ASSESSMENT OF RELAP5/MOD3.3 FOR SUBCOOLED BOILING, FLASHING AND CONDENSATION IN A VERTICAL ANNULUS

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ABSTRACT

Continued development of system analysis codes has resulted in the recovery of conservatisms originally imposed on nuclear power reactors, allowing for an increase in the capacity of the nuclear power fleet. These codes also play an instrumental role in the design and certification of new reactor systems. With the increased demand for passive natural circulation and gravity driven cooling options, these codes are met with the new challenge of simulating low pressure, low flow conditions. The objective of this work is to demonstrate the effectiveness of the widely used RELAP5/MOD3.3 code to simulate boiling, condensing and flashing flows under such conditions. Several conditions of significance were selected from a published database of two-phase flow data in a vertical annulus with inner diameter of 19.1mm and outer diameter of 38.1mm. The code calculation of pressure, temperature, void fraction, interfacial area concentration, and void weighted gas velocity along the 4.5 m test section is compared with data at five axial locations. In the 2.8 m heated section of the channel the code predictions compare favorably in general, although the error does increase at low system pressure. Beyond the heated length, code predictions of condensation and flashing show more noticeable disagreement along the 1.7m unheated section. Condensation appears to be consistently under-predicted. Flashing varies from relatively good agreement to complete failure, depending on the conditions at the exit of the heated section.

KEYWORDS
RELAP5, subcooled boiling, flashing, condensation, validation

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1. INTRODUCTION

Reactor safety codes have become increasingly relied upon for determination of safety margins, course of accident progression, design of new reactor concepts and systems, regulatory justification, as well as recovery of conservatism imposed by regulations. These code functions have fueled much of the understanding of reactor thermal hydraulics over the past several decades. Even with the emergence of higher fidelity computational tools such as CFD, the complexity of reactor systems will continue to demand accurate system codes for practical engineering solutions. Safety analysis codes will continue to play an important role in reactor analysis given the diversity of system phenomena and wide range of system conditions. It remains critical for current and future reactor concepts that safety analysis codes such as RELAP5 and TRACE continue to be improved through better modeling and comprehensive validation.

Historically, these safety analysis codes have been developed for high pressure, high flow and are considered to perform well under these conditions [1]. However under low pressure conditions several researchers have observed large errors in REALP5 [1-3]. Each of these past studies have assessed previous versions of RELAP and found that the code significantly under predicted the void fraction in boiling flow at low pressures, however little effort has been found for condensing and flashing flows. The demand for reliable code prediction in low pressure, low flow conditions comes as a direct result of a change in accident mitigation strategies throughout the nuclear industry. The new standard for reactor safety requires passive systems to provide long term cooling capability without operator intervention. The use of long term passive systems results in low pressure, low flow conditions within the reactor for decay heat removal. Furthermore the emergence of small modular reactors, many of which rely on natural circulation during startup, normal operation, and accident mitigation, provide an additional need for more accurate system codes and additional experimental validation within this operational space. Under natural circulation cooling the coupling of the flow rate, heat transfer, and pressure drop result in the need for highly accurate prediction of void fraction. Natural circulation flows are also much more susceptible to thermal-hydraulic instabilities which may cause dangerous fluctuations in the flow, challenging the integrity of the fuel. The new concepts for light water reactors, and the reactor safety systems, present a new challenge for safety analysis codes and more development is necessary to determine their applicability.

In this study, an assessment of RELAP5/MOD3.3 is presented for gas-dispersed flows with phase change. A well-documented, highly-accurate database which isolates the codes ability to predict boiling, condensation, and flashing in an annulus channel is chosen for this assessment. The objective of the paper is to identify possible areas of improvement necessary to apply RELAP5/MOD3.3 to low pressure systems and inform future efforts to improve constitutive models.

2. EXPERIMENTAL DATABASE

A complete description of the experimental data used for the present work is given in the original database publication [4], however it is summarized here for completeness of the RELAP5 assessment. The annulus test section with inner diameter of 19.1 mm and outer diameter of 38.1 mm is scaled based on a Boiling Water Reactor (BWR) subchannel and used to study boiling, condensing, and flashing steam-water flows. The subcooled liquid flow from the inlet of the vertical test section passes along 2.845 m of heated length provided by the cartridge heater, which also forms the inner wall of the annulus. An additional 1.632 m of unheated length continues downstream of the heated section to form the total 4.477 m test section length. The piping which forms the outer wall of the annulus channel is well insulated along the entire length, and small guide pins are required at five locations (immediately downstream of the measurement ports) to ensure proper alignment of the inner rod. The heat loss from the test section and pressure loss from the guide pins where found to be small. A sketch of the experimental test section is provided in Fig. 1.

