Downcomer Boiling Phenomena Analysis during Large Break Loss of Coolant Accident In APR1400

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ABSTRACT

The Blowdown is one of the research areas of interest to the Emirates Nuclear Energy Corporation (ENEC) in the United Arab Emirates. The investigation and the assessment of these complex phenomena occurring at the blowdown and reflood periods either as separate effects or as aggregate contribution to the integral system are of primordial importance to the nuclear power plants safety studies. In particular, the ability of system codes (such as RELAP, MARS, and TRACE) to correctly reproduce the coolant behavior and thermodynamic properties under these conditions has to be continuously validated and improved [8]. Examples of similar studies can be found in [4], [5], and [6].

Hence, the aim of the present study is to conduct a numerical study using the system codes (TRACE and RELAP) to predict the Downcomer boiling phenomena occurring during the reflood phase of a large-break LOCA for the APR1400 and compare with the experimental data obtained from the Downcomer Boiling (DOBO) test facility reported in [4]. Although this test case has been already studied using the system codes mentioned above, it is revisited herein using the latest versions of the codes to examine the effect due to the codes recent modifications in terms of correlations and their implementation and to understand the main factors affecting the discrepancies between the codes predictions observed in the previous studies.

1 INTRODUCTION

The new design features of the APR1400 include four trains of the safety injection system with Direct Vessel Injection (DVI) line. Each of the four trains consist of a safety injection pump (SIP) and a safety injection tank (SIT). With this change of APR1400 the Downcomer boiling phenomena is slightly changed and thus worth revisit and reproduce the downcomer boiling phenomena occurring during the reflood phase of large-break LOCA for the APR1400. The lumped system codes; RELAP and TRACE; will be employed to reflect the physical phenomena. Finally, the experimental data of the downcomer test facility will be used to compare with the system codes predictions.
In order to understand the physical phenomena occurring during the loss of coolant accidents and then reproduce the downcomer boiling phenomena for the APR1400 occurring during the reflood stage of Large-Break LOCA using lumped system codes many research studies, experimental test facilities and numerical studies were viewed and considered.

Yun et al. [4] [5] conducted an experiment in the downcomer boiling test facility (DOBO) to identify the thermal hydraulic coolant behavior of the downcomer boiling phenomena of a postulated LBLOCA in the cold leg of APR1400. The experiment was divided into two phases. The first phase aims to visually observe and obtain the two-phase flow parameters; void fraction and bubble velocity. The second phase aims to measure the local bubble flow parameters at five different elevations. Based on the results of this experiment, two research have been performed to analyze the data using different system codes. In the first study [4], RELAP5, TRAC-M and TRAC-original analytical codes were used while MARS code was utilized in the second study [5]. One of the major findings reported in [4] is the appearance of the bubbly boundary layer with different thickness depending on the applied heat flux. System codes analysis employed in the first research [4] has evaluated the interfacial friction coefficient and it was concluded that TRAC-M, RELAP5 and TRAC-original models for interfacial friction coefficients need improvements in predicting the downcomer boiling phenomena. Also, MARS code results of the subcooled boiling, reported in [5] of the subcooled boiling need enhancement in the area of the wall nucleation and interfacial heat transfer.

Huh et al. [6] relied on the experimental data of the DOBO testing facility conducted by Yun et al. [4] to evaluate the prediction capability of the TRACE code for the downcomer boiling phenomena. The measured parameters of void fractions and liquid subcooling degree at the bottom of the heated section obtained from the previous study were compared with the TRACE version 4.160 simulation results. A single and multi-channel models have been conducted to precisely analyze the multidimensional phenomena. The injected water flow rate and temperature besides pressure at the bottom test section obtained from the experiment were used as boundary conditions. The results of this study show that the multi-channel model were better in predicting the void fraction. In addition to that, the code results show that the models are not sensitive numerically to change of the heat flux in the predictions of the void fraction in the middle of test section. Furthermore, the code model overestimated and underestimated the subcooling degree of the water drained from the bottom of the test section and thus these models should be enhanced for the flow regime map, wall nucleation and interfacial heat transfer to improve the code capability of capturing this phenomena.

Besides the above mentioned studies that relied on the DOBO test facility results to evaluate the capability of different system codes in predicting the downcomer boiling phenomena, Cho et al. [7] utilized CUPID code to analyze the two dimensional phenomena using two phase flow models and a numerical solver. The code simulation successfully reproduced the local bubble flow parameters which are the void fraction distribution profile in the lowest and highest elevations and the flow regime pattern changes from bubbly type of flow to mist and churn types of flow. However, this code has a limited capability in the void fraction and velocity predictions in the middle region of the test section and thus the two phase models should be improved.

