Modeling of the Water-Based NSTF  
September 2022

Figure 4.8: The partitioning of flow oscillations.

Figure 4.9: Comparison of the pressure drop with respect to the system mass flow rate from (a) volume-1 to 20, (b) volume-17 to 20, and (c) volume-19 to 20 in the chimney.

4.1.6 Framatome Accident Scenario

A transient accident scenario case is simulated with the RELAP5 model. In the NSTF program, an ‘Accident Scenario’ test case is defined as the facility transitioning from a ‘normal’ single-phase steady-state operation with active cooling to an extended ‘accident' two-phase transient operation with continuous inventory boil-off. This specific test case centers on incorporating the power-time history of thermal load on a water-based RCCS during an accident scenario, and has been conducted in the test of DataQuality074.’

Similar to the previous simulations, the cavity is not included in the model and heat flux is directly applied to the surfaces of the riser tubes. The heat load applied to the riser tubes is
illustrated in Figure 4.11 labeled as ‘Power input to risers’. The heat load is calculated based on the mass flow rate and the bulk temperature rise between the inlet and outlet of the riser channels. Additionally, two other curves that represent the electrical power produced by the heaters and the thermal power that enters the cavity are added to the same figure. The differences between the three power curves are due to heat loss from the heaters, cavity, and the primary loop of the facility. It is observed that a constant heat load of roughly 32 kW is applied in the first 24 hours of the simulation to ensure that the system reaches a single-phase steady state with active cooling prior to varying the heat load. During transient, the heat load is reduced to roughly 25 kW within roughly an hour, and is increased gradually until it reaches a maximum value of roughly 46 kW at about 42 hours from the start of the simulation. Finally, it is reduced gradually until roughly hour-70 before it is decreased abruptly as the heater is turned off.

It should be noted that the steady-state condition in the first 24 hour of simulation is achieved through a simplified active cooling system where water is continuously added to the tank to keep the riser header inlet temperature at approximately 30°C throughout the steady-state phase. The active cooling system is deactivated at the start of the transient phase of the simulation.

Figure 4.12 compares the experimental and predicted mass flow rates for the accident scenario simulation. Note that the predicted mass flow rate shows a sudden increase from zero to roughly 1 kg/s early in the simulation compared to the gradual increase observed in the experiment. This is because the heater power in the experiment is ramped up gradually while the power in the model is increased abruptly from zero to the nominal value of 32 kW. However, the difference is deemed inconsequential as the steady-state flow rates from the experiment and the simulation eventually converge prior to the start of the transient accident scenario. In future work, a better fit will be
Figure 4.11: Heat load curve applied to the riser tubes in the accident scenario simulation.

applied to the heat flux to obtain a good agreement between the predicted and experimental results in the single-phase region.

Figure 4.12: Comparison of the experimental (Run074) and predicted mass flow rates for the accident scenario case.
Once the transient accident scenario is initiated, the predicted and experimental mass flow rates increase at almost the same rate from roughly 1 kg/s to 1.6 kg/s until boiling incipience at approximately hour-35. Once boiling is initiated, large flow oscillations are observed in the experimental and predicted mass flow rates. However, the predicted oscillations last for less than an hour while those in the experiment last for more than 15 hours before diminishing at roughly hour-50. The discrepancy in oscillation duration between the two sets of results could possibly be due to the difference in vapor generation rate predicted by the model and that in the experiment. As shown previously in Figure 4.6, the oscillation duration is shorter when the vapor generation rate is higher as it allows the boiling boundary in the chimney to develop quicker. Nevertheless, both sets of results show that the mass flow rate continues to increase once the oscillations stop.

As the water level in the tank drops below the tank inlet, the predicted and experimental mass flow rates start to decrease. As mentioned previously, the RELAP5 model likely predicts a higher vapor generation during flashing. This causes the inventory in the tank to be boiled off more quickly compared to the experiment which leads to an earlier uncovering of tank inlet in the simulation, and subsequently an earlier drop of mass flow rate.

It should be emphasized that in the NSTF, the chimney outlet is connected to the tank on the side wall. However, in the model, due to RELAP5’s limitation, the chimney is connected to the branch (Vol. 969) on the bottom surface. Consequently, partial uncovering of tank inlet as seen in the experiment cannot be simulated by the model. Furthermore, even though water level is not tracked directly by RELAP5, it can be inferred from the void fraction of the tank components, as shown in Figure 4.13, where a void fraction of 1.0 indicates that a volume is fully depleted. Note that ‘Vol. 969’ represents the branch of the tank, and ‘Vol. 950 - 1:5’ represents the pipe section located below the branch, with ‘1’ being the top node and ‘5’ the bottom node. In both cases, it is observed that once the tank inlet is uncovered, the mass flow rates start to decrease monotonically.

However, at approximately hour-60, the predicted mass flow rate experiences large oscillations that last for about 10 hours with an amplitude of up to 10 kg/s. Similar oscillations are not observed in the experiment. The negative flow rates of the oscillations indicate the occurrence of flow reversal, which suggests the possibility of geysering. Geysering or condensation-induced instability occurs when void generated in the heated region (risers) is condensed in the subcooled chimney section, thus leading to an increase of system pressure and causing the flow to slow down and eventually reverse. Figure 4.14 shows the void fraction at the inlet of the chimney where it is observed to oscillate from zero to 0.7, thus indicating that boiling (voiding) indeed occurs in
the risers. On the other hand, Figure 4.15 compares the saturation and bulk temperatures at the midpoint of the chimney where it is observed that a large part of the chimney remains subcooled during the oscillations. The combination of voiding in the risers and subcooled condition in the chimney further supports the claim that the oscillations predicted by the model from hour-60 to 70 are due to geysering.

