Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-27, 2017

Comparing different wall heat transfer packages of MARS-KS and TRACE

Sung Gil Shin, Min-Gil Kim, Jeong Ik Lee*
Department of Nuclear and Quantum engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, (373-1, Guseong-dong), Yuseong-gu, Daejeon 34141, Republic of KOREA
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

System thermal hydraulic analysis codes, such as MARS-KS in Korea or TRACE in the US, are commonly used for reactor simulation to analyze and evaluate the safety of a nuclear power plant. These system thermal hydraulic analysis codes are composed of governing equations, physical models and correlation packages. Due to the use of different equations and models, it is expected that some differences in the code calculations can be observed. The major physical models and correlation packages are for the wall heat transfer, wall and interfacial friction, interfacial heat and mass transfer modeling. In order to understand the difference in the code system, the above-mentioned constitutive relations are investigated in this study. To compare different wall heat transfer packages, heat transfer coefficient is first compared while assuming the same TH conditions. The objective of this study is to analyze the difference of wall heat transfer packages between MARS-KS and TRACE. MAS-KS version 1.4 and TRACE version 5.0 are used.

2. Methods

2.1 Comparison of Wall Heat Transfer Packages, Coefficients and Correlations

The wall heat transfer package consists of heat transfer mode transition map and heat transfer correlations & models/correlations for each region.

2.1.1. Logic diagram of system thermal hydraulic analysis code

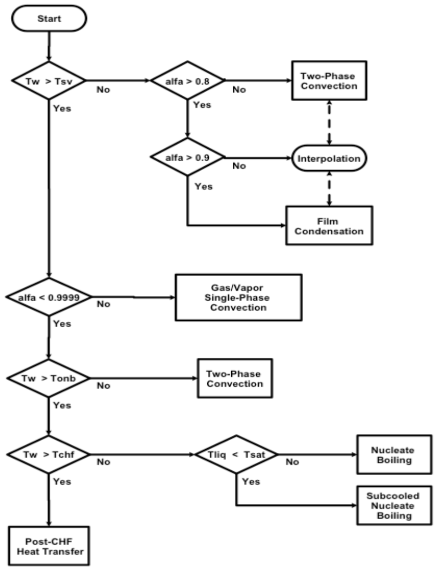

Fig. 1 TRACE wall heat transfer logic diagram for the pre-CHF and condensation regimes [1].

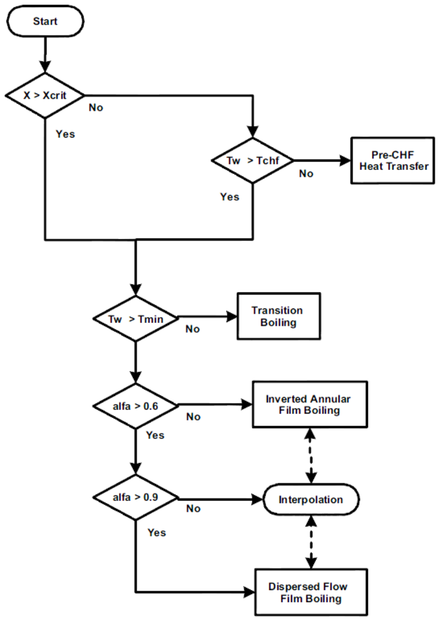

Fig. 2. TRACE wall heat transfer logic diagram for the Post-CHF [1]

