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International Agreement Report

Assessment of Condensation Heat Transfer Models of TRACE V5.0 Patch 5 Using PASCAL Tests

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ABSTRACT

The passive auxiliary feedwater system (PAFS) is one of the advanced safety features of the Advanced Power Reactor Plus (APR+) and Advanced Power Reactor 1000 (APR1000). During a plant transient, the PAFS cools down the secondary side of the steam generator, and removes the decay heat of the reactor core by condensing steam in nearly-horizontal U-shaped tubes submerged inside the passive condensation cooling tank. This study investigated the predictive capability of TRACE V5.0 patch 5 for the cooling and operational performance of the PAFS. For this purpose, the predictive capability of the code for the condensing heat transfer in the horizontal stratified flow was assessed using the results of a PASCAL experiment. The filmwise condensation heat transfer model and horizontal stratified condensation model of TRACE were evaluated. In addition, a new condensation model developed by Pusan National University (PNU model) was implemented and evaluated. The filmwise condensation heat transfer model and horizontal stratified condensation model generally overestimated the pressure and the steam flow rate of the steam generator. The PNU condensation model, on the other hand, predicted well the pressure and the steam flow rate of the steam generator under various heater powers.

FOREWORD

Since the accident of Fukushima nuclear power plants, the interest in passive safety systems has increased worldwide. South Korea has also made efforts to improve the safety of nuclear power plant by introducing the passive safety systems to its design. As a part of this effort, extensive studies on the passive auxiliary feedwater system (PAFS) have been conducted to complete its design and to verify its feasibility.

The Korea Atomic energy Research Institute (KAERI) performed the experimental investigation using the PASCAL and ATLAS-PAFS facilities to examine the condensation heat transfer and the operational performance of the PAFS. In addition, by performing the experimental and analytical studies, the Pusan National University (PNU) has developed the new condensation heat transfer model that can be applied to the steam condensation in horizontal and inclined tubes under stratified flow conditions.

Assessments of the predictive capability of safety analysis codes, such as MARS-KS and SPACE, have been also performed. A comparison of results against the PASCAL data showed that the existing condensation models of MARS-KS and SPACE codes significantly under-predicted the condensation heat transfer inside the condensation heat exchanger of the PAFS. It was also found that the predictive capability of codes for the PAFS was improved by implementing a new PNU condensation model into the codes.

This study aimed to assess the predictive capability of TRACE V5.0 patch 5 against the PASCAL test. For this purpose, the filmwise condensation heat transfer model and horizontal stratified condensation model of TRACE were evaluated. In addition, a new condensation model, the PNU condensation model, was also implemented and evaluated.

This report was prepared by the Korea Institute of Nuclear Safety (KINS), under the Implementing Agreement on Thermal-Hydraulic Code Applications and Maintenance Program between the United States Nuclear Regulatory Commission (USNRC) and the KINS (signed in 2018).

The KINS presented the result of this study at the 2018 Fall CAMP meeting and proposed it as an in-kind contribution at the Technical Program Committee (TPC) meeting.

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EXECUTIVE SUMMARY

The passive auxiliary feedwater system (PAFS) is an advanced safety feature of Advanced Power Reactor Plus (APR+) and Advanced Power Reactor 1000 (APR1000). The PAFS was design to replace the conventional active auxiliary feedwater system and is composed of a steam-supply line, a passive condensation heat exchanger (PCHX), a water-return line, and a passive condensate cooling tank (PCCT). During a plant transient, the PAFS cools down the secondary side of the steam generator, and removes the decay heat of the reactor core by condensing steam in nearly-horizontal U-shaped tubes submerged inside the PCCT.

When the PAFS is actuated, a horizontal stratified flow is formed inside the PCHX. To evaluate the performance of PAFS with thermal-hydraulic code, the condensing heat transfer in the horizontal stratified flow is particularly important.

To validate the cooling and operational performance of the PAFS, the Korea Atomic Energy Research Institute (KAERI) has performed an experimental investigation using the PASCAL (PAFS Condensing heat removal Assessment Loop) test facility. To simulate the geometry of the PAFS, a single U-shaped PCHX tube with an inclination of 3 degrees was submerged in the PCCT. For the required heat removal rate, the PCHX of PASCAL needs to be able to remove a thermal energy of 540 kW as a scale-downed reference. For the sensitivity study of thermal power, the experiments with various steam generator powers of 200, 300, 400, 650, and 750kW were also performed.

This study aimed to assess the predictive capability of TRACE V5.0 patch 5 against the PASCAL test. For this purpose, a filmwise condensation heat transfer model (the default model) and a horizontal stratified condensation model (the J-K model) of TRACE were evaluated. In addition, a new condensation model, developed by Pusan National University (the PNU model), which can be applied to a nearly-horizontal tube was also evaluated. Each of those condensation heat transfer models was investigated in this study.

Two types of input models, namely, the simplified model and the total PASCAL input models, were developed.

In the simplified model, the PCHX was modeled using the PIPE component with the 28 nodes. The PCCT was modeled using a 3-D vessel component with one node in the x-coordinate direction (x1), 16 nodes in the y-coordinate direction (y1~y16), and 22 nodes in the z-coordinate direction (z1~z22). The steam-supply line was modelled using the FILL component. The injected mass flow rate of steam was the same as the measured value. The water-return and the steam discharge lines were modeled with the BREAK components. The entire PASCAL facility was modeled by adding the SG, steam supply line and water-return line to the PCHX of the simplified input model.

Using the simplified input model, the effect of three condensation heat transfer models on the thermal-hydraulic parameters were investigated with the same boundary conditions. The calculation result of the default condensation model overestimated the heat transfer rate at the upper half of the PCHX and under-predicted it at the lower half of the PCHX. The J-K model failed to capture the heat fluxes, and considerably underestimated the heat transfer rate. The PNU model well captured the values and distribution of the heat transfer rate along the PCHX.

Using the total PASCAL input model, the effect of three condensation heat transfer models on the overall system behavior were evaluated. The calculation results of the SG pressure and the steam flow rates at various SG heater powers (200 ~ 750 kW) were compared with measured data.

The default model generally over-predicted the SG pressure and steam flow rates at the PCHX inlet under all SG heater powers. The maximum error for the SG pressure occurred at the lowest SG heater power, and its value was about 220%. The error gradually decreased to about 25% as the SG heater power increased up to 540 kW or more. The errors for the steam flow rate were within 12%. The J-K model also generally overestimated the SG pressure and steam flow rates. The larger the SG heater power, the larger the error for the SG pressure and steam flow rate. The stratified flow weighting factor (wfhf) was greatly affected by the thermal-hydraulic conditions. The PNU model predicts well the SG pressure and steam flow rates at the PCHX inlet under all SG heater powers.

To improve the predictive capability of TRACE V5.0 Patch 5 for the condensing heat transfer in the horizontal stratified flow, the condensation heat transfer model of the code needs to be improved.

ABBREVIATIONS AND ACRONYMS

APR	Advanced Power Reactor
APR+	Advanced Power Reactor Plus
ATLAS	Advanced Thermal-hydraulic test Loop for Accident Simulation
HTC	Heat Transfer Coefficient
HTSTR	Heat Structure
ID	Inner Diameter of Tube
KAERI	Korea Atomic Energy Research Institute
MSSV	Main Steam Safety Valve
OD	Outer Diameter of Tube
PAFS	Passive Auxiliary Feedwater System
PASCAL	PAFS Condensing Heat Removal Assessment Loop
PCCT	Passive Condensation Cooling Tank
PCHX	Passive Condensation Heat Exchanger
PNU	Pusan National University
TRACE	TRAC/RELAP Advanced Computational Engine
WFHF	Horizontal Stratified Flow Weighting Factor (wfhf)

1 INTRODUCTION

The passive auxiliary feedwater system (PAFS) is one of the advanced safety features of the Advanced Power Reactor Plus (APR+) and Advanced Power Reactor 1000 (APR1000) [1-2].

The PAFS was designed to replace the conventional active auxiliary feedwater system, and is composed of a steam-supply line, a passive condensation heat exchanger (PCHX), a water-return line, and a passive condensate cooling tank (PCCT), as shown in Figure 1-1.

During a plant transient, the PAFS cools down the secondary side of the steam generator, and remove the decay heat of the reactor core by condensing steam in nearly-horizontal U-shaped tubes submerged inside the PCCT. When the water level in the steam generator becomes lower than the pre-determined value, the actuation valve at the water-return line opens and then the natural circulation flow is formed.

When the PAFS is actuated, the horizontal stratified flow is formed inside the PCHX. For a horizontal stratified flow, liquid condensate accumulates at the bottom of the pipe. The thin film above the pool can experience significant condensation which then drains to the pool at the bottom of the pipe. To evaluate the performance of PAFS with a thermal-hydraulic code, the condensing heat transfer in the horizontal stratified flow is particularly important.

To validate the cooling and operational performance of the PAFS, the Korea Atomic Energy Research Institute (KAERI) has performed an experimental investigation using the PASCAL (PAFS Condensing heat removal Assessment Loop) test facility [2-3]. To simulate the geometry of the PAFS, a single U-shaped PCHX tube with an inclination of 3 degrees was submerged in the PCCT. With a given thermal power of electrical heaters in the steam generator, the heat removal rate in the condensation heat exchanger was measured and the characteristics of the natural circulation in the loop were examined.

This study aimed to assess the predictive capability of TRACE (TRAC/RELAP Advanced Computational Engine) V5.0 patch 5 against the PASCAL test. For this purpose, the filmwise condensation heat transfer model and horizontal stratified condensation model of TRACE were evaluated. In addition, a new condensation model developed by Pusan National University (PNU), that can be applied to the nearly-horizontal tube was also evaluated.

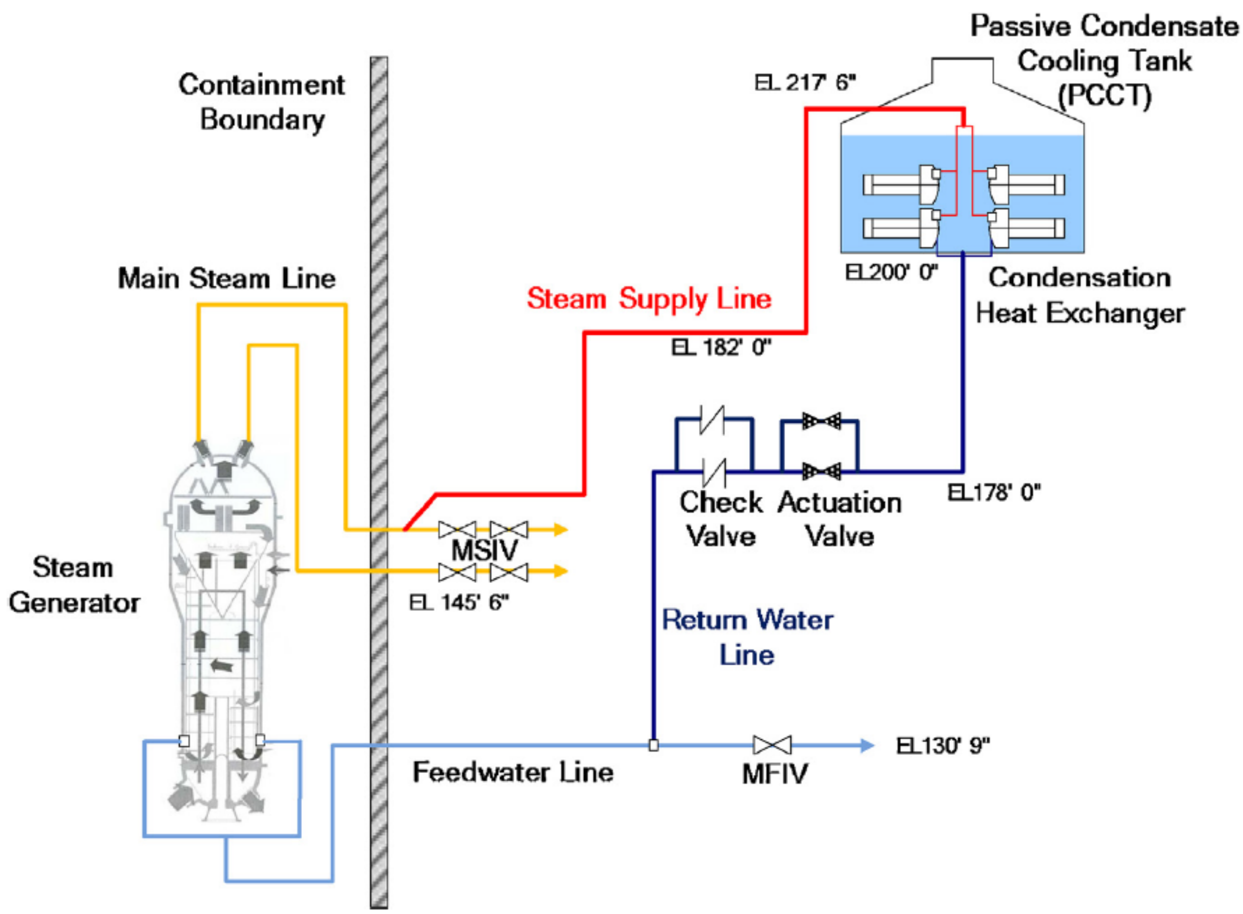


Figure 1-1 Schematic Diagram of APR+ PAFS

2 DESCRIPTION OF THE PASCAL EXPERIMENT

Figures 2-1 and 2-2 show the design of the PASCAL facility. The main components of the facility are the steam generator (SG), the PCHX, the steam-supply line and the water-return line, and the PCCT as shown in Figure 2-1. The SG supplies saturated steam to the top header of the PCHX tube. The condensate flows back to the SG.