Based on the earlier mentioned studies, numerical and experimental data, the new feature of APR1400 with DVI mode will be considered to reproduce the downcomer boiling phenomena occurring during the reflood phase of LBLOCA. TRACE and RELAP system codes will be employed to reflect the physical phenomena and compare their predictions with the experimental data of the DOBO test facility.
2 METHODOLOGY

To precisely reproduce the large-break LOCA in the presence of the direct vessel injection mode in APR1400 and focus on the reflood phase in the downcomer region for the system codes validation, the Downcomer boiling (DOBO) test facility was chosen for this project. Later on, the system codes RELAP5 and TRACE will be used to simulate the downcomer region of the test facility and the results will be compared with the collected data from the test facility for validation purposes.

2.1 Downcomer Boiling Test Facility

As shown in figure 1 below, the facility has been designed based on APR1400 where the elevation, gap size, temperature, pressure, and velocity are matching those in APR1400 [5]. The scaling law has been employed for the flow rate and width ratios as shown in table 1 below. The circumferential wall length of downcomer was reduced to 47.08 fold. Scaling distortion of the circumferential length and flow rates need to be considered to predict the actual multidimensional downcomer boiling phenomena occurring in APR1400.

Table 1: Downcomer boiling test facility scaling ratio [4]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling ratio</th>
<th>DOBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gravity ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flow rate ratio</td>
<td>$\alpha_R$</td>
<td>1/47.08</td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gap size ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Elevation</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Width ratio</td>
<td>$I_R$</td>
<td>1/47.08</td>
</tr>
<tr>
<td>Area ratio</td>
<td>$\alpha_R$</td>
<td>1/47.08</td>
</tr>
<tr>
<td>Volume ratio</td>
<td>$\alpha_R$</td>
<td>1/47.08</td>
</tr>
</tbody>
</table>

The bubbly boundary layer thickness, the axial void fraction distribution and the emergency core cooling water subcooling degree parameters will not be affected by the scaling law.

The test section of the DOBO test facility consists of heated wall that simulate active core region with high flux. The DVI nozzle is installed at the top of the heated test section wall. The maximum pressure and heat flux the facility can handle are 500 kPa and 100 kW/m² respectively. The dimensions of the test facility are listed in table 2.

Referring to table 2, the heat transfer area was found to be 5.1 m². Opposite the heated section wall, a glass window was installed to enable visual observations of the downcomer boiling phenomena with the two phase flow conditions. A steam vent is located in the top of the test section with a diameter of 7.8 centimeters. To avoid the uncovering of the heated section, the water will be drained with specific flow rate from the bottom of the test section to maintain a certain level in the section. The DVI nozzle will inject a maximum of 3.3 kg/s and it was found that 1.33 kg/s of emergency core cooling water is required during the reflood phase after 250s from the large-break LOCA establishment time. Two heat exchangers are placed to cool...
and condense the water leaving from the steam vent and water drainage and they are used too to control the temperature of the safety injection tank.

Table 2: Downcomer boiling test section dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>0.3</td>
</tr>
<tr>
<td>Depth</td>
<td>0.25</td>
</tr>
<tr>
<td>Test section total height</td>
<td>6.4</td>
</tr>
<tr>
<td>Heated section height</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Effective instrumentation tools have been used to measure and check the temperature, pressure, axial void fraction and water level in the heated section. The local bubble parameters

Figure 1: Geometrical configuration of the downcomer region of Downcomer Boiling test facility and the reactor downcomer of APR100 [5]
were measured using 5-cinductance probes. These probes were installed at five axial elevations and have the capability to move in two dimensions to measure the local void fraction and bubble velocity parameters.

Five postulated large-break LOCA tests were conducted and the data were collected for the reflood phase only after reaching steady state condition. A summary of the conditions of the experiment is listed below.

Table 3: Downcomer boiling test facility experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T_{ECC} (°C)</th>
<th>P_{SYS} (kPa)</th>
<th>W_{ECC} (kg/s)</th>
<th>q'' (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>110.1</td>
<td>162.8</td>
<td>1.22</td>
<td>50.2</td>
</tr>
<tr>
<td>R2</td>
<td>110.2</td>
<td>161.4</td>
<td>1.16</td>
<td>69.7</td>
</tr>
<tr>
<td>R3</td>
<td>109.6</td>
<td>166.5</td>
<td>1.2</td>
<td>82.1</td>
</tr>
<tr>
<td>R4</td>
<td>109.5</td>
<td>170.8</td>
<td>1.2</td>
<td>91.1</td>
</tr>
<tr>
<td>R2-1a</td>
<td>110.7</td>
<td>158.5</td>
<td>1.33</td>
<td>70.5</td>
</tr>
</tbody>
</table>

The R2 and R2-1a conditions were thermodynamically the same and the good agreement in the void fraction distribution profile resulting from these two tests confirms the reliability of this DOBO test facility data.