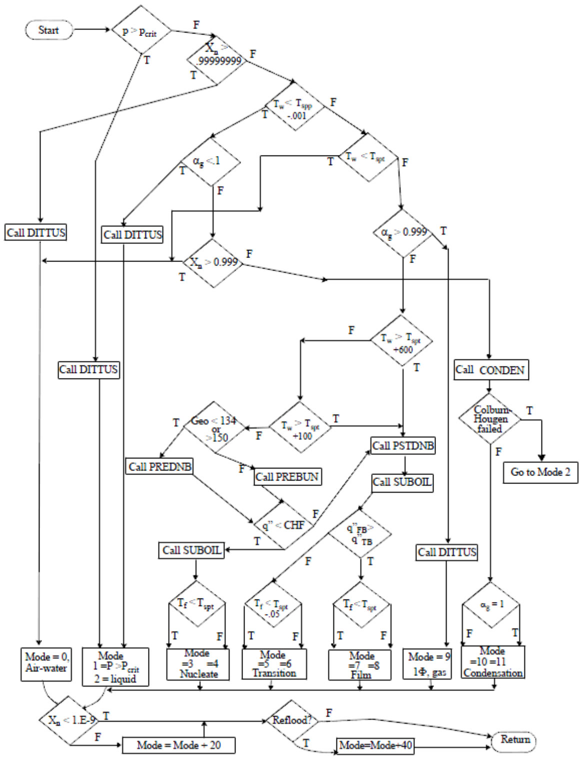

Fig. 3. MARS-KS wall heat transfer logic diagram [2].

The wall heat transfer package first classifies each heat transfer mode to model the boiling curve. The logic diagrams in Figs. 1-3. show the heat transfer mode transition map of TRACE and MARS-KS. Most of logic between them are similar, but there is a difference in film boiling regime. While MAS-KS has only one film boiling regime, TRACE distinguishes three film boiling regime for different void fraction.

2.1.2. Correlations of system thermal hydraulic analysis code

Heat transfer models and correlations are summarized in Table I.

Table I: Correlations for heat transfer mode

		MARS-KS	TRACE
Single	Laminar	Kays (1955)	Sellars (1956)
	Turbulent	Dittus-Boelter (1930)	Gnielinski (1976)
	Natural convection	Churchill-Chu (1975)	Holman (1981)
Bubbly/Slug	Laminar	Chen (1963) h_{PB}: Forester-Zuber (1955)	Sellars (1956)
	Turbulent		Gnielinski (1976)
Nucleate boiling	Pool boiling model (h_{PB})	S: Bjornard-Griffith (1977)	Steiner-Taborek (1992) h_{PB}:Gorenflo (1994)
	Suppression coefficient (S)		-
Film boiling	Inverted annular	Bromley (1950) Dittus-Boelter (1930) Sun (1976)	Self-developed
	Inverted slug		
	Dispersed flow		

(1) Single Phase Forced Convection

In MARS-KS, Dittus-Boelter correlation is used, which is equation (1) below. On the other hand, in TRACE, liquid single phase HTC is calculated with the Gnielinski correlation shown in equations (2) & (3).

$$Nu = 0.023\, Re^{0.8} Pr^{0.4} \quad (1)$$

$$Nu = \frac{(f/2)(Re - 1000)Pr}{1 + 12.7(f/2)^{0.5}(Pr^{2/3} - 1)} \times \left(\frac{Pr}{Pr_w}\right)^{0.11} \quad (2)$$

$$f = [1.58 \ln Re - 3.28]^{-2} \quad (3)$$

(2) Nucleate boiling

In MARS-KS, Chen correlation is used, shown in equations (4), (5) & (8). In Chen correlation, heat transfer by single phase flow is considered as h_{mac} term (macroscopic convection part), and that by pool boiling is considered as h_{mic} term (microscopic pool boiling part). Equations (6) & (7) are used to correct h_{mac}, and (9) & (10) are correction coefficient designed to correct h_{mic}, and they are determined by flow variables.

$$q''_{wl} = h_{mac}(T_w - T_l) + h_{mic}(T_w - T_{sat}) \quad (4)$$

$$h_{mac} = h_{sg} F \quad (5)$$

$$F = \begin{cases} 2.35(X_{tt}^{-1} + 0.213)^{0.736} \\ (0.1 < X_{tt}^{-1} < 100 \ \ in\ saturated) \\ 1 \\ (subcooled\ or\ X_{tt}^{-1} \le 0.1\ in\ saturation) \end{cases} \quad (6)$$

$$X_{tt}^{-1} = min\left[100, \left(\frac{G_v}{G_l}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_v}{\mu_l}\right)^{0.1}\right] \quad (7)$$

$$h_{mic} = 0.00122 \frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma_l^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_v^{0.24}} (\Delta T_w)^{0.24} (\Delta p)^{0.75} S \quad (8)$$

