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Study of Wall Friction models implemented in US TRACE code and Korean MARS-KS code.

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1. Introduction

System thermal hydraulic analysis codes, such as RELAP5, TRACE, COBRA-TF, CATHARE, and MARS-KS are commonly used for reactor thermal hydraulic simulation to analyze and evaluate the safety of a nuclear power plant. TRACE in the US and MARS-KS in Korea are used in each country by the regulating body. TRACE is the latest in a series of advanced, best-estimate reactor codes developed by U.S.NRC for analyzing transient and steady-state neutronic-thermal-hydraulic behavior in light water reactors [1]. MARS-KS has been developed by Korea atomic energy research institute (KAERI) for the realistic multi-dimensional thermal-hydraulic system analysis of reactor transients. The physical model basis of MARS-KS is mostly derived from RELAP5/MOD3.2.1.2 and COBRA-TF in the early development phase. The two codes were consolidated into a single code [2] and has been extensively upgraded with new models since the first version.

TRACE and MARS-KS code typically solve governing equations of mass, momentum and energy conservation equations for multiple phases. Closure of field equations is provided through the use of constitutive relations packages (= physical models packages) such as wall heat transfer, wall friction, interphase heat transfers and interphase friction including flow regime.

Each system thermal hydraulic analysis code, TRACE and MARS-KS, consists of different sets of constitutive relations packages, and code calculation will vary, because of using different constitutive relation package. It can make uncertainties in these codes, and this physical models effect has the greatest uncertainties except user effect [3]. However, the packages of each code were not compared quantitatively yet, nor were code calculation results analyze how much and how differ due to the distinction of the packages.

It should be evaluated how different each package is configured. The former study by the authors was comparing the wall heat transfer package of both codes [4]. Continuing from the previous work by the authors, in this study, the wall friction package is compared. The object of this study is to analyze qualitatively and quantitatively the difference of wall friction packages between TRACE and MARS-KS. A separate computational platform is constructed for this purpose, and this is separately prepared within an in-house code.

2. Wall Friction models packages

Firstly, wall friction package were compared qualitatively by analyzing the code manuals and source codes of TRACE [1] and MARS-KS [2], respectively. Based on qualitatively compared, in-house code was completed. Wall friction modules for each codes are summarized below.

Wall friction package is used to solve wall drag force in momentum and energy conservation equation. In this study, sum of wall drag forces, same as total pressure drop, will be evaluated and compared.

In the wall friction package of TRACE, wall friction model switches depending on the flow regime. The same holds true for MARS-KS. TRACE and MARS-KS has different flow regime map. Flow regime map will be compared.

2.1. Flow Regime

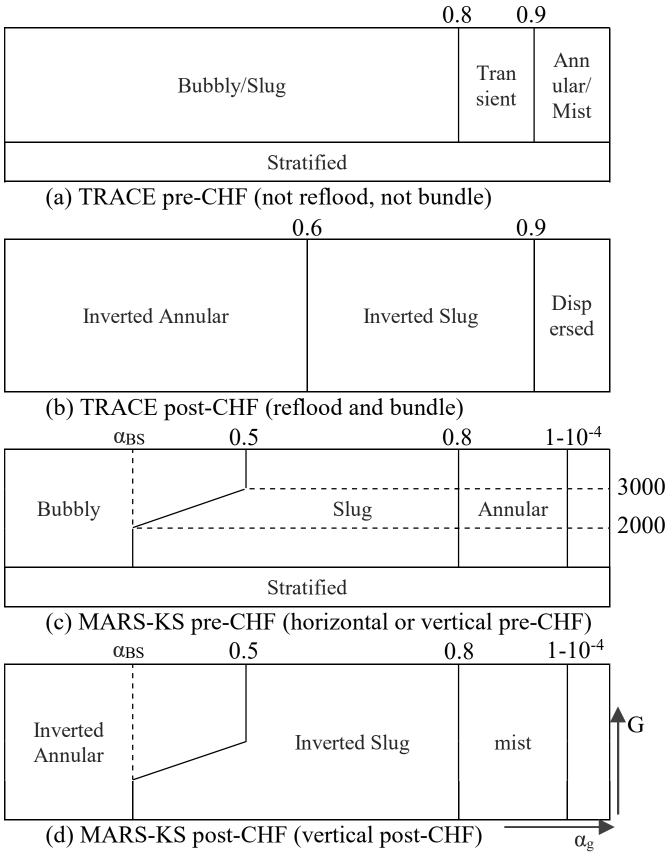


Fig. 1. Flow regime map of TRACE and MARS-KS [1, 2]

In wall friction package of TRACE, flow regime described in Fig. 1. (a) is used in case when reflood is off and geometry is not bundle. It is bubbly/slug flow regime with void fraction smaller than 0.8, annular/mist flow regime larger than 0.9, and between them, transient regime from bubbly/slug to annular/mist. MARS-KS determines the flow regime by using flow regime map drawn in Fig. 1. (c) and (d). In case of horizontal flow, flow regime map (c) is used. For the case of vertical flow, flow regime map (c) or (d) is used depending on pre-CHF or post-CHF condition.