Five measurement locations (six including the inlet) provide detailed information about the flow conditions at axial lengths z/D_h=0, 51.6, 108.2, 148.8, 189.3 and 229.9, where D_h = 19 mm is the hydraulic diameter of the annulus. At the single-phase, subcooled inlet, bulk liquid temperature and pressure are measured and the flow rate is given up stream of the inlet by a magnetic flow meter. Five measurement ports along the test section provide data for bulk liquid temperature, pressure, void fraction, interfacial area concentration, gas velocity, and Sauter mean diameter. For the purposes of this study the local two-phase measurements are area-averaged across the flow area. The third measurement port is positioned at the end of the heated length providing inlet conditions to the unheated section. Therefore the development and transport of boiling flow is observed from the inlet to the third port, while flashing and/or condensing flow is observed from the third to the fifth measurement port. Unlike data used in past RELAP5 low pressure boiling assessments, this data employs highly accurate measurement technique in a scaled geometry with significant heated and unheated length.

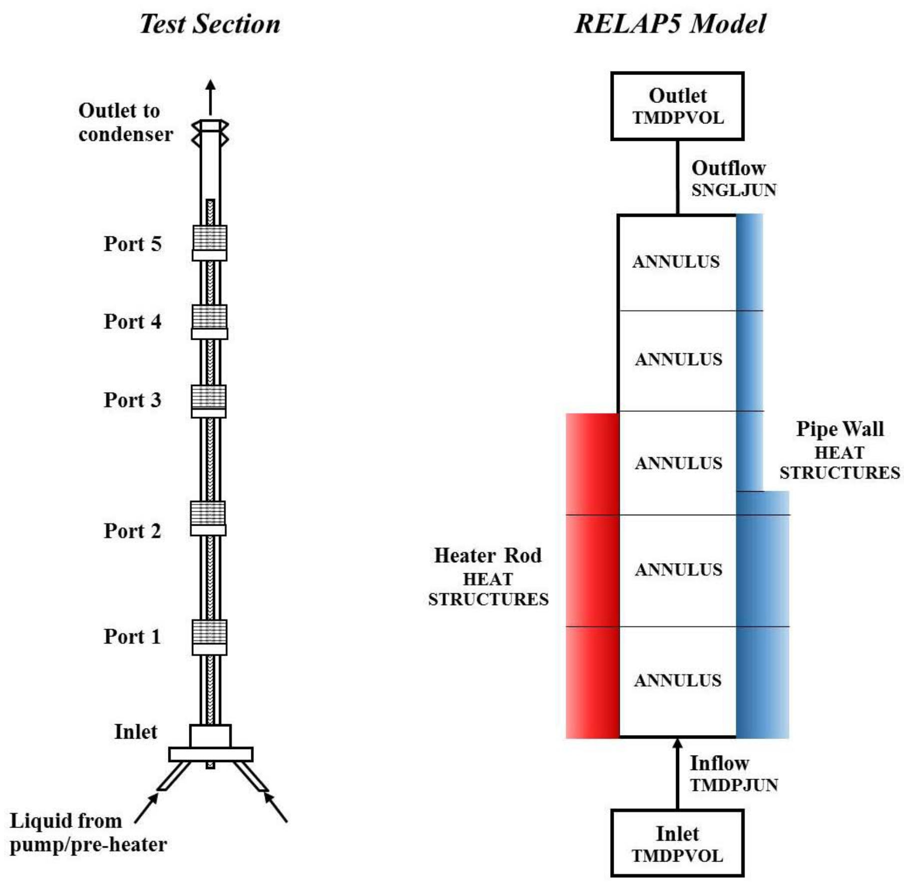

Figure 1. Sketch of the experimental test section (left) and RELAP5 nodalization (right).

