Assessment of RELAP5/MOD3.3 Condensation Models for the Tube Bundle Condensation in the PCCS of ESBWR

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Abstract

The passive containment condenser system (PCCS) in an ESBWR reactor consists of vertical tube bundle submerged in a large pool of water. The condensation model for the PCCS in a thermalhydraulics code RELAP5/MOD3.3 consists of the default Nusselt model and an alternate condensation model from UCB condensation correlation. An assessment of the PCCS condensation model in RELAP5/MOD3.3 was carried out using experiments conducted on a single tube and tube bundle PCCS tests at Purdue University. The experimental conditions were simulated with the default and the alternate condensation models in the REALP5/MOD3.3 beta version of the code. The default model and the UCB model (alternate model) give quite different results on condensation heat transfer for the PCCS. The default model predicts complete condensation well whereas the UCB model predicts the through flow condensation well. Based on this study it was found that none of the models in REALP5 can predict complete condensation as well as the through flow condensation well.

Keywords: RELAP5, condensation models, assessment, tube bundle.

1. Introduction

In the General Electric's Economic simplified boiling water reactor (GE-ESBWR) the PCCS is a passive heat exchanger that allows the transfer of reactor heat via steam condensation to the outer water pool (GE Nuclear Energy, 1992, 2006). Following a loss of coolant accident and steam discharge into the containment, the containment has mixture of steam and non-condensable (NC) gas (nitrogen gas). The PCCS consists of a vertical tube bundles submerged in a large pool of water. The steam intake to the PCCS is from drywell (DW) and the condensate drains into the gravity driven core cooling system (GDCS) as shown in Figure 1. There is vent line from the PCCS that is submerged into the suppression pool (SP). The vent line enables venting of non-condensable or steam – NC mixture should the DW pressure is higher than the SP pressure by the submerged height of vent lines. The PCCS condenser must be able to remove sufficient energy from the reactor containment to prevent containment from exceeding its design pressure following a design basis accident. The PCCS operates in three modes as shown in Figure 2. The through flow mode refers to condensation where there is net outflow of the uncondensed steam. The complete condensation refers to the condensation of all steam entering the tube. The PCCS may cycle between through flow and complete condensation mode where periodic venting occurs is referred as cycling venting mode of condensation.

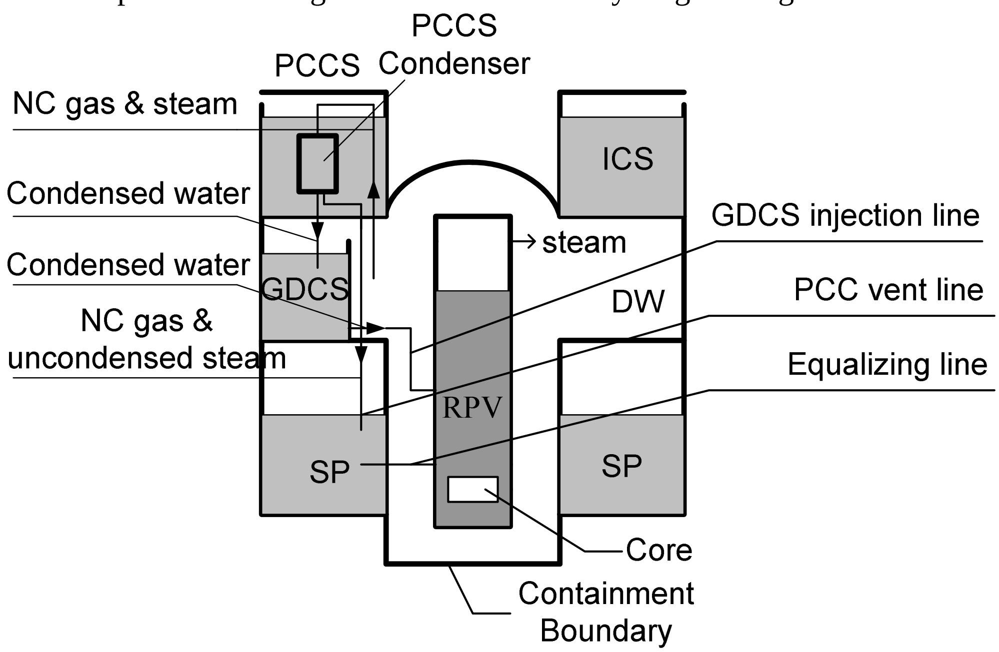


Figure 1. Schematic of the ESBWR PCCS, RPV- reactor pressure vessel, SP-suppression pool, DW-drywell, ICS- isolation condenser system, GDCS-gravity driven cooling system

