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IMPROVEMENT OF THE RELAP5-3D MODEL OF CONDENSATION IN THE PRESENCE OF NONCONDENSABLES

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ABSTRACT

Condensation of steam on the primary side of a steam generator in a pressurized water reactor (PWR) is one means of removing decay heat during some accident scenarios, including small break loss of coolant accident (SBLOCA). However, when noncondensable gasses mix with steam, it impairs condensation. To correctly predict plant behavior, nuclear power plant (NPP) safety analysis codes such as RELAP5-3D must model the effect of condensation in the presence of noncondensables properly.

A potential error in the RELAP5-3D code was reported in the condensation model in the presence of noncondensables by the University of Wisconsin[1]. The report indicated that the calculated condensation heat flux was under-predicted due to the modeling of the mass transfer in the gas mixture. The original documentation describing the implementation of the model was reviewed and compared with alternative formulations. An alternative that uses saturation vapor density at temperature of total pressure instead of the saturation vapor density at vapor partial pressure for calculating vapor mass flux was implemented. Comparison of the alternative method with the original against experimental data for several test cases showed improvement for most test cases.

NOMENCLATURE

h_m = mass transfer coefficient (1/s)
j_v = vapor mass flux (kg/m^{3}s)
N = Number of experimental data points
P_{vb} = vapor partial pressure in the bulk (kg/ms^2)
P_{vi} = vapor partial pressure at the liquid-vapor/gas interface (kg/ms^2)
P = total pressure (kg/ms^2)
q'' = heat flux (kW/m^2)
ρ_{mb} = combined vapor and gas density in the bulk at the bulk vapor/gas temperature (kg/m^3)
ρ_{vb} = saturation vapor density (kg/m^3)
T_w = wall surface temperature (K)
T_{gi} = liquid-vapor/gas interface temperature (K)
X_n = noncondensable mass quality.

INTRODUCTION

Condensation of steam on the primary side of a steam generator in a pressurized water reactor (PWR) is one means of removing decay heat during some accident scenarios, including small break loca (SBLOCA). However, noncondensable gasses may mix with steam generated in the core and affect condensation. Some sources of such gasses include dissolved nitrogen in the accumulators or the emergency core cooling system (ECCS) and hydrogen generated by fuel-cladding reacting with water during an accident.

The presence of noncondensable gases in the wall condensation process has been shown to have an insulating effect on the heat transfer between the vapor/gas and the wall [some references]. Further, when vapor condenses, some noncondensable gas is dissolved in the condensate while the remaining gasses accumulate in the steam generator tubes, increasing their concentration and further degrading the condensation process. Eventually, the tubes become filled with noncondensable gasses and cease to effectively remove decay heat. Therefore to correctly predict plant behavior, it is important that the effect of condensation in the presence of noncondensables be modeled properly.

Some methods for calculating the effects on condensation of steam on the outer wall of a vertical tube in the presence of noncondensable gasses have been developed. For example, in 2008, Ganguli, et al[2] developed a steam condensation model for the outside of vertical tube geometries in the presence of noncondensable gases such as air and helium. In 2014, J. Su, et al[3] Analyzed experiments for the effect of noncondensable gases on steam condensation over a vertical tube external surface under low wall subcooling.

The RELAP5 condensation model in the presence of noncondensables was developed by Babcock & Wilcox for the

RELAP5/MOD2 code by Nithianandan[4] and later made the default model in the RELAP5 series of codes. Fig. 1 depicts a schematic of film condensation on a vertical surface. The vapor flows radially toward the cold wall and transports the noncondensables to the wall, where they accumulate due to condensation of the vapor. The resulting noncondensable concentration gradient causes noncondensable diffusion back toward the mainstream counter to the vapor flow direction. The vapor partial pressure and temperature are lower in the noncondensable buffer layer than in the mainstream. The presence of the noncondensable gas results in a reduced temperature difference (T_{gi}-T_w) and reduced heat flux through the liquid film[5].