At around hour-70, refilling is initiated where cold water is added directly to the tank to simulate inventory replenishment. The experimental flow rate experiences large oscillations upon the introduction of cold water to the system. The introduction of cold water to the system stops the voiding in the chimney and causes flow to stagnate. This in turn increases the hydrostatic pressure in the system and suppresses the localized boiling in the risers. With the fluid sitting stagnant in the risers, strong localized heating with suppressed boiling creates a superheated condition. Eventually, the fluid temperature rises above the local saturation temperature, thus triggering a violent flow excursion and abrupt large voiding. Conversely, the effects of cold refilling are not clear in the predicted mass flow rate where the oscillations are observed to continue for roughly an hour before stopping due to the suppression of voiding in the chimney, as shown by the comparison of the chimney outlet void fraction in Figure 4.16. The system then transitions to single-phase natural circulation where the flow rate continues to decrease gradually until the simulation is terminated.

The analysis shows that the RELAP5 model is able to predict the accident scenario relatively
Figure 4.14: Predicted void fraction at the chimney inlet.

Figure 4.15: Comparison of the predicted bulk and saturation temperatures at the chimney mid-point.

accurately where the major trends of the flow are captured. However, due to the difference in the predicted and experimental vapor generation rates, the oscillations predicted by the model only last for a fraction of the duration of oscillations observed from the experiment. The partial uncovering of tank inlet is also not simulated due to RELAP5’s limitation. As a future step, more analysis
needs to be performed to improve the vapor generation rate predicted by the RELAP5 model.

4.2 Simulation results with cavity model

4.2.1 Base model

The cavity model is tuned by Lv et al. (2021c) and benchmarked with steady-state single-phase experimental data. The benchmark focuses on three aspects, namely the cavity internal natural convective heat transfer due to the additional curvatures in the riser assembly induced by the round riser tubes, the heater surface emissivity, and the external natural convection heat loss. Based on the work by Lv et al. (2021c), the fouling factor for the heat transfer coefficient in the cavity is set to 1.24, the heater surface emissivity is set to 0.317, and the cavity external heat loss enhancement factor is set to 1.084. These factors are adopted for the current work.

With the cavity added, the model is benchmarked with the two-phase baseline case, Run057 by Lisowski et al. (2020). The baseline case has a heater electric power of 72 kW_e (targeted thermal power of 51.6 kW_t) and an initial inventory level of 80%. The heater power is applied across a 90-minute linear power ramp and then maintained constant to allow the facility and the inventory to heat up. Upon reaching saturation, flashing is first observed in the upper region of the chimney and lasts for 4 hours, followed by the ramping down of power. More details on the experiment can
Figure 4.17 compares the mass flow rate from the experiment with that predicted by the RELAP5 model. The experiment lasts for roughly 22 hours while the simulation is performed for 100,000 seconds, which is roughly 28 hours. Note that the experiment is terminated after 22 hours before the inventory level in the tank drops below the tank inlet as this would introduce additional two-phase phenomena that are beyond the scope of this test. The power ramp is initiated 5000 s after the start of the simulation to ensure that the system is in steady-state. Once the 90-minute full power ramp is initiated, the mass flow rate of the system starts to increase due to natural circulation caused by the thermal driving head originating from the difference in fluid density at different elevations of the system.

In the single-phase region, the experimental data and the prediction agree well. However, the occurrence of two-phase flow in the system, marked by the onset of flow oscillations, is predicted approximately two hours earlier at roughly the 11th hour by the model. In the model, the two-phase oscillations last for about an hour. The flow steadies at about 4 kg/s and slowly increases for the remainder of the simulation. Conversely, the oscillations in the experiment last for about 4 hours from the 14th to the 18th hour. According to Lisowski et al. (2020), the main instabilities encountered are the natural circulation oscillations and density wave oscillations (DWO). The former is caused by flashing in the upper chimney region and lasts for most of the two-phase duration when the voiding is not continuous with intermittent excursions. As the test proceeds and the inventory level continues to decrease, vapor generation transitions to a continuous mode as hydrostatic head dropped, and the instability mechanism slowly transitions towards the DWO. The experiment shows a decrease of mass flow rate at roughly the 18th hour mark due to the ramping down of the heater power, which is not included in the RELAP5 model.

The earlier onset of oscillations predicted by RELAP5 is likely due to the inadequate modeling of the heat loss experienced by the cavity, thus leading to more heat being transferred from the heater to the risers compared to the experiment. The cavity is modeled as insulated with a convective heat loss boundary condition on its outer surface. However, in reality, certain parts of the cavity, such as the support structures, might not have been properly insulated and might have led to a higher heat loss from the cavity to the surrounding. Similarly, the pipe walls in the primary loop are modeled as insulated with a convective heat loss boundary condition on their outer surfaces. Given that heat could possibly escape to the environment through structures that are not included in the current model, it is likely that heat loss is underestimated in the model. The modeling of
the heat loss in the cavity will be discussed in more details in a later section.

Figure 4.17: Comparison of the mass flow rate between the experimental data and the RELAP5 simulation for Run057.

Figure 4.18 compares the inlet and outlet temperatures of the riser between RELAP5 and Run057. The overall trends between the experimental and the simulation results are similar. The temperatures show an exponential trend in the first five hours and then increase almost linearly until two-phase condition is achieved at which point the temperatures remain relatively constant for the remainder of the test. Despite the earlier prediction of the onset of two-phase oscillations, the inlet and outlet riser temperatures predicted by RELAP5 agree well with the experimental data where the temperature increase across the riser is no more than 10 °C.

The inlet and outlet temperatures of the chimney are compared in Figure 4.19 where they share a similar trend as the riser temperatures. A good agreement is obtained between the RELAP5 simulation and the experimental data where the outlet temperatures are marginally lower than the inlet temperatures. This is because as the heated water travels downstream along the chimney, the bulk temperature remains unchanged while the local saturation temperature decreases due to increasing elevation. Near the exit of the chimney, the bulk temperature exceeds the local saturation temperature and leads to flashing which then decreases the bulk fluid temperature to the local saturation temperature.

Figure 4.20 shows the comparison of the void fraction near the chimney outlet between Run057
Figure 4.18: Comparison of the inlet and outlet temperatures of the riser between the experimental data and the RELAP5 simulation for Run057.