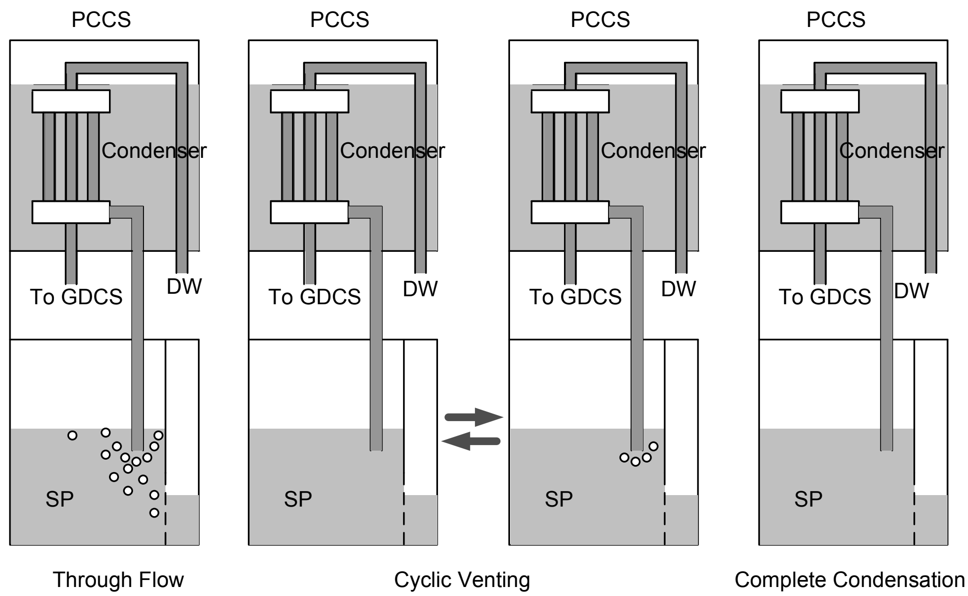


Figure 2 Three modes of PCCS operation

In order to predict the transient behavior of a reactor during an accident best estimate thermalhydraulics codes such as RELAP5 are used. The code predictions are as good as the models they contain. Here in the present work the PCCS condensation model in the REALP5/Mod3.3 code (NUREG/CR-5535/Rev1 2001) is assessed using an experimental data. RELAP5 is a light water reactor transient analysis code developed for US NRC for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for a nuclear plant analyzer. RELAP5 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixture of steam, water, noncondensable, and solute.

RELAP5/MOD3.3 beta version has two wall film condensation models, the default and the alternate model. The default model uses the maximum of the Nusselt (1916) model for laminar film and Shah (1979) correlation for turbulent film with a diffusion calculation by Colburn and Hougen (1934) when noncondensable gases are present. The alternate model uses the Nusselt model with UCB multipliers (Vierow and Schrock 1991), which is considering the effects of the noncondensable gases and the interfacial shear.

In order to assess the wall condensation model in RELAP5/MOD3.3 code, the PCCS single tube and tube bundle experimental data by Revankar et al (2006, 2008) are used. In the RELAP simulation experimental loop with tube bundle test section and secondary pool boiling section are simulated and the wall condensation model in the code is analyzed with the default and alternate (UCB) condensation models.

2. Tube Bundle Condenser Experiments

The multi-tube test facility consists of a steam generator (SG), steam and air supply line, tube bundle test section, secondary pool, condensate tank, SP, and a storage tank. A general schematic of the test facility is displayed in Fig 3. The SG is made from a 45.7 cm diameter, 3.05 m height, schedule 40 stainless steel pipe. It is powered by a 100 kW immersion type sheathed electrical heater, mounted at the lower flange. At maximum power, the SG can produce steam at a flow rate of 50 g/s. The steam supply line directs the vapor to the test section.

Three condenser test sections were used in the experiments. Two single tube test sections were made of tube of 25.4 mm (1 inch) diameter and 50.8 mm (2 inch) diameter each (Fig. 4). The tube bundle consisted of four tubes of diameter 50.8 mm each. The specific design of the test sections were based on the scaling analysis results from the prototype design (Revankar et al 2008).

