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Modification of the Condensation Heat Transfer Model of RELAP5/MOD3.1 for the simulation of Secondary Condensers

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Abstract

The dependence of the node size in the condensation heat transfer coefficient for an inclined surface is eliminated and two correlations applicable for laminar and turbulent regimes are implemented in RELAP5/MOD3.1. The newly implemented correlations are used according to their applicable ranges of the film Reynolds numbers Re_Γs which are calculated recursively to track the condensate film thickness along the condensation length. The modified version is compared with the original one through comparison with an analytical solution and the simulation of the Secondary Condensers (SC). It turns out that the simulation results by this modified version are independent of the node size and are better agreement with the analytical solution than those by the original one.

1. Introduction

RELAP5/MOD3.1 is applied to the evaluation of performance of the Secondary Condensers (SC) which is the passive decay heat removal system in Pressurized Water Reactor (PWR) replacing the emergency feed water system after reactor trip. The condensation phenomenon plays an important role in the heat transfer process of SC. The steam from the main steam line is condensed in the vertical tubes immersed in the water pools outside the containment.

The models for wall condensation heat transfer can be broadly classified into two: laminar flow and turbulent flow. For stationary pure vapor, Nusselt[1] analyzed laminar film condensation on an isothermal inclined surface by predicting the conduction across the film thickness. Numerous experimental investigations of laminar film condensation subsequent to the Nusselt theory have been reported. Empirical correlations of Zazuli[2], McAdams[3] and Labuntsov[4] are the surface-average heat transfer coefficients (HTCs) rather than local values due to the relative ease in obtaining accurate overall measurements. These correlations are related to the total condensate flow rate and in turn the film Reynolds number Re_Γ.

At high Re_Γs the experimental condensation HTCs are consistently above the Nusselt prediction. Kirkbride[3] obtained an empirical relation for heat transfer in the case of combined laminar and turbulent flow. Chun and Seban[2] presented results for the HTCs for evaporation from the surface of water films flowing along the outside surface of a vertical tube for the case of laminar and turbulent flows.

The condensation model in RELAP5 should account for the physical phenomena under all ranges of Re_Γ normally encountered in engineering practice. However, the Nusselt HTC adopted in RELAP5/MOD3.1 is based on very strict assumptions such as linear temperature profile in the liquid film and laminar film flow which are rarely encountered in practice. Moreover, the condensation HTCs predicted by RELAP5/MOD3.1 is dependent on the node size of the condenser. For the production of the reliable results the code should be independent of the node size.

2. Problems of the Condensaton Model

In RELAP5/MOD3.1 the condensation heat transfer is modeled based on laminar film condensation on an inclined or vertical surface and laminar film condensation inside a horizontal tube with a stratified liquid surface. RELAP5/MOD3.1 first calculates a condensation HTC for an inclined or horizontal surface and then considers turbulent flow and non-condensible gas effects using the UCB correlation by Vierow and Schrock[8][9].

For the condensation of pure steam in a vertical tube the condensation HTC h_{nss} is

$$h_{nss} = 0.943 \left[\frac{\rho_f(\rho_f - \rho_g)g\ h_{fg}k_f^3}{\mu_f L_c(T_s - T_w)} \right]^{\frac{1}{4}}. \tag{1}$$

Now we can get the same condensation HTC as that by the Nusselt theory[1] which represents a HTC averaged over the condensation length L_c with zero film thickness at its top.

As shown in Eq.(1), the HTC is a function of L_c. As the smaller the size of nodes becomes, the larger condenstion HTCs are calculated by RELAP5/MOD3.1. As a result, the condensation HTC in RELAP5/MOD3.1 is calculated for each node as if new condensation from its top starts.

Another problem is that substantial discrepancies exist between results from the Nusselt theory and the experimental data when the condensate flow becomes turbulent or when the vapor velocity is high.

3. Modification of the Condensaton Model

The condensation model is modified to overcome the limitations of the original RELAP5/MOD3.1 model as pointed out above. This work is done by the following two steps:

1. Investigate the correlations applicable for laminar and turbulent film-wise condensation, respectively.
2. A new method, which is able to track the condensate film thickness along the series of nodes continuously, is developed to remove the node-size dependence of the condensation HTCs.