Figure 4.19: Comparison of the inlet and outlet temperatures of the chimney between the experimental data and the RELAP5 simulation for Run057.

and RELAP5. Note that in the NSTF, void fraction is only measured near the chimney outlet. As the water in the system is heated and the bulk fluid temperature at the chimney outlet exceeds the local saturation temperature, flashing occurs and the void fraction increases drastically from near
zero to up to roughly 0.6. The sudden increase of void fraction reduces the hydrostatic head of the hot leg, thus increasing the driving force and causes the system flow to increase drastically, which in turn pushes the void out of the chimney, restores the hydrostatic head, and causes the flow rate to reduce. The process is then repeated which leads to flow oscillations in the system.

Despite the similarity in the peak void fraction value, RELAP5 predicts the void fraction to increase from roughly 0.5 to 0.6 once stable flashing is achieved. Conversely, the experimental data show a much lower void fraction of less than 0.2 during the stable flashing period. The overprediction of void fraction by RELAP5 could be attributed to the underestimation of heat loss in the model. However, the large discrepancy between the prediction and the experimental data also suggests that the vapor (void) generation rate predicted by the RELAP5 model might be higher than that of experiment. As described by the RELAP5 (2015) theory manual, the vapor generation rate in RELAP5 is essentially modeled as a product of the superheat, interfacial area concentration, and a heat transfer coefficient obtained either from empirical or ad-hoc correlations. Given the good agreement of the chimney temperatures between Run057 and the model as shown in Figure 4.19, the discrepancy likely originates from the calculation of the interfacial area concentration or the heat transfer coefficient.

Figure 4.20: Comparison of the chimney outlet void fraction between the experimental data and the RELAP5 simulation for Run057.

Figure 4.21 shows the comparison of the tank gas space pressure between the experiment and
the RELAP5 simulation. In the single-phase region, the gas space in the experiment and the model remains at atmospheric pressure. However, as the flow condition transitions to two-phase and vapor starts to accumulate in the tank, the pressure starts to build up to approximately 120 kPa, after which it remains relatively unchanged for the remainder of the two-phase oscillations. The pressure in the experiment decreases at roughly the 18th hour mark as heater power is ramped down and the steam by-pass valve is opened to release the vapor to the environment. Note that this is not seen in the RELAP5 results because the ramping down of heater power and the release of vapor are not included in the RELAP5 model.

![Comparison of the tank gas space pressure between the experimental data and the RELAP5 simulation for Run057.](image)

Figure 4.21: Comparison of the tank gas space pressure between the experimental data and the RELAP5 simulation for Run057.

Figure 4.22 shows the system inventory level predicted by the RELAP5 model. The inventory remains unchanged at approximately 3700 kg during the single-phase region. Conversely, in the two-phase region, the inventory level decreases linearly as water is boiled off and vapor accumulated in the tank gas space is discharged from the system.

The analysis shows that the RELAP5 model is able to predict the base case satisfactorily where the major trends are captured. Nevertheless, some discrepancies in terms of the onset and duration of oscillations still remain. To improve the model, it is insightful to first understand how different factors affect the prediction of the model. In the next section, parametric studies are performed to investigate the impact of various parameters such as the heater power, initial inventory level, and
4.3 Parametric study

4.3.1 Heater power

Parametric study is performed to investigate the effects of heater power on the RELAP5 simulation. The electrical power of the heater is varied from 50% to 150% of its nominal value of 72 kW\textsubscript{e}. Figure 4.23 compares the system mass flow rate at various power levels. By increasing the heater power, the onset of oscillations is predicted earlier as water is heated up faster in the risers, which then allows flashing to happen earlier and leads to oscillations. Furthermore, it is observed that the duration of oscillations decreases with increasing heater power, with that at $\times 1.5$ lasting for shorter than an hour while that at $\times 0.5$ lasting for more than 10 hours. As the heater power increases, the vapor generation rate is higher, which promotes a quicker development of the boiling boundary in the chimney, thus diminishing the oscillations and allowing stable flashing to establish earlier. The overall system mass flow rate is also higher when the heater power is increased due to higher thermal driving head.

The void fractions at the exit of the chimney at various power levels are shown in Figure 4.24. The overall trend of the void fraction is similar to that of the mass flow rate where the oscillation duration decreases with increasing heater power. The void fraction also increases with heater power.
Figure 4.23: Comparison of the system mass flow rates at different heater power levels with respect to the experimental data from Run057.

due to higher vapor generation rates in the chimney. Figure 4.25 shows the gas space pressure in the tank. Due to the higher void fraction and vapor generation rate, more vapor accumulates in the tank gas space as heater power is increased, thus leading to a higher gas space pressure.

Figure 4.24: Comparison of the void fractions at the chimney outlet at different heater power levels with respect to the experimental data from Run057.
4.3.2 Initial inventory level

The effects of the inventory levels are investigated by varying the initial water level in the tank from 60% to 90% of the tank’s volume. Figure 4.26 shows the system mass flow rate predicted by RELAP5 with different initial tank levels. The onset of oscillations is predicted earlier by RELAP5 when the initial tank level is lower as it takes less time for the bulk liquid in the tank to heat up and reach saturation.

Furthermore, the oscillations last shorter with decreasing initial tank level. At lower tank inventory level, as shown by Figure 4.27, the hydrostatic pressure in the chimney is lower. This indicates that the saturation temperature in the chimney is also lower, which in turn allows an earlier onset of flashing in the chimney. Given that the bulk temperature at the chimney inlet is largely the same for all inventory levels, a lower saturation temperature in the chimney means that the superheat is higher, leading to a higher vapor generation rate and a higher void fraction, as shown in Figure 4.28 and Figure 4.29, respectively. The higher vapor generation rate allows the boiling boundary to develop faster in the chimney which leads to stable flashing as the oscillations diminish.