$$S = \begin{cases} (1 + 0.12 Re_{tp}^{1.14})^{-1}, & Re_{tp} < 32.5 \\ (1 + 0.42 Re_{tp}^{0.78})^{-1}, & 32.5 \le Re_{tp} < 70 \\ 0.0797, & Re_{tp} \ge 70 \end{cases} \quad (9)$$

$$Re_{tp} = min[70, 10^{-4} Re_l F^{1.25}] \quad (10)$$

On the other hand, in TRACE, Steiner-Taborek correlation is used and, in macroscopic convection part, the single phase Gnielinski correlation is used again. For the microscopic pool boiling part, the Gorenflo correlation is used and suppression coefficient is not used. Equations (11) & (12) show Steiner-Taborek and Gorenflo correlations, respectively. Equations (13) – (15) are used to solve equation (12).

$$q''_{wl} = h_{FC}(T_w - T_l) + h_{PB}(T_w - T_{sat}) - q''_{\text{sat}} \quad (11)$$

$$h_{PB} = 5600 F_P \left(\frac{q''}{20000}\right)^n \left(\frac{R_P}{0.4}\right)^{0.133} \quad (12)$$

$$F_P = 1.73 P_r^{0.27} + \left(6.1 + \frac{0.68}{1 - P_r}\right) P_r^2 \quad (13)$$

$$P_r = P/P_{crit} \quad (14)$$

$$n = 0.9 - 0.3 P_r^{0.15} \quad (15)$$

In nucleate boiling regime, MARS-KS and TRACE calculate HTC in a similar way using macroscopic convection and microscopic pool boiling part. However, in TRACE, heat flux decrease because heat flux q''_{sat} will be used to generate vapor directly. This heat flux q''_{sat} is calculated using the temperature of onset of boiling and equation (12).

(3) Film boiling

In MARS-KS, HTC is calculated by summation of each part. (conduction, convection, and radiation) Conduction and radiation part use equation (17) and (18) - (20), respectively. In equation (20), ε is emissivity. In convection part, single phase Dittus-Boelter correlation is used.

$$h = h_{con} + h_{cov} + h_{rad} \quad (16)$$

$$h_{con} = 0.62 \left[\frac{g \rho_g k_g^2 (\rho_f - \rho_g) h'_{fg} C_{pg}}{L(T_w - T_{spt}) Pr_g}\right]^{0.25} Ma \quad (17)$$

$$\begin{aligned} q_{wf} &= F_{wf} \sigma (T_w^4 - T_{sat}^4) \\ q_{wg} &= F_{wg} \sigma (T_w^4 - T_g^4) \end{aligned} \quad (18)$$

$$\begin{aligned} F_{wf} &= \left(R_2 \left(1 + {R_3}/{R_1} + {R_3}/{R_2}\right)\right)^{-1} \\ F_{wg} &= \left(R_1 \left(1 + {R_3}/{R_1} + {R_3}/{R_2}\right)\right)^{-1} \end{aligned} \quad (19)$$

$$\begin{aligned} R_1 &= \frac{1 - \varepsilon_g}{\varepsilon_g (1 - \varepsilon_g \varepsilon_f)} \\ R_2 &= \frac{1 - \varepsilon_f}{\varepsilon_g (1 - \varepsilon_g \varepsilon_f)} \\ R_3 &= \frac{1}{1 - \varepsilon_g \varepsilon_f} + \frac{1 - \varepsilon_w}{\varepsilon_w} \end{aligned} \quad (20)$$

In TRACE, there are self-developed correlations in 3 film boiling regime, which are inverted annular film boiling (IAFB), dispersed flow film boiling (DFFB), and Inverted slug film boiling (ISFB). Firstly, in IAFB regime, equation (21) & (22) are used to solve vapor HTC, and liquid HTC is calculated using radiation equation (23).

