Comparing different wall heat transfer packages in the pre-CHF regime of various system analysis codes

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1. Introduction

System thermal hydraulic analysis codes such as MARS-KS, SPACE, TRACE, or RELAP5 are commonly used for reactor simulation to analyze and evaluate the safety. 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. To develop a platform to compare different physical models and correlation packages of each code, each correlation package is implemented in the separate computational environment. The objective of this study is to develop a platform for comparing various correlation packages of each system analysis code. In this paper the authors first focused on the wall heat transfer pre-CHF region first.

2. Methods

2.1 Comparison of pre-CHF Wall Heat Transfer Packages, Coefficients and Correlations

The wall heat transfer package determines the energy transfer from a heat structure to a fluid cell. The wall heat transfer package consists of heat transfer mode transition map and heat transfer models for each region.

2.1.1. Logic diagram of system thermal hydraulic analysis code

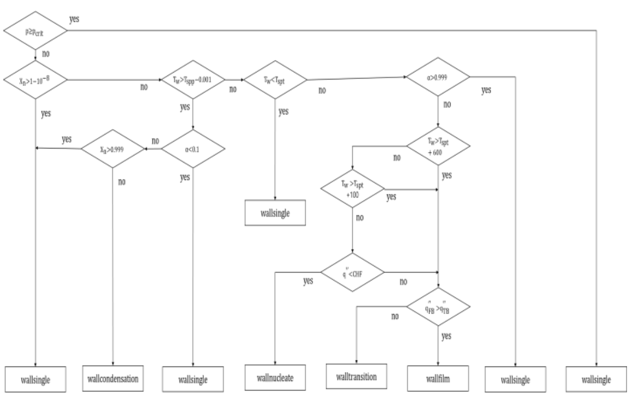

Fig. 1. MARS-KS wall heat transfer logic diagram [1].

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 MARS-KS, SPACE, and TRACE, respectively. In pre-CHF regime, there are some differences in using the number of void fraction to differentiate from nucleate boiling regime to gas single phase regime. In addition, the use of onset of boiling for switching from liquid single phase to nucleate boiling is also different between codes.

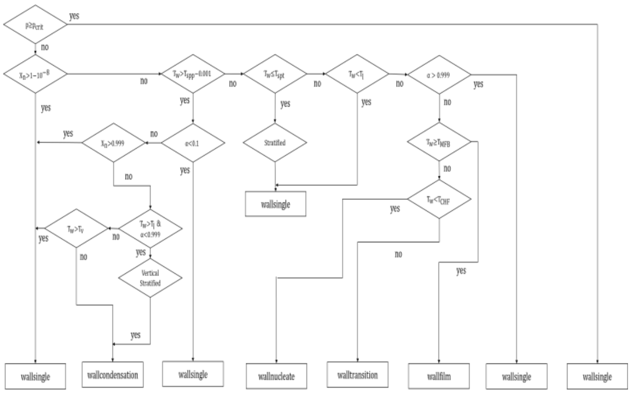

Fig. 2. SPACE wall heat transfer logic diagram [2].

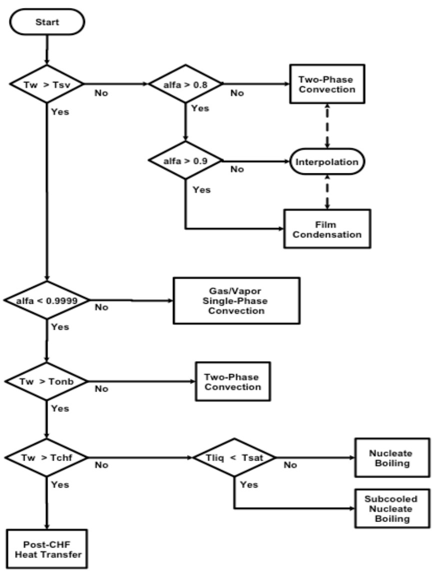

Fig. 3. TRACE wall heat transfer logic diagram for the pre-CHF and condensation regimes [3]

2.1.2. Correlations of system thermal hydraulic analysis code

Heat transfer models and correlations in pre-CHF are summarized in Table I. In TRACE, heat transfer coefficient (HTC) is calculated with modified Reynolds number corrected by void fraction. Since MARS-KS and SPACE codes share the same heat transfer correlations in the pre-CHF regime, two codes will not be differentiated in this paper from hereon. The laminar flow and natural convection heat transfer parts are omitted for simplicity.

