New condensation correlation test of TASS/SMR-S code for PRHRS

Hyungjun Kim*, Young-Jong Chung, Hyungrae Kim and Kyoo-Hwan Bae
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057
** Corresponding author : jun@kaeri.re.kr*

1. Introduction

The TASS/SMR (Transients and setpoint simulation/system-integrated modular reactor) code is developed for conservative thermal-hydraulic (TH) simulation of SMART by KAERI [1]. The major components of RCS (reactor coolant system) in SMART, advanced integral reactor which is designed to generate 330-MWt, eliminate the possibility of a large break loss of coolant accident (LBLOCA). Also, passive residual heat removal system (PRHRS) is adopted to improve native safety feature by removing decay heat through the steam generator and the condensate heat exchanger after a reactor shutdown.

In PRHRS, condensation of steam in vertical tube occurs during operation and its performance is very important for long-term cooling of reactor after trip. In previous TASS code, the maximum value of Nusselt and Shah correlation [2, 3] for condensation in PRHRS tube is used. However, it is well known that Nusselt correlation is developed to condensation in vertical plate and Shah correlation, developed using vertical, horizontal and inclined tube condensation result in various condition, is not good at low flow rate condition. In this paper, several condensation correlations are reviewed and new condensation correlation is suggested for PRHRS and test results are compared with previous.

2. Review of previous condensation correlations

The heat transfer correlations for PRHRS in TASS code are shown in Fig. 1 [4]. In previous, when void fraction $\alpha>0.1$, Nusselt and Shah correlations are used and linear interpolation between single phase liquid (Dittus-Boelter correlation) is used when $\alpha<0.1$.

To find new correlation for condensation in PRHRS, some correlations for condensation in vertical tube are reviewed.

2.1 S. Kim [5]

This correlation is developed on high pressure steam condensation heat transfer in a large diameter condenser tube. Tube length is 1.8 m and inner/outer diameter of tubes are 46/50.8 mm. Test pressure is varied from 0.35 to 7.2 MPa.

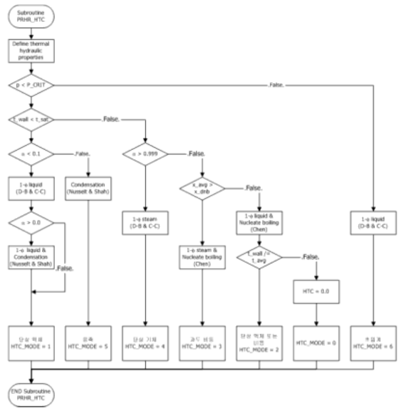

Fig. 1. PRHRS heat transfer mode in TASS code

$$h=\frac{f_D}{(1-\alpha)}\mathrm{Re}_f^{0.8}\,\mathrm{Pr}_f^{0.4}\,\frac{k_f}{D}$$

$$\alpha=\left(1+X_{tt}^{0.6}\right)^{-0.15}$$

$$X_{tt}=\left(\frac{\mu_f}{\mu_g}\right)^{0.25}\left(\frac{1-x}{x}\right)^{0.75}\left(\frac{\rho_g}{\rho_f}\right)$$

$$f_D=0.0182\left[1-0.24\left(1-4.47D^{0.5}\right)\right]^4$$

2.2 K.Y. Lee [6]

Originally, test is focused to investigate the effect of noncondensable gas on condensation in a vertical tube. Tube length is 2.8 m which has inner/outer diameter of 13/18 mm and test pressure is 0.1 – 0.13 MPa. Correlations are obtained from the study of interfacial shear stress and condensation correlation for pure steam is also stated as;

$$h=h_{Nu}\times 0.8247\tau_g^{0.3124}$$

$$\tau_g=\frac{0.5\rho_g u_g^2 f}{g\rho_f L}$$

2.3 F.P. Incropera [7]

They suggested a series of film condensation correlation on a vertical plate from laminar (wave free)-laminar (wavy)-turbulent with liquid film Reynolds number as criterion.

$$\mathrm{Re}_\delta=\frac{4g\rho_f\left(\rho_f-\rho_g\right)\delta^3}{3\mu_f^2},\; L_c=\left(v_f^2/g\right)^{1/3}$$

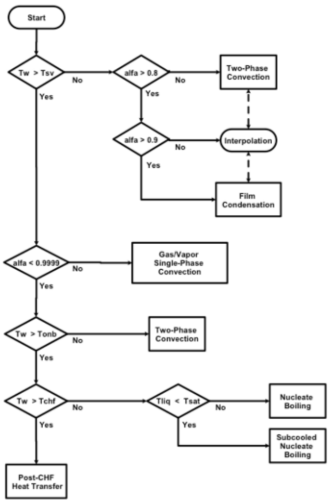

Fig. 2. Heat transfer regime selection in TRACE [8]

$$\frac{hL_c}{k_f}=\begin{cases}1.47\,\mathrm{Re}_\delta^{-1/3}\ \text{ for }\ \mathrm{Re}_\delta\le 30\\ \dfrac{\mathrm{Re}_\delta}{1.08\,\mathrm{Re}_\delta^{1.22}-5.2}\ \text{ for } 30\le\mathrm{Re}_\delta\le 1800\\ \dfrac{\mathrm{Re}_\delta}{8750+58\,\mathrm{Pr}^{-0.5}(\mathrm{Re}_\delta^{0.75}-253)}\ \text{ for }\ \mathrm{Re}_\delta\ge 1800\end{cases}$$