The bundle is made of four condenser tubes arranged as a square so that the boiling condition in the center of the bundle can be well achieved. Each tube has a length of 1.80 m, which is the same as the prototype design. The pitch between two tubes is 6.35 cm and p/D=1.25. On the top of the condenser there is a one meter long insulation part, which is used to measure the pool water level change. This part is also used to minimize the inlet effect. After the insulation part, a top header was designed to distribute the incoming steam into four condenser tubes. The volume of the header was calculated from the volumetric ratio between test loop and prototype. To keep the volumetric ration as well as the header length, the header is comprised of two parts: the upper cylinder and lower cylinder. The 4-tube condensation bundle is connected right after the top header. The bottom header, which is the last part of the condenser, is connected with the tube bundle. The structure and dimension of the bottom header is exactly the same as the top header. An axial and cross sectional schematic of the bundle condenser is displayed in Fig 4. The condensed steam, from the condenser tubes, leads out of the test section to a condensate tank. The condensate tank is made of 1.5 m tall, 30.5 cm diameter schedule 40 stainless steel pipe, and is mounted vertically under the test section.

The outer tube, which is also displayed in Fig 4 (b), represents the secondary pool. As steam passes through the condenser tubes, heat is transferred to the water inside the secondary pool. This heat transfer process results in steam being condensed inside the condenser tubes and water boiling off in the secondary pool. The secondary pool is made of schedule 10 stainless steel pipes consisting of a 25.4 cm diameter bottom section and a 40.6 cm diameter top section. The two different size pipes are welded together by a reducing section that bridges the two sizes. The total length of the entire secondary pool is 4.1 m.

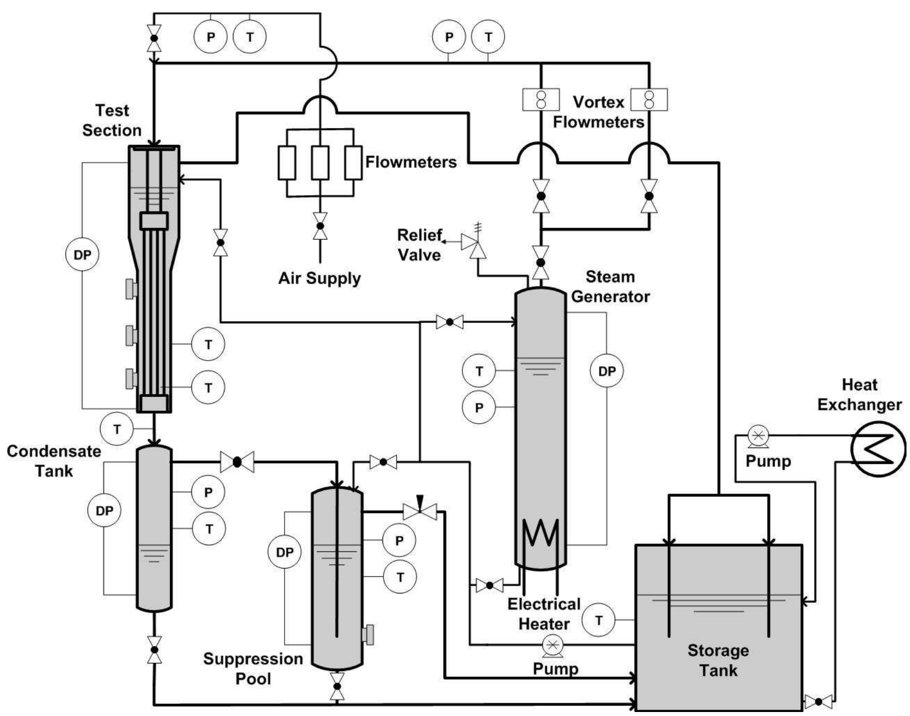
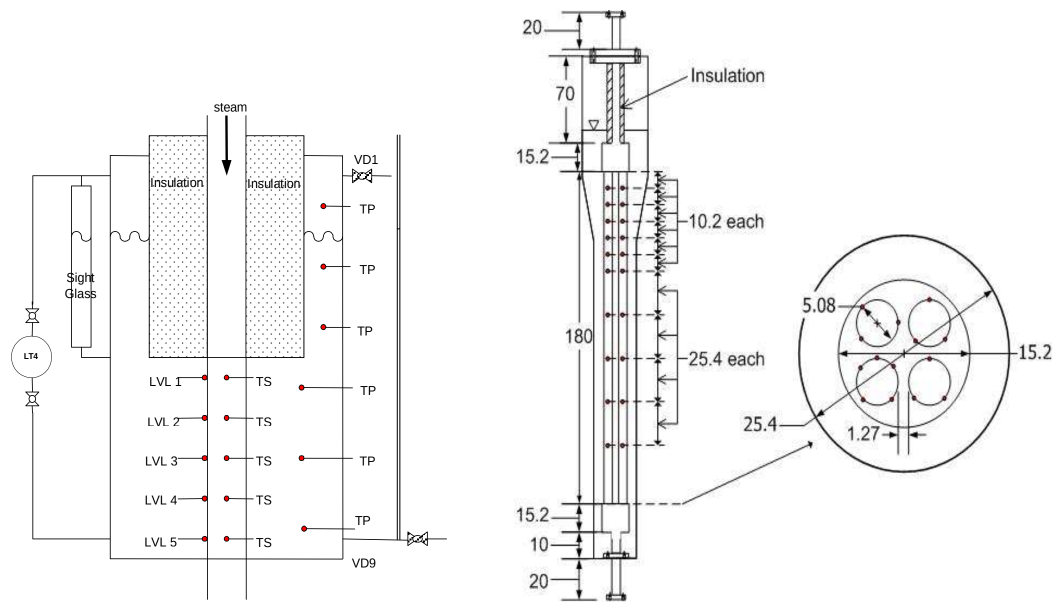