For the average condensation HTC $\overline{h}$ along the condensation length, the average Nusselt number is defined as

$$\overline{\mathrm{Nu}} \equiv \frac{\overline{h}}{k_f} \left[\frac{\mu_f^2}{\rho_f(\rho_f - \rho_g)g\ sin\theta} \right]^{\frac{1}{3}}. \tag{2}$$

Figure 2 shows the average Nusselt numbers calculated from several correlations for laminar and turbulent flow. Kim's correlation[5] is a semi-empirical average heat transfer correlation applicable for both laminar and turbulent film-wise condensation but has somewhat complex form. Here, Labuntsov[4] and Kirkbride[3] correlations are adopted for code modification:

$$\overline{\mathrm{Nu}} = a\mathrm{Re}_\Gamma^b, \tag{3}$$

where

$$\begin{array}{lll} a = 1.39, & b = -22/75 & \text{for } \mathrm{Re}_\Gamma \le 1800, \\ a = 0.0077, & b = 0.4 & \text{for } 1800 < \mathrm{Re}_\Gamma. \end{array}$$

These correlations are chosen because of their easy implementation in RELAP5 and no need for interpolation between these two correlations because they produce the same value at $\mathrm{Re}_\Gamma = 1800$.

For the modification of condensation model, let us derive the condensation HTC which replaces h_{nss} in Eq.(1).

The mass flow rate per unit width Γ is given by

$$\Gamma = \frac{\overline{h}(x)}{h_{fg}}(T_s - T_w)x, \tag{4}$$

and Re_Γ is

$$\mathrm{Re}_\Gamma \equiv \frac{4\Gamma}{\mu_f}$$

$$= \frac{4(T_s - T_w)}{\mu_f h_{fg}} \overline{h}(x) x. \tag{5}$$

The average condensation HTC in Eq.(2) is related to the local HTC $h(x)$ as follows:

$$\overline{h}(x) = \frac{1}{x} \int_0^x h(x)\, dx. \tag{6}$$

The local Nusselt number is defined as

$$\mathrm{Nu}(x) \equiv \frac{h(x)}{\mathrm{K}}, \tag{7}$$

where

$$\mathrm{K} = k_f \left[\frac{\rho_f (\rho_f - \rho_g) g \ sin\theta}{\mu_f^2} \right]^{\frac{1}{3}}.$$

From Eqs.(2), (6) and (7) the following equation can be obtained:

$$\overline{\mathrm{Nu}}(x) = \frac{1}{x} \int_0^x \mathrm{Nu}(x) dx. \tag{8}$$

Then, the local Nusselt number becomes

$$\begin{aligned} \mathrm{Nu}(x) &= \frac{\partial}{\partial x}(x \overline{\mathrm{Nu}}) \\ &= \overline{\mathrm{Nu}} + \frac{\partial \overline{\mathrm{Nu}}}{\partial \mathrm{Re}_\Gamma} \frac{\partial \mathrm{Re}_\Gamma}{\partial x} x, \end{aligned} \tag{9}$$

and from Eqs.(5) and (6)

$$\frac{\partial \mathrm{Re}_\Gamma}{\partial x} = \frac{4(T_s - T_w)}{\mu_f h_{fg}} h(x) \tag{10}$$

$$= \frac{\mathrm{Re}_\Gamma}{\overline{h}(x) x} h(x). \tag{11}$$

Applying Eq.(11) to Eq.(9) yields

$$\begin{aligned} \mathrm{Nu}(x) &= \overline{\mathrm{Nu}}(x) + \frac{\partial \overline{\mathrm{Nu}}}{\partial \mathrm{Re}_\Gamma} \mathrm{Re}_\Gamma \frac{h(x)}{\overline{h}(x)} \\ &= \overline{\mathrm{Nu}} + ab \mathrm{Re}_\Gamma^b \frac{\mathrm{Nu}}{\overline{\mathrm{Nu}}}. \end{aligned} \tag{12}$$

Equation(12) is rearranged as follows:

$$\mathrm{Nu}(x) = \frac{\overline{\mathrm{Nu}}}{1 - b}. \tag{13}$$

Also from Eqs.(7), (10) and (13) we have

$$d\mathrm{Re}_\Gamma = \mathrm{A} \ \mathrm{Re}_\Gamma^b(x)\, dx, \tag{14}$$

where

$$A = \frac{4ak_f(T_s - T_w)}{h_{fg}(1-b)} \left[\frac{\rho_f(\rho_f - \rho_g)g \ sin\theta}{\mu_f^5} \right]^{\frac{1}{3}}$$