2.4 TRACE [8]

TRACE uses three regimes in condensation: film condensation, two-phase convection and their interpolation by void fraction as shown in Fig. 2. Nu_{lam} are comes from K-S-P correlation [9] and Nu_{turb} is from Gnielinski correlation for single-phase forced convection [10]. Also, both are properly modified to TRACE. For two-phase convection, two-phase Reynolds number is defined and used in single-phase liquid convection correlation.

$$Nu_{wl}=\left(Nu_{lam}^2+Nu_{turb}^2\right)^{1/2}$$

$$Nu_{lam}=2\left(1+1.83\times10^{-4}\,\mathrm{Re}_f\right)$$

$$Nu_{turb}\approx\frac{1}{4}Nu_{Gnielinski}$$

$$Nu_{Gnielinski}=\frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/2)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}$$

$$f=\left[1.58\ln\left(\mathrm{Re}_f\right)-3.28\right]^{-2}$$

$$\text{for } 2300\le\mathrm{Re}_f\le5\times10^6,\ 0.5\le\mathrm{Pr}\le2000$$

3. Development of new correlation

Whenever the wall temperature of a heat structure is less than the saturation temperature corresponding to the vapor partial pressure, condensation will occur. When condensation occurs, the flow changes as; annular or laminar wavy film-transition-turbulent film-single phase liquid flow. Hence, it's reasonable to separate the condensation correlation followed by condensation regime.

Table 1. New condensation correlation of TASS for PRHRS

Criterion	Correlation
α>0.9	$h_{Lee}=h_{Nu}\times0.8247\tau_g^{0.3124}$ $\tau_g=\dfrac{0.5\rho_g u_g^2 f}{g\rho_f L}$
0.8<α<0.9	Interpolation
α<0.8	Nu=Max(4.36,$\mathrm{Nu}_{\mathrm{Gnielinski}}$) $\mathrm{Re}_{2\phi}=\dfrac{G_l\cdot D_h}{(1-\alpha)\cdot\mu_l}=\dfrac{\rho_l\cdot V_l\cdot D_h}{\mu_l}$

For the new condensation correlation in TASS code, after several tests, the regime selection in TRACE is adopted and Lee [6]'s correlation is selected in film condensation. For two-phase convection correlation, Nusselt number is selected of maximum of 4.36 for laminar and Gnielinski correlation for turbulent with two-phase Reynolds number as shown in Table 1.

4. Validation of new correlation

Validation of new condensation correlation is performed using experimental results in [11] and compared with previous TASS code result.

4.1 POSTECH Ambient Pressure Test

Condensation experiment of pure steam in a vertical tube under ambient pressure with various steam flow rate is used for validation of new correlation. Six cases are tested with increasing steam flow rate. Tube inner/outer diameter is 13/18 mm and tube length is 3 m.

Using the experiment and previous TASS result, heat transfer coefficients are compared as shown in Fig. 3. All heat transfer coefficients are normalized with inlet value of test #3. From the new correlation, rapid decrease of heat transfer coefficient from tube inlet can be predicted, but not in previous TASS code. Also in Fig. 4, heat transfer coefficients from experiment and calculation are compared and the statistical results are obtained in Table 2. Deviation of heat transfer coefficient is decreased in new correlation but root-mean-square error (RMSE) is still high. In Fig. 5, the normalized heat removed from tube is plotted for comparison of test, previous TASS and new correlation. New correlation shows conservative heat remove rate to experiment.