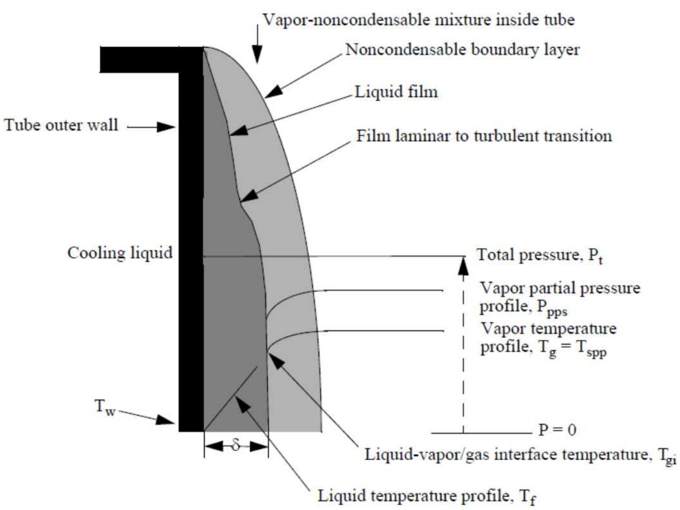

Figure 1. Noncondensable influence on condensation

In the model the vapor mass flux (j_v) is calculated in RELAP5-3D 2015 by Eqn. (1).

$$j_v = h_m \rho_{vb} \ln\left(\left[1 - \frac{P_{vi}}{P}\right] / \left[1 - \frac{P_{vb}}{P}\right]\right) \quad (1)$$

where P_{vb} is the vapor partial pressure in the bulk, P_{vi} is the vapor partial pressure at the liquid-vapor/gas interface, P is the total pressure, h_m is a mass transfer coefficient, and ρ_{vb} is the saturation vapor density at P_{vb}.

The formula for saturation vapor density ρ_{vb} is given by Eqn. (2).

$$\rho_{vb} = (1 - X_n)\rho_{mb} \quad (2)$$

where ρ_{mb} is the combined vapor and gas density in the bulk at the bulk vapor/gas temperature and X_n is the noncondensable mass quality.

ALTERNATIVE FORMULATION

The University of Wisconsin[1] examined and compared the basic condensation models used by the MELCOR and RELAP5-3D codes. This examination found that RELAP5-3D should to be corrected to properly account for the presence of noncondensables. The heat fluxes calculated from the two different code models was compared to AP600 test data and found that the RELAP5-3D model underestimated the condensation heat flux, but the results from MELCOR closely followed the data. The difference in the two models was found to primarily lie in the density used in the calculation of the vapor mass flux. RELAP5-3D uses the variable ρ_{vb} and MELCOR uses the variable ρ_{mb}. Thus, it was recommended that RELAP5-3D switch to the density used in MELCOR to calculate the vapor mass flux.

The original RELAP5-3D source documents that describe the model implementation were investigated. The model description document by Nithianandan, et al[4] indicates that the saturation vapor density at the bulk vapor partial pressure (ρ_{vb}) is used in the calculation of the heat flux due to condensation of vapor at the liquid-vapor interface. The implementation report indicates that the equation for the condensation heat flux comes from the 2nd edition of Collier[6]. However in the 3rd edition[6], the ρ_{vb} notation is not used. Instead the density that is used is noted as ρ_g, which is interpreted as the combined vapor and gas density in the bulk, or ρ_{mb} in the notation used above.

The derivation by Collier[6] indicates that the combined vapor and gas density in the bulk should be used. In order to determine the effect of making the proposed change in the RELAP5-3D code, the alternative formulation provided in Collier was implemented and the RELAP5-3D calculated results for both methods were compared to experimental data.

UCB-KUHN TESTS

The UCB-Kuhn tests[7] are described in detail in the report by Shumway[8]. The experiment is depicted in Fig. 2. The test section (condenser tube) was a vertical pipe with a downflow of steam at constant pressure and noncondensable mass fraction (for the tests with noncondensables). Cooling water was pumped upward through an annular jacket around the condenser tube to absorb energy.

The test section was instrumented with thermocouples to measure temperature and pressure transducers at the inlet and outlet to measure system pressure and mass flow rate. Some of the UCB-Kuhn tests were repeated to verify the results. It was found that many of the repeated tests fell outside of the original error bands indicating that the error bands in the test were underestimated[8].

The RELAP5-3D models used for Shumway original assessment[7] were recovered and used for the current assessment. The input model was developed such that the center of each volume corresponds to the approximate location of a thermocouple. A heat structure was attached to the pipe wall with a convective boundary condition. The outer wall of the heat structure is set to a fixed temperature boundary condition which uses the temperature values obtained from the thermocouple measurements. The inlet and outlet pressure conditions correlate to the measured system pressure and the measured mass flow rate was specified at the top of the test section.