2.2. Wall Friction package of TRACE

Algorithms of two codes for calculating wall friction is quite different. In TRACE, wall friction is obtained by calculating wall drag friction coefficient for the corresponding flow regime. Whereas MARS-KS solves overall friction pressure drop firstly, and then total pressure drop is divided into liquid and vapor pressure drop with liquid or vapor fraction on the wall depending on the flow regime. More details are given below.

$$\left.\frac{dP}{dz}\right|_{\text{total}} = -C_{wl}\overline{V_l}\left|\overline{V_l}\right| - C_{wg}\overline{V_g}\left|\overline{V_g}\right| \tag{1}$$

$$f_{wk} = -C_{wk}\overline{V_k}\left|\overline{V_k}\right| \tag{2}$$

As mentioned earlier, TRACE calculates wall drag force with wall drag coefficient shown in equations (1) & (2), and TRACE has only one non-zero wall drag coefficient among liquid or vapor. Subscript k means phasic, i.e. liquid or vapor

In the single phase, wall drag coefficient is defined by equation (3) and fanning friction factor f_{wk} is solved by Churchill formula [5].

$$C_{wk} = f_{wk}\frac{2\rho_k}{D_h} \tag{3}$$

$$f_w = 2\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + \frac{1}{(a+b)^{3/2}}\right]^{1/12} \tag{4}$$

$$a = \left\{2.457\ln\left[\frac{1}{\left(\frac{7}{\mathrm{Re}}\right)^{0.9} + 0.27\left(\frac{\varepsilon}{D_h}\right)}\right]\right\}^{16} \tag{5}$$

$$b = \left(\frac{3.753\times10^4}{\mathrm{Re}}\right)^{16} \tag{6}$$

Total pressure drop can be written as equation (7). Meanwhile, in pre-CHF flow regime, all the wall drag is applied to the liquid phase alone, so the second term of right side will be zero in equation (1). From this, wall drag coefficient can be obtained as shown in equation (8).

$$\left.\frac{dP}{dz}\right|_{\text{total}} = -\Phi_l^2\left[\frac{2f_{2\Phi,l}\left|G_l\right|G_l}{D_h\,\rho_l}\right] \tag{7}$$

$$C_{wl} = \Phi_l^2\left[\frac{2f_{2\Phi,l}(1-\alpha)^2\rho_l}{D_h}\right] \tag{8}$$

In TRACE code, void fraction based two-phase multiplier model was developed [1] and in the bubbly/slug flow regime, two-phase multiplier model is defined as equation (9). Enhancement of wall friction due to wall nucleation is addressed by the second multiplied term shown in equation (10). The bubble diameter in equation (10) is computed with Levy model. Wall drag coefficient is shown in equation (12) and in this equation, fanning friction factor is from Churchill formula.

$$\Phi_l^2 = \frac{1}{(1-\alpha)^2}\left(1+C_{NB}\right)^2 \tag{9}$$

$$C_{NB} = 155\left(\frac{d_B}{D_h}\right)\left[\alpha(1-\alpha)\right]^{0.62} \tag{10}$$

$$\frac{d_g}{D_h} = 0.015\left[\frac{\sigma}{\tau_w D_h}\right]^{1/2} \tag{11}$$

$$C_{wl} = f_{wl}\frac{2\rho_l}{D_h}\left(1+C_{NB}\right)^2 \tag{12}$$

In the annular/mist regime, two-phase multiplier is already defined by annular flow theory [6] shown in equation (13), so wall drag coefficient becomes equation (14). f_{wet} is wetted fraction, which has a value between 0 and 1 depending on the film thickness. Fanning friction factor is calculated by a power law combination of the laminar and turbulent values (16, 17).

$$\Phi_l^2 = \frac{1}{(1-\alpha)^2} \tag{13}$$

$$C_{wl} = f_{wet}f_{film}\frac{2\rho_l}{D_h} \tag{14}$$

$$f_{film} = \left(f_{lam}^3 + f_{turb}^3\right)^{1/3} \tag{15}$$

$$f_{lam} = \frac{16}{\mathrm{Re}_{2\varphi,l}} \tag{16}$$

$$f_{turb} = \frac{1}{\left\{3.6\log_{10}\left[\frac{6.9}{\mathrm{Re}_{2\varphi,l}} + \left(\frac{\varepsilon/D}{3.7}\right)^{1.11}\right]\right\}^2} \tag{17}$$

When the wall is wet, vapor wall drag coefficient is zero, but if wall is not completely wet, i.e. when f_{wet} is not one, vapor wall drag coefficient is not zero and calculated with Churchill formula likewise in single phase vapor flow.

$$C_{wg} = (1-f_{wet})f_{2\varphi,g}\frac{2\rho_g}{D_h} \tag{18}$$

In the transient regime from bubbly/slug to annular/mist, interpolation is performed with the void fraction. During interpolation, vapor wall drag coefficient from annular flow model is set to zero instead of calculating with equation (18). It is because that vapor phase pressure drop is zero in wetted wall.

2.3. Wall Friction package of MARS-KS.

MARS-KS solves the overall friction pressure drop first of all. To obtain total pressure drop (19), two-phase friction multiplier is used and Lockhart-Martinelli method [7] is considered as basic underlying theory. The total pressure drop can be arranged as in equation (20) with adding HTFS correlation [8] for two-phase multiplier. Darcy friction factor is solved by Darcy-Weisