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RELAP5/MOD2.5 Simulation Results for the Separate Effects Test Experiment Series: Phase I

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1. INTRODUCTION

The Separate Effects Test (SET) facility is a one-fourth linear scale model of a portion of a production reactor at the Savannah River Site.^{1,2} The Phase I configuration is prototypical of a one-sixth sector of the moderator tank and a portion of a single pump suction piping (PSP) loop. The purpose of this work was to perform a preliminary investigation into the suitability of the full-scale SRL reactor modeling methodology to the one-fourth linear scale SET facility. The resulting model will also aid in understanding the experimental results produced by the SET experimental test series.

Section 2 gives a brief description of the experimental facility. Section 3 describes the code version of RELAP5 used for this work and the SET input model constructed for the simulations. Section 4 describes the results of the model tuning and the single and two-phase simulations. Sections 5 and 6 contain the conclusions and references respectively.

2. FACILITY DESCRIPTION

The SET facility is instrumented to provide liquid and air flowrate, void fraction, and pressure data. The simulated reactor components in the fluid system include: the moderator tank sector and assemblies, the tank exit nozzle or muff, and the pump suction piping. The fluid circuit is as follows (see Figure 1): the deionized water is pumped to the top of the assemblies where it flows down through the assemblies, out the shell holes at the bottom of the assemblies, and into the moderator tank. Then the liquid flows out the vaned nozzle (or muff), into the pump suction piping and into the separator tank where the liquid is pumped back to the assemblies. An air injection capability also exists in which air is pumped into the assemblies near the bottom of the tank.

Measurements of tank liquid height are made using the Lundel instruments which use ultrasound travel times to deduce liquid height in the level probes. Tank liquid heights can also be deduced from the absolute pressure measurement at the tank apex and a tank bottom differential pressure measurement from tank apex to muff inlet. Void fraction measurements are made using multiple beam densitometers at vertical and horizontal points along the pump suction piping, and a single beam densitometer at the muff. Liquid and air flowrates are measured by turbine flowmeters and thermal mass flowmeters, respectively.

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3. CODE AND MODEL DESCRIPTION

The version of RELAP5/MOD2.5 that was used for the calculations in this report and the RELAP5 model of the SET facility are described below.

3.1 Code Description

RELAP5 is an advanced, one-dimensional, thermal-hydraulic systems analysis computer code. RELAP5 has been used for many different applications. These applications include thermal-hydraulic analysis of commercial light water reactors (both pressurized and boiling water reactors), advanced light water reactor concepts, production reactors, and various experimental facilities. The code has benefited from extensive application and comparison with experimental data by many different organizations throughout the world.

All simulations for this study used the most recent RELAP5/MOD 2.5 version 3f based version used in the analysis of the K-reactor (3fv39). However, two minor modifications were required to apply this version to the SET model. First, the list of junction numbers representing the shell holes had to be expanded to be consistent with the SET nodalization (i.e., flowzone 5 flowing assemblies present in ring 5 of the moderator tank). Second, the flow values used in the muff update³ were reduced to be consistent with the one-fourth linear scale SET facility. Appendix A of Reference 4 includes the specific code changes required.

3.2 Model Description

All geometric data used for the RELAP5 model of the SET facility were obtained from SET facility drawings. The RELAP5 SET model used a four-level, five-ring two-dimensional model of the one-sixth sector moderator tank SET component. The component numbering scheme was chosen to be consistent with the recently adopted scheme used for the full-scale five-ring moderator tank model. The attempt to match distribution of the flow zones used in the SET facility caused the moderator tank nodalization to be slightly inconsistent with full-scale nodalization in that flowing assemblies are present in the fifth ring. Axial nodalization was identical to the four-level, full-scale moderator tank nodalization. Figure 2 shows the moderator tank in relation to connecting components.

The tank vent is connected only to Ring 3 to prevent any artificial mixing that may occur if the vent is connected to multiple tank volumes. The vent is currently modeled using a long (0.762 m, 2.5 ft) pipe with the appropriate vent loss resistance. The level probes were initially included in the model, but were later removed to reduce model complexity. Calculation results were insensitive to the presence of the level probe component models.