To simulate the geometry of the PAFS, a single U-shaped PCHX tube with a length of 8.4 m is submerged in the PCCT. The tube has an inclination of 3 degrees to prevent the water hammer from occurring. The dimensions and material of the tube are the same as in the prototype. The inner and outer diameters of the PCHX are 44.8 mm and 50.8 mm, respectively. The PCHX is made of stainless steel 304. The width and depth of the PCCT are 6.7m and 0.112 m, respectively. The height of the PCCT is 11.484 m. The thermocouples are installed to measure the distribution of the coolant temperature inside the PCCT. Table 2-1 shows the scaling parameters of the PASCAL facility [2-3].

To evaluate the local heat fluxes and the heat transfer coefficients, the temperatures of the fluid and the tube surface are measured at 11 points along the PCHX length as shown in Figure 2-2. A total of 9 thermocouples are installed at each measurement point.

For the required heat removal rate, the PCHX of PASCAL needs to be able to remove a thermal energy of 540 kW as a scale-downed reference. Therefore, in the reference test, called the SS/PL-540-P1, 540 kW of thermal power was supplied in the steam generator heater as a rated power. The acronym SS/PL indicates a combined experiment of the continuous simulation for a quasi-steady state condition (SS) and a decrease of the PCCT water level (PL). For the sensitivity study of thermal power, the experiments with various steam generator powers of 200, 300, 400, 650, and 750kW were also performed.

In each test case, the water in the PCCT was maintained in the saturated state at an atmospheric pressure. When the pressure, temperature, and flow rate reached a steady state at the constant thermal power condition, the heat removal rate and the natural convection flow were measured. The thermal-hydraulic parameters, such as local and overall heat transfer coefficients, heat flux, fluid temperature inside the tube, wall temperature of the tube, and temperature distribution of pool in the PCCT, were produced.

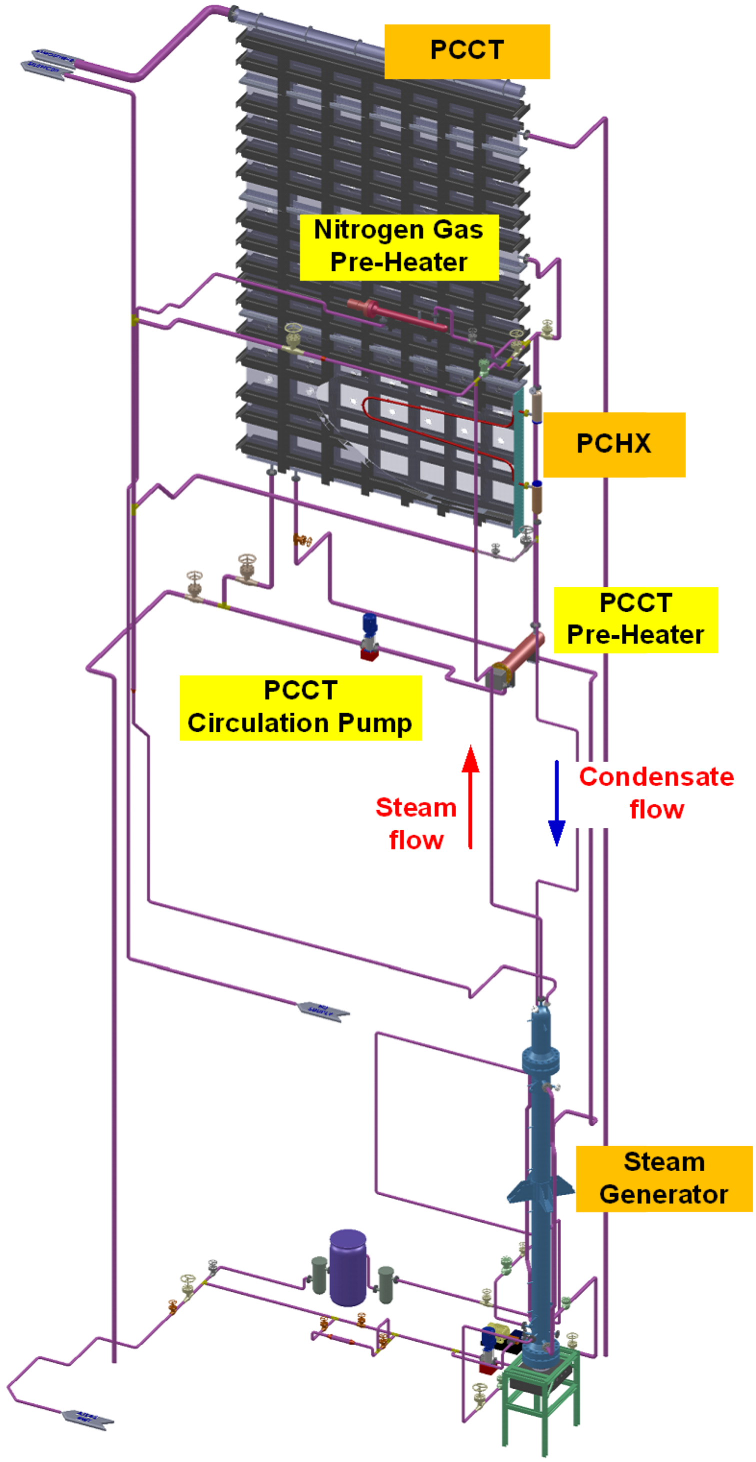


Figure 2-1 Schematic Diagram of PASCAL Test Facility [Ref.3]

Table 2-1 Scaling Parameters of PASCAL Facility [Ref. 3]

Parameter		APR+ PAFS	PASCAL	Ratio
PCHX tube	ID / OD	44.8 mm / 50.8 mm	44.8 mm / 50.8 mm	1/1
	Length	8.4 m	8.4 m	1/1
	no. of tubes	240	1	1/240
	Operating condition	7.4 MPa, 563K	7.4 MPa, 563K	1/1
PCCT	Height	7.62 m	8.9 m	1/0.86
	Length	18.29 m	6.7 m	1/2.7
	width	13.56 m	0.112 m	1/121

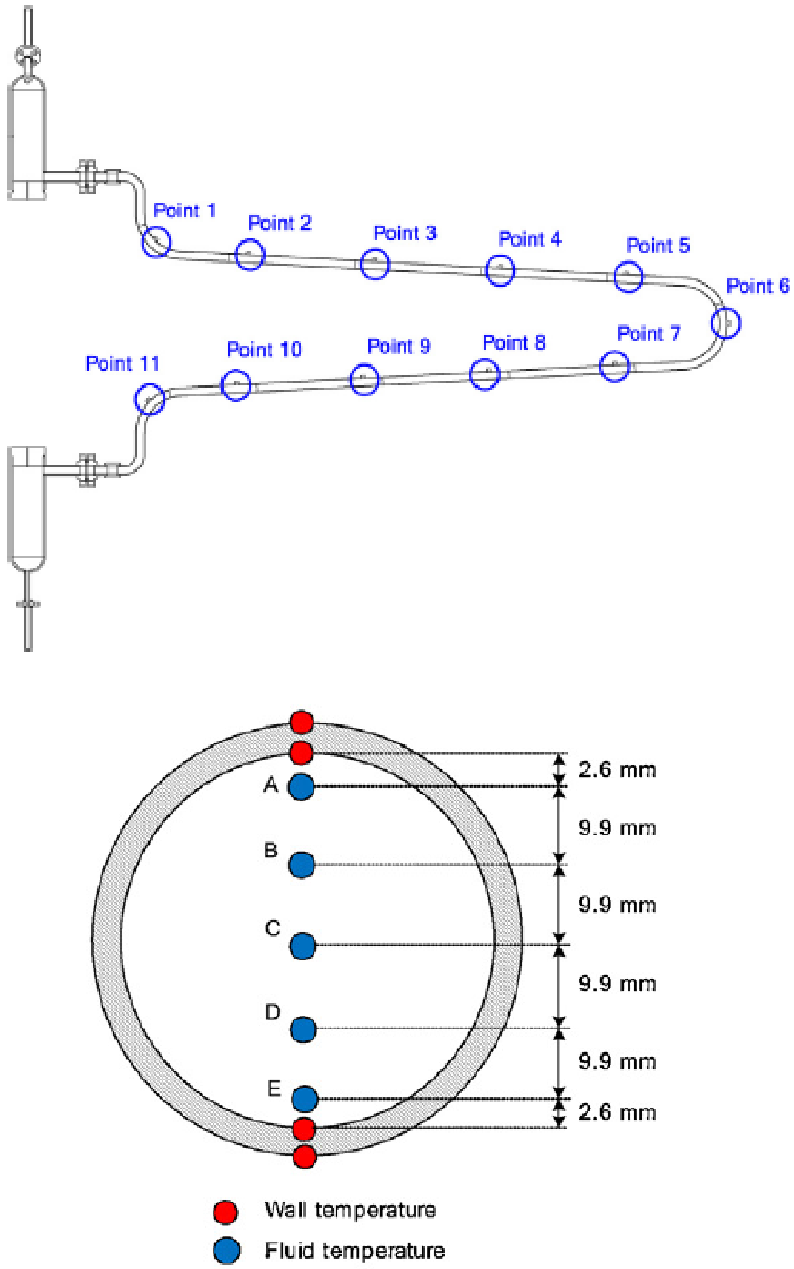


Figure 2-2 Measurement Points of Temperature [Ref.3]

3 CONDENSATION HEAT TRANSFER MODELS

3.1 Film Condensation Heat Transfer Model (hereafter Referred to as the Default Model)

Whenever the surface temperature of a heat structure is less than the saturation temperature corresponding to the vapor partial pressure, condensation will occur. In TRACE, models for condensation heat transfer either with or without non-condensable gases have been implemented and are invoked whenever the above wall temperature criterion is met and the void fraction is greater than 90%. Condensation heat transfer that occurs when the void fraction is less than 80% is handled using the normal models for two-phase convection. In addition, for void fraction values between these two limits (0.8 and 0.9), interpolation is used [4].

The primary mode for condensation heat transfer is filmwise. One of the requirements for the TRACE condensation model was that it must be applicable to both falling films (such as occur on containment structures) and sheared films (e.g., high velocity flows in condenser tubes).

The film condensation model (hereafter referred to as the default model) of TRACE must be applicable over a wide range of film Reynolds numbers. To accomplish this, the interfacial heat transfer coefficient (HTC) and wall-liquid HTC are computed using a power-law weighting of values for laminar and turbulent film flow.