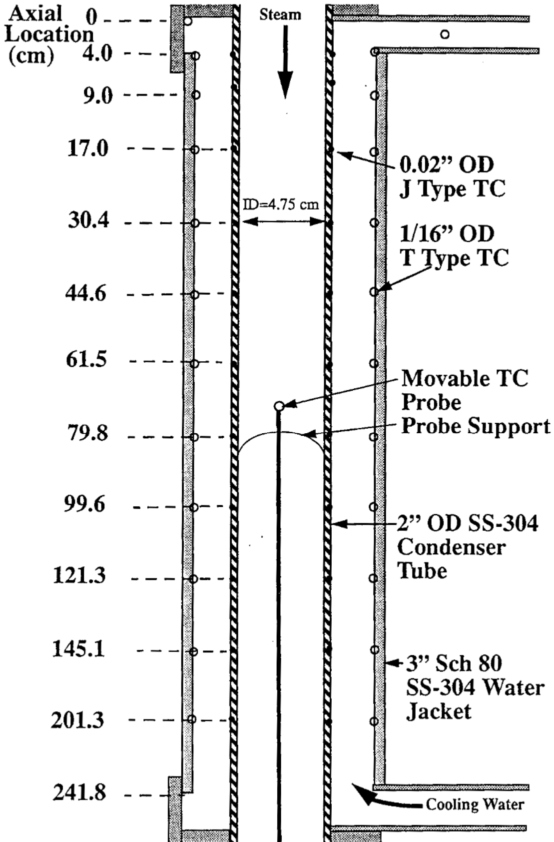

FIGURE 4. UCB-Kuhn test section.

Figure 2. UCB-Kuhn test

The tests varied only in the system pressure, mass flow rate, wall temperatures, and noncondensable mass fractions. The inlet pressure, mass flow rates, and noncondensable mass fractions are listed in Table 1.

Table 1. UCB-Kuhn test case conditions.

Test Case	Inlet Pressure (MPa)	Gas Mass Flow Rate (kg/s)	Noncondensable Mass Fraction
1.1-1	0.1161	0.01672	0.0
1.1-2	0.2020	0.01708	0.0
1.1-3	0.3071	0.01667	0.0
1.1-4	0.4074	0.01672	0.0
1.1-5	0.5040	0.01694	0.0
1.4-1	0.1106	0.008333	0.0
1.4-3	0.3105	0.007861	0.0
1.4-5	0.5015	0.008194	0.0
2.1-1	0.4203	0.01406	0.00988 / Air
2.1-7	0.4003	0.01558	0.0988 / Air
3.1-2	0.2081	0.01647	0.0108 / Air
3.1-5	0.5174	0.01660	0.0109 / Air
3.2-2	0.1998	0.01664	0.0503 / Air
3.3-2	0.2012	0.01840	0.102 / Air
3.3-5	0.5043	0.01839	0.103 / Air
3.4-2	0.2120	0.01664	0.196 / Air
3.5-2	0.2059	0.01661	0.396 / Air
3.5-5	0.4948	0.02637	0.372 / Air
4.1-2	0.2050	0.008393	0.0104 / Air
4.3-2	0.2128	0.009653	0.0935 / Air
4.3-5	0.5039	0.01007	0.0924 / Air
4.5-2	0.2046	0.01394	0.402 / Air
4.5-5	0.5056	0.01390	0.382 / Air
5.2-1	0.3990	0.01256	0.00289 / Helium
5.2-3	0.4305	0.01287	0.00932 / Helium
5.2-6	0.4330	0.01407	0.109 / Helium
6.1-5	0.4969	0.01644	0.0

UCB-KUHN HEAT FLUX COMPARISONS

The RELAP5-3D heat flux calculations were compared with the UCB-Kuhn data for the cases. The data and calculations were compared with a root-mean square (RMS) calculation given by Eqn. (3).

$$RMS = \sqrt{\frac{\sum_1^N \left| \frac{q''_{predicted} - q''_{measured}}{q''_{measured}} \right|^2}{N-1}} \quad (3)$$

where q'' is the heat flux, and N is the number of data points.

The values for RMS are given in **Table 2**. The calculated values for the original code version and the modified version are presented.

Table 2. RMS comparison results for UCB-Kuhn test data and RELAP5 predictions.

RELAP5 Version	RMS all 205 points	RMS steam only 62 points	RMS air only 119 points	RMS helium only 24 points
Original	0.178	0.204	0.172	0.139
Modified	0.184	0.204	0.183	0.129

The results show that the modified version of the code produces slightly larger RMS overall. As expected, the results are unchanged for the steam cases as the condensation model was not modified for the cases without noncondensables present, the results for air cases are worse with the modified code, and the results are improved for the smallest data set, the helium cases.