A total of 57 conditions are reported for this database, ranging in pressure (180-950 kPa), heat flux (55-265 kW/m^2), inlet liquid subcooling (7-30 °C), and average inlet liquid velocity (0.23-2.52 m/s). The result of this test matrix are conditions of subcooled boiling, bulk boiling, flashing, and condensation covering conventional flow regimes of bubbly through churn-turbulent flow [5]. It is worth elaborating on the phenomena downstream of the third measurement port as the boundary condition changes from heated to unheated. In this unheated section the pressure and bulk liquid temperature will dictate the observed phenomena. In the case where the bulk liquid is still subcooled at the exit of the heated section, the vapor generated through subcooled boiling will condense in the unheated region due to the loss of the wall superheat. If the heated section has achieved bulk boiling, the bulk liquid temperature at the end of the heat length will have reached saturation and condensation in the unheated region will not occur. A wrinkle to this intuitive effect of the bulk liquid temperature is the influence of pressure. Since the pressure is decreasing as the fluid moves up the test section, there will also be a decreasing saturation temperature. At elevated pressure, the relative change in pressure in the unheated section to the total system pressure is small and therefore there is very little effect on saturation temperature. However at lower pressures, this is not the case and the decrease in saturation temperature through decreasing pressure will cause phase-change, often referred to as flashing. Therefore these effects of temperature and pressure result in four phase-change scenarios in the unheated region as discussed by Ozar et. al. [4]: constant void fraction (negligible flashing and condensation), pure condensation, pure flashing, and the combination of condensation followed by flashing.

3. RELAP5/MOD3.3 MODELING AND NODALIZATION

The experimental test section was discretized in RELAP5/MOD3.3 using five "annulus" components connected in series by standard single junctions as shown in Fig. 1. Annuli were discretized with a uniform 40 mm nodalization – except for a single node that was set at 45 mm which was required to get the proper spacing for the heated length. This nodalization gives a non-dimensional grid size of approximately two, i.e., $\Delta z / D_h \cong 2$. Increased grid refinement was found to cause a boiling induced instability in a significant number of simulations. Thus far, the convergence of coarser nodalizations to the provided solutions has not been studied. The minor flow restriction caused by the guide pins was included in the model by reducing the area of the junction downstream of the five measurement ports. The abrupt area change model was used to internally calculate the loss coefficient. The effect of the pins on the over-all solution is very small, however their local effect can be observed in the pressure profile.

The inflow condition, i.e., the liquid velocity, is set with a time-dependent junction that connects the inlet conditions to the first annulus. The inlet conditions, i.e., pressure and temperature, are specified through a time-dependent volume. At the exit a standard single junction connects to a time dependent volume to set the exit pressure. Unfortunately, this exit pressure is used to set the hydrostatic pressure in the test section due to the difference in junction specification, i.e., time-dependent vs. standard. Therefore if this exit pressure is set arbitrarily, it can result in a discontinuity in pressure at the inlet. This issue was resolved by setting the outlet pressure with a control variable that integrated a function ensuring the correct pressure gradient from the inlet condition to the first annulus node.

The heater rod was modeled with three heat structures. Only two radial nodes are used corresponding to the centerline and the inside wall. The boundary conditions are symmetric (insulated) at the centerline and convective at the wall and are connected to the hydrodynamic nodes of the first three heated annuli. There is a one-to-one correspondence in the axial nodalizations of the heat structures and the annuli. The heat flux is set in a general table which is converted to a power source in the heat structures using the nodal surface as an internal source multiplier.

While the experimental test section was well insulated, five heat structures representing the outer wall were also included in the model. Mirroring the inner wall, the outer wall structures contain only two radial nodes, convective and symmetric, and are connected to the corresponding hydrodynamic nodes with a one-to-one axial nodalization. Conservative values of Q = -500 W between the inlet and port two and Q = -120 W between port two and the exit were applied to model the heat loss. Here, by conservative it is meant that the largest values of heat loss observed during characterization tests are used. This will in turn give a conservative estimate of void fraction when studying boiling and condensation phenomena, but not for flashing. Including this heat loss, compared to the perfectly insulated case, produces a perceptible, but rather insignificant change in the results of the simulations.

It was found that when the simulation was run in a steady-state mode, the code could return a false temporal convergence, i.e., some variables were still changing, however slowly. Therefore the code was run in transient mode with an ending simulation time of 100 seconds and results were determined to be insensitive to increases in this simulation time. The maximum time step is restricted to 10 ms, although in a significant number of cases the actual time step is restricted even further by internal code checks, typically to satisfy the Courant number.