TRACE uses the correlation of Kuhn, Schrock and Peterson for a laminar-wavy film condensation given by

$$Nu_{lam} = 1 + 1.83 \times 10^{-4} \cdot \ Re_f \ , \qquad \textbf{(3-1)}$$

where Re_f is the film Reynolds number. This is an empirical correlation fitted to their pure steam condensation data for co-current downflow.

For a turbulent film, TRACE uses Gnielinski's correlation given by

$$Nu_{turb} = \frac{\left(\frac{f}{2}\right)(Re - 1000) \cdot Pr}{1 + 12.7 \left(\frac{f}{2}\right)^{\frac{1}{2}} \left(Pr^{\frac{2}{3}} - 1\right)}, \qquad \textbf{(3-2)}$$

where f is the friction factor, and Pr is the Prandtl number.

When implemented in TRACE, each correlation is apportioned using multipliers to the interfacial heat transfer and the wall heat transfer.

3.2 Horizontal Stratified Condensing Heat Transfer Model (hereafter Referred to as the J-K Model)

Jaster and Kosky [5] developed a horizontal tube condensing heat transfer correlation given below:

$$Nu_{J-K} = 0.725 \left[\frac{\rho_f\ (\rho_f - \rho_g) g\ h_{fg}\ \alpha^3 D^3}{k_f\ \mu_f\ |T_w - T_{sat}|}\right]^{\frac{1}{4}}. \quad \textbf{(3-3)}$$

The Jaster and Kosky correlation is used for condensation heat transfer in horizontal pipes with stratified flow in TRACE. Activating the horizontal stratified condensing heat transfer regime requires that the PIPE component be PIPETYPE=12. In addition, the fluid component connected to the heat structure surface and the heat structure axial level must have an absolute value of GRAV less than or equal to 0.7071. This value of GRAV corresponds to the angle of inclination from 0 to 45 degrees. The heat structure surface temperature must be less than the saturation temperature based on the steam partial pressure. The pipe fluid cell must be in a horizontal stratified flow (horizontal stratified flow weighting factor, wfhf > 0.0), and the void fraction must be non-zero. When all of these criteria are satisfied, the Jaster and Kosky HTC is calculated [4].

In the situation of stratified condensing heat transfer, the Jaster and Kosky HTC is weighted by the horizontal stratified flow weighting factor (wfhf). The liquid phase convective heat transfer correlation is also evaluated and used for the wall to liquid heat transfer. The wall to liquid HTC is weighted by (1-wfhf) as follows:

$$\text{hgamma} = \frac{k_f\ Nu_{J-K}}{D} \times \text{wfhf}\ , \quad \textbf{(3-4)}$$

$$\text{hlWall} = \frac{k_f\ Nu_{Conv}}{D}(1 - \text{wfhf})\ , \quad \textbf{(3-5)}$$

where hgamma is the direct condensation HTC at the wall, and hlWall is the wall to liquid HTC. The Nu_{Conv} is the Nusselt number for the liquid phase in a forced convection, and is the maximum value among laminar, turbulent, and natural circulation Nusselt numbers.

In TRACE, three separate criteria are used to determine whether or not the flow can be stratified: (1) it must first satisfy the modified form of the Taitel-Dukler criterion (Eq. **3-6**) that represents the transition from a stratified to an intermittent flow, (2) the mass flux must be low enough (Eq. **3-7**) so that the flow is not in the dispersed bubble regime, and (3) the flow must not be flooded, that is, the CCFL criterion given by Eq. (**3-8**) must be satisfied. The three criteria are as follows:

$$wf_{T-D} = \max\left[0, \min\left(1, 2 - \frac{V_r}{V_{r,crit}}\right)\right], \quad \textbf{(3-6)}$$

$$wf_{C-W} = \max\left[0, \min\left(1, \frac{2700 - G}{2700 - 2000}\right)\right], \quad \textbf{(3-7)}$$

$$wf_{CCFL} = \max\left[0, \min\left(1, \frac{1.2 - \left(j_g^{*0.5} + j_f^{*0.5}\right)}{1.2 - 0.65}\right)\right]. \quad \textbf{(3-8)}$$

These three criteria are implemented as stratification weighting factors. To provide a smooth continuous transition from a stratified to a non-stratified flow, these weighting factors are combined multiplicatively as follows:

$$\text{wfhf} = 1.6 \times wf_{T-D} \cdot wf_{C-W} \cdot wf_{CCFL} \cdot \text{rampSPV}\,, \tag{3-9}$$

where rampSPV is the void fraction ramp given by

$$\text{rampSPV} = \min\left[1.0,\ \left(\frac{0.999999 - alpm}{0.999999 - 0.999}\right)\right], \tag{3-10}$$

where $alpm$ is the momentum cell average void fraction. The rampSPV gradually shuts stratification off as the flow becomes single-phase vapor.

The value of wfhf is 0.0, when the flow is not a horizontally stratified flow. The wfhf is 1.0, when the flow is a horizontally stratified flow. As the flow regime transitions from well mixed to a horizontal stratified flow, the wfhf factor moves from 0.0 to 1.0, to smooth the transition.

3.3 PNU Horizonal Condensation Heat Transfer Model (hereafter Referred to as the PNU Model)

Ahn et al. [6] developed the PNU horizontal condensation heat transfer model. When the heat transfer area is separated into the upper and lower regions in a horizontal separated flow as shown in Figure 3-1, the average heat flux is calculated as follows:

$$q"_{avg} = \frac{q"_{upper}(\pi - \theta_H) + q"_{lower}\,\theta_H}{\pi}\,, \tag{3-11}$$

where θ_H is the heat partition angle, $q"_{upper}$ and $q"_{lower}$ are the average heat flux of the upper and lower regions calculated by:

$$q"_{upper} = h_{upper}\left(T_{sat} - T_{w,upper}\right), \tag{3-12}$$

$$q"_{lower} = h_{lower}\left(T_{sat} - T_{w,lower}\right). \tag{3-13}$$

Here, h_{upper} is the film condensation HTC and h_{lower} is the convective HTC.

Using the ATLAS and PASCAL experimental data [3, 7-8], the film condensation HTC was developed in consideration of the heat partition angle and the effect of turbulence created by the steam flow from the Nusselt's laminar film condensation heat transfer model as follows:

$$h_{upper} = \max\left[1 - 2.2 \times 10^{-4} Re_{gs}\,, 0.63 + 3.1 \times 10^{3}\, {Re_{gs}}^{0.46}\right] \times h_f\,, \tag{3-14}$$

where $h_f = \left[0.9 - 0.17\left(1 - \frac{\theta_H}{\pi}\right)^{2.4}\right]\left[\frac{g(\rho_f - \rho_g)\rho_f h'_{fg} k_f^3}{D\,\mu_f\,(T_{sat} - T_{w,upper})}\right]^{1/4}$ and Re_{gs} is the superficial steam Reynolds number.

The convective HTC was developed by applying the two-phase multiplier to the single-phase convective HTC as follows:

$$h_{lower} = 0.023\, Re_{fs}^{0.8}\, Pr_f^{0.4}\left(\frac{k_f}{D}\right)\left[\frac{0.8\,(\theta_1/\pi)^{0.1}}{(1-\alpha)^{0.8}}\right], \tag{3-15}$$

where Re_{fs} and Pr_f are the superficial liquid Reynolds number and the Prandtl number, respectively.

The heat partition angle (θ_H) was derived from the inflection point of the circumferential distribution curve of the heat flux to distinguish the upper and lower regions representing film condensation and convective heat transfers, respectively. The heat partition angle is a function of the predicted wetted wall angle in the concave-shaped interface (θ_1) and minimum wetted wall angle (θ_0) in the flat-shaped interface.

$$\theta_H = \min[\theta_1 - 0.87(\theta_1 - \theta_0),\ \pi]\ , \tag{3-16}$$

θ_0 is the half angle subtended at the center of the tube by the chord forming the flat steam-water interface and is calculated only from the void fractions using the approximation correlation proposed by Biberg [9]:

$$\theta_0 = \pi(1-\alpha) + \left(\frac{3\pi}{2}\right)^{\frac{1}{3}}\left\{1 - 2(1-\alpha) + (1-\alpha)^{\frac{1}{3}} - \alpha^{\frac{1}{3}}\right\} - \frac{1}{200}(1-\alpha)\alpha[1-2(1-\alpha)][1+4\{(1-\alpha)^2+\alpha^2\}]\ . \tag{3-17}$$

When the relative velocity of two phases increases, the condensate spreads along the tube wall and the wetted wall angle becomes larger than the minimum wetted angle at a given void fraction. The θ_1 is evaluated by considering the liquid velocity, tube diameter and inclination, and physical properties of the fluids. Ahn et al. [10] proposed the following model for the wetted wall angle:

$$\begin{aligned} &\theta_1 = \theta_0 + (\pi - \theta_0)K^{1/C}, && \text{for } \theta_1 < (\pi+\theta_0)/2\ , \\ &\theta_1 = \theta_0 + (\pi - \theta_0)\left[1 - \mathrm{sgn}(2^{1-C} - K)\left|2^{1-C} - K\right|^{1-C}\right], && \text{for } \theta_1 \geq (\pi+\theta_0)/2\ , \end{aligned} \tag{3-18}$$

where $K = \frac{0.69\, E_0^{-0.53}\, Fr_f^{0.16 M_0^{-0.072}}\, (e^{0.36\beta} + e^{0.035\beta})}{2^{1-C}\, (0.1\alpha^{21} + 0.4\alpha^{1.65})}$ and $C = 1.65$.

β is the inclination angle for the flow channel in degrees. E_0, Fr_f, M_0 are Eotvos, Froude, and Morton numbers defined as follows:

$$E_0 = \frac{gD^2(\rho_f - \rho_g)}{\sigma}\ , \tag{3-19}$$

$$Fr_f = \frac{\rho_f}{\rho_f - \rho_g}\frac{u_f^2}{gD\cos\beta}\ , \tag{3-20}$$

$$M_0 = \frac{g\mu_f^4(\rho_f - \rho_g)}{\rho_f^2\sigma^3}\ . \tag{3-21}$$

In this study, the PNU horizontal condensation heat transfer model was implemented into TRACE v5.0 Patch 5 as follows:

$$qwLiq = \text{hlWall}\ (\text{tWall} - \text{tl})\ , \quad \textbf{(3-22)}$$

$$qwSat = \text{hgamma}\ (\text{tWall} - \text{tSat})\ , \quad \textbf{(3-23)}$$

where $qwLiq$ is the heat flux between the wall and the liquid, and $qwSat$ is the heat flux by film condensation.

The HTCs, hlWall and hgamma, are calculated as follows:

$$\text{hlWall} = h_{lower}\left(\frac{\theta_H}{\pi}\right), \quad \textbf{(3-24)}$$

$$\text{hgamma} = h_{upper}\left(1 - \frac{\theta_H}{\pi}\right). \quad \textbf{(3-25)}$$

The PNU horizontal condensation model is activated when all of the following conditions are met.
(1) PIPETYPE is 12,
(2) the inclination of tube is from 0 to 10 degrees,
(3) the heat structure surface temperature must be less than the saturation temperature based on the steam partial pressure,
and (4) the void fraction must be non-zero.