Figure 3. Schematic of test facility

For complete condensation experiments, there is no NC gas present and the vent line to the SP is kept closed. The experiment is initiated by starting up the data acquisition system and heating up the SG. The valve above the SG is kept closed during the heating period. When the pressure in the SG is high enough to start conducting an experiment, the valve is then opened to bleed any air out of the system. The air is bled through the steam line and test section then out the bottom of the condensate tank to the storage tank.

After all the air has been bled out of the system, a valve below the condensate tank is shut. Once this valve is shut, the system pressure increases as more steam accumulates and the secondary water pool heats up. The experiment begins when the water in the secondary pool reaches saturation temperature and the pressure becomes a steady state condition. Data is taken with the data acquisition system as long as the pressure remains at a steady state or until a sufficient amount of data has been recorded.

In case of through flow condensation, when the secondary water temperatures reach saturation condition (~100^{o}C), the required steam flow rate and air flow rate were established. The test section pressure was maintained at a desired level by use of the blow-down valves or air supply line valve. The steam temperature, flow rate, secondary water pool temperature and the system pressure were checked to verify the steady state. Data was taken once the steady state was established.



(a) Single tube (b) Four tube bundle

Figure 4. Axial and cross sectional schematic of condenser test sections (all units in cm)

3. RELAP5 Nodalization

The RELAP5 nodalization for the tube bundle experimental loop is presented in Fig. 5. Similar nodalization was also developed for single tube experiment. Major components of the test loop are modeled with appropriate simplification. For the tube bundle test section, each condenser tube test section is modeled as a PIPE component 301, heat conduction in the condenser tube wall is modeled using a heat structure component 1301, and the secondary side pool boiling section is modeled as an ANNULUS component 321. RELAP5 calculates the condensation heat transfer between the condenser tube inside wall (1301) and the PIPE 301, the conduction heat transfer in tube wall (1301), and the boiling heat transfer between the condenser tube outside wall (1301) and the ANNULUS 321.