The PSP modeling methodology closely followed the methodology used for the full-scale model. During Phase I tests, no pump was present; instead an exit valve was affixed to the end of the PSP. Figure 3 shows the component connections for the PSP. The tank liquid level was controlled by a proportional-integral type controller which adjusted assembly liquid flowrates to attain the desired level. The remainder of this report covers the RELAP5 simulations of the SET facility Phase I tests.

4. PHASE I SIMULATION RESULTS

All simulations use the tank level controller to match the experimentally reported tank level (with the exception of the slow drain run (DRSGF1) which matches experimentally reported total liquid flowrates). These calculations include: a single-phase simulation at full flow, the simulation of a slow tank drain and refill, several two-phase steady state simulations with no air injection, and several two-phase steady state simulations with air injection into the assembly components. Also, tuning of the muff and tank radial loss factors is described. It should be noted that the SET experimental data used for comparison purposes in this report are currently being qualified and are preliminary.

4.1 Single-Phase Simulations and Loss Tuning

The tuning of loss factors for the one-fourth linear scale model followed the procedure used in the full-scale model. First, deterministic values were determined for the tank radial loss factors and all losses in the pump suction piping. The procedure used for the deterministic tank radial loss values takes into account the increasing radial flowrate as one moves from the inner ring to the outer ring. Then the tank loss factors were increased by a factor of 2.5 to be consistent with full-scale modeling. With these tuned loss coefficients, the RELAP5 model predicts air aspiration occurs at 0.25 m (9.8 in) which agrees well with 0.243 m (9.57 in) as reported in the Flow Regime Sensitivity Gravity Flow Tests.

Figure 4 shows the tank surface as a function of distance from tank apex as predicted by the RELAP5 model. As a check on the predicted shape, it is instructive to compare it to the shape reported in the L-Area tests and the SET facility. In both L-Area tests and SET facility tests, the shape of the tank surface at aspiration initiation can be derived from apex and muff inlet tank bottom pressures. The L-Area data must not only be scaled down but also compensated for using heavy instead of light water. Using the gravity driven flowrate reported in the SET facility (which is about midway between the scaled AC and DC flowrates), interpolated values for tank heights at apex and outer tank radius can be derived from the L-Area test data. Figure 5 shows a comparison of tank surface (inner and outer ring liquid heights) between L-Area data, SET data and RELAP5 data for aspiration initiation conditions. The L-Area data lie above the SET data, while RELAP5 predicts liquid heights in between these two data sets. It is also seen that SET data scale reasonably well to L-area data.

As in the full-scale model, the muff loss factor was used to represent the actual losses of the muff and transition elbow as well as any other losses in the PSP that were not represented by the deterministically derived loss factors. The experimental liquid flowrate for an essentially full moderator tank was matched by increasing the full-scale muff loss factor by a factor of 3. Note that although this loss is somewhat higher than previous work, it is still not a large fraction of the overall loss factor for the PSP for the Phase I configuration and thus seems reasonable. The required amount of muff loss tuning represents about 20% of the total PSP loss resistance. From the MF1GF1A test, for a average tank level of 1.1267 m (44.36 in), a total liquid flowrate of 2680 lpm (708 gpm) was reported compared to a RELAP5 prediction of 2703 lpm (714 gpm) which overpredicts by less than 1 percent.

Previous experience indicated that RELAP5 will overpredict air flow rates if atmospheric boundary conditions do not take into account the head of air due to elevation change between atmospheric boundary conditions. Starting from a hand calculated estimate for the head of air between the tank vent and the exit of the PSP, a dry simulation was

performed with the SET facility model. The exit pressure boundary condition was modified until the air flow rate was less than 10^{-6} kg/s. The amount of pressure differential applied to the atmospheric boundary condition was 36 Pa.

Finally, in the full-scale model, the hydraulic diameter of the muff volume was based on the flow area assuming cylindrical pipe geometry and did not account for the wetted perimeter of the muff vanes. The vane loss was accounted for through the muff loss factor. The mechanistic hydraulic diameter which accounts for the wetted perimeter of the vanes was about 15 times smaller than the hydraulic diameter actually used in the model. However, it was found, with the RELAP5 SET model, that the larger hydraulic diameter resulted in more accurate prediction of PSP liquid flow rates at lower tank levels. It is believed this happens because the smaller hydraulic diameter distorts the difference in liquid heights across the crossflow junction thereby distorting the gravity driven liquid flow-rate through the muff junction component. Using the smaller hydraulic diameter resulted in underprediction of liquid flow rates by about 10 to 20%. Hence, the calculations described in this report use the larger value of the hydraulic diameter for the muff volume which more closely matches experimental data than the smaller hydraulic diameter.