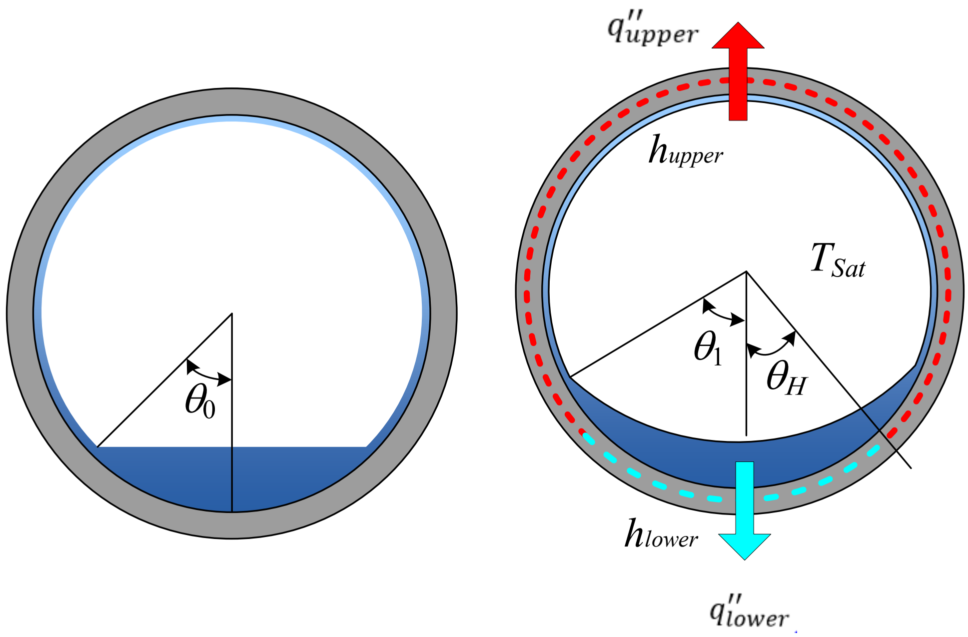


Figure 3-1 Schematic of Heat Transfer in Horizontal Stratified Flow

4 DESCRIPTION OF TRACE INPUT MODELS

Figure 4-1 shows the simplified TRACE input model in which the steam-supply line and the water-return line were modeled as boundary conditions using experimental data.

The PCHX is modeled using the PIPE component with the 28 nodes. The inclination of each node is determined in consideration of the tube shape. The steam-supply line is modelled using the FILL component. The injected mass flow rate of steam is the same as the measured value. The water-return line and the steam discharge line are modeled with the BREAK components. The heat structure component is used to model the heat transfer between the PCHX and the PCCT.

The PCCT is modeled using the 3-D vessel component with one node in the x-coordinate direction (x1), 16 nodes in the y-coordinate direction (y1~y16), and 22 nodes in the z-coordinate direction (z1~z22). The steam discharge line is connected to the upper side of the 1st-16th-22nd node. The initial water level is about 9.8 m and the initial water temperature is saturated temperature. The steam discharge line and the upper region of the PCCT are filled with saturated steam at atmospheric conditions.

The form loss coefficients at each junction of the PCCT are determined by a sensitivity test so that the calculated temperature distribution of fluid in the PCCT is similar to the measured data.

Using the simplified input model, the effect of 3 different condensation heat transfer models on the thermal-hydraulic parameters (such as, heat flux, fluid temperature, and steam mass flow rate, and so on) are investigated in the same boundary conditions.

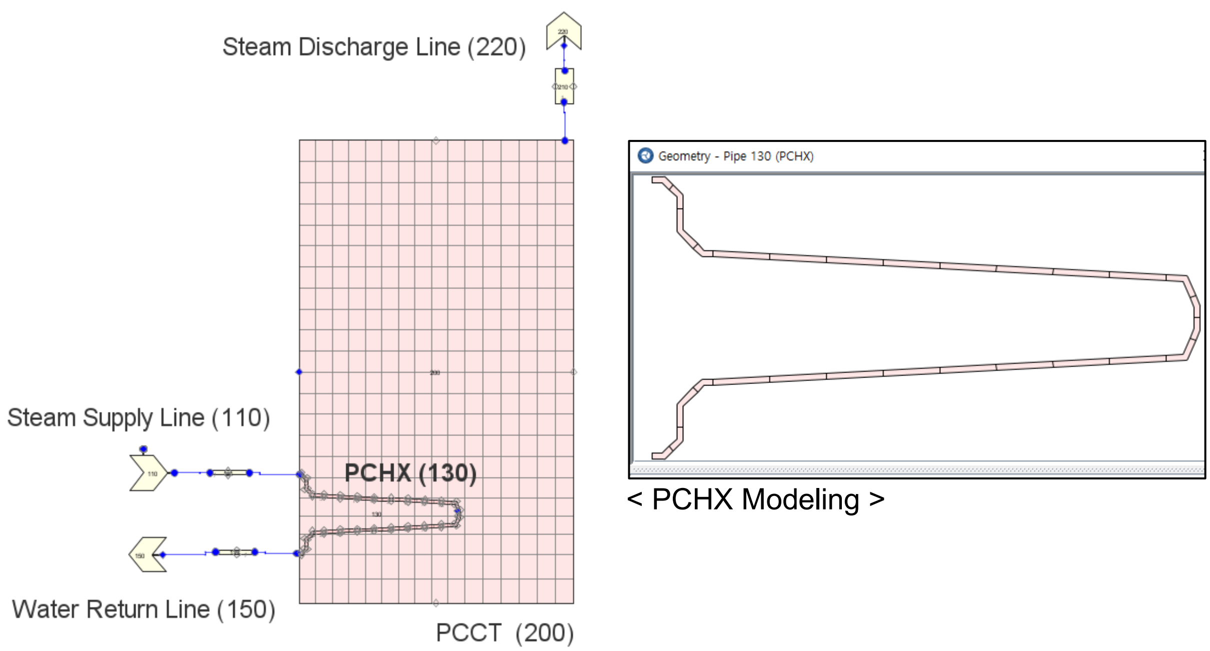
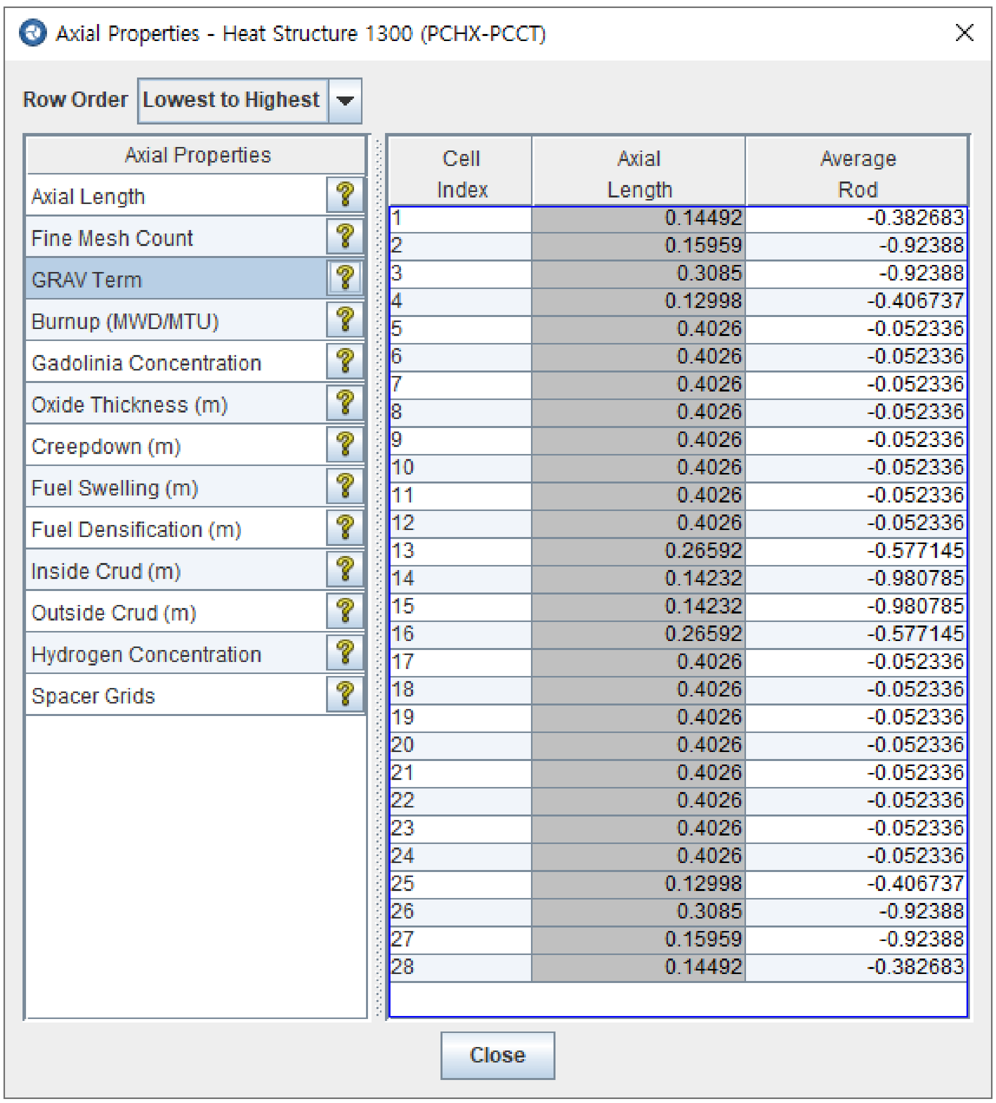


Figure 4-1 Simplified TRACE Input Model

Figure 4-2 shows the axial length and GRAV input of the heat structure (HTSTR) node. The value of GRAV is the cosine of the angle between the gravity vector and the direction that each of the HTSTR axial levels are pointing. For example, GRAV(j) = 1.0 or -1.0 implies a vertical HTSTR node, while GRAV(j) = 0.0 implies a horizontal HTSTR node. The GRAV input is enabled when the HSGRAVINP (Activate GRAV in Heat) namelist variable is set to TRUE. If FALSE, then GRAV input for HTSTR components is determined from the orientation of the fluid component cells associated with the HTSTR axial levels. In the TRACE code, the GRAV input takes precedence over the value from the orientation of the fluid component cells.

The activation of the default condensation model is independent of the GRAV input. However, the J-K model and the PNU model are activated when the absolute value of GRAV is less than or equal to 0.7071 (≤ 45 degrees) and less than or equal to 0.1736 (≤ 10 degrees), respectively.



Cell Index	Axial Length	Average Rod
1	0.14492	-0.382683
2	0.15959	-0.92388
3	0.3085	-0.92388
4	0.12998	-0.406737
5	0.4026	-0.052336
6	0.4026	-0.052336
7	0.4026	-0.052336
8	0.4026	-0.052336
9	0.4026	-0.052336
10	0.4026	-0.052336
11	0.4026	-0.052336
12	0.4026	-0.052336
13	0.26592	-0.577145
14	0.14232	-0.980785
15	0.14232	-0.980785
16	0.26592	-0.577145
17	0.4026	-0.052336
18	0.4026	-0.052336
19	0.4026	-0.052336
20	0.4026	-0.052336
21	0.4026	-0.052336
22	0.4026	-0.052336
23	0.4026	-0.052336
24	0.4026	-0.052336
25	0.12998	-0.406737
26	0.3085	-0.92388
27	0.15959	-0.92388
28	0.14492	-0.382683

Figure 4-2 GRAV Input of Heat Structure Nodes

Figure 4-3 shows the TRACE input model of the PASCAL facility. The entire PASCAL facility is modeled by adding the SG, steam supply line and water-return line to the PCHX of a simplified input model.

This input model is used to assess the effect of condensation heat transfer models on the overall system behavior of the SG pressure and the steam flow rates. The calculation results at various SG heater powers (200 ~ 750 kW) are compared with measured data.