4. RESULTS AND DISCUSSION

4.1. Subcooled boiling

In this section we will focus on subcooled boiling results in the heated region, i.e., from the inlet to port three at $z/D_h = 148.8$. While none of the experiments were carried out at high pressures, $P_{in} < 1$ MPa for all cases, the 57 case test matrix can be generally divided into elevated, intermediate and low pressures. The significance of this pressure range is important because it represents one order of magnitude change in the density ratio. The effect of pressure in two-phase flow is dominated by its impact on the density ratio which decreases by roughly two orders of magnitude from atmospheric to BWR operating pressure. Therefore, this database quantifies the pressure affect within this first order of magnitude change in the density ratio. The matrix can also be divided into high and low flow conditions, however our results indicate that the flow dependence – particularly in comparison with the data – does not display a distinct trend as does the dependence on pressure. The following results show one case from each pressure range that resulted in a significant void fraction at the end of the heated section. These cases were also selected because condensation and flashing are minimal beyond port three.

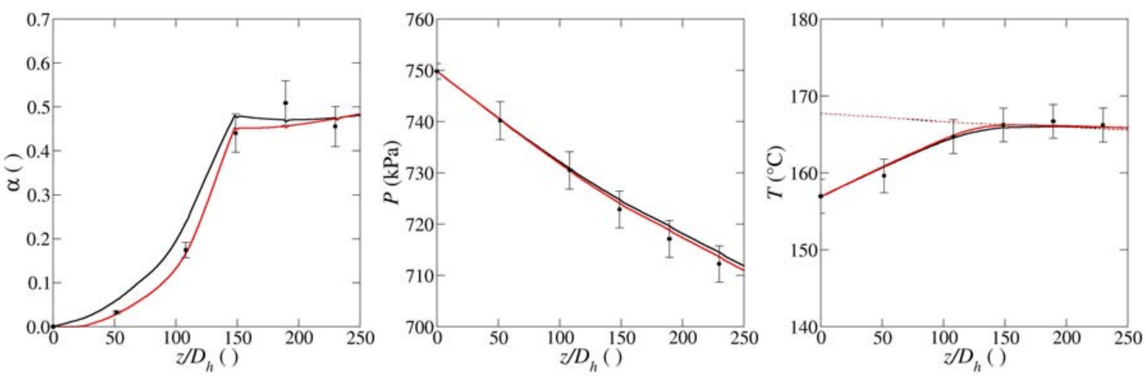

Figure 2. Comparison of baseline results (black) and original RELAP5 subcooled boiling model (red) at elevated pressure and high flow conditions: a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 750 kPa, $j_{f,in}$ = 1.0 m/s, $\Delta T_{sub,in}$ = 11°C, q_w''= 241 kW/m².

Figure 2 shows a comparison of the RELAP5/MOD3.3 simulation to the data of Ozar et al. [4]. The case shown in Fig. 2 is at elevated pressure and a low inlet flow ($j_{f,in} \cong 1$ m/s). Also shown for comparison (in red), are the results when the model is run using developmental option 24 which activates the original RELAP5 subcooled boiling model [6]. The default subcooled boiling model, which we refer to as part of the "baseline" results, is the SRL model [6], which is expected to be better low pressures. For this elevated pressure case, the void fraction profile predicted by the original RELAP5 subcooled boiling model is exceptional. The baseline case tends to over-predict the void fraction but not significantly. The maximum void fraction difference between the two simulations is approximately 7% between ports two and three. With this case and others, this over-prediction seems to stem from an early (i.e. too far upstream) prediction of the onset of nucleate boiling (ONB), which in this case occurs immediately.

The pressure and temperature profiles for both simulations are very similar and compare well to the data. There is a minor over-prediction of the pressure (under-prediction of pressure drop), particularly downstream of the heated region. However, all results fall within the measurement error of the data. There is a slight discrepancy in the comparison of the liquid temperatures which merits discussion. In the RELAP5/MOD3.3 model the fluid temperature is a v olume averaged value, specifically averaged throughout the channel cross-section. On the other hand, the reported experimental data is for the channel centerline temperature. Due to the axial development of the thermal boundary there is bias toward lower temperature measurements. This bias is most noticeable at the first port where the thermal boundary layer is small and the flow is not well mixed.