$$\delta = \frac{Dh}{2}(1 - (1 - \alpha)^2) \quad (21)$$

$$Nu_g = \frac{2Cp}{\delta} \quad (22)$$

$$h_l = \frac{\sigma (T_w^2 + T_l^2)(T_w + T_l)}{{1}/{\varepsilon_f (1 - \alpha)^{1/2}} + {1}/{\varepsilon_w} - 1} \quad (23)$$

$$\begin{aligned} h_{wf} &= F_{wf} \sigma (T_w^2 + T_l^2)(T_w + T_l) \\ h_{wg} &= F_{wg} \sigma (T_w^2 + T_g^2)(T_w + T_g) \end{aligned} \quad (24)$$

$$x_{var} = \frac{\alpha_{DFFB} - \alpha}{\alpha_{DFFB} - \alpha_{IAFB}} \quad (25)$$

$$wf = x_{var}(2 - x_{var}) \quad (26)$$

$$\begin{aligned} h_l &= (1 - wf) h_{l,DFFB} + wf\, h_{l,IAFB} \\ h_g &= (1 - wf) h_{g,DFFB} + wf\, h_{g,IAFB} \end{aligned} \quad (27)$$

In DFFB regime, vapor HTC is solved using single phase Gnielinski correlation and then it is corrected using enhancement factor. In addition, radiation effect is considered using same Sun equation (19) and (20) with MARS. There are some difference with MARS, TRACE use equation (24), not (18).

In ISFB regime, HTC is calculated using interpolation of IAFB and DFFB HTC with weighting factor equation (25) & (26) like (27)

2.2 Calculation conditions

Table II: Input variables

	Dh (m)	Gl (kg/m2s)	Gg (kg/m2s)	P (MPa)	Tl (K)
Case I	0.012	330	330	15.5	573
Case II		170	170		Saturation temp

To calculate a wall HTC, some values need to be assumed: equivalent diameter (Dh), mass flux of gas (Gg), and liquid phase (Gl), pressure (P), liquid temperature (Tl). Additionally, flow geometry assumed as a tube.

Frist case assume that mass flow rate is 300 kg/m^2-sec and liquid temperature is 573 K to make single phase liquid or subcooled nucleate boiling. Additionally, to make saturated nucleate boiling and film boiling, mass flow rate and liquid temperature are assume as 170 kg/m^2-sec near the saturation temperature.

3. Results and Discussion

3.1 Case I

In single phase regime, calculated HTC is shown in Fig. 4. HTC of MARS-KS is slightly larger than that of TRACE, and HTC of MARS-KS is constant but HTC of TRACE decreased with for different wall temperature (Tw).

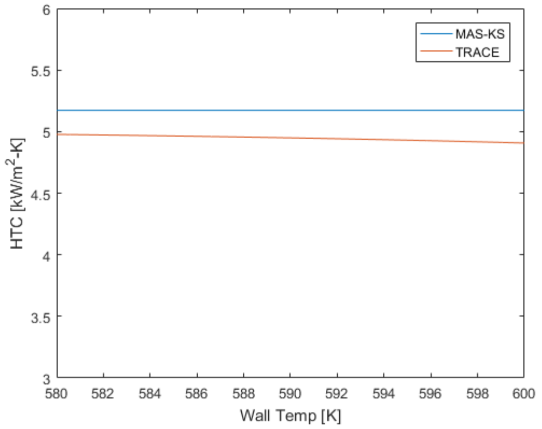

Fig. 4. Difference of HTC in MARS-KS and TRACE by Tw in liquid single phase regime.

There is difference in subcooled nucleate boiling regime in Fig. 5. At Tw = 618 K, regime is changed from the single phase liquid to subcooled nucleate boiling. Near the 620 K, increasing amount of HTC in TRACE is reduced. It is because boiling HTC, which is used directly for vapor generation in equation (11). It is checked by Fig. 6. In Fig. 6, summation of the heat flux for direct vapor generation and heat to liquid is same with total heat flux. It is said that increase in HTC rate decrease or HTC decreases after onset of boiling in TRACE.

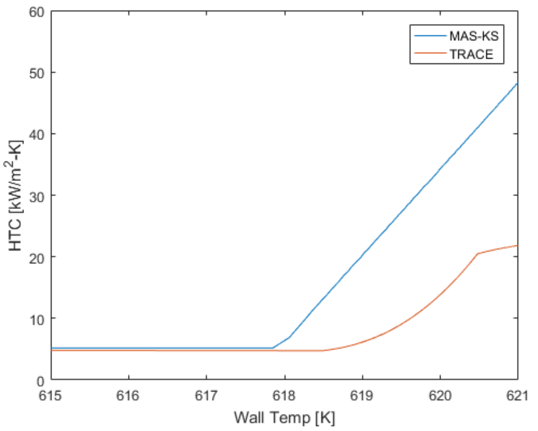

Fig. 5. Difference of HTC in MARS-KS and TRACE by Tw in subcooled nucleate regime.