If the x values at the mesh points over the condensation length are denoted by $x_0, x_1, \cdots, x_n, \cdots$ and their corresponding Re$_\Gamma$s are $Re_0, Re_1, \cdots, Re_n, \cdots$, respectively, integrating Eq.(14) from x_{n-1} to x_n yields

$$Re_n = [\ A(1-b)(x_n - x_{n-1}) + Re_{n-1}^{1-b}\ ]^{\frac{1}{1-b}}.$$

With the information of $Re_0 = 0$ at x_0, Re_n is recursively obtained as follows:

$$\begin{aligned} Re_1 &= [\ A(1-b)x_1\ ]^{\frac{1}{1-b}}, \\ Re_2 &= [\ A(1-b)(x_2 - x_1) + Re_1^{1-b}\ ]^{\frac{1}{1-b}}, \\ &\vdots \\ Re_n &= [\ A(1-b)(x_n - x_{n-1}) + Re_{n-1}^{1-b}\ ]^{\frac{1}{1-b}}. \end{aligned} \tag{15}$$

Integrating the local HTC $h(x)$ produces the average HTC between x_{n-1} and x_n defined as

$$\overline{h_{x_n}} \equiv \frac{1}{(x_n - x_{n-1})} \int_{x_{n-1}}^{x_n} h(x)\, dx. \tag{16}$$

From Eqs.(7), (13) and (14), Eq.(16) becomes

$$\overline{h_{x_n}} = \frac{aK}{A(1-b)(x_n - x_{n-1})} [\ Re_n - Re_{n-1}\ ]. \tag{17}$$

Equation(17) is the final form to be calculated in the modified conden.f subroutine. The term, $x_n - x_{n-1}$, in Eq.(17) corresponds to the cell length at the n-th node.

4. Simulation Results

First, the modified model is tested in the idealized conditions, where all thermal properties of fluid and wall are constant along the condensation length of 1.8 m. This condensation length is divided by 3, 6 and 12 nodes for each case. The calculation results of HTCs by the orignal and the modified models are shown in Figure 3. As the number of nodes increases, the HTCs calculated by the modified model approach the original values calculated directly from the Nusselt correlation, while the HTCs calculated by the original method of RELAP5/MOD3.1 increase. Since the film thickness is the heat resistance, the HTCs by the Nusselt theory decrease as the film thickness grows along the condensation length. However, the calculation method of RELAP5/MOD3.1 cannot track this growing film thickness. Therefore, it keeps average HTCs corresponding to the node size overpredicting the HTCs from the Nusselt correlation.

The modified model is applied to the transient simulation of a two-loop PWR with the thermal capacity of 3914MW and Secondary Condensers (SC) developed at CARR (Center for Advanced Reactor Research). Figure 1 shows the nodalization diagram of this plant.

From the steady-state conditions of full-power operation the transient simulation starts with the reactor and Reactor Coolant Pump (RCP) trips followed by

- Instantaneous complete loss of the main and auxiliary feed water flow
- Instantaneous closing of all the main steam isolation valves and turbine trip
- Actuation of SC valves

After the actuation of SC valves, steam produced in the secondary side of the steam generator flows down the SC immersed in the pool outside the containment. Decay heat is removed by condensing this steam in SC and the condensate returns to the steam generator through the main feed water line. The Reactor Coolant System (RCS) is cooled down and depressurized with this heat removal of SC.

SC consists of bundles of vertical condensers with the length of 1.8 m. The simulations of SC are performed changing the number of nodes in these condenser tubes. As shown in Figures 4 through 6, the results of the original RELAP5/MOD3.1 depend on the node size. The primary and secondary pressures fall faster and the heat removal rates by SC increase as the number of nodes increases. However, the results of the modified version are independent of the node size.

As expected, condensation HTCs provided by the original version increase as the number of nodes increases. The much lower HTCs predicted by the original version than those by the modified one come from the use of the Nusselt correlation in the original one even in turbulent regime in which the present calculation is dominant; the Nusselt correlation guesses much lower condensation HTCs in turbulent regime.

5. Conclusions

The condensation heat transfer model of RELAP5/MOD3.1 is modified. The condensation HTC in RELAP5/MOD3.1 is calculated as if new condensation starts from the top of each node. As the smaller the size of nodes becomes, the larger condensation HTCs are calcualted by RELAP5/MOD3.1.

A new model, which is able to track the condensate film thickness along the series of nodes continuously, is developed to remove the node-size dependence. This model is implemented in RELAP5/MOD3.1, and SC is simulated with the original and modified versions. It is found that the results by the modified version are independent of the node size of the condenser volumes while the original version predicts higher condensation HTCs as the node size increases.

References

[1] John G. Collier *Convective Boiling and Condensation*, 2nd ed., pp.328–330, McGraw-Hill, New York, 1981.

[2] Chun, K.R., and Seban, R.A. *Heat Transfer to Evaporating Liquid Films*, ASME J. Heat Transfer, Vol.93, pp.391–396, 1971.