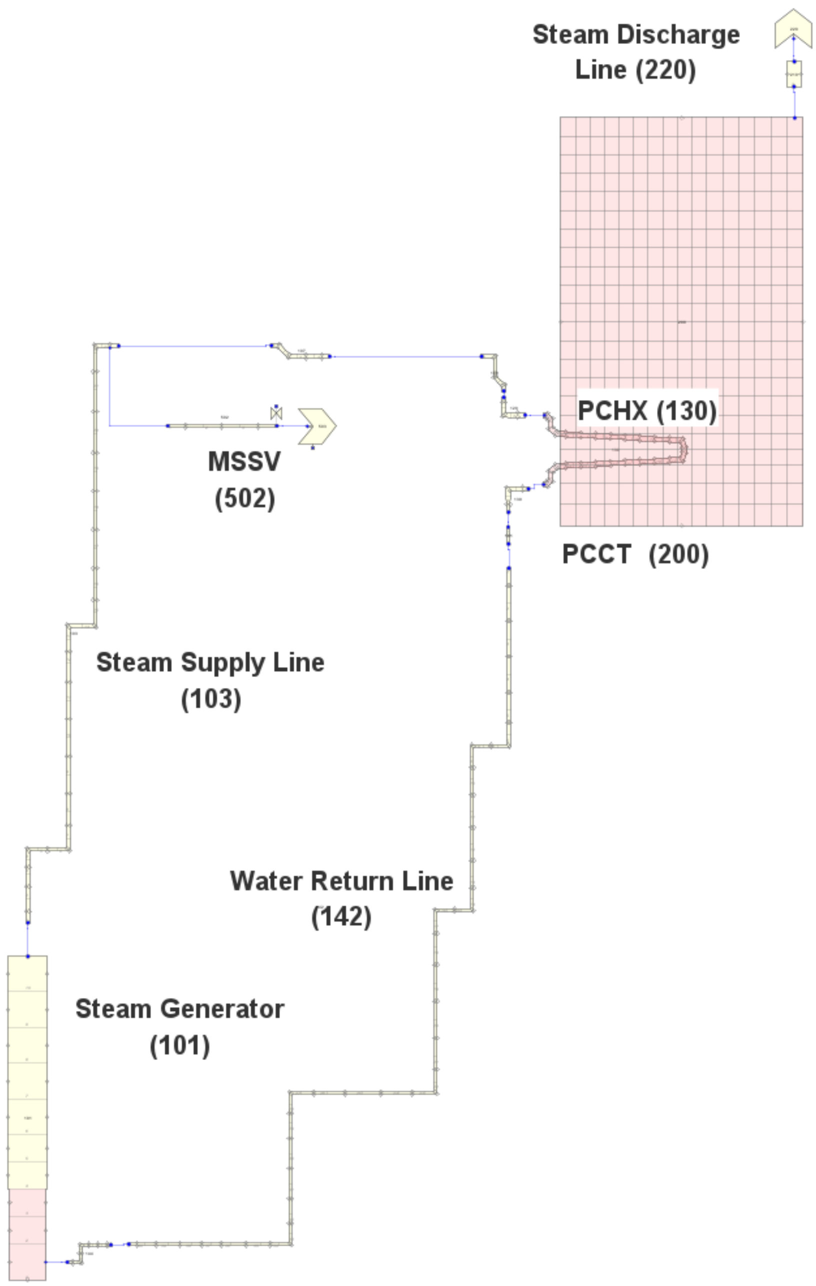


Figure 4-3 PASCAL TRACE Input Model

5 RESULTS AND DISCUSSION

5.1 Results of 540kW SG Power at Simplified Model

The transient calculation was run for the SS/PL-540-P1 test. The calculated values are taken at the quasi-steady state condition when the collapsed water level of the PCCT reaches 9.3 m. The calculated results of the heat flux, inner wall surface temperature, fluid temperature inside the PCHX, and steam mass flow rate are compared with the experimental data. The measured values are extracted from Ref. [2].

5.1.1 Heat Fluxes

Figure 5-1 shows the result of heat flux at the tube's inner surface along the PCHX tube. In the experiment, the measured heat flux of the top region inside tube was larger than that of the bottom region. This was due to the fact that the top part of the tube was filled with the steam flow and the condensate flows in the bottom region. The distribution of heat flux at the upper half of the PCHX was almost uniform, and the values gradually decreased at the lower half of the PCHX.

The calculation result of the default condensation model overestimates the heat flux at the upper half of PCHX and under-predicts it at the lower half of the PCHX. The J-K model fails to capture the heat fluxes and shows abnormal heat flux distribution. The J-K condensation model considerably underestimates the heat fluxes and shows very low heat transfer. The PNU condensation model generally well captures the values and distribution of heat flux along the PCHX.

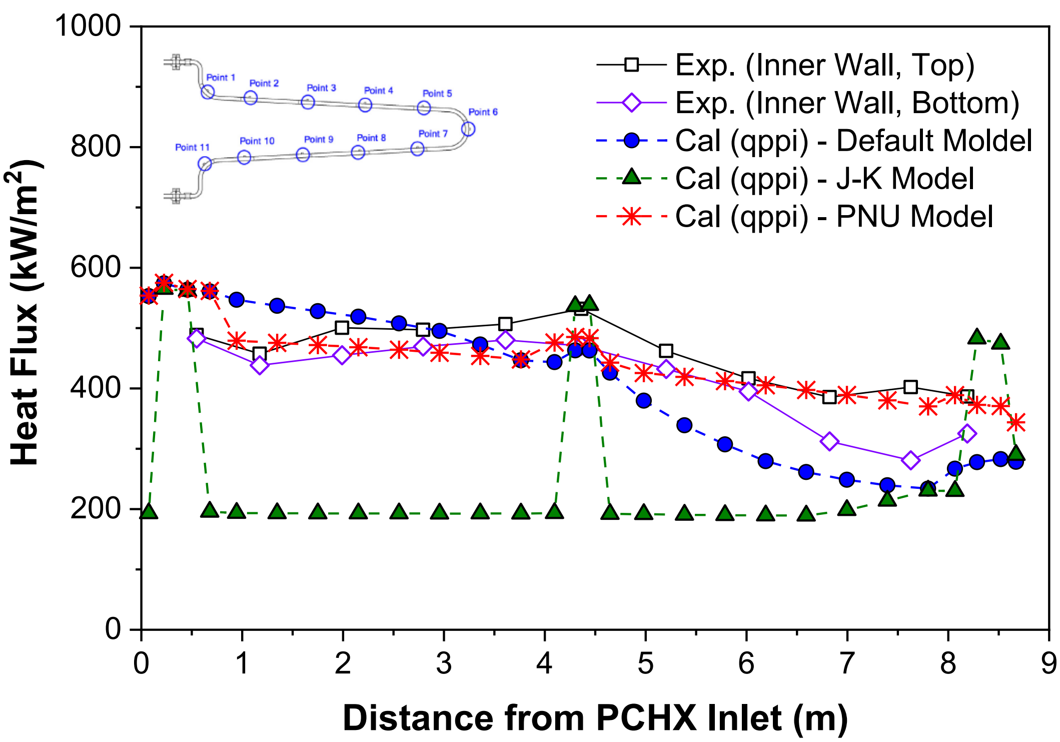


Figure 5-1 Heat Fluxes along the PCHX

5.1.2 Stratified Flow Weighting Factors

Figure 5-2 shows the result of stratified flow weighting factors (wfhf) along the PCHX tube. The condensation heat transfer in the default and PNU models is independent of the value of wfhf.

In the TRACE output of the J-K model, the calculated values of wfhf are 0.0 from the PCHX tube inlet to about 6.5 m. After that, the wfhf gradually increases and shows a value of about 0.43 at the PCHX outlet. Considering that one of the requirements for activating the J-K model is wfhf > 0.0, the actual values of wfhf from the PCHX tube inlet to about 6.5 m are not 0.0 but are very small values.

As described in Section 3.2, the Jaster and Kosky HTC is weighted by the horizontal stratified flow weighting factor (wfhf). This explains why the J-K model shows an abnormal and considerably small heat transfer rate. In the calculation of SS/PL-540-P1, very small wfhf values significantly reduce the contribution of Jaster and Kosky HTC to the total heat transfer rate and results in a convective-dominant heat transfer.

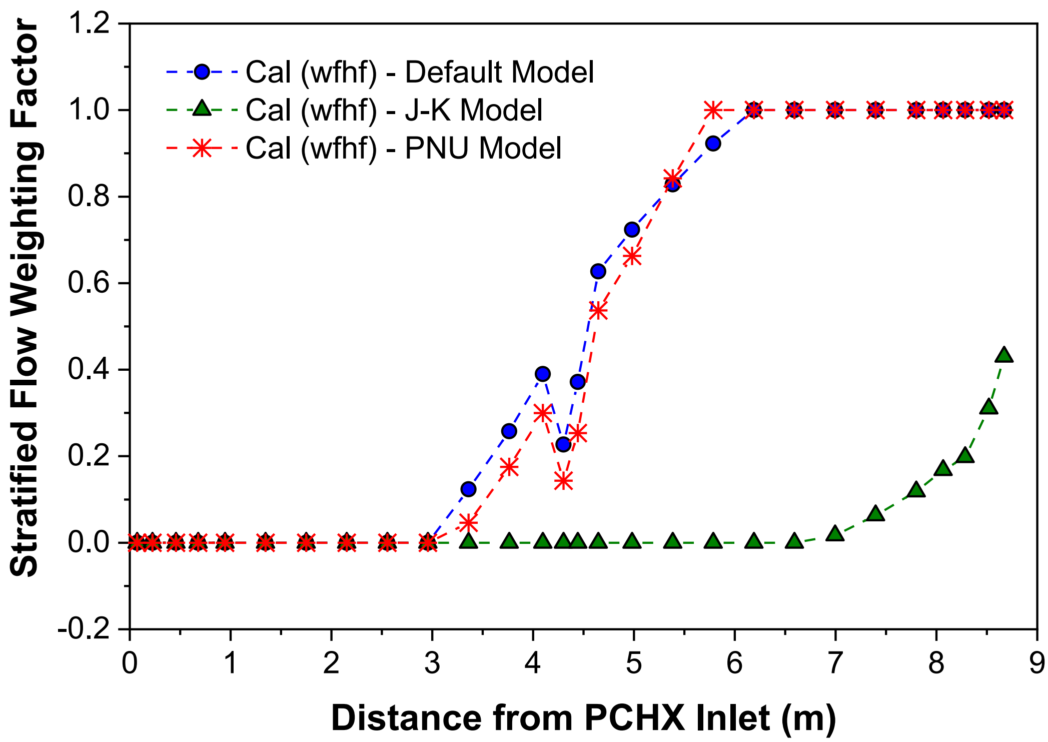


Figure 5-2 Stratified Flow Weighting Factor (wfhf) along the PCHX

5.1.3 Inner Wall Surface Temperatures

Figure 5-3 shows the distribution of the tube inner wall surface temperature along the PCHX tube. In the experiment, the trend of the surface temperature distribution was similar to that of the heat flux. The distribution of the surface temperature at the upper half of the PCHX was almost uniform, and the values gradually decreased at the lower half of the PCHX.

The default model does a good job achieving satisfactory results for the upper half of PCHX and under-predicts the temperature at the lower half of PCHX. The J-K condensation model considerably underestimates the surface temperatures. Like the results for heat flux, the J-K model fails to capture the surface temperatures.

The PNU model, on the other hand, does good job of approximating the trend of surface temperature with it being a little closer to the bottom side temperature.

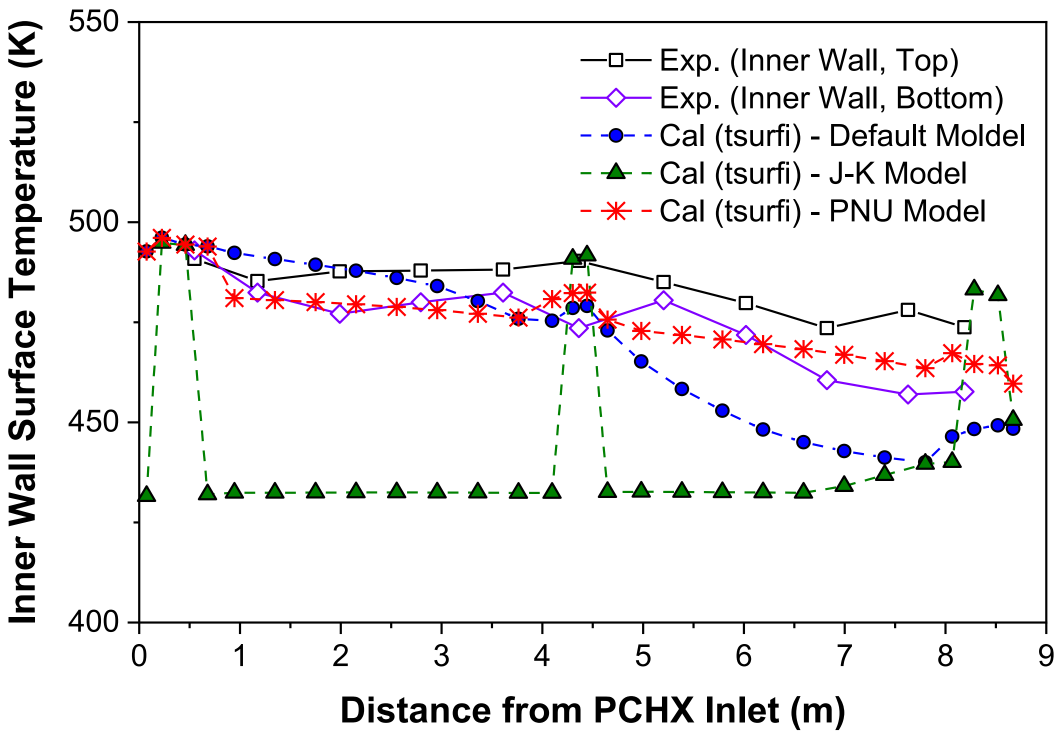


Figure 5-3 Inner Wall Surface Temperatures

5.1.4 Fluid Temperatures

Figure 5-4 shows the fluid temperatures along the PCHX tube. The experimental data shows the fluid temperatures at the vicinity of the tube bottom (measurement point E in Figure 2-2). The fluid temperature at point E was lower than the saturation temperature along the whole PCHX length. The fluid temperature at the vicinity of the tube bottom is mainly the condensate temperature. As is goes to the PCHX outlet, the condensate temperature gradually decreases. The condensate temperature at the bent region (measurement point 6 in Figure 2-2) jumped to about saturated temperature.

The calculated results show the water temperatures. The default model underestimates the condensate temperature, and the difference between the calculated value and the measured data is relatively large at the lower half of the PCHX. The result of J-K model shows a significant difference between the predicted values and experimental data.

The result for the condensate temperature using the PNU model is satisfactory. The PNU model predicts the condensate temperature at the PCHX outlet well, but is not able to reproduce the gradual decrease in condensation temperature at the upper half of the PCHX.

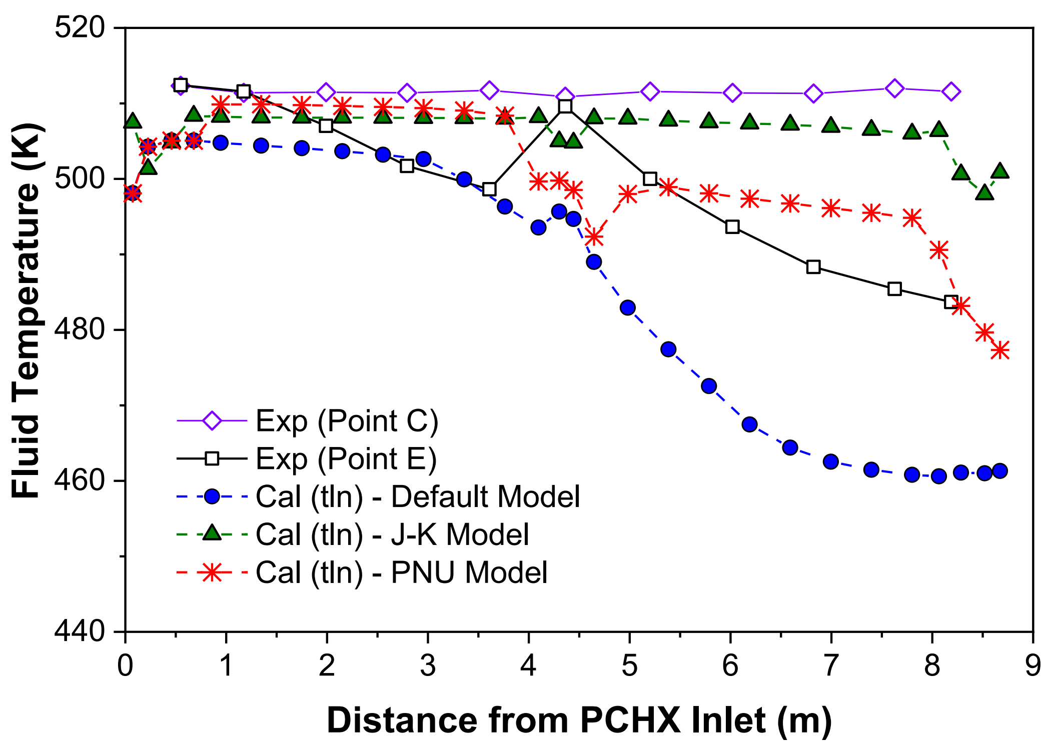


Figure 5-4 Fluid Temperatures inside PCHX

5.1.5 Condensation Rate and Void Fraction

Figure 5-5 shows the calculated mass flow rates of steam along the PCHX tube. The values are normalized to the injection flow rate of steam. The J-K model shows a relatively low condensation rate due to the low heat transfer rate. This results in the relatively high steam mass flow rates.

The default and PNU models show similar results for steam mass flow rates at the upper half of the PCHX, but there is a difference at the lower half of the PCHX. While the basic model shows that about 85% of the injected steam is condensed inside the PCHX tube, the PNU model shows that about 95% of the steam is condensed inside the PCHX tube.

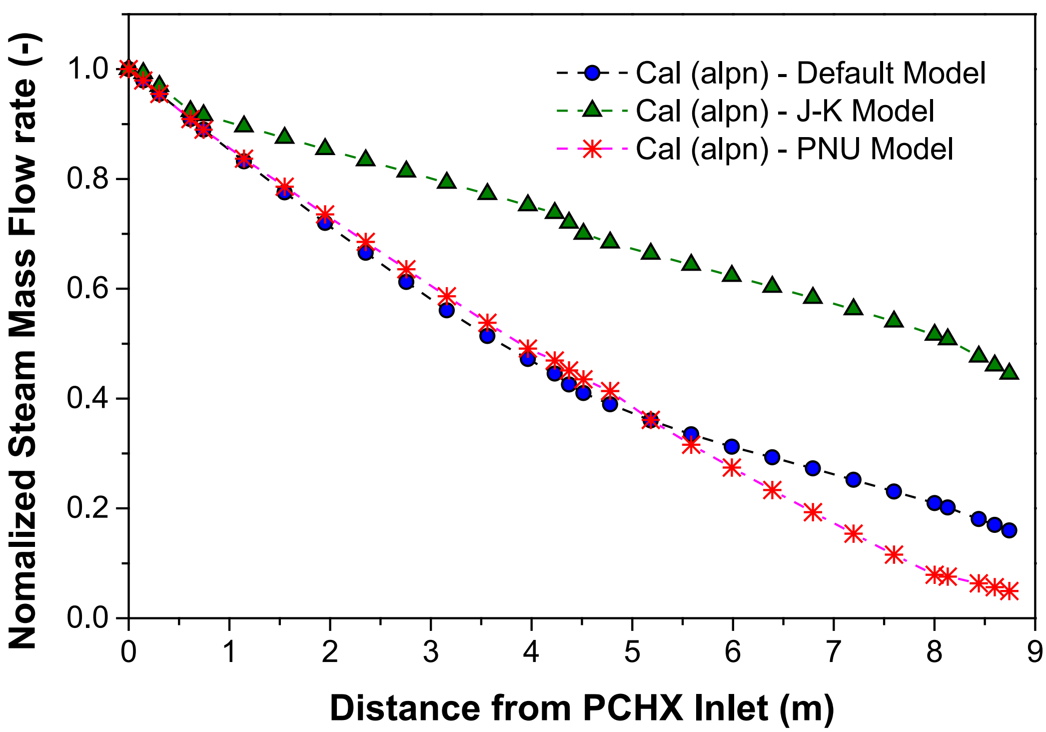


Figure 5-5 Steam Mass Flow Rates along the PCHX

Figure 5-6 shows the values of the void fraction along the PCHX tube. When compared to the default and PNU models, the J-K model shows a relatively large void fraction. At the bent region and outlet region, the void fraction increased due to the change of flow regime and heat transfer regime. The minimum void fraction is about 0.83 in the PNU model and occurs at the end of nearly-horizontal tube.

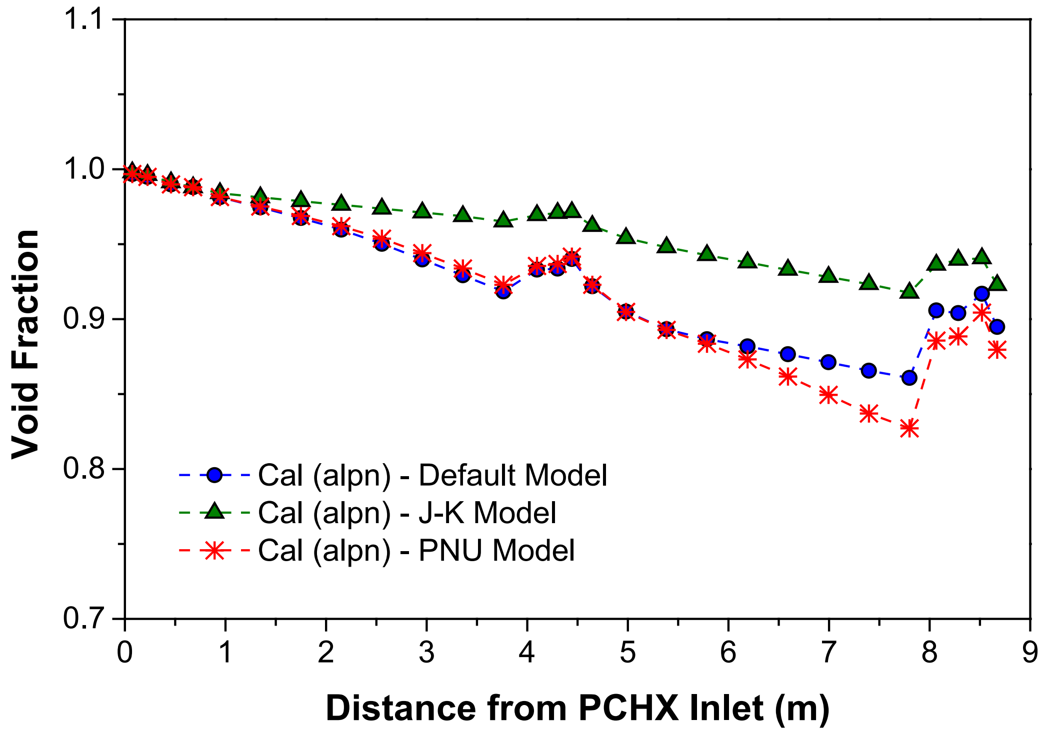


Figure 5-6 Void Fractions along the PCHX

5.1.6 Heat Transfer Regime

Figure 5-7 shows the heat transfer regimes along the PCHX tube. In the TRACE output, heat transfer regime numbers 7,8 and 11 indicate film condensation, transition (film condensation heat transfer - liquid phase convective heat transfer), and horizontal stratified condensing heat transfer regime, respectively.

In the default model, the film condensation regimes occur at the upper half of PCHX tube, and the flow regimes change to the transition regimes at the lower half of the PCHX tube. In the J-K model and the PNU model, the horizontal stratified condensing heat transfer regimes occur at the nearly-horizontal region where the inclination of the tube is less than or equal to 45 degrees and less than or equal to 10 degrees, respectively. The film condensation or transition regimes occur at the PCHX inlet, outlet and bent regions where the horizontal condensation model is not activated.

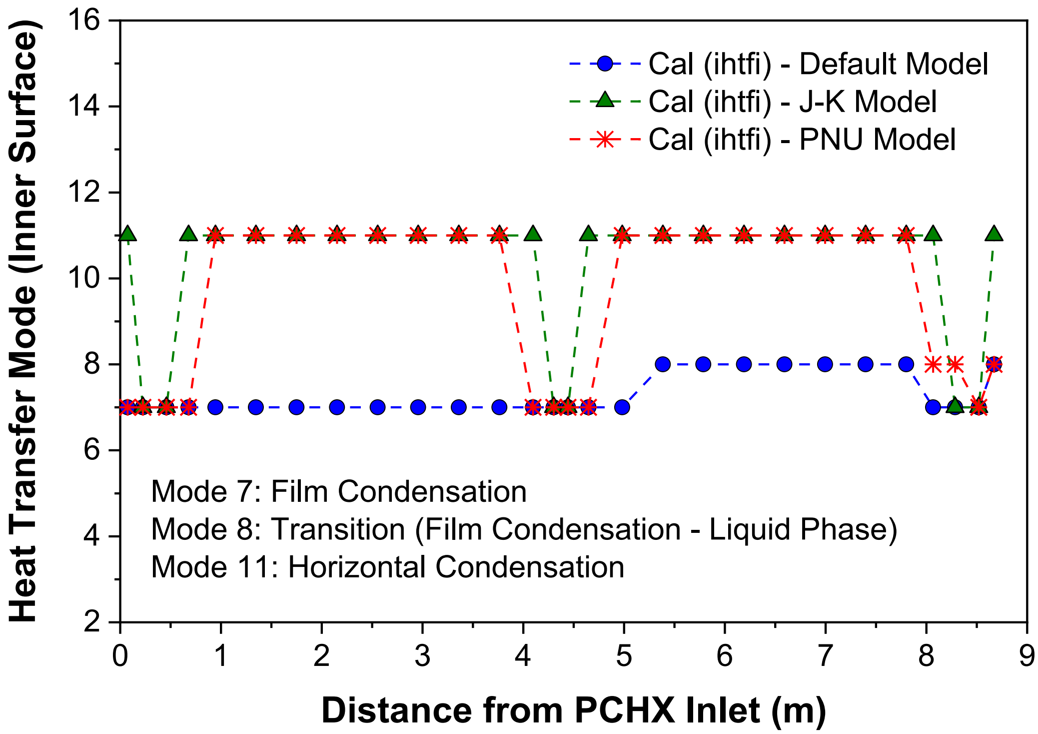


Figure 5-7 Heat Transfer Regimes along the PCHX

5.2 Results at Total PASCAL Model

The transient calculation was run for the SS/PL-540-P1 test where the SG heater power was 540 kW. In addition, the experiments with SG heater powers of 200, 300, 400, 650 and 750 kW were also simulated. The initial water temperature inside the PCCT was the saturation temperature.

In the PASCAL tests, the moment when the PCCT water level reached 9.3m at the saturated condition was considered to be a quasi-steady state. At the quasi-steady state, the heat removal rate in the PCHX tube was equivalent to the SG heater power. The calculated results were taken at the same PCCT water level as in the experiment.

5.2.1 SG Pressure at the SG Heater Power of 540kW

Figure 5-8 shows the calculated results of variation of SG pressures at the SG heater power of 540 kW. The values are normalized to the measure data.

Because of the relatively large heat transfer rate, the result of the default model reaches the quasi-steady state more quickly than those of J-K and PNU models at the same initial and boundary conditions. At the quasi-steady condition, the PNU model predicts the SG pressure well. While the default model overestimates the SG pressure by about 25%, the J-K model overestimates the pressure by about 236%.

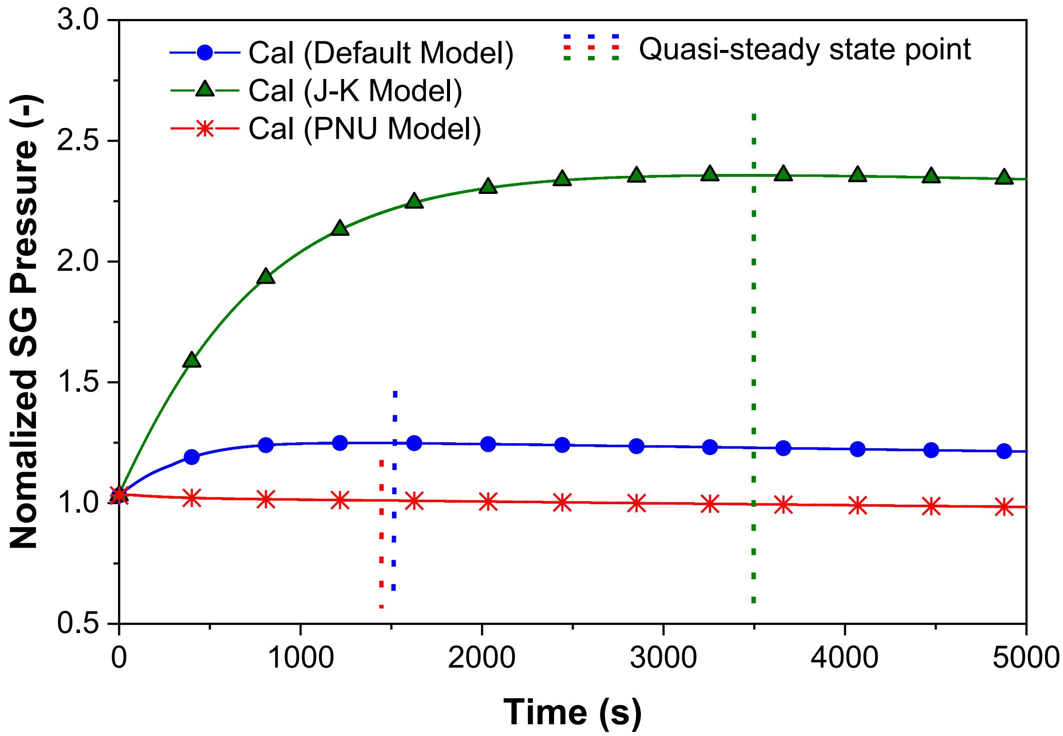


Figure 5-8 Variation of SG Pressures (SG Heater Power of 540kW)

5.2.2 Steam Flow Rates at the SG Heater Power of 540kW

Figure 5-9 shows the calculated results of variation of steam mass flow rate at the PCHX tube inlet. The PNU model accurately reproduces the experimental data at the quasi-steady state point. On the other hand, the default and PNU models overestimate the steam mass flow rate at the PCHX inlet by about 6.4% and by about 25.1%, respectively.

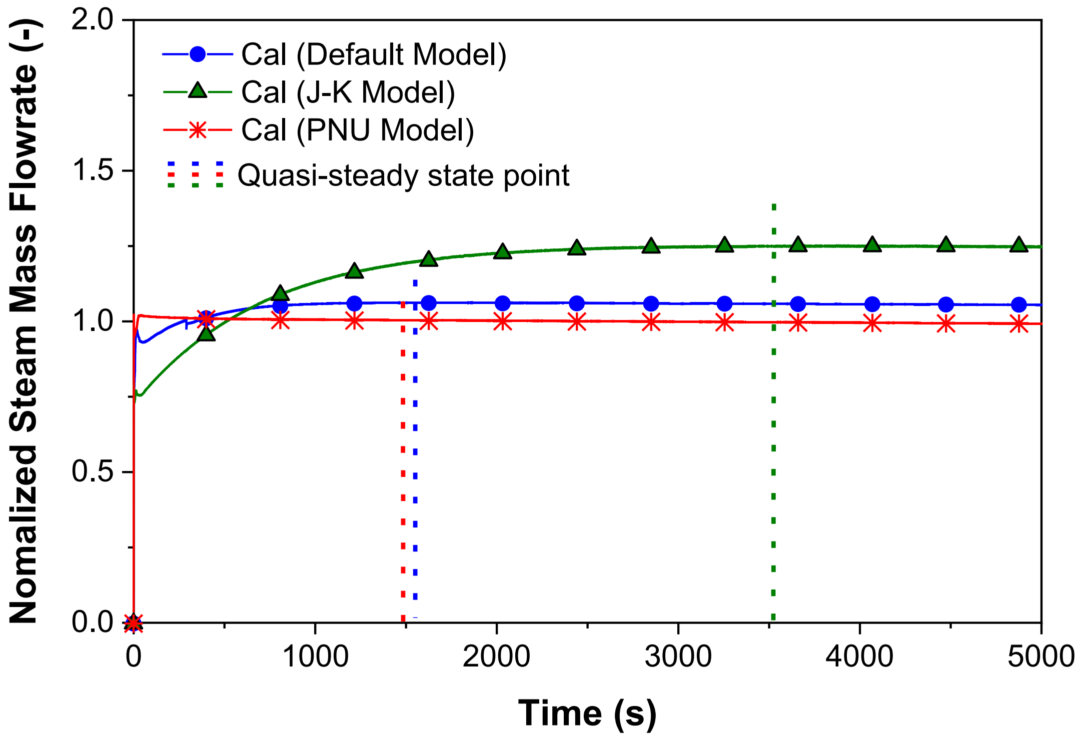


Figure 5-9 Variation of Steam Mass Flow Rates (SG heater power of 540kW)

5.2.3 Heat Removal Rates at the SG Heater Power of 540kW

Figure 5-10 compares the heat removal rates of the PCHX tube. The heat removal rate of the PCHX is calculated from the sum of the wall heat transfer rate of each node. At the quasi-steady state point, the heat removal rates in the PCHX tube were equivalent to the supplied power.

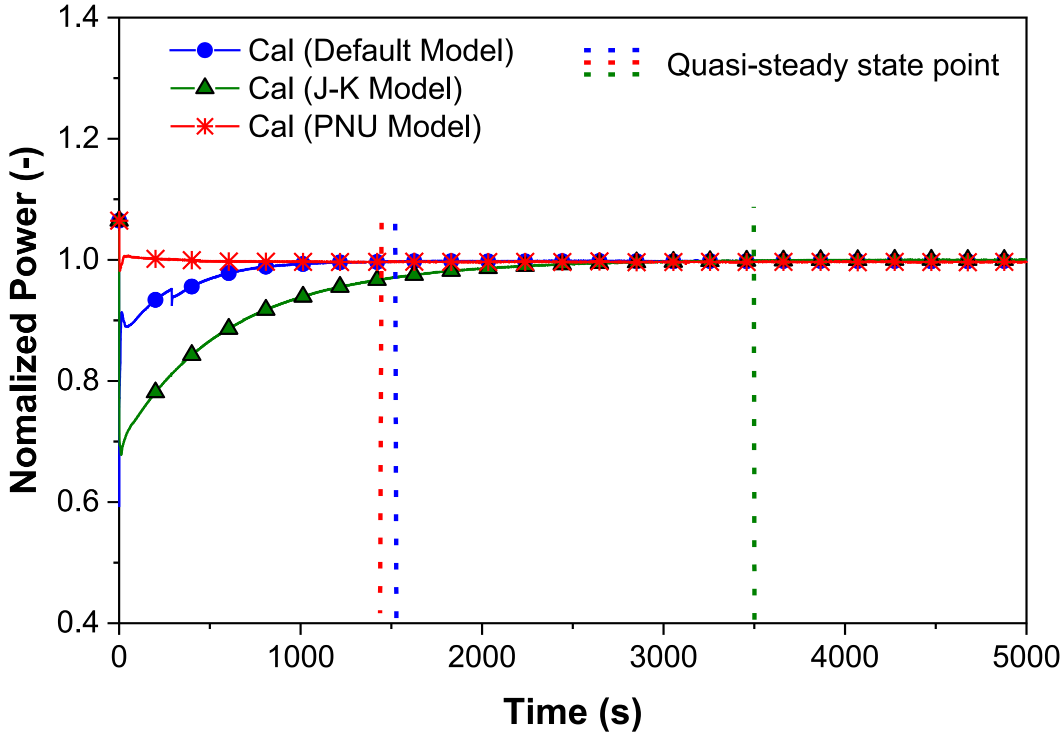


Figure 5-10 Heat Removal Rates (SG Heater Power of 540kW)

5.2.4 Effect of SG Power on SG Pressures and Steam Flow Rates

Figure 5-11 shows the results for SG pressures at various SG heater power conditions of 200-750 kW. The values are normalized using the measured data.

When compared with the measured data, the default model has a large error of about 220% at a low SG heater power of 200 kW. However, the error gradually decreases to about 25% as the SG heater power increases up to 540 kW. There is little difference in errors when the SG heater powers are from 540 to 750 kW.

The J-K model overestimates the SG pressure by about 18% at a low SG power of 200 kW. The larger the heater power, the larger the error. At an SG heater power of 650 kW, the J-K model overestimates the SG pressure by about 325%. The J-K model failed to reach the quasi-steady state at a high SG heater power of 750 kW during the entire calculation time.

Figure 5-12 shows the values of the stratified flow weighting factor (wfhf) along the PCXH tube at various SG heater powers in the calculation of the J-K model. The result indicates that the wfhf is greatly affected by the thermal-hydraulic conditions. The wfhf value of the PCHX inlet is nearly zero at a low SG heater power of 200 kW, but it gradually increases to a value of 1.0 at a 5 m distance from the inlet. As the SG heater power increases, the tube length at which the wfhf is zero increases.