Figure 4.30 shows the system inventories with different initial tank levels. Despite the difference in the initial tank level, the overall behavior of system inventory is similar where it remains constant.
in the single-phase region and decreases linearly in the two-phase region as water is boiled off in the system and released to the environment. For the 60% case, the system inventory stops decreasing at hour 26 and remains roughly constant for the remaining of the simulation. The cause behind this change remains unclear and is being investigated.
4.3.3 Tank gas space pressure

In the current model, a discharge line is added to the top of the tank to allow steam to escape from the tank to the environment. By changing the loss coefficient of the line, the steam discharge rate could be altered to change the amount of steam accumulated in the tank gas space, which
in turn affects the pressure in the tank. To investigate the effects of tank gas pressure on the simulation, the loss coefficient of the steam discharge line is varied from 0 to 150. Figure 4.31 compares the tank gas space pressures at different tank discharge line loss coefficients where the pressure is observed to increase with the loss coefficient. When the flow is in single-phase, the predicted pressures are the same for all loss coefficients and are in a good agreement with the experimental value. As the flow transitions into two-phase, vaporization occurs in the tank and chimney, thus causing more steam to accumulate in the gas space of the tank and increasing the tank pressure. As shown in Figure 4.32, when the flow transitions into two-phase, the steam discharge rate from the tank is the highest when the loss coefficient is the lowest. However, as the flow transitions into stable flashing, the steam discharge rate converges to the same value of roughly 0.22 kg/s.

As shown in Figure 4.33, the effects of the discharge line loss coefficients (tank gas space pressure) on the system mass flow rate are minimal. During single-phase, the mass flow rates are the same for all cases. Furthermore, the onsets of oscillations for all cases happen at roughly the same time. However, the oscillations are observed to last longer at higher loss coefficients. This is because the vapor generation rate in the chimney is lower when the loss coefficient (hence, system pressure) is higher, as shown in Figure 4.34, thus delaying the development of the boiling boundary in the chimney. Due to the difference in vapor generation rate, the chimney outlet void fraction is
Figure 4.31: Comparison of tank gas space pressures at different tank discharge line loss coefficients with respect to the experimental data from Run057.

Figure 4.32: Comparison of the steam discharge rate at different tank discharge line loss coefficients.

observed to be highest when the discharge line coefficient and the system pressure are lowest, as depicted in Figure 4.35.

The parametric study shows that different parameters can have varying degree of impact on the model prediction. Heater power appears to have the most severe impact on the onset and duration
Figure 4.33: Comparison of the system mass flow rates at different tank discharge line loss coefficients with respect to the experimental data from Run057.

Figure 4.34: Comparison of chimney outlet vapor generation rate at different tank discharge line loss coefficients.

of oscillations, whereas the effects from the initial inventory level and tank gas space pressure appear to be less significant in comparison. In the next section, the impact of vapor generation rate is investigated by changing the heat transfer coefficient correlation.
Figure 4.35: Comparison of chimney outlet void fraction at different tank discharge line loss coefficients with respect to the experimental data from Run057.

4.4 User-option study

RELAP5 provides a number of user options that can be activated to allow the users to choose certain models, correlations, or numerical schemes for their simulations. The discussion so far has shown that the vapor generation rate plays a significant role in the accuracy of RELAP5’s predictions, particularly in the two-phase oscillatory region. As shown by the parametric study of heater power, the vapor generation rate directly impacts the development of boiling boundary in the chimney region and thus dictates the duration of oscillations. The underprediction of oscillation duration by RELAP5 could likely be attributed to the overprediction of vapor generation by RELAP5. To further investigate the effects of vapor generation rate on the RELAP5 prediction, a different vapor generation model is used. This is achieved by enabling Option-61 in the model, which according to the RELAP5 (2015) manual, ‘modifies constitutive relationships to reduce numerical oscillations at low pressure’ specifically affecting the ‘interfacial heat transfer for bubbly and slug flow regimes, where the liquid-side interfacial heat transfer coefficient has been modified to replace “ad hoc” correlations with more physical models’.

Figure 4.36 compares the mass flow rates predicted by the model with and without Option-61. The mass flow rates in the single-phase region and the onsets of oscillations remain the same for both cases. However, with Option-61, the oscillations are observed to last for about 10 hours, which
is closer to the experimental data of roughly 12 hours, compared to the 2 hours predicted by the model using the default option. Furthermore, the flow rate in the steady-state two-phase region predicted by the model with Option-61 is lower. The model with Option-61 also predicts a second set of oscillations in the steady-state two-phase region which is not seen when the default option is used. The origin of these oscillations is still being investigated.

Figure 4.36: Comparison of the system mass flow rates predicted by the model with the default option and Option-61 with respect to the experimental data from Run057.

Figure 4.37 and Figure 4.38 compare the vapor generation rates and the void fractions at the chimney exit predicted by RELAP5 with the default option and Option-61, respectively. With Option-61, the vapor generation rate at the chimney exit is lower, leading to a lower void fraction. Furthermore, the lower vapor generation rate slows the growth of boiling boundary in the chimney, thus delaying the establishment of the steady two-phase flow. Nevertheless, the void fraction at the chimney exit predicted in the steady two-phase region with both options remains significantly higher than the experimental value.

The analysis shows that by changing the correlation used by the model to calculate heat transfer coefficient, the vapor generation in chimney can be lowered, which leads to an improved prediction of oscillation duration. The improvement suggests that the usage of Option-61 should be considered in future work. However, despite the improvement, the model still predicts an earlier onset of oscillation compared to the experiment, likely due to the underprediction of heat loss by the model.
Figure 4.37: Comparison of the chimney outlet vapor generation rates predicted by the model with the default option and Option-61.

Figure 4.38: Comparison of the chimney outlet void fractions predicted by the model with the default option and Option-61.

Further analysis is performed in the coming section to improve the modeling of heat loss.
4.5 Heat loss modeling

The discussion so far shows that the RELAP5 model predicts an earlier onset of oscillations compared to the experimental data. The early prediction could signify that the amount of heat transferred to the risers is higher in the RELAP5 model than in the experiment, which could be due to the underprediction of heat loss in the cavity by the model. In the NSTF, even though the cavity panels are insulated, heat could still be lost to the surrounding through various support structures that might not have been properly insulated due to their complex geometries and positions in the cavity. These structures are not included in the RELAP5 model to minimize the complexity of the cavity model. Similarly, heat can also be lost to the environment via the support structures of the heaters that are also not included in the RELAP5 model. In this model, the cavity panels and the heaters are insulated. Heat loss is modeled by prescribing temperature-dependent heat transfer coefficients on the external surfaces of these panels. The heat transfer coefficients are calculated using the correlation for natural convection on a vertical plate given by Cengel (2002).