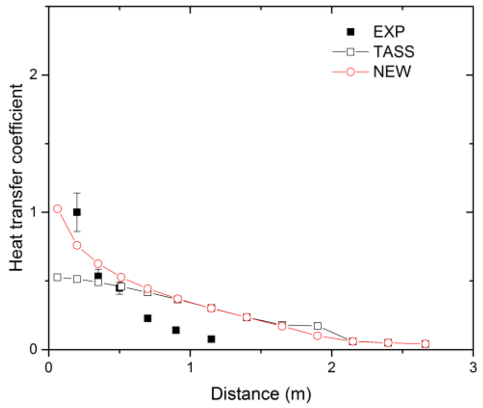

Fig. 3. POSTECH ambient test #3 - heat transfer coefficient

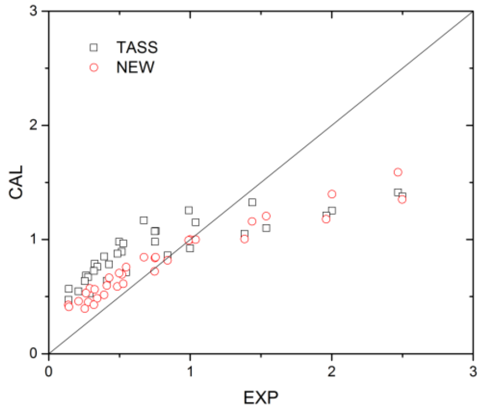

Fig. 4. POSTECH ambient test – heat transfer coefficient comparison

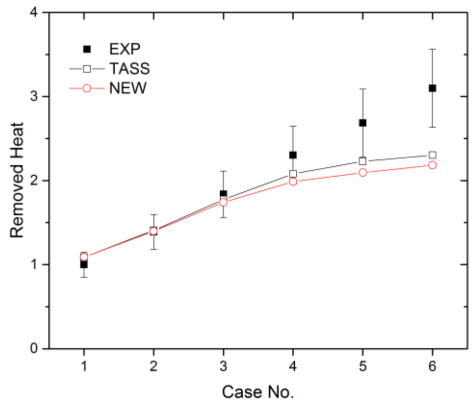

Fig. 5. POSTECH ambient test – heat removed

Table 2. POSTECH ambient test – correlation comparison

	TASS	NEW
Avg. Std. Dev. (%)	80.001	41.765
Avg. RMSE (kW/m^{2}K)	5.018	3.862

4.2 POSTECH high pressure test

This test is focused on steam condensation in vertical tube with high pressure. Tube length is 1.5 m and have

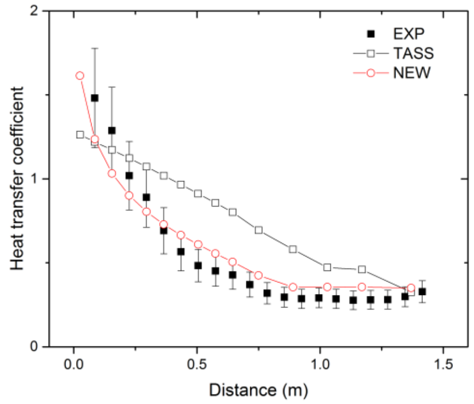

Fig. 6. POSTECH high pressure test – 2MPa, high steam flow rate

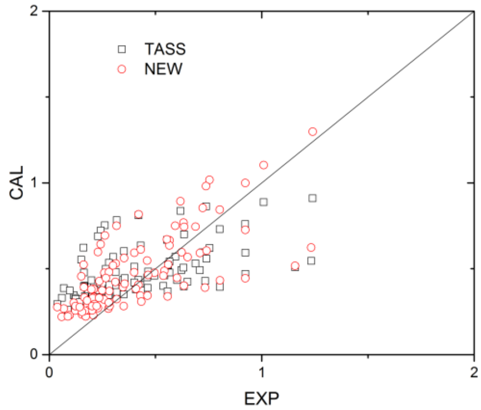

Fig. 7. POSTECH high pressure test – heat transfer coefficient comparison

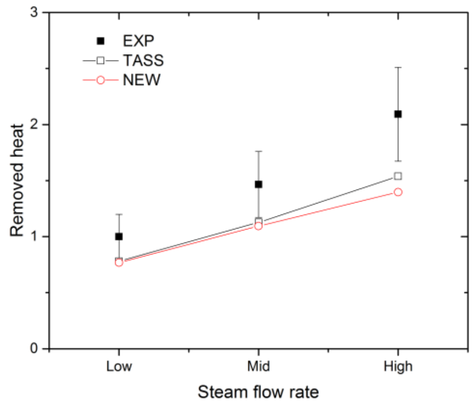

Fig. 8 POSTECH high pressure test – heat removed at 2 MPa

Table 3. POSTECH high pressure test – correlation comparison

	TASS	NEW
Avg. Std. Dev. (%)	91.7444	64.362
Avg. RMSE (kW/m^{2}K)	1.835	1.892

15.80/21.34 mm of inner/outer diameter. Pressure varies from 1, 2, 4 and 6 MPa and three different steam flow rates (low-medium-high) are tested in each pressure condition.

As shown in Fig. 6, heat transfer coefficients are normalized to test value of high steam flow rate at 2 MPa. In Fig. 7, condensation heat transfer coefficient of calculation and test are compared and is analyzed in Table 3. Deviation of heat transfer coefficient is considerably decreased but RMSE is little increased. From Fig. 8, the heat removed from tube by new correlation is still conservative than experimental one.

5. Conclusion

New condensation correlation is suggested and validated to enhance the ability of predicting condensation heat transfer in PRHRS for TASS/SMR code. Compared to previous one, new correlation subject to condensation flow regime in vertical tube is suggested and the comparison result shows better agreement to experiments. But there still exist some disagreement depending on pressure in tube. Also, correlation used in film condensation regime is laminar flow, not for turbulent. Hence, the optimization of correlation for wide range of pressure and steam flow rate and consideration of condensation of turbulent flow in film condensation regime must be followed for next work.

Acknowledgments

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