Table I: Correlations for heat transfer mode

		MARS-KS	SPACE	TRACE
Single	Laminar	Kays (1955)	Sellars (1956)	
Single	Turbulent	Dittus-Boelter (1930)		Gnielinski (1976)
Single	Natural convection	Churchill-Chu (1975)	Spore (2000)	Holman (1981)
Bubbly/Slug	Laminar	Chen (1963) h_{PB}: Forester-Zuber (1955) S: Bjornard-Griffith (1977)		Sellars (1956)
Bubbly/Slug	Turbulent			Gnielinski (1976)
Nucleate boiling	Pool boiling model (h_{PB})			Steiner-Taborek (1992) h_{PB}:Gorenflo (1994)
Nucleate boiling	Suppression coefficient (S)			-

(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). In case of bubbly or slug flow, the corrected Reynolds number is used such as equation (4).

$$Nu = 0.023\, Re^{0.8} Pr^{0.4} \tag{1}$$

$$Nu = \frac{(f/2)(Re-1000)Pr}{1+12.7(f/2)^{0.5}(Pr^{2/3}-1)} \tag{2}$$

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

$$Re_l = \frac{G_l D_h}{(1-\alpha)\mu_l} \tag{4}$$

(2) Nucleate boiling

In MARS-KS, Chen correlation is used, shown in equations (5), (6) & (9). 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 (7) & (8) are used to correct h_{mac}, and (10) & (11) are correction coefficient designed to correct h_{mic}, and they are determined by flow variables.

$$q''_{wl} = h_{mac}(T_w - T_l) + h_{mic}(T_w - T_{sat}(p_{total})) \tag{5}$$

$$h_{mac} = h_{sg} F \tag{6}$$

$$F = \begin{cases} 2.35(X_{tt}^{-1}+0.213)^{0.736} \\ (0.1 < X_{tt}^{-1} < 100 \ \ in\ saturated) \\ 1 \\ (subcooled\ or\ X_{tt}^{-1} \le 0.1\ in\ saturation) \end{cases} \tag{7}$$

$$X_{tt}^{-1} = min\left[100, \left(\frac{G_v}{G_l}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_v}{\mu_l}\right)^{0.1}\right] \tag{8}$$

$$h_{mic} = 0.00122\,\frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma_l^{0.5}\mu_l^{0.29} h_{fg}^{0.24}\rho_v^{0.24}}(\Delta T_w)^{0.24}(\Delta p)^{0.75} S \tag{9}$$

$$S = \begin{cases} \left(1+0.12Re_{tp}^{1.14}\right)^{-1}, & Re_{tp} < 32.5 \\ \left(1+0.42Re_{tp}^{0.78}\right)^{-1}, & 32.5 \le Re_{tp} < 70 \\ 0.0797, & Re_{tp} \ge 70 \end{cases} \tag{10}$$

$$Re_{tp} = min[70, 10^{-4} Re_l F^{1.25}] \tag{11}$$

On the other hand, in TRACE, Steiner-Taborek correlation is used with n=3, and, for two phase forced convection heat transfer, the single phase Gnielinski correlation is used again with a correction of void fraction in the Reynolds number like equation (4). For the microscopic pool boiling part, the Gorenflo correlation is used and suppression coefficient is not used. Equations (12) & (13) show Steiner-Taborek and Gorenflo correlations, respectively. Equations (14) – (16) are used to solve equation (13).

$$h_{NB} = [h_{FC}^n + (Sh_{PB})^n]^{1/n} \tag{12}$$

$$h_{PB} = 5600 F_P \left(\frac{q''}{20000}\right)^n \left(\frac{R_P}{0.4}\right)^{0.133} \tag{13}$$

$$F_P = 1.73 P_r^{0.27} + \left(6.1 + \frac{0.68}{1-P_r}\right) P_r^2 \tag{14}$$

$$P_r = P/P_{crit} \tag{15}$$

$$n = 0.9 - 0.3 P_r^{0.15} \tag{16}$$

2.2 Quantitative Analysis of pre-CHF Wall Heat Transfer Packages

In-house code was developed for analyzing difference between system thermal hydraulic codes: MARS-KS and TRACE. The wall heat transfer mode selection logic and correlation are implemented in the code. The heat transfer package, heat transfer mode transition map and correlations are all referred from the code manuals MARS-KS [1], SPACE [2], and TRACE [3].