To improve the cavity model, it is insightful to first analyze the breakdown of heat transfer from the heater to the cavity and from the cavity to the risers and the environment. Note that the experimental data from Run057 by Lisowski et al. (2020) are used for comparison in this section. Figure 4.39 shows the breakdown of heat leaving the heater where it is observed that of the 72 kW of power provided to the heater, roughly 45 kW is radiated to the stainless-steel plate, about 25 kW is convected through air flow in the gap between the heater and the stainless-steel plate, and the remaining is lost to the environment from the external surface of the insulation. Figure 4.40 shows the breakdown of heat entering the cavity where it is seen that the cavity receives only about 51.6 kW of heat from the heater. The discrepancy between the heat leaving the heater and the heat entering the cavity is due to heat loss to the environment via the air flow in the gap between the heater and the stainless-steel plate. Figure 4.39 shows the breakdown of heat leaving the cavity. Note that ‘HS-101’ to ‘HS-105’ represent the external surfaces of the cavity panels. The heat entering the risers from the experiment is denoted as ‘exp’ and is calculated from the temperature difference between the inlet and the outlet of the risers. It is observed that the model predicts negligible heat loss from the panels and almost all of the heat from the cavity is transferred to the risers. Furthermore, the analysis shows that the heat entering the risers from the cavity predicted by the model is roughly 8 kW higher than the experimental value, thus possibly leading to an earlier prediction of the onset of oscillations by the model.
4.5.1 Exposed-cavity model

To better model the heat loss from the cavity through the support structures, the insulation on the top-most nodes of the cavity side panels (HS-101 and HS-102) are removed. This approach allows heat to directly escape from the cavity to the environment without adding components and introducing further complexity to the current cavity model. Figure 4.42 compares the system mass
Figure 4.41: Breakdown of heat leaving the cavity predicted by the model in comparison with the heat entering the risers in Run057.

Flow rates predicted by the default RELAP5 model and the exposed-cavity model. It is observed that with the top-most nodes of the cavity side panels exposed, the onset of oscillations is delayed by approximately an hour compared to the default model. However, the onset of oscillations is still predicted roughly 3 hour too early by the exposed-cavity model compared to the experimental data.

Figure 4.43 shows the breakdown of heat leaving the cavity predicted by the exposed-cavity model. Note that ‘exposed’ represents the total amount of heat leaving the cavity from the exposed side panel surfaces. It is observed that the riser channels remain as the main heat sink for the cavity. On the other hand, roughly 3 kW of heat escapes from the cavity to the environment via the exposed surfaces, which is substantially higher than the nearly non-existent heat loss via the insulated surfaces. However, a discontinuity is observed in the ‘riser’ curve at roughly hour-13 where the heat input to the riser channels shows a sudden increase of approximately 7 kW. Based on the RELAP5 (2015) theory manual, it is possible that the discontinuity is due to the switching of the heat transfer coefficients correlations used by RELAP5 due to changing flow conditions. As shown by Figure 4.44, the mean heat transfer coefficient of the riser channels depicts a sudden jump at hour-13 from roughly 8 kW/m²s to 18 kW/m²s. The increased heat transfer coefficient improves the heat transfer from the cavity to the risers thus causing an increase of heat input to the risers.
Figure 4.42: Comparison of the system mass flow rates predicted by the default model and the exposed-cavity model with respect to the experimental data from Run057.

Figure 4.43: Breakdown of heat leaving the cavity predicted by the exposed-cavity model in comparison with the heat entering the risers in Run057.

4.5.2 Exposed-heater model

A similar approach is used to improve the modeling of heat loss from the heater to the environment. In the NSTF, the heaters have support structures that can act as a pathway for heat
to escape to the environment. Due to their complex geometries, these structures are not included in the RELAP5 model which leads to an underestimation of heat loss experienced by the heaters. Thus, to improve the modeling of heat loss while maintaining the simplicity of the heater model, the insulation of the top-most node of the heater back is removed to increase the heat loss to the environment. Figure 4.45 compares the mass flow rates predicted by the default RELAP5 model and the exposed-heater model where it is observed that the onset of oscillations predicted by the latter is delayed and is closer to the experimental data. Figure 4.46 shows the breakdown of heat transfer from the heater predicted by the exposed-heater model. Compared to that of the default model shown in Figure 4.39, in the exposed-heater model, the heat loss from the back of the heater, represented by the green solid line, is substantially higher. The higher heat loss from the back of the heater means that the heat entering the cavity and the riser channels is reduced, thus delaying the onsets of two-phase flows and oscillations.

4.5.3 Combined exposed heater and cavity model

The analysis in the previous section indicates that increasing the heat loss from the cavity and the back of the heater can improve the prediction of the RELAP5 model by delaying the onsets of two-phase flow and oscillations. However, the heat loss from the cavity or the back of the heater individually are shown to be inadequate. In this section, the exposed-cavity and exposed-heater
Figure 4.45: Comparison of the system mass flow rates predicted by the default model and the exposed-heater model with respect to the experimental data from Run057.

Figure 4.46: Breakdown of heat transfer from the heater predicted by the exposed-heater model.

models are combined where insulation on the top-most nodes of the heater and the cavity side panels are removed to allow heat to escape from the back of the heaters as well as the cavity. Figure 4.47 depicts the system mass flow rate predicted by the exposed-heater-cavity model. The prediction of the onsets of two-phase flow and oscillations is improved significantly compared to
the previous approaches. Figure 4.48 shows the breakdown of the heat escaping from the cavity where it is seen that the heat entering the riser channels predicted by the model is in a good agreement with respect to the experimental value. Similar to the previous model, almost all of the heat in the cavity is transferred to the risers with only a small amount being lost to the surrounding via the exposed surfaces of the cavity side panels. Despite the improvement, the exposed-heater-cavity model continues to predict an early onset of oscillations with respect to the experimental data even though the predicted amount of heat entering the risers from the cavity matches the experimental value. More work is continuously being performed to better understand the cause of this discrepancy.