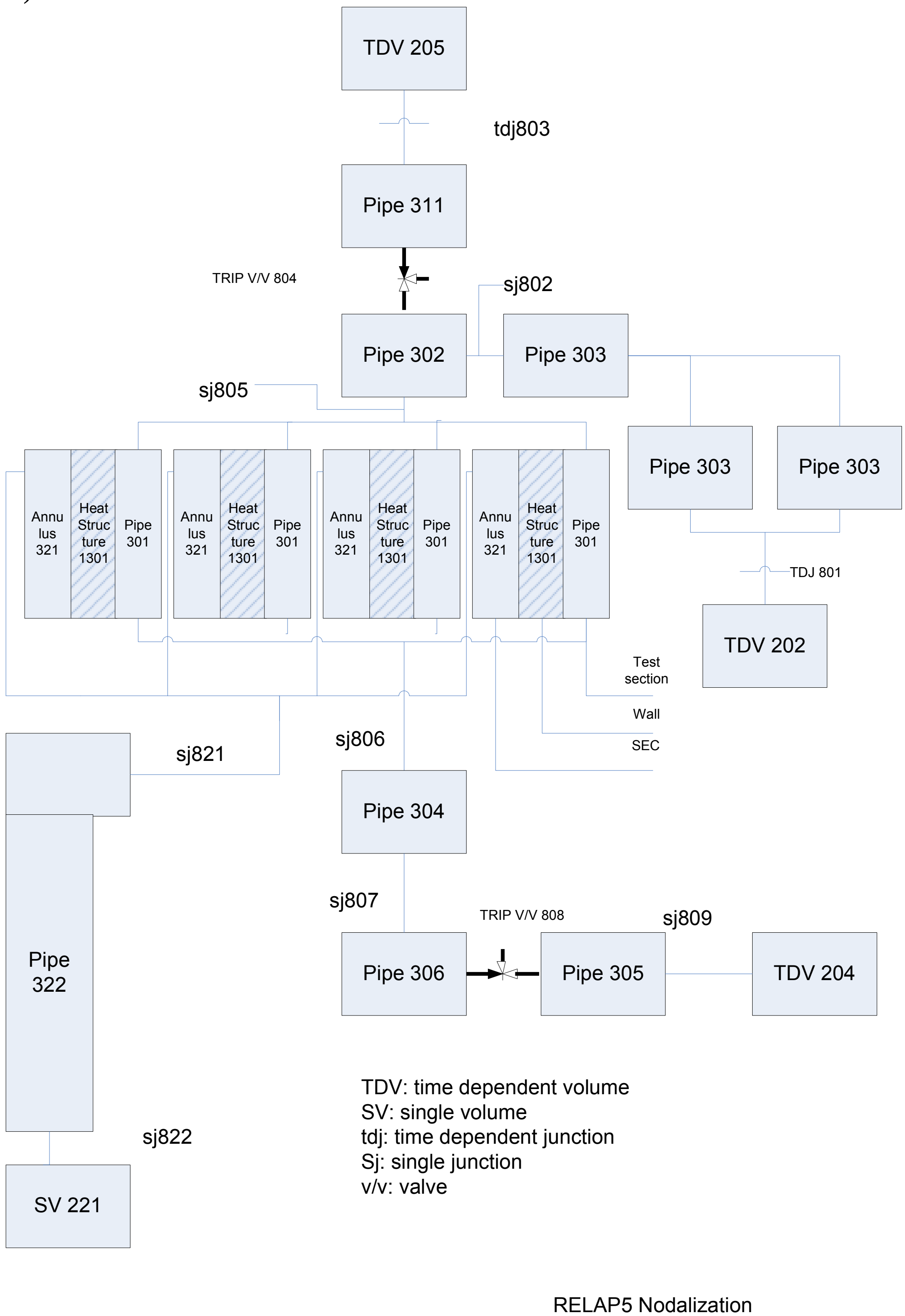


Figure 5. RELAP5 nodalization for tube bundle PCCS loop

The steam source is modeled as a time dependent volume component (TDV 202). The steam pressure is set to the value measured at the vortex flow meter from the experiment. The time dependent junction component (TDJ 801) is used to set the steam mass flow rate input.

The air source is modeled as a time dependent volume component (TDV 205). The air flow rate is set to the value measured from the experiment at the time dependent junction component (TDJ 803). Air pressure is set to the same pressure at TDV202. This prevents the air flow to the TDV 202. The steam and air temperatures are set to the test section steam inlet temperature (TS4). So, there is no need to consider the thermal mixing between the air and steam and heat loss in the supply pipe.

The condensate tank is modeled as a PIPE component (306). The level tracking option is used to see the level change in the tank. The suppression pool is modeled as a time dependent volume component (TDV 204). This component has very big volume to act as a mass sink.

To simulate the different mode of operation between the complete condensation mode without air and the through flow mode with air, the TRIP VALVE components are used. TRIP VALVE 804 is installed between the air supply line (PIPE 311) and the steam supply line (PIPE 302). If no air flow condition is simulated, this valve remains closed. TRIP VALVE 808 is installed between the condensate tank (PIPE 306) and the vent line (PIPE 305). For the complete condensation mode, the valve remains closed. For the through flow condition, this valve is opened and vent the air and uncondensed steam to the suppression pool.

The secondary steam blowdown tank is modeled as a single volume component (SV 221). Steam generated from the secondary boiling pool (ANNULUS 321) is discharged to this tank

4. RELAP5 Analysis Results

For the comparison between the experimental data and the code analysis results, the code outputs are integrated for the entire condenser tube length. For the calculation of the average condensation heat transfer coefficient, the following equation is used instead of the arithmetic mean of local condensation heat transfer coefficient.

$$h_{c,avg} = \frac{Q_{TOT}}{A_i (T_{SAT,avg} - T_{Wi,avg})} \tag{1}$$

Here, A_i is the total heat transfer area of the condenser tube inside. Total heat transfer rate from the condenser tube to the secondary pool, Q_{TOT}, average steam saturation temperature, $T_{SAT,avg}$, and average tube inside wall temperature, $T_{Wi,avg}$ are calculated as follows:

$$Q_{TOT} = \sum_{j=1}^{N} Q_j \tag{2}$$

$$T_{SAT,avg} = \frac{1}{N} \sum_{j=1}^{N} T_{SAT,j} \tag{3}$$

$$T_{Wi,avg} = \frac{1}{N}\sum_{j=1}^{N} T_{Wi,j} \quad (4)$$

Here, N is total number of condenser meshes.