Figs. 3a through 3d show code calculations vs. data for several representative tests. Fig. 3a shows identical results between the original and modified results as expected because no noncondensables were present in this case. Fig. 3b shows improved results for Test 3.5-2 (Air) with the modified code. However Fig. 3c shows worse results overall for Test 4.5-2 (Air). In Fig. 3d the results for Test 5.2-6 (Helium) show improved results overall.

Heat flux comparison plots were developed for all of the test cases, but only a few representative plots are shown.

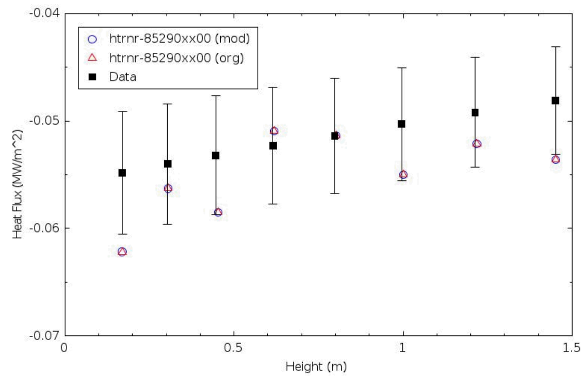

Figure 3a. UCB Test 1.1-1

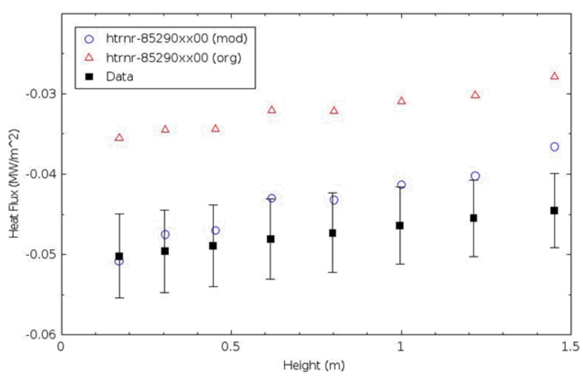

Figure 3b. UCB Test 3.5-2

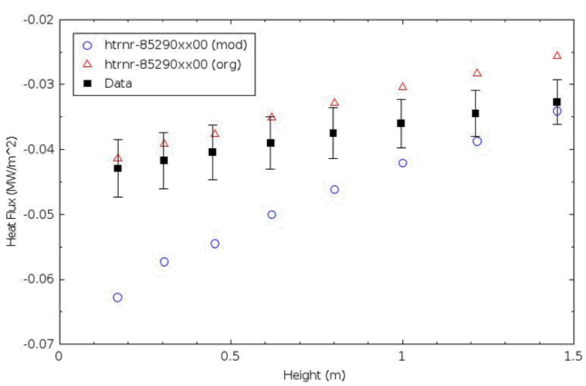

Figure 3c. UCB Test 4.5-2

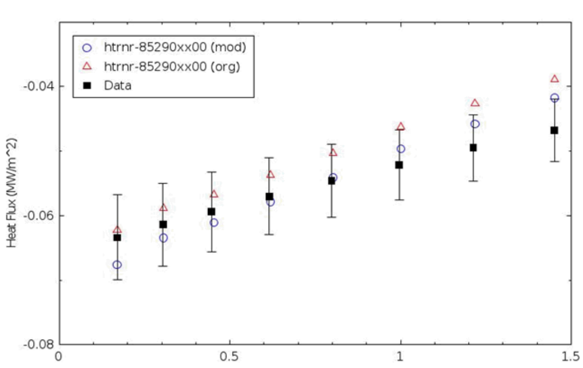

Figure 3d. UCB Test 5.2-6

MIT TESTS

The MIT tests conducted by Siddique[9] are described in detail in the report by Shumway[8]. These tests are only summarized here. The MIT test setup was similar to UCB-Kuhn tests. The experimental setup is shown in Fig. 4. The test section consisted of a downward flowing mixture of steam and noncondensable (either helium or air) that is cooled by a concentric cooling water jacket.