2.3Calculation conditions

Table II: Input variables

Dh (m)	vg (m/s)	vl (m/s)	P (MPa)	x	Tw (K)	Tb (K)
0.012	6	5	15.5	5e-6	controlled	

To calculate a wall HTC, some values need to be assumed: equivalent diameter (Dh), velocity of gas phase (vg) and liquid phase (vl), equilibrium quality (x_e), pressure (P), wall temperature (Tw), bulk temperature (Tb), and static quality (x). Additionally, flow geometry is assumed as a tube and heat flux is smaller than the critical heat flux. HTC was observed while varying Tw and Tb.

3. Results and Discussion

3.1 Difference in heat transfer regime selection

Wall heat transfer flow mode was chosen as shown in Table III.

Table III: Selection regime by Tw & Tb in MARS-KS, SPACE and TRACE

<table>
<tr><th>Wall temperature</th><th colspan="2">Bulk temperature</th><th>MARS -KS</th><th>SPACE</th><th>TRACE</th></tr>
<tr><td>Tw <Tsat</td><td colspan="2">Tb<Tsat</td><td colspan="3">Liquid single
(α < 0.8 in TRACE)</td></tr>
<tr><td>Tw = Tsat</td><td colspan="2">Tb≤ Tsat</td><td>Subcooled nucleate</td><td>Liquid single</td><td rowspan="4">Two phase
(α < 0.8)</td></tr>
<tr><td rowspan="4">Tw > Tsat
&
Tw ≤ Tonb</td><td colspan="2">Tb< Tsat</td><td colspan="2">Subcooled nucleate</td></tr>
<tr><td rowspan="3">Tb≥Tsat
&
Tb< Tw</td><td>α < 0.999</td><td colspan="2">Saturated nucleate</td></tr>
<tr><td>α > 0.999
&
α < 0.9999</td><td colspan="2">Vapor single</td></tr>
<tr><td>α ≥ 0.9999</td><td colspan="3">Vapor single</td></tr>
<tr><td rowspan="4">Tw > Tonb
&
Tw < Tchf</td><td colspan="2">Tb< Tsat</td><td colspan="3">Subcooled nucleate</td></tr>
<tr><td rowspan="3">Tb≥Tsat
&
Tb< Tw</td><td>α < 0.999</td><td colspan="3">Saturated nucleate</td></tr>
<tr><td>α > 0.999
&
α < 0.9999</td><td colspan="2">Vapor single</td><td>Saturated nucleate</td></tr>
<tr><td>α ≥ 0.9999</td><td colspan="3">Vapor single</td></tr>
</table>

3.2 Wall HTC difference between codes for varying Tw & Tb

Fig. 4. shows the similarity of heat transfer mode calculated in MARS-KS and TRACE. The number 1 means that the heat transfer mode is similar in MARS-KS and TRACE. It is noticeable that heat transfer mode is the same in most sections of Tw and Tb, except for the region between saturation and onset of boiling of Tw. Fig. 5. shows the HTC calculated in TRACE minus that of MARS-KS for ranges of Tw and Tb. In every region, there are some differences in HTC. In the single phase boiling, the difference of HTC is larger than that in nucleate boiling region. The greatest difference is in the section before going to nucleate boiling region from single phase.

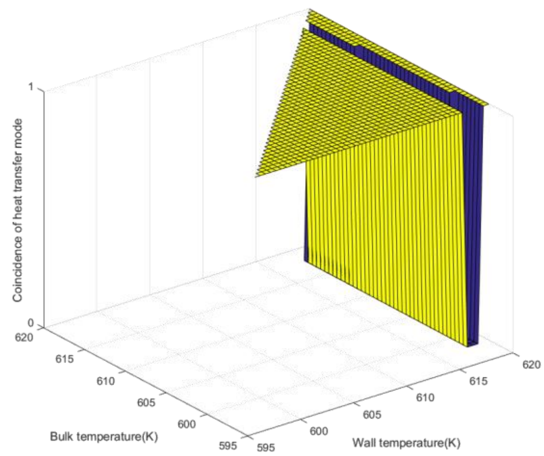

Fig. 4. Similarity of heat transfer mode between MARS-KS and TRACE.