[3] W.H. McAdams *Heat Transmission*, 3rd edition, Chap.13, McGraw-Hill, New York, 1954.

[4] S.S Kutateladze and I.I. Gogonin *Heat Transfer in Film Condensation of Slowly Moving Vapor*, Int. J. Heat Mass Transfer, Vol.22, pp.1593–1599, 1979.

[5] Kyun-Tae Kim *A Semi-Empirical Heat Transfer Coefficient for Laminar and Turbulent Film Condensation on a Vertical Surface*, KAIST PhD Thesis, 1991.

[6] C. D. Flether, et al. *RELAP5/MOD3 Code Manual*, NUREG/CR-5535, EGG-2596, August, 1991.

[7] V.H. Ransom, et al. *RELAP5/MOD3.2 Code Manual, Vol.IV*, NUREG/CR-5535, INEL-95/0174, June, 1995.

[8] K.M. Vierow and Virgil E. Schrock *Condensation in a Natural Circulation Loop with Noncondensable Gases Part I - Heat Transfer*, Intl. Conf. On Multiphase Flows, '91-Tsukuba, Vol.1, pp.183–186, 1991.

[9] K.M. Vierow and Virgil E. Schrock *Condensation in a Natural Circulation Loop with Noncondensable Gases Part II - Flow Instability*, Intl. Conf. On Multiphase Flows, '91-Tsukuba, Vol.1, pp.187–190, 1991.

[10] Chato, J.C. *Laminar Condensation Inside Horizontal and Inclined Tubes*, ASHRAE, 4, pp.52–60, 1969.