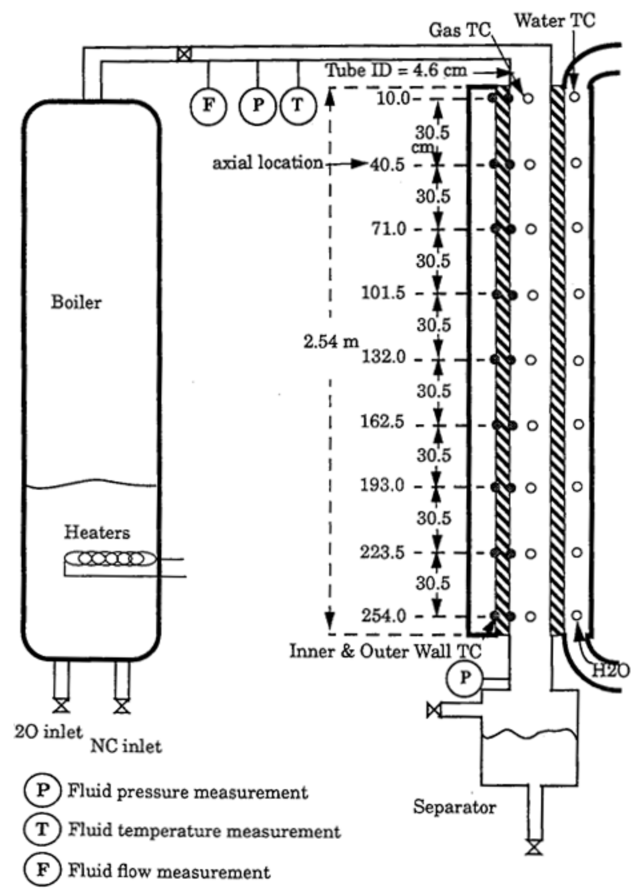

Figure 4. MIT-Siddique experiment from 1992

The MIT RELAP5 input decks were developed by modifying the UCB-Kuhn input decks to the slightly different geometry and conditions. The test conditions are summarized in Table 3.

Table 3. MIT test case conditions

Test Case	Inlet Pressure (MPa)	Gas Mass Flow Rate (kg/s)	Noncondensable Mass Fraction
6H	0.244	0.00255	0.0479 / Helium
7A	0.209	0.00284	0.0802 / Air
8A	0.217	0.00299	0.137 / Air
14H	0.144	0.00545	0.0532 / Helium
16H	0.214	0.00526	0.0213 / Helium
17H	0.252	0.00549	0.0536 / Helium
18H	0.271	0.00553	0.0731 / Helium

19A	0.114	0.00663	0.168 / Air
19H	0.293	0.00553	0.0932 / Helium
22H	0.465	0.00596	0.0543 / Helium
24A	0.214	0.00639	0.113 / Air
25A	0.221	0.00685	0.155/ Air
26A	0.233	0.00740	0.224 / Air
27A	0.243	0.00786	0.269 / Air
28A	0.252	0.00814	0.306 / Air
29A	0.266	0.00890	0.356 / Air
31A	0.403	0.00644	0.148 / Air
42A	0.221	0.0101	0.149 / Air

Figs. 5a and 5b show two representative calculations with comparisons to data for the MIT-Siddique test. Fig. 5a shows that the results for Test 8A (Air) improved for this case. Fig. 5b shows improved results at lower heights, but slightly worse at the higher heights.

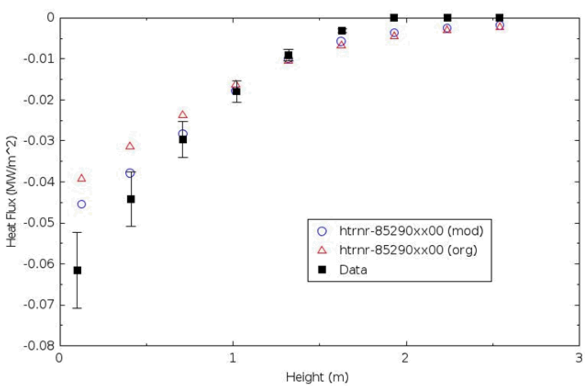

Figure 5a. MIT-Siddique Test 8A

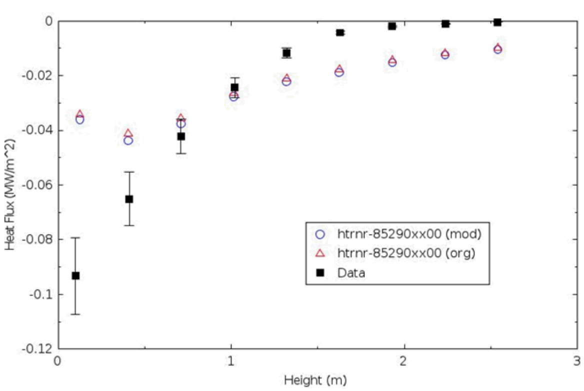

Figure 5b. MIT-Siddique Test 18H

The RELAP5 heat flux calculations were compared to the MIT test data and an RMS value was calculated. The original assessment report by Shumway[8] presented RMS data for heat flux points above 1, 2, and 5 kW/m^2. It was noted in the assessment report that the experimental errors became large at low heat flux values, so the data is considered less reliable at lower heat fluxes. The RMS results are reported similarly here and are shown in **Table 4**.