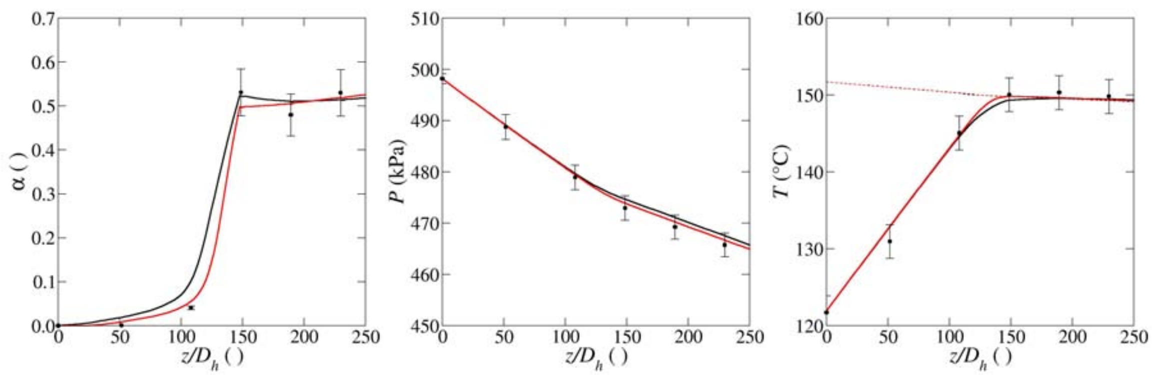

Figure 3. Comparison of baseline results (black) and original RELAP5 subcooled boiling model (red) at intermediate pressure and low flow conditions: a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 498 kPa, $j_{f,in}$ = 0.24 m/s, $\Delta T_{sub,in}$ = 30°C, q_w"= 156 kW/m^2.

Figure 3 shows a similar comparison at an intermediate pressure and low flow. Similar to the previous case, both simulations show excellent agreement with the data. Again, the delayed point of ONB allows the original subcooled boiling model to predict the void fraction at the first two ports more accurately; although both fall within the measurement uncertainty at the end of the heated section.

In general, the agreement with the experimental data deteriorates as the system pressure continues to decrease as previously reported by [1-3]. One such low pressure case is shown in Fig. 4. In this case the delayed ONB of the original subcooled boiling model no longer improves the comparison. The two models appear to bound the void fraction data at the first two ports. However, both models significantly over-predict the void fraction at port three by at least 20% void fraction (50% relative error). This leads to a considerable error in the pressure profile downstream. Despite all of the problems with this case, the liquid temperature still compares favorably throughout the channel (except at the first port due to the previously mentioned measurement bias). This case was not an exception; good temperature profile comparisons were a noticeable trend among all cases. In fact, only 3 of the 57 cases resulted in poor temperature predictions. The previous subcooled boiling assessments [1-3] report an under prediction of RELAP5 which is consistent with the prediction using the 'original subcooled boiling model' but only for the first two measurement ports. The data used in the previous assessments have very short heated lengths (0.3 m and 1m) and therefore were unable to capture this void development.

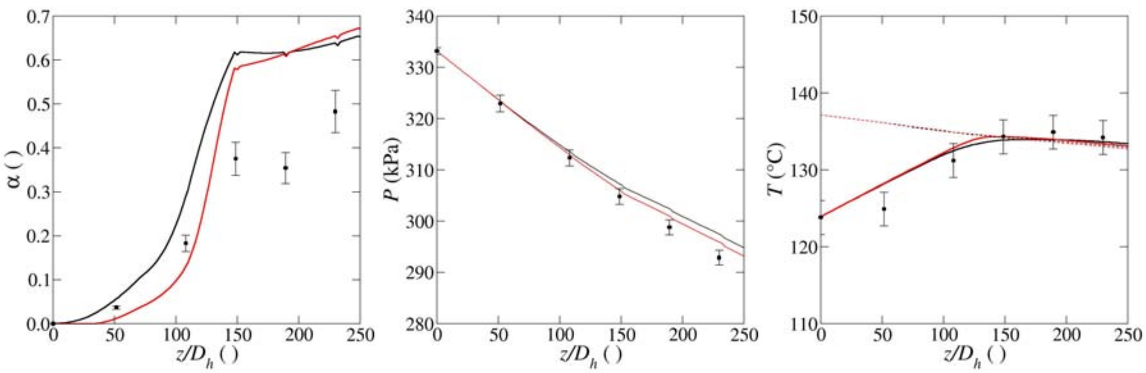

Figure 4. Comparison of baseline results (black) and original RELAP5 subcooled boiling model (red) at low pressure and high flow conditions: a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 333 kPa, $j_{f,in}$ = 1.0 m/s, $\Delta T_{sub,in}$ = 13°C, q_w"= 264 kW/m^2.

4.2. Condensation and flashing

In this section we will focus on results in the downstream unheated section. In general four scenarios are possible: 1) the fluid remains subcooled at the end of the heated section and condensation occurs, 2) the fluid is at or near saturation at the end of the heated section and becomes superheated, causing flashing, due to the continued pressure drop, and 3) a combination of the first two. Since the numerical model considers the entire experimental test section, it can be difficult to isolate errors related to one single phenomenon. We have taken care to select cases in which the boiling region is well predicted, by at least one of the two subcooled boiling models.