As explained in Section 5.1.2, a very small wfhf value significantly reduces the contribution of the J-K HTC to the total heat transfer rate and results in a convective-dominant heat transfer. This result explains well that the error increases as the SG heater power increases in the calculation of the J-K model.

The PNU model predicts the SG pressures at all SG heater powers well. The maximum error is 11% and occurs at the SG heater power of 750 kW.

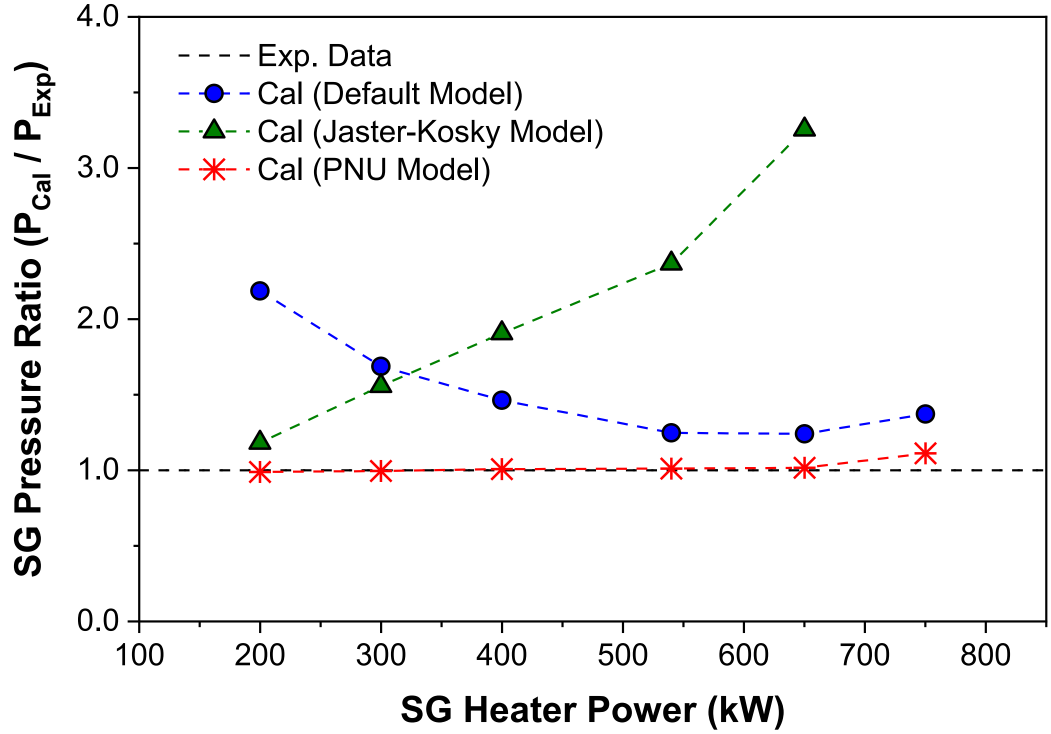


Figure 5-11 SG Pressures at Various SG Heater Powers

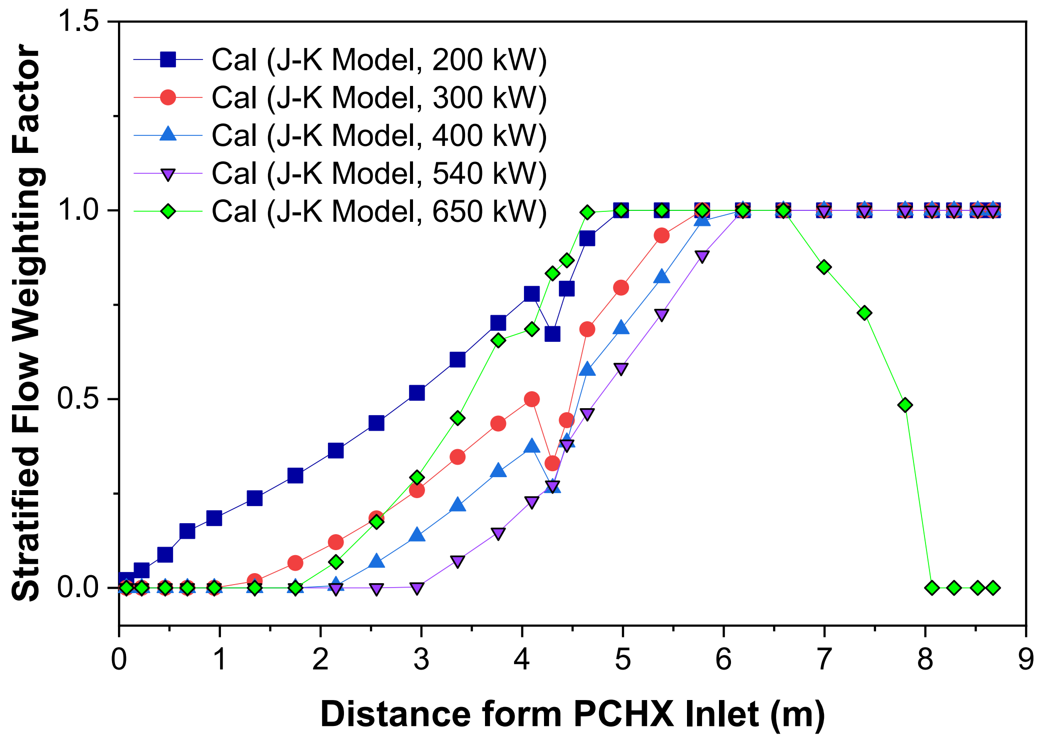


Figure 5-12 Values of wfhf at Various SG Heater Powers in the J-K Model

Figure 5-13 shows the results of steam mass flow rates at the PCHX inlet at various SG heater power conditions of 200-750 kW.

The default model generally overestimates the steam mass flow rates. The maximum error occurs at the SG heat power of 200 kW, and its value is 12%. Except for the 750 kW, the error decreases as the SG heater power increases.

The J-K model overestimates the steam flow rates by about 5.7% at a low SG power of 200 kW. As with the results of SG pressure, the larger the heater power, the larger the error. At the SG heater power of 650 kW, the J-K model overestimates the steam flow rates by about 45%.

The PNU model predicts the steam flow rates at all SG heater powers well. The maximum error is 4.0% and occurs at the SG heater power of 750 kW.

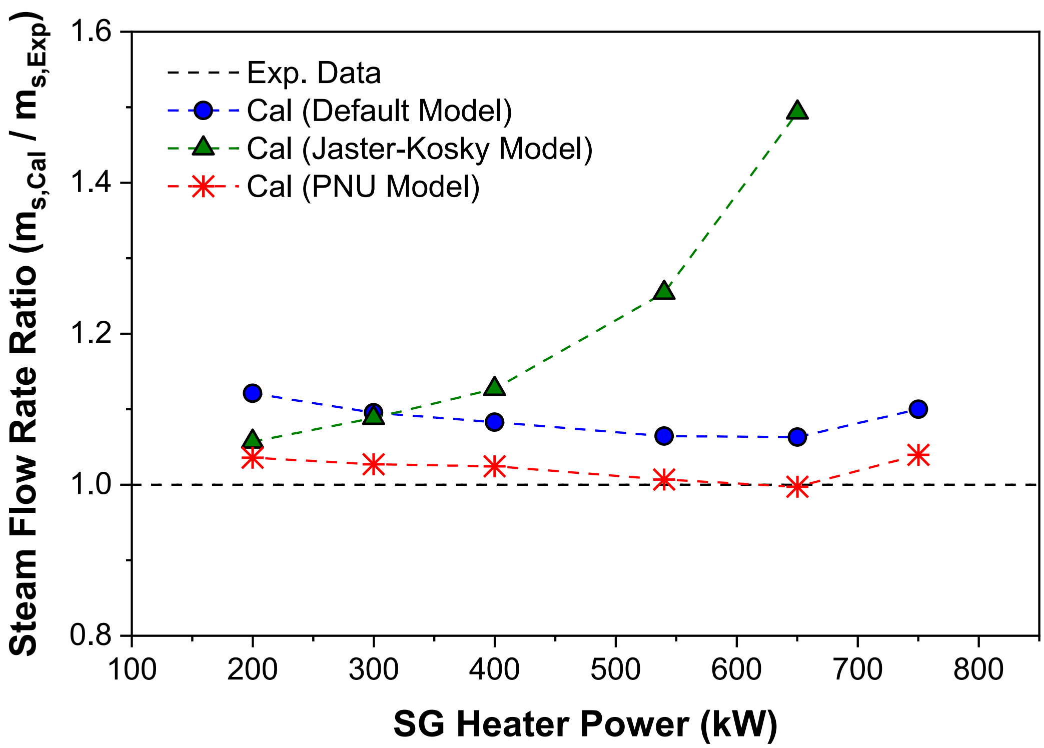


Figure 5-13 Steam Mass Flow Rates at Various SG Heater Powers

6 CONCLUSIONS

The predictive capability of TRACE V5.0 patch 5 for the condensing heat transfer in the horizontal stratified flow was assessed using the results of a PASCAL experiment.

The filmwise condensation heat transfer model (default model) and horizontal stratified condensation model (J-K model) of TRACE were evaluated at various SG heater powers. In addition, a new condensation model developed by Pusan National University (PNU model) was implemented and evaluated.

Using a simplified input model, the effect of three condensation heat transfer models on the thermal-hydraulic parameters were investigated at the same boundary conditions. The calculation result of the default condensation model overestimated the heat transfer rate at the upper half of the PCHX and under-predicted it at the lower half of the PCHX. The J-K model failed to capture the heat fluxes and considerably underestimated the heat transfer rate. The PNU model well captured the values and distribution of the heat transfer rate along the PCHX.

Using the total PASCAL input model, the effect of three condensation heat transfer models on the overall system behavior were evaluated. The calculation results of SG pressure and steam flow rates at various SG heater powers (200 ~ 750 kW) were compared with the measured data.

The default model generally over-predicted the SG pressure and steam flow rates at the PCHX inlet under all SG heater powers. The maximum error for the SG pressure occurred at the lowest SG heater power, and its value was about 220%. The error gradually decreased to about 25% as the SG heater power increased up to 540 kW or more. The errors for the steam flow rate were within 12%.

The J-K model also generally overestimated the SG pressure and steam flow rates. The larger the SG heater power, the larger the error for SG pressure and steam flow rate. The stratified flow weighting factor (wfhf) was greatly affected by the thermal-hydraulic conditions.

The PNU model predicted well the SG pressure and steam flow rates at the PCHX inlet under all SG heater powers.

To improve the predictive capability of TRACE V5.0 Patch 5 for the condensing heat transfer in the horizontal stratified flow, the condensation heat transfer model of the code needs to be improved.

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10. SUPPLEMENTARY NOTES

K. Tien, NRC Project Manager

11. ABSTRACT (200 words or less)

The passive auxiliary feedwater system (PAFS) is one of the advanced safety features of the Advanced Power Reactor Plus (APR+) and Advanced Power Reactor 1000 (APR1000). During a plant transient, the PAFS cools down the secondary side of the steam generator, and removes the decay heat of the reactor core by condensing steam in nearly-horizontal U-shaped tubes submerged inside the passive condensation cooling tank. This study investigated the predictive capability of TRACE V5.0 patch 5 for the cooling and operational performance of the PAFS. For this purpose, the predictive capability of the code for the condensing heat transfer in the horizontal stratified flow was assessed using the results of a PASCAL experiment. The filmwise condensation heat transfer model and horizontal stratified condensation model of TRACE were evaluated. In addition, a new condensation model developed by Pusan National University (PNU model) was implemented and evaluated. The filmwise condensation heat transfer model and horizontal stratified condensation model generally overestimated the pressure and the steam flow rate of the steam generator. The PNU condensation model, on the other hand, predicted well the pressure and the steam flow rate of the steam generator under various heater powers.

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Assessment of Condensation Heat Transfer Models of TRACE V5.0 Patch 5
Using PASCAL Tests

September 2022