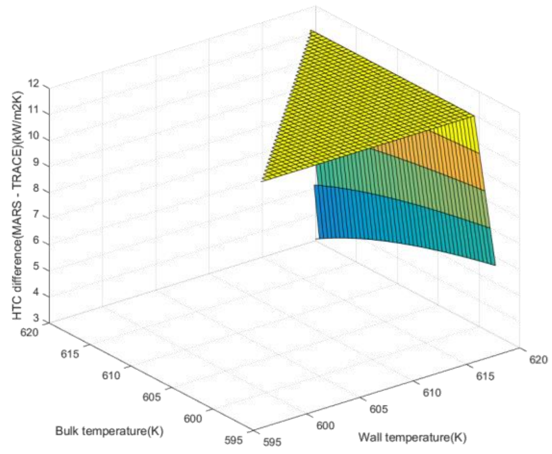

Fig. 5. Difference of HTC between MARS-KS and TRACE.

The biggest difference is near the boundary between nucleate boiling and single phase. That is, the wall temperature is the temperature at which the onset of boiling occurs in TRACE code and saturation temperature (Tsat) in MARS-KS. Near the saturation temperature of Tw & Tb, calculation was performed.

Firstly, at Tb = Tsat – 20, HTC is calculated. Results are shown in Fig. 6. It is noted that TRACE code enters the nucleate boiling regime (Tw=619K) later than the MARS-KS code (Tw=618K).

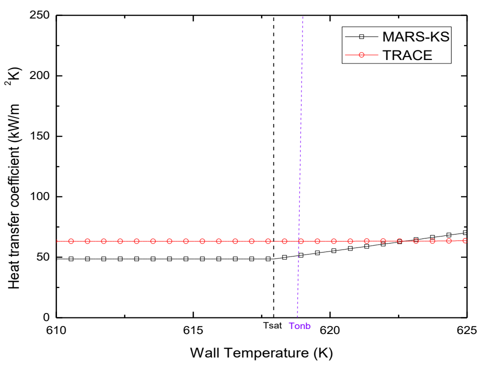

Fig. 6. HTC by Tw at constant Tb.

The difference is maintained at constant between TRACE and MARS-KS when Tw is smaller than Tsat. After Tw exceeds Tsat, the HTC of MARS-KS becomes closer to that of TRACE due to the transition to nucleate boiling regime.

The code comparison for varying Tb was performed under Tw = Tsat+0.5. The HTC is shown in Figure. 7. In TRACE code, heat transfer mode enters the nucleate boiling regime from single phase at the Tb=612K. It is because that TRACE code is constructed to use onset of boiling when dividing the section from single phase to nucleate regime. And this onset of boiling is calculated using Tw & Tb. However, MARS code delimits the regime based on Tsat of Tw. By this, in MARS-KS code, all of the section are nucleate boiling regimes regardless of Tb. In both codes, heat transfer mode is changed from the subcooled nucleate boiling mode to the saturated nucleate boiling mode at Tb = Tsat (618K). In general, TRACE predicts higher HTC than MARS-KS due to difference in the correlations.

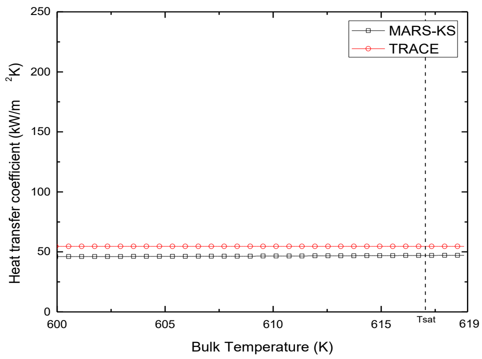

Fig. 7. HTC by Tb at constant Tw.

4. Summary

In-house code was prepared for analyzing different heat transfer coefficient in pre-CHF wall heat transfer regime between system thermal hydraulic codes, which are MARS-KS, SPACE, and TRACE. In pre-CHF region, there are many differences in selection logic and correlations between TRACE and other codes. Between codes, HTC differs in the vicinity of Tw and Tb approaching Tsat. The TRACE code tends to predict HTC larger in most regimes.

ACKNOWLEDGEMENT

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