![Graph showing comparison of system mass flow rates predicted by the combined exposed-heater-cavity model with respect to the experimental data from Run057.](image)

**Figure 4.47:** Comparison of the system mass flow rates predicted by the combined exposed-heater-cavity model with respect to the experimental data from Run057.

### 4.6 Throttling of riser inlet

#### 4.6.1 Default loss-coefficient curve

To further benchmark the RELAP5 model, a throttling valve is added at the header inlet located upstream of the riser channels. The simulation results are compared with the experimental results Run071 performed by Lv et al. (2021a). In the experiment, a 4.0-inch nominal sized full-bore ball valve controlled pneumatically by an intelligent controller is installed at the header inlet. The valve can be proportionally controlled across the entire range of positions, from fully open
Figure 4.48: Breakdown of heat transfer from the cavity predicted by the combined exposed-heater-cavity model in comparison with the heat entering the risers in Run057.

(0° valve angle, 100% valve position) to fully closed (90° valve angle, 0% valve position). The $C_v$ (represents the flow of water at 60 °F through the valve in U.S. gallons per minute at a pressure drop of 1 psi) of the valve is included in Figure 4.49 where it is observed to have a non-linear relationship with respect to the valve flow area and position. Furthermore, this test utilizes a continuous refill of boil-off condensate back into the loop to ensure that the loop operates at a true thermal and hydraulic steady-state mode of operation. The condensate refill system is used to maintain a constant inventory level inside the water tank by manually adjusting the refill rate to match the steam/condensate generation rate. Once the facility reaches a two-phase thermal and hydraulic steady-state condition, ten stages of inlet restriction were imposed on the operating test loop, beginning with fully open to severely restricted. The summary of the stages for restricted inlet throttle is included in Table 4.1.

For the simulation, a simplified refilling system is added to the water tank where water at 25 °C is added continuously into the tank. The refilling rate is the same as the mass flow rate of vapor discharged by the tank to the environment. With the refilling system and by enabling Option-61, a quasi-steady oscillatory flow that lasts for the remainder of simulation is established, as shown in Figure 4.50. Furthermore, the loss coefficients of the valve at the header inlet are set as the values from the experiments. The stages of the closing of the valve also follow those from the experiment. Note that the insulation on the top-most nodes of the heater and the cavity side panels are removed.
Figure 4.49: $C_v$ of ball valve with respect to the valve position and area (Lv et al. (2021a)).

Table 4.1: Summary of stages for restricted inlet throttle (Lv et al. (2021a)).

<table>
<thead>
<tr>
<th>Stage</th>
<th>Averaging window (Hr)</th>
<th>Valve position (°)</th>
<th>Valve position (%)</th>
<th>Flow area (%)</th>
<th>$C_v$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.83 - 16.13</td>
<td>0</td>
<td>100</td>
<td>100</td>
<td>2096</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>16.13 - 16.50</td>
<td>22</td>
<td>75</td>
<td>77</td>
<td>1460</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>16.50 - 16.85</td>
<td>36</td>
<td>60</td>
<td>57</td>
<td>1035</td>
<td>0.22</td>
</tr>
<tr>
<td>4</td>
<td>16.85 - 17.17</td>
<td>45</td>
<td>50</td>
<td>44</td>
<td>760</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>17.26 - 17.53</td>
<td>54</td>
<td>40</td>
<td>33</td>
<td>509</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>17.60 - 17.88</td>
<td>57</td>
<td>36</td>
<td>29</td>
<td>433</td>
<td>1.25</td>
</tr>
<tr>
<td>7</td>
<td>17.88 - 18.23</td>
<td>60</td>
<td>33</td>
<td>25</td>
<td>361</td>
<td>1.79</td>
</tr>
<tr>
<td>8</td>
<td>18.31 - 18.57</td>
<td>63</td>
<td>30</td>
<td>22</td>
<td>293</td>
<td>2.73</td>
</tr>
<tr>
<td>9</td>
<td>18.62 - 18.92</td>
<td>65</td>
<td>27</td>
<td>20</td>
<td>246</td>
<td>3.87</td>
</tr>
<tr>
<td>10</td>
<td>19.02 - 19.26</td>
<td>68</td>
<td>25</td>
<td>17</td>
<td>202</td>
<td>5.72</td>
</tr>
</tbody>
</table>

to improve the modeling of heat loss, as discussed in the previous section.

Figure 4.51 shows the comparison between the mass flow rates predicted by the RELAP5 model and the experimental data with the inlet of the risers throttled according to the stages described in Table 4.1. Note that the normalized valve area is also included in the figure. Some discrepancies are observed between the predicted mass flow rate and the experimental data. The predicted onset of oscillations is in a decent agreement with the experimental data with a minor delay of roughly 15 minutes. Furthermore, the amplitude of oscillations predicted by RELAP5 is shown to be greater than the experimental data. During stage-2 of throttling, the mass flow rate from the experiment is reduced by roughly 1 kg/s while that predicted by the model remains largely unchanged and only starts to reduce in stage-3 of throttling. As the valve continues to close, the experimental and predicted mass flow rates decrease accordingly. By stage-5, the experimental data shows a significant reduction in oscillation whereas the reduction in oscillation amplitude in
the predicted mass flow rate is comparatively smaller. At stage-7, the experimental data shows an increase of oscillation amplitude, which is not observed in the predicted flow rate. According to Lv et al. (2021a), the reintroduction of oscillations is due to Type-II density wave oscillation (DWO) instabilities. This is the most commonly observed form of density wave oscillation, and is due to multiple regenerative feedbacks between the flow rate, vapor generation rate and pressure drop. The flow stabilizes as the valve is closed further from stage-8 to stage-9.