4.1 Complete Condensation Mode

For the comparison of the complete condensation mode, trip valve 808 is closed during the simulation. Results are shown in Figs. 6-8. Figure 6 shows the condensation heat flux with the system pressure. For a fixed pressure, the calculated condensation heat flux for the default model is low. It means the default model underestimate the condensation heat flux. The discrepancy is much more severe at high pressure. But for the UCB model, the condensate rate is very close to the test results although it is slightly lower. This difference is due to the facts that the total heat flux from the condenser tube to the secondary pool, Q_{TOT} contains the condensation heat flux plus sensible heat flux.

Figure 7 presents the condensation HTC with system pressure. Default model shows similar trend to the test data. However, the condensation HTC from UCB model shows very small dependency with system pressure. This result can be more easily described with Fig. 8 inside wall temperature data. From Fig. 8, inside wall temperature for the default model is almost same with test data. It means the temperature difference between the saturation and inside wall is same between the test and default model. So the condensation HTC follows the trend of the condensation heat transfer rate. However, the inside wall temperature for the UCB model is higher than test data at high pressure condition. Then the temperature difference is smaller than test data. Since condensation rate is similar to the test data, the condensation HTC is higher than the test data at high pressure condition.

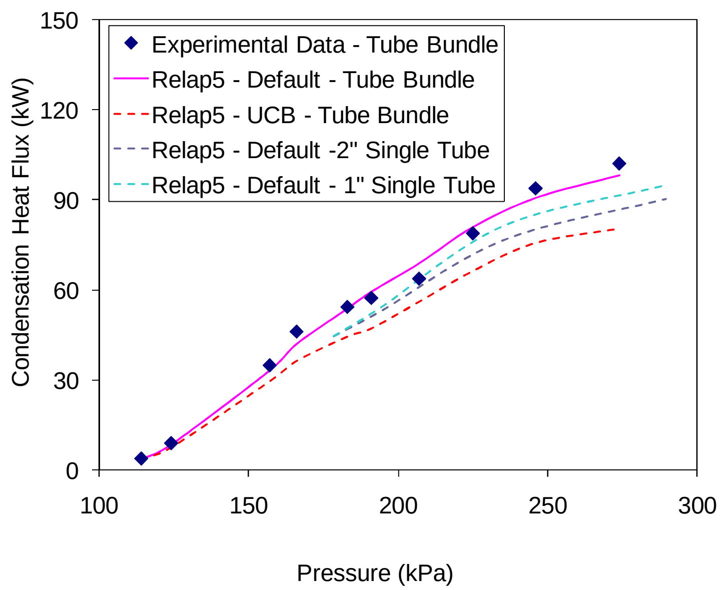


Figure 6 Comparison of condensation heat flux for complete condensation

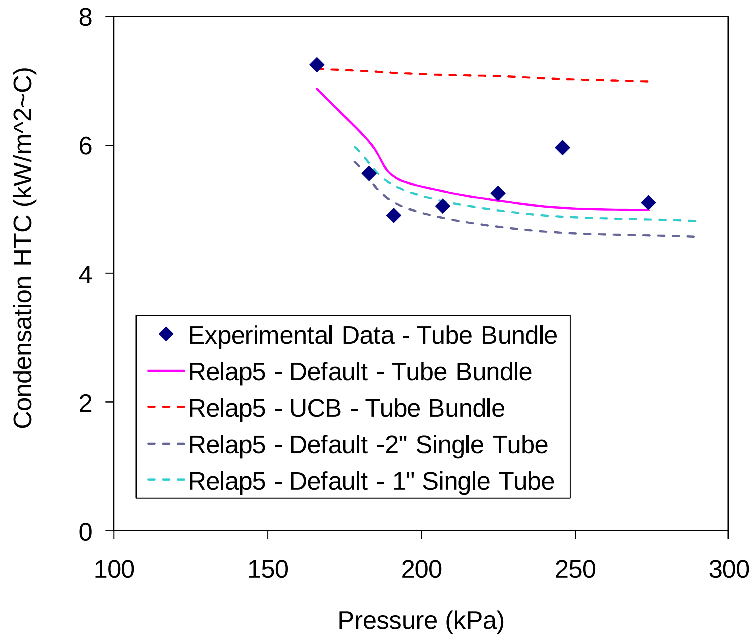


Figure 7 Comparison of condensation HTC for complete condensation

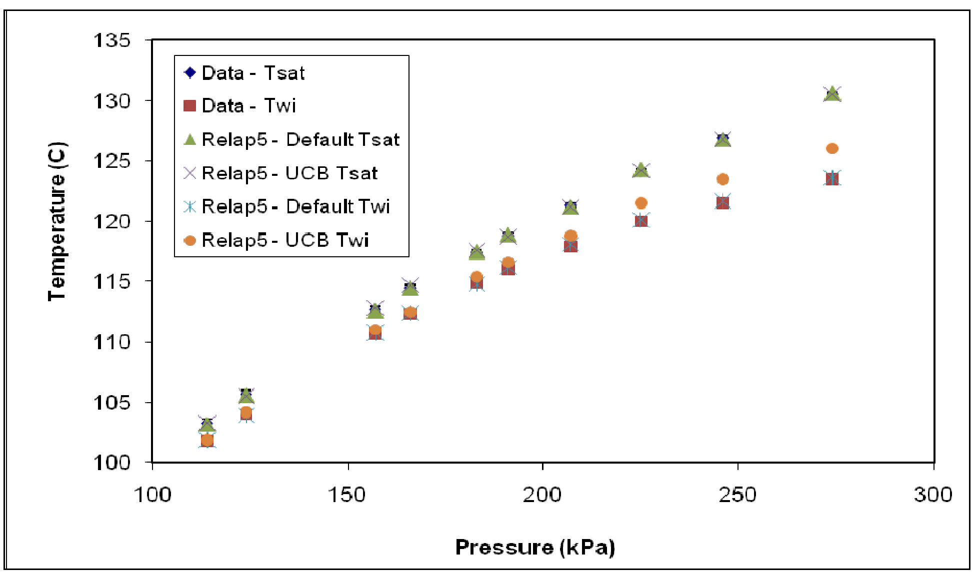


Figure 8 Comparison of temperatures for complete condensation

4.2 Through Flow Mode

For the comparison of the through flow mode with noncondensable gas, trip valve 808 is opened during the simulation. The representative case for the through flow mode is selected when system pressure is 165kPa and inlet steam flow rate is 40 g/s and the results are shown in Figs. 9-11