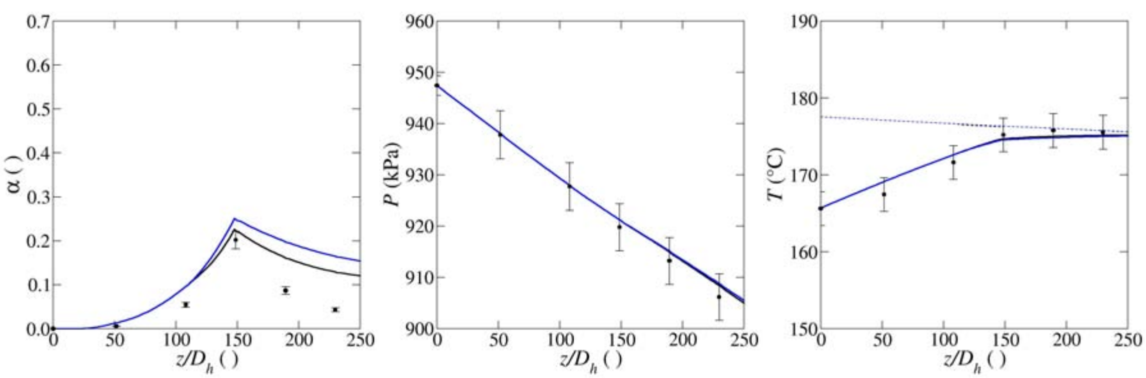

Figure 5. Comparison of baseline results (black) and the new condensation model (blue): a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 947 kPa, $j_{f,in}$ = 1.0 m/s, $\Delta T_{sub,in}$ = 12°C, q_w"= 209 kW/m^2.

First we consider a case where only condensation occurs in the unheated, downstream region as shown in Fig. 5. Upstream of port three, the baseline model does accurately predicts the subcooled boiling region and the starting condition for condensation is within experimental measurement error; again demonstrating RELAP5's predictive ability of boiling flow at elevated pressures. Downstream of port three condensation occurs and the void fraction decreases. However, the condensation rate is significantly underestimated. The change in void fraction from port three to port five is measured at $\alpha_5 - \alpha_3$ = -16.0% experimentally and only estimated at $\alpha_5 - \alpha_3$ = -9.7% by the baseline RELAP5/MOD3.3 model. Developmental option 45 was also tested which activates "the newly developed model for condensing interphase heat transfer" [6]. Results with the new condensation model are shown in blue in Fig. 5. The condensation rate is not improved. In fact, the overall comparisons are slightly worse due to an increased void fraction at port three. The pressure and temperature profiles compare quite well to the data. If anything, it can be said that the predicted pressure is too high and the predicted temperature is too low. Both of these errors contribute to an increase in subcooling and therefore would increase the condensation rate, however slight. In other words, it can be argued that if the pressure and temperature were more accurately predicted, the resulting void fraction prediction would only become worse. Finally, it is worthwhile to note that while there are quantitative issues, the key qualitative trend is captured: the bulk liquid temperature is less than saturation throughout the test section and the void fraction continually decays downstream of port three.

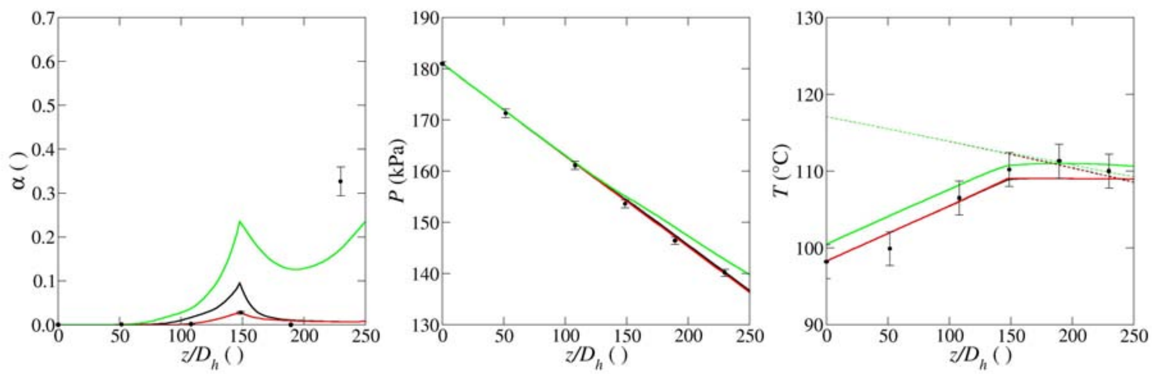

Figure 6. Comparison of baseline results (black), original RELAP5 subcooled boiling model (red) and the baseline model with artificially high inlet temperature (green): a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 181 kPa, $j_{f,in}$ = 0.24 m/s, $\Delta T_{sub,in}$ = 19°C, q_w"= 56 kW/m^2.