4.2 Moderator Tank Slow Drain Simulation

The first two-phase flow simulation presented is a slow tank drain and refill [DRSGF1]. In both the experiment and the RELAP5 model, the inlet liquid flowrate to the assemblies was controlled to effect the tank drain and refill transient.

Figures 6 through 9 display transient comparisons of tank levels, air flow rates, and vertical and horizontal void fractions. Figure 6 shows the RELAP5 predicted collapsed tank levels and the SET reported tank levels as measured by the level probe instruments. During the single-phase portion of the transient (before about 850 s and after about 1900 s), RELAP5 overpredicts the data by about 7 cm (2.75 in) in ring 1 and by about 13 cm (5 in) in ring 5. This situation is absent in the two-phase flow portion of the transient where ring 1 agrees well with the liquid heights reported for flowzone 1. RELAP5, however, slightly underpredicts the flowzone 5 liquid height during this transient portion. It must be noted that RELAP5 predicts the onset of aspiration (indicated by the sharp decrease in ring 5 liquid level) quite well. The reason(s) for the RELAP5 SET models' misprediction of liquid levels may be due to multi-dimensional effects not accounted for in the current model and/or code errors related to the air flow rate prediction anomaly described in the next paragraph. This behavior will be investigated in future work.

In Figure 7, the air flowrates through the moderator tank vent are shown. The shape of the SET data is reasonable since one would expect a jump in air flow rate at the initiation of aspiration then a gradual decrease in air flowrate as the flow regime in the PSP becomes more stratified, followed by the opposite trend as the tank is refilled. The RELAP5 air flow rate prediction, although lower in magnitude than the SET data, begins a similar trend at aspiration initiation but then undergoes a significant jump at about 1175 s after a smaller jump at 1100 s. The behavior is somewhat symmetric about the minimum tank level. This phenomena is currently being investigated.

Figures 8 and 9 show that the RELAP5 predictions of transient vertical and horizontal void fractions agree well with the SET data from the vertical and horizontal densitometers. RELAP5 slightly overpredicts the horizontal void fraction throughout the transient.

Figure 10 displays the tank differential height between apex and outer radius predicted by RELAP5 and the differential height derived from the reported level probe readings, both as a function of tank liquid level for the slow drain and refill transient. Both

levels first slowly rise as the aspiration point is approached, peaking at the aspiration point (where liquid flowrates are highest during gravity driven two-phase flow conditions), then decreasing with decreasing flowrate at lower tank levels. Although both RELAP5 and the SET data have similar trends and match well in the two-phase region after the aspiration point, RELAP5 underpredicts the differential height in the single-phase region before the aspiration point. This is expected from an inspection of Figure 6. Comparisons are difficult below about 12 cm (4.75 in) tank liquid level because of the apparent uncertainty in the SET data.

Finally, Figure 11 compares the muff junction and volume void fractions predicted by RELAP5 and the reported experimental muff void fraction. It is seen that, except for the jumps in experimental void fractions near the aspiration point (which will be examined in detail in later work), the experimental void fraction lies above the predicted muff junction void fraction (which is following the connecting tank volume void fraction) and lies below the predicted muff volume void fraction. This is due in part to the lumping of the unknown PSP loop resistances into the muff junction loss factor which causes RELAP5 to underpredict the pressure immediately after the muff junction component. With better characterization of the deterministic PSP loop losses this predicted void difference should decrease and more closely match the reported experimental void fraction.

4.3 Two-Phase Simulations without Assembly Air Injection

This set of RELAP5 simulations are compared to the MF1CF-1, 2, 4, and 5 series of tests. These tests consisted of steady state points where tank liquid level is maintained at a few points just above and several points below the air aspiration point. Test MF1CF3 was considered a special case of the next series of experiments (because of air injection through the assemblies) and was not considered here. The main consideration in this series of tests is the behavior of the air and liquid mass flowrates as well as the PSP void fractions at very low tank levels. Steady state calculations were run using each of the tank levels reported in the MF1CF1-5 series of tests. The data near the end of each steady state time interval was chosen for SET data comparison.