At stage-10, the experimental data shows another increase of oscillation amplitude. As explained by Lv et al. (2021a), with the flow through the valve restricted, the residence time of fluid in the test section is increased to a level that allows for local voiding. Unlike previous stages where voiding is driven primarily due to a reduction in hydrostatic head pressure, these low flow rates allow enough power to enter the local fluid that the saturation temperatures are reached even before rising in elevation through the chimney. The phenomena drives the onset of the parallel channel instability (PCI) mechanism, which drives out-of-phase voiding and independent flow excursions across the 8 parallel riser channels. Lv et al. (2021a) further describes the PCI instability as a unique phenomenon that arises from coupled influences of flashing, boiling, and geysering. The behavior of PCI can be chaotic in nature, with random flow reversals in individual channels a common occurrence. On the other hand, PCI is not observed in the RELAP5 prediction. The
amplitude of oscillations decreases as the valve closes and the oscillations are nearly diminished by stage-10.

Figure 4.52 compares the void fraction at the chimney outlet from the experiment to that predicted by RELAP5. Prior to the throttling of the valve, the void fractions from both sets of results appear to be similar, with a maximum value of roughly 0.7. However, as the valve closes, the void fraction from the experiment decreases to roughly 0.35 before increasing back to 0.6 due to DWO. Lastly, due to the reduction of flow and voiding in the risers, the void fraction at the chimney outlet increases significantly to more than 0.9. Conversely, the RELAP5 model predicts a less chaotic behavior where the oscillation amplitude decreases but the overall value of the void fraction increases until it settles down at roughly 0.5 after stage-10 of throttling.

4.6.2 Modified loss-coefficient curve

The analysis from the previous section shows that the RELAP5 model is unable to capture the flow behaviors observed in the experiment when the valve at the header inlet is throttled. Given that the reduction in mass flow rate predicted by the model is smaller than that from the experiment, it is likely that the valve in the model is not imposing sufficient restriction to the flow. To further investigate this postulation, a different set of loss-coefficient curve, obtained from VAL-MATIC, is used in the model. To ensure that the flow is the same as experimental data when
the valve is fully open, the new curve is scaled in such a way that its maximum $C_v$ matches that of the experimental value. Note that $C_v$ is largest when the valve is fully open. Figure 4.53 compares the experimental and the new (reference) $C_v$ curves. It is observed that the experimental curve has an almost linear relationship with respect to the valve area while the reference curve exhibits an exponential trend. Furthermore, the $C_v$ of the reference curve is consistently smaller than that of the experimental curve, which means that it imposes more restriction to the flow through the valve.

Figure 4.54 shows the mass flow rate predicted by the RELAP5 model with the reference curve for the throttling valve. Overall, given that the reference curve is more restrictive, the mass flow rate is observed to decrease more compared to that with the experimental curve. At stage-4, the predicted mass flow rate decreases below the experimental value. Unlike the experimental flow rate that stabilizes at stage-4, the predicted flow rate remains oscillatory even though the amplitude of oscillations decreases as the valve closes. Based on Figure 4.54(b), it is also noted that the frequencies of the oscillations agree well qualitatively between the experimental and predicted results.

At stage-5, the predicted flow rate reduces further and starts to exhibit irregular oscillatory patterns. As the valve continues to close from stage-6 to stage-10, the irregular oscillatory pattern
persists where flow reversals occur intermittently as indicated by the negative flow rate values. This suggests the occurrence of geysering as the flow is slow enough that voiding occurs in the riser channels. This is evident by the void fraction predicted by the model at the outlet of the riser channels, as shown in Figure 4.55. Consistent production of void fraction at the riser outlet is first observed at stage-6 which coincides with the observation of flow reversals. Furthermore, the oscillatory pattern from stage-6 onward resembles that observed in the experiment at stage-10, suggesting that the RELAP5 model is predicting parallel channel instability (PCI). Figure 4.56 compares the flow rates of individual risers, namely Riser-1, 3, 5, and 8. Prior to stage-6, the flow rate of each risers is observed to be almost identical to each other. However, at stage-6, the flow rates start to vary and become out-of-phase from each other. On top of that, the oscillation patterns appear to be random. This further indicates the occurrence of PCI when the valve is closed from stage-6 and beyond.

Figure 4.57 compares the chimney outlet void fraction between the experiment and the RELAP5 simulation with the reference \( C_v \) curve. A better agreement is obtained between the experimental data and the prediction compared to the previous simulation with the experimental \( C_v \) curve. The oscillations in void fraction are observed to reduce but the overall value of void fraction is seen to increase as the valve closes. However, at stage-6 where voiding starts to occur in the riser channels
leading to geysering and PCI, the void fraction at the chimney outlet starts to oscillate again with amplitude ranging from 0 to 1.

With the reference $C_v$ curve, it is shown that the RELAP5 model is able to predict the overall
trend and behavior of the flow relatively well. The frequency of oscillations, reduction of the amplitude of oscillations, geysering, and PCI are captured by the model. On the other hand, the model also fails to capture some features seen in the experimental data, including flow stabilization that is observed at stages-4, 5, 6, 8, and 9 and the DWO at stage-7. The missing features from the RELAP5 prediction are potentially due to the difference in the $C_v$ curve used in the experiment and the model. Nevertheless, the analysis shows that the model performs satisfactorily with the
reference $C_v$ curve and more work will be performed in the future to improve the accuracy of the model for riser inlet-throttling cases.

### 4.7 Depleted inventory scenario

To further benchmark the RELAP5 model, a depleted inventory scenario is simulated. Similar to the analyses in the previous section, part of the insulation on the back of the heater and the cavity side panels are removed to better model heat loss. In this scenario, boiling/flash is allowed to happen such that the system inventory would fall to a low level and result in the stagnation of the flow in the primary system. As explained by Lv et al. (2021a), this scenario reflects a depletion state where the heat removal is severely compromised and the facility is no longer able to perform its safety related function. The prediction from the model is compared with the experimental data for Run069 by Lv et al. (2021a).

Before analyzing the results, it is important to note the differences between the tank model and the design of the actual tank. In the NSTF, the chimney outlet is connected to the tank on the side. However, in RELAP5, volumes are connected to each other at the top and bottom faces. This means that the model is unable to simulate the scenario where the tank inlet is partially exposed as observed in the experiment. Following the setup by Lv et al. (2021a), the facility is filled to an
The heater is ramped up to 72 kW\textsubscript{e} over 150 minutes. Once two-phase flow is achieved, the facility is allowed to operate normally with natural boil-off for 30 minutes, after which the draining of the tank is accelerated through a drain line located at the bottom of the tank at a rate of approximately 0.5 GPM.