Next we consider a case with significant vapor generation due to flashing. In this case it is also valuable to look at the phenomena preceding the flashing. Figure 6 shows a low pressure, low flow case that also has a low wall heat flux so that the developed void fraction due to boiling is very low. As seen in previous results, the major difference between the SRL and original subcooled boiling models appears to stem from the predicted location of ONB. In this instance the original model preforms better. However, in both cases the condensation is captured quite accurately between ports three and four. Unfortunately, the flashing that should have occurred between ports four and five is essentially missed by both simulations. The predicted liquid pressure, and therefore the saturation temperature, in both instances agree well with the experimental data. The temperature predictions on the other hand are slightly low. While both results fall within the measurement uncertainty, the predicted onset of flashing (approximately at ΔT_{sub} = 0) does not occur until after port five. In the experiment, this occurs at some point between ports four and five, as evidenced by the substantial jump in void fraction. This makes it difficult to assess the flashing model itself.

Therefore, in an effort move to move ΔT_{sub} = 0 further upstream, the inlet liquid temperature is artificially increased. These results are shown in green in Fig. 6 using the baseline model except for the exaggerated inlet temperature. Upstream of port four the results become significantly degraded. The developed void fraction due to boiling is significantly over estimated. Due to the reduced liquid subcooling, the condensation model is no longer able to quench the extra void fraction between ports three and four. Additionally, the pressure curve deviates appreciably above the measurements. However, the $\Delta T_{sub} = 0$ location is now positioned immediately upstream of port four. While the "starting point" for flashing in this simulation is quite different than the experimental conditions – specifically the void fraction begins at 12.5% vapor rather than nearly single phase liquid – the simulation is still unable to capture the measured jump in void fraction.

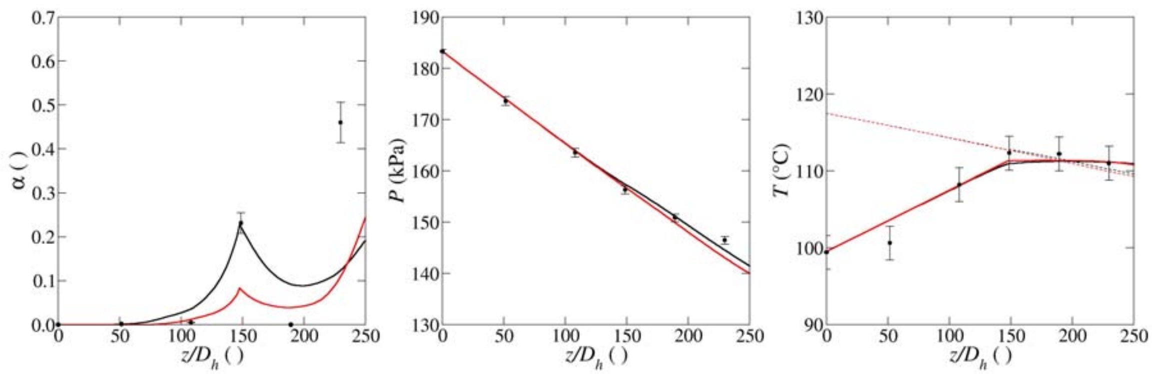

Figure 7. Comparison of baseline results (black) and original RELAP5 subcooled boiling model (red): a) void fraction, b) pressure, c) liquid (solid) and saturation (dashed) temperatures. Conditions: P_{in} = 183 kPa, $j_{f,in}$ = 0.24 m/s, $\Delta T_{sub,in}$ = 18°C, q_w''= 61 kW/m^2.