Table 4. RMS comparison results for MIT test data and RELAP5 predictions.

RELAP5 Version	RMS 136 pts $q'' \geq 1$ kW/m^2	RMS 132 pts $q'' \geq 2$ kW/m^2	RMS 123 pts $q'' \geq 5$ kW/m^2	RMS 61 pts air $q'' \geq 5$ kW/m^2	RMS 62 pts He $q'' \geq 5$ kW/m^2
Original	1.66	1.04	0.368	0.279	0.4412
Modified	1.74	1.08	0.344	0.209	0.4407

The results show very poor agreement with data at the lower heat flux values. Of the 136 total data points, only 13 were below the 5 kW/m^2 heat flux value where the results are significantly improved. The results with the modified code are shown to be improved above the 5 kW/m^2 heat flux threshold, but are worse below this value. *It is significantly better for air above 5 kW/m^2, but virtually the same for Helium.*

Heat flux comparison plots were developed for all of the test cases, but only a few representative plots are shown.

CONCLUSIONS

Because an error was reported in the calculation of condensation heat flux in the presence of noncondensable gases, the model implementation documentation was reviewed. Theory indicates that the density used in the calculation of the vapor mass flux should be the combined vapor and gas density in the bulk at the bulk vapor/gas temperature, rather than changed from the saturation vapor density at the vapor partial pressure. The alternate model was programmed and its calculations compared with the UCB-Kuhn and MIT-Siddique experimental data. For the UCB data the alternative formulation produced slightly higher RMS measures overall and for air, but is lower for Helium. For the MIT data the alternative method produces slightly higher RMS measures against data for the full set of data, is about the same for Helium at higher heat fluxes, and produces much lower values for air at higher heat fluxes. Thus the two tests show opposite trends.

Since comparison with experimental data favored neither method, but theory justifies the alternative method, the latter will supplant the former method in future releases of RELAP5-3D.

REFERENCES

1. Fu, W., Yoon, D., and Corradini, M. L. “Assessment of the MELCOR and RELAP5-3D Code for Condensation in the Presence of Noncondensable Gas.” *NURETH-16.* Chicago: American Nuclear Society, 2015.

2. Ganguli, A., Patel, A.G., Maheshwari, N.K., Pandit, A.B., “Theoretical modeling of condensation of steam outside different vertical geometries (tube, flat plates) in the presence of noncondensable gases like air and helium,”

Nuclear Engineering and Design, 2008, Vol.238(9), pp. 2328-2340.

3. Su, J., Sun, Z., Ding, M., Fan, G., "Analysis of experiments for the effect of noncondensable gases on steam condensation over a vertical tube external surface under low wall subcooling," Nuclear Engineering and Design, 15 October 2014, Vol.278, pp. 644-650.

4. Nithianandan, C. K., Morgan, C. D., Shah, N. H., and Miller, F. R. "RELAP5/MOD2 Model for Surface Condensation in the Presence of Noncondensible Gases." *Proceedings of 8th International Heat Transfer Conference.* San Francisco, 1986. 1627-1633.

5. RELAP5-3D, Code Development Team. *RELAP5-3D Code Manual, Volume IV: Models and Correlations.* Idaho Falls: INL, 2015.

6. Collier, J. G. and Thome, J. R. *Convective Boiling and Condensation, 3rd ed.* Oxford University Press, 1994.

7. Kuhn, S. Z., Schrock, V. E., and Peterson, P. F. "Final Report on U. C. Berkley Single Tube Condensation Studies." UCB-NE-4201, 1994.

8. Shumway, R. W. *Assessment of RELAP5/MOD3.2 Condensation Models.* Developmental Assessment Test Report, Idaho Falls: INEL, 1995.

9. Siddique, M. *The Effects of Noncondensable Gases on Steam Condensation Under Forced Convection Conditions.* PhD Thesis, Department of Nuclear Engineering, MIT, 1992.