Figure 4.58 compares the experimental and predicted mass flow rate for the depleted inventory scenario. The mass flow rates are annotated to highlight the phenomena observed at different depletion stages. Note that ‘Vol. 969’ represents the branch used to model the thermal mixing region in the tank while ‘Vol. 950’ represents the pipe located below branch. The pipe is made up of five nodes where node-1 is the top-most node and node-5 is the bottom-most node. It is observed that the RELAP5 model is able to capture the overall trend of experimental data. The onset of boilings, represented by the oscillations, from both sets of results appear to agree well. However, the model predicts a higher mass flow rate during the non-oscillatory two-phase period. In the experiment, a spike is observed when the water level in the tank falls below the top lip of the tank inlet. Similar spike is also predicted by the model at around the same time when Vol. 969 is depleted. Furthermore, the flow rates in both cases start to decrease when the tank inlet is uncovered.

Figure 4.58: Comparison of the experimental and predicted system mass flow rates for the depleted inventory scenario of Run069.
On the other hand, the RELAP5 model is unable to simulate water level falling below the inlet top lip and inlet centerline due to the placement of the junction connecting the volumes. Nevertheless, when the inlet is fully exposed, represented by the depletion of Vol. 969, the predicted flow rate experiences a spike and starts to decrease, as seen in the experiment. As the water level in the tank drops, the mass flow rate continues to decrease. At hour-16, small oscillations are observed in the experimental flow rate as the flow shifts away from stable continuous two-phase flow into a regime of moderate amplitude, high-frequency oscillations. Meanwhile, similar oscillations are predicted by the model roughly 2 hours later at hour-18. Finally, at around hour-22 when cold refill is initiated by directly feeding cold water into the tank, both sets of results show violent oscillations as the introduction of cold water leads to geysering and parallel channel instability (PCI). As the heater power is ramped down and more water is added to the system, the oscillations diminish and the natural circulation eventually stops.

Figure 4.59 shows the void fraction of different tank components predicted by the model. Given that RELAP5 does not provide water level directly, the void fraction of a volume is used to infer its water level where a void fraction of one signifies that a volume is completely depleted. The simulation shows that the tank is almost fully depleted as water level drops below Vol. 950 - 4. Figure 4.60 shows the total system inventory level predicted by the model. The system inventory remains constant during the single-phase period and starts to drop once boiling occurs. As refill is initiated the level then starts to increase again before settling down as refill is terminated.

Overall, the RELAP5 model performs relatively well in simulating the depleted inventory scenario despite not being able to simulate the partial uncovering of tank inlet due to RELAP5’s limitations. Nevertheless, major trends and features observed in the experiment are captured by the model.

5 Conclusions

This report presents the modeling of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) at the system level completed in FY22. As a continuation of the modeling effort from FY21, this year’s work focuses primarily on the two-phase system-level modeling of the NSTF using RELAP5-3D, with the cavity included to the model. The results from the simulations are also compared with the experimental data from Lv et al. (2021b) to benchmark the RELAP5 model.

In the first part of this work, the cavity model is omitted and heat flux is applied directly
Figure 4.59: Void fraction of different tank components predicted by RELAP5 for the depleted inventory scenario.

Figure 4.60: Total system inventory level predicted by RELAP5 for the depleted inventory scenario.

as a boundary condition to the risers. For the two-phase baseline test case, the general trend predicted by the RELAP5 model matches that from the experimental data where a single-phase natural circulation flow is first established followed by an oscillatory two-phase flow and finally a stable two-phase flow. However, the onset of oscillations is predicted early by the model due to
the smaller thermal mixing region in the tank. By expanding the thermal mixing region in the tank, the onset of oscillations predicted by the model matches that from the experiment. The oscillations predicted by the model are studied closely where they are deduced to flashing-induced instability. An accident scenario case is also simulated where heat load scaled based on the full-scale Framatome’s 625 MW$_t$ SC-HTGR is applied directly to the riser channels. Decent agreement is obtained between the prediction and experimental data. However, some discrepancies remain and are likely due to the overprediction of vapor generation rate by the model.

With the cavity model included, the RELAP5 prediction is able to capture the major trends of the flow. However, the onset of oscillations is once again predicted early by the model. Upon closer inspections, it is postulated that the discrepancy is caused by the underprediction of heat loss from the heater and cavity. To improve the prediction of heat loss, instead of adding complexity to the existing model by including additional heat structures to the cavity, insulation on a part of the cavity side panels and the back of the heaters are removed to allow heat to escape to the environment. Furthermore, parametric studies are performed to investigate the effects of heater power, tank inventory level, and tank gas space pressure on the flow behaviors. User option-61 which changes the heat transfer coefficient correlations used for calculating the vapor generation is also investigated. It is found that by enabling the option, the overall duration of oscillations is increased and matches that from the experiment better. The RELAP5 model is further benchmarked with a riser inlet-throttling case where it is observed that the prediction from the model fails to capture some of the major features observed in the experiment. By using a modified loss coefficient curve, the accuracy of the prediction is improved where most of the major features seen in the experiment are predicted by the model. Lastly, the model is benchmarked with an inventory depletion scenario where it is observed that despite the modeling limitation of RELAP5, the prediction shows good agreement with the experimental data where major trends and features are captured by the model.

For future work, efforts will be put into further improving the current RELAP5 model, such as the consideration of conduction in the fins of the riser channels and detailed analysis of the oscillation mechanisms. The model will also be benchmarked with additional experimental data, particularly accident scenario-like transient cases to further evaluate the performance of the model.
ACKNOWLEDGEMENTS

This work is supported by the U.S. Department of Energy, Office of Nuclear Energy, Office of Nuclear Reactor Technologies, Advanced Reactor Technologies. The submitted manuscript has been created by UChicago Argonne LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.
REFERENCES