Figures 12 through 15 show the comparison between RELAP5 prediction and SET experimental results of liquid flowrate, air flowrate, vertical void fraction and horizontal void fraction versus tank level. Figure 12 shows that RELAP5 liquid flowrate predictions compare well with SET data. Figure 13 shows the calculated air flowrates responding in an opposite fashion from the SET data. This discrepancy is currently being investigated. Figure 14 shows RELAP5 void fraction prediction in the vertical section of the PSP compares well with the SET data. Figure 15 shows that RELAP5 overpredicts the void fraction near the end of the PSP (before the last elbow) by several percent except at the highest tank level where it overpredicts the SET data by 25%.

4.4 Two-Phase Simulations with Assembly Air Injection

This set of RELAP5 simulations is compared to the FRSGF1-11 series of tests. These tests are similar to the MF1CF1-5 tests described in the previous section except that air was injected through the assemblies in an attempt to make the air flow rate through the tank vent approximately zero. Again the main consideration in this series of tests is the behavior of the air and liquid mass flowrates as well as the PSP void fractions at tank levels ranging from just above the aspiration point to various points below the air aspiration point.

Figures 16 through 19 show the comparison between RELAP5 prediction and SET experimental results of liquid flowrate, air flowrate, vertical void fraction (in vertical pipe section) and horizontal void fraction (near end of pump suction piping) versus tank level. Figure 16 shows that RELAP5 predicts the liquid flowrates well compared to SET data. Figure 17 shows the discrepancy in RELAP5 air flow rate prediction that was seen in previous simulations. The RELAP5 air flow rate prediction follows a somewhat flat curve until about 0.12 m (4.7 in) where it severely overpredicts the air flowrate. Figure 18 displays the vertical void fraction predictions of RELAP5 agree very well with experiment. Figure 19 shows a somewhat close correspondence between SET data and RELAP5 prediction of void fraction in the horizontal section of the PSP with an overprediction of SET data by RELAP5 for points from aspiration until the lower tank levels.

5.0 CONCLUSIONS

The RELAP5 simulations generally compared well with SET data except for the air flow rate predictions. Liquid flow rates and vertical and horizontal void fractions were typically within about 10% of the SET data with some exceptions. The general agreement in these parameters indicates that the nodalization and modeling methodology based on the full-scale model adequately represents the one-fourth linear scale SET facility.

The SET air flow rates predicted by RELAP5, although unphysical, were improved over the full-scale benchmarking described in Reference 5. In particular, air aspiration began at about the correct tank level in the SET model. Furthermore, the predicted air flow rates were no longer consistently greater than the measured values as was the case in the full scale model. However, the predicted trend was unphysical in that the measured air flow rate decreased as the tank level decreased while the predicted air flow rate increased. The comparisons with the SET data indicate that additional code development is required to improve the air flow rate prediction. With SET data now available, a more mechanistic model can be developed to better represent air flow. In addition, possible important multi-dimensional effects will also be investigated.

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Figure 1. SET facility instrumentation and flow path schematic.

Figure 2. Nodal schematic of tank and associated components.

Figure 3. Noding scheme for pump suction piping model.

Figure 4. Moderator tank surface gradient at aspiration initiation.

Figure 5. Liquid height comparison at aspiration initiation.

Figure 6. Tank level comparison for slow drain test DRSGF1.

Figure 7. Air flow rate comparison for drain test DRSGF1.

Figure 8. Vertical void fraction comparison for drain test DRSGF1.

Figure 9. Horizontal void fraction comparison for DRSGF1.

Figure 10. Tank height differential comparison for DRSGF1.

Figure 11. Muff void fraction comparison for test DRSGF1.

Figure 12. Liquid flow rate comparison for MF1CF1-5 tests.

Figure 13. Air flow rate comparison for MF1CF1-5 tests.

Figure 14. Vertical void fraction comparison for MF1CF1-5 tests.

Figure 15. Horizontal void fraction comparison for MF1CF1-5 tests.

Figure 16. Liquid flow rate comparison for FRSGF1-11 tests.

Figure 17. Air flow rate comparison for FRSGF1-11 tests.

Figure 18. Vertical void fraction comparison for FRSGF1-11 tests.

Figure 19. Horizontal void fraction comparison for FRSGF1-11 tests.

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