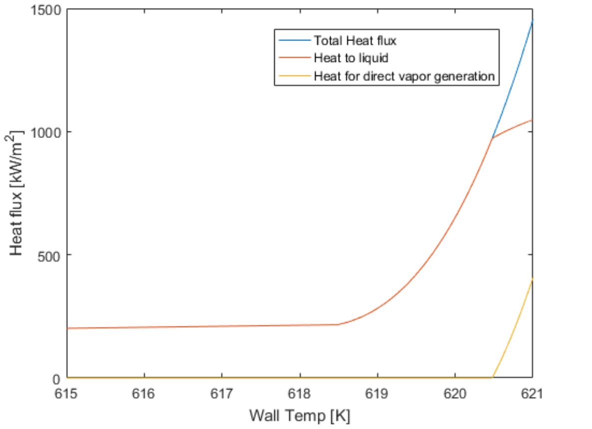

Fig. 6. Calculated heat flux in TRACE in subcooled nucleate regime.

3.2 Case II

The effect of eliminating heat flux can be further shown in Fig. 7. Near 618.5 K, heat transfer regime is changed from single phase liquid to subcooled nucleate boiling and near 619 K, is changed to saturated nucleate boiling. Boiling HTC from 619 K is not zero.

In film boiling regime, HTC of MARS-KS is about six times bigger than that of TRACE. While TRACE calculates HTC by considering the phenomenon according to the identified regime, MARS always calculate all of the conduction, convection and radiation HTC and solve HTC by summation. This makes a big difference of HTC between MARS-KS and TRACE.

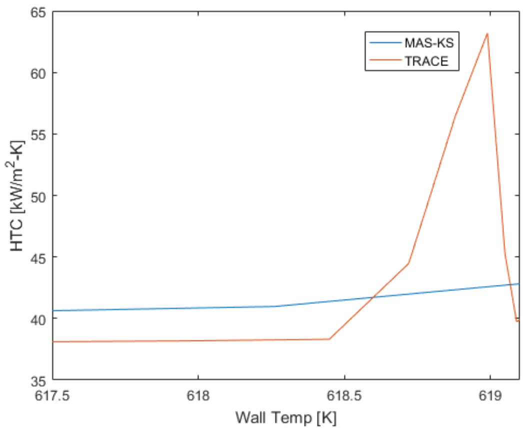

Fig. 7. Difference of HTC in MARS-KS and TRACE by Tw from liquid single to saturated nucleate regime.

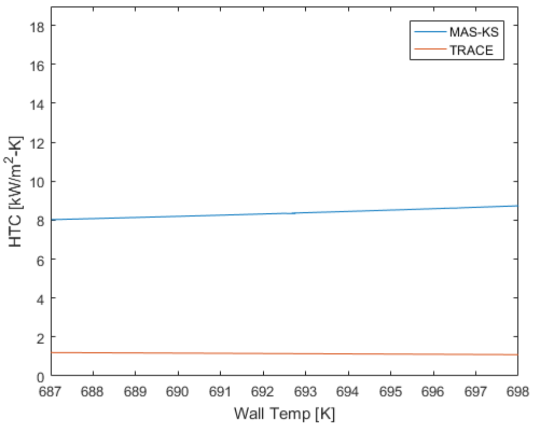

Fig. 8. Difference of HTC in MARS-KS and TRACE by Tw in film boiling regime.

4. Summary

Difference of wall heat transfer package between MARS-KS and TRACE is analyzed. In single phase regime, there are little differences but the difference in boiling regime is substantial owing to the difference in heat transfer correlations & models.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS), granted financial resource from the Nuclear Safety and Security Commission(NSSC), Republic of Korea. (No. 1603010)

REFERENCES

[1] U.S. Nuclear Regulatory Commission, "TRACE V5.840 Theory Manual",2013

[2] KAERI, "MARS CODE MANUAL", KAERI/TR-2811/2004, 2009