Finally, it should be mentioned that when $\Delta T_{sub} = 0$ occurs much closer to the end of heated section at port three, i.e., when significant condensation does not occur, the predicted flashing in the downstream region is considerably improved. While the combination of boiling, condensation and flashing is a challenging task, these are important processes in low pressure natural circulation and influence the flow stability. The combination of these processes can result in flow excursion instabilities such as geysering [7] or flashing-induced density wave oscillations [8]. Although system codes can rarely be relied on for predicting flow instabilities directly due to excessive numerical diffusion, such codes are frequently used in conjunction with stability maps to determine where within the stability plane the system is operating. The current inability of the code to predict condensation and flashing would suggest large uncertainty in determining the system operation relative to the stability region and therefore uncertainty about the presence of flow instabilities. One of these challenging cases is shown in Fig. 7, further highlighting the difficulty of predicting steam-water flows even in an unheated region. Between ports two and three, the void fraction spikes from near zero to 23%. Immediately downstream, and within the same distance, all of that developed void fraction condenses. Beyond port four the continuing pressure drop causes the saturation temperature to fall below the liquid bulk temperature and a substantial amount of flashing causes the void fraction to spike once again, reaching nearly 50% by port five. Qualitatively, RELAP5/MOD3.3 is able to capture all of these trends. Quantitatively, however, there remains considerable disagreement with the experimental data.

5. CONCLUSIONS

This assessment of RELAP5/MOD3.3 has revealed several strengths and weaknesses in the prediction of two-phase flows with phase change. For all cases the axial temperature and pressure distributions are shown to agree well with the experimental data. At elevated pressures the prediction within the heated region captures the developing boiling flow well. However, the void fraction prediction in the heated region is shown to deteriorate with decreasing system pressure resulting in very large relative errors. Furthermore, the assessment is unable to recommend either the original or SRL boiling model based on their varied success in low pressure conditions. The previous RELAP5 boiling assessments may be incomplete in their benchmark due to very short heat length, limiting the possible range of conditions and down-stream over prediction of the modeling. While the trend of decreasing void fraction due to condensation in the upper, unheated region is captured by the simulations, the condensation rate is consistently under-predicted leading to large relative errors in void fraction. This result has been demonstrated under low as well as elevated pressure conditions, and the new condensation model is shown to give no measureable improvement. Lastly, the rate of flashing in the unheated section is shown to be significantly under predicted. Although flashing is a downstream phenomena, requiring accurate prediction of boiling and condensation, the assessment indicates that rapid void fraction production from a steady pressure reduction is suppressed. Under low pressure conditions, which can undergo all three events within a relatively short distance, leads to very large relative error in RELAP5/MOD3.3 predictions.

The common theme through each of these processes (boiling, condensation, flashing) is the requirement to correctly predicting a relative temperature. The error in prediction of saturation temperature and bulk liquid temperature alone may be small, but conditions driven by the difference between the two temperatures will present a fundamental difficulty for the code. The propagation of even small errors in temperature or pressure can result in significant phase change errors when the two temperatures are similar. Historically, this error has not been an insurmountable issue as design basis accidents employed pump-driven long-term cooling. The benefit of forced convection boundary conditions to the accuracy of system codes cannot be overstated. In forced convective flows, the error in void fraction has very low impact on the flow rate and, in-turn, cooling capability. However in natural circulation flows, the void fraction prediction will drive the flow condition. The error in void fraction prediction will propagate directly to error in flow rate and cooling capability. While the large errors demonstrated in the assessment may be manageable for the classic approaches to reactor cooling, the applicability of the current generation of safety codes to new natural circulation strategies is unclear. Furthermore in a natural circulation system the coupling between the flow rate, pressure, and heat transfer complicates the traditional approach of dealing with code error, which is to justify conservatism in assumptions or modeling. For example, a 'conservatively-low' heat transfer model may apply to flow boiling, however in natural circulation boiling the low heat transfer effects the flow rate which may not result in a 'conservative estimate' under all conditions. Improvement of the constitutive relations should be revisited to meet these challenges.

NOMENCLATURE

Latin

D_h	hydraulic diameter [m]
j_f	superficial liquid velocity [m/s]
P	pressure [kPa]
Q	power [W]
q_w''	wall heat flux [W/m^2]
T	temperature [°C]
z	axial location [m]

Greek

α	void fraction
ΔT_{sub}	liquid subcooling, $T_{sat}(P) - T_f$,
Δz	node length

Subscripts

1 - 5	port number
f	liquid (fluid) condition
g	vapor (gas) condition
in	inlet or inflow condition
sat	saturation condition

ACKNOWLEDGMENTS

The authors would like to thank Dr. Basar Ozar for providing supplementary information related to the experiment.

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