The glass window on the opposite side of the heated wall allowed visual observation of the flow regimes occurring during the downcomer boiling phenomena. The flow regimes are expected as bulk boiling is dominant at the top of the test section whereas a distinctive bubble boundary layer takes place at the bottom and the middle sections.

![Figure 2. Nodalization of Single-channel model(a) and Multi-channel model(b)](image-url)
2.2 Input Generation of RELAP5 and TRACE

Two models were composed using SNAP for RELAP5 and TRACE. The first model was created to study the multidimensional phenomena and the local bubble parameters in the axial direction only thus it can be considered a one dimensional scheme and is called single channel model. The second model was composed to study the phenomena in two dimensions thus the models was refined to include four nodes in the radial direction (4x24) and is called multichannel model. Figure 2. (a) and (b) represents the single and multi-channel respectively.

3 RESULTS AND DISCUSSION

Simulation results of RELAP5/MOD3.3 and TRACE5.4 were plotted for single-channels and multi-channels and compared with the experimental data of DOBO test facility and the simulation results conducted by Huh et al.[6].

3.1 Void Fraction Distribution Profile

![RELAP5: Axial void profile in the heated section for 69.7 kW/m²](image)

**Figure 3:** RELAP5 axial void fraction in heated section for 69.7 kW/m²

Simulation results show that multi-channel models are better in capturing the multidimensional downcomer phenomena compared to the single channel models as shown in figure 3 for a heat flux of 69.7 kW/m². The differences between the code simulation results and the experimental data can be justified by three main factors which are the heat structure, drain mass flow rate and void fraction averaging procedure.

Figure 4 through 5 shows that RELAP5.33 overestimated the experimental values whereas TRACE5.4 and TRACE4.160 underestimated the experimental values. TRACe4.160 code simulation in the reference study was the closest to the experimental data. The lack of information about the time averaging procedure, the drain mass flow rate and the heat structure cladding material types and dimensions have led to the overestimation and underestimation of simulation results in this study.
3.2 Degree of subcooling

The degree of subcooling of the drain water at the bottom of the test section was calculated to see how much decay heat has been removed from the system during the reflood phase where the steam blanket and downcomer bypass governs its flow. Figures 6 and 7 shows the effect of heat flux on the subcooling degree at the bottom of the heated wall. The degree of subcooling at the bottom of the test section was determined by subtracting the saturation temperature at the bottom of the heated section from the fluid temperature at the top of the test section.
Figure 6: Liquid subcooling at the bottom of the test section comparison using RELAP

Figure 6 shows that this project RELAP code simulation results are in good agreement with the experiment results unlike the predictions of the reference study that underestimated and overestimated the experimental data for the single channel and multi-channel models respectively. In addition to that, multi-channel model predictions of this project were even better in capturing the phenomena compared to the single channel model.

Figure 7: Liquid subcooling at the bottom of the test section comparison using TRACE

On the other hand, the prediction of this project by TRACE code simulations for the single channel were the closest to the experimental data whereas predictions of the single model in the reference study underestimated the cooling degree. The multi-channel predictions of this project overestimated the subcooling experimental data similar to the reference study multi-channel model.
4 CONCLUSION

The main goal of this study was to investigate the large-break LOCA during the reflood phase in the downcomer region in the APR1400 with the new design feature of direct vessel injection using RELAP5 and TRACE lumped code systems.

The experimental data from the Downcomer Boiling test facility was used for the validation and verification of RELAP5 and TRACE codes. It was found that results of RELAP5 are more sensitive to axial elevations compared to TRACE code. In addition to that, the results of RELAP5 and TRACE regarding liquid subcooling showed closer prediction to the experiment data. Furthermore, it was found that the drain mass flow has a huge impact on void fraction distribution profile.

Additionally, a major finding is that the lumped code results heavily rely on the generated input such as the drain mass flow rate, heat structure cladding material type and dimensions. Moreover, it was concluded that the multi-channel models are better in capturing the downcomer phenomena compared to single channel models.

Besides the major findings from the validation steps, it was found that the scattering of void fraction at the highest elevation was justified by the direct condensation between the downward subcooled emergency core cooling water and the upward steam in the heated section.

Finally, it was found that higher temperature of emergency core cooling leads to less degree of subcooling at the bottom of the test section.

REFERENCES