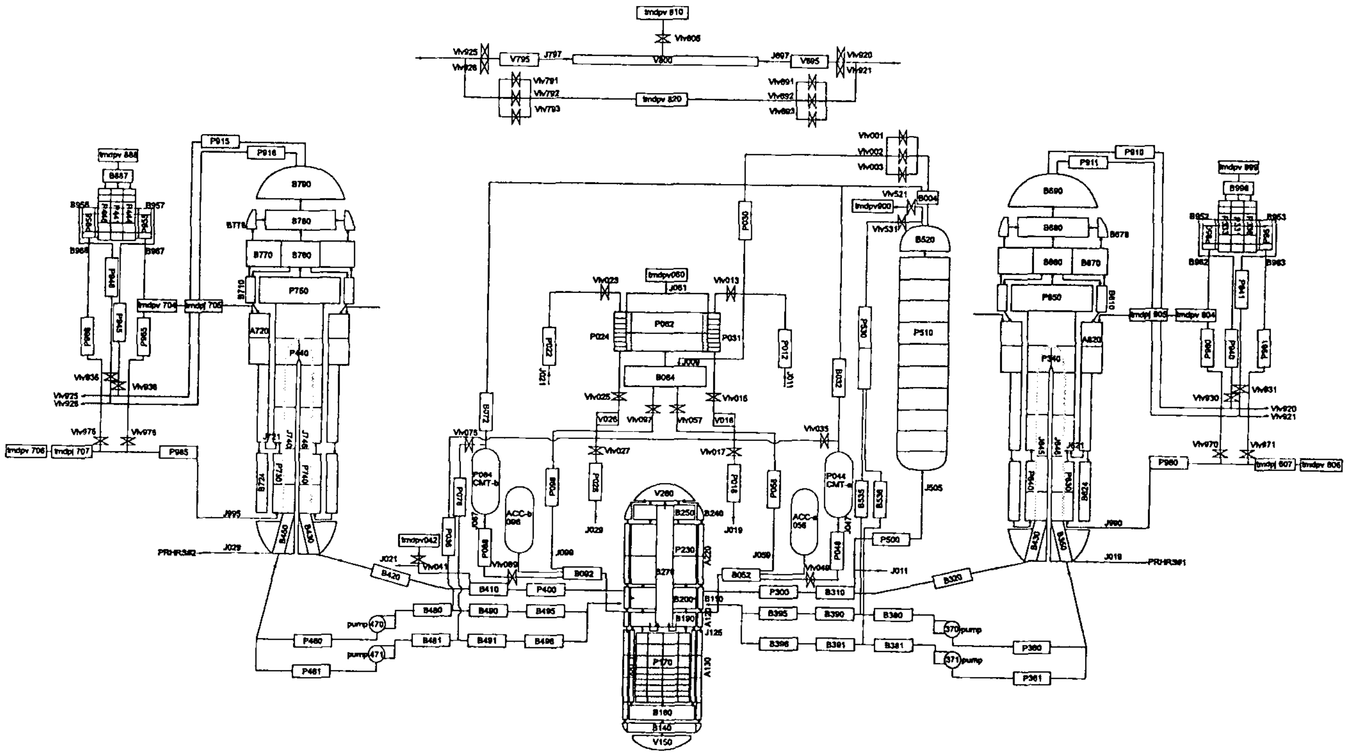


Figure 1: RELAP5 nodalization of the CARR plant with SC

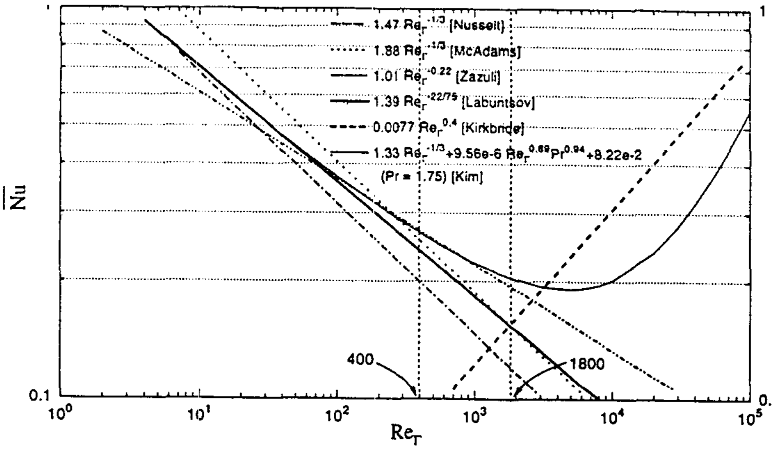


Figure 2: Average Nusselt numbers vs Re_Γ

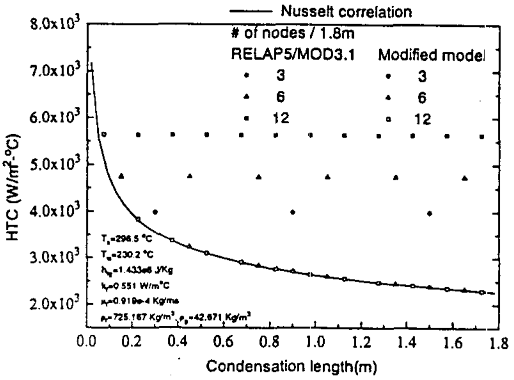
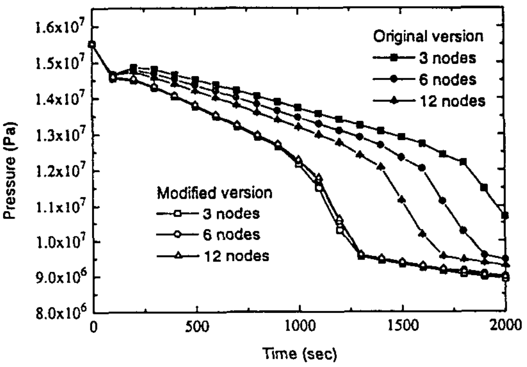
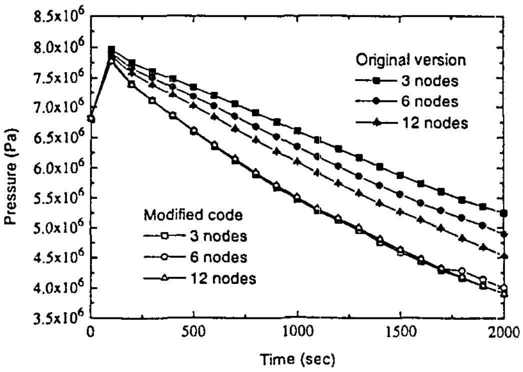


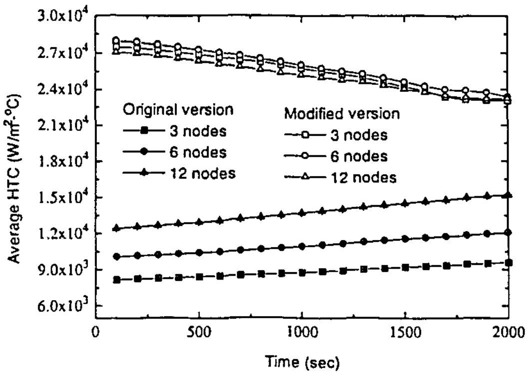
Figure 3: Test calculations
by the original and the modified models



Fiugre 4: Effect of node size
on the primary pressure



Fiugre 5: Effect of node size
on the secondary pressure



Fiugre 6: Effect of node size
on the condensation HTC