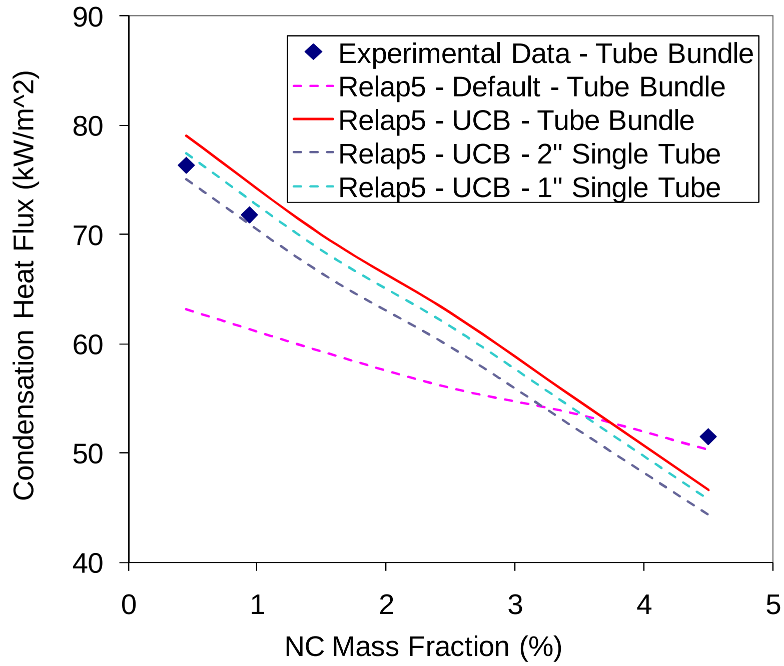


Figure 9 Comparison of Condensation Heat Flux for Through Flow

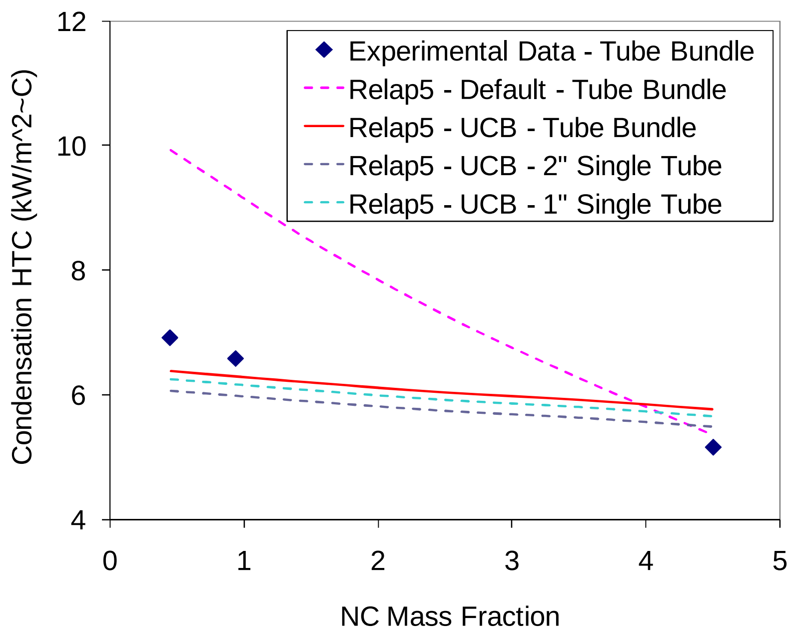


Figure 10 Comparison of condensation HTC for through flow

Figure 9 shows the condensation heat flux with noncondensable gas mass fraction. Default model underestimate especially at the low gas fraction region. UCB model predict very well at low gas fraction region. But as gas fraction increases, the condensation rate decreases very rapidly comparing test data. Condensation HTC is plotted in Fig. 10. This plot shows more evident trend of UCB model, which has large negative slope with gas fraction. This large slope can be explained by the inside wall temperature in Fig. 11.

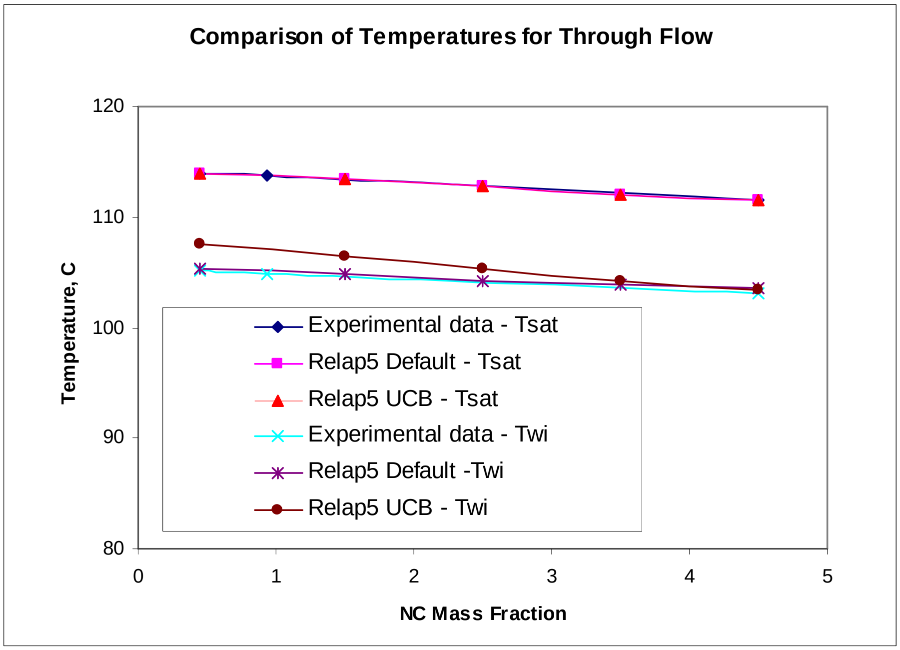


Figure 11 Comparison of temperatures for through flow

5. Conclusion

The assessment of wall condensation model in RELAP5 code, was carried out by simulating experiments for single and tube bundle PCCS condensers. RELAP5/MOD3.3 beta code default model and the alternate condensation model predictions were compared with experimental data. The default model and the UCB model (alternate model) show quite different results on the condensation heat transfer rates for complete condensation and through flow condensation mode of operations. The default model agrees with data for complete condensation mode than the UCB model. However for the through flow mode of condensation heat transfer, UCB model shows better result than the default model. It should be noted that the UCB model was primarily based on experimental data obtained for through flow mode of operation. When the condensation heat transfer coefficient predicted by the UCB model shows large discrepancy when compared with test data. Either default or UCB model in RELAP5 cannot satisfactorily predict complete condensation and through flow simultaneously. This suggest that condensation model in

RELAP5 needs to be improved for better predictions of PCCS condensation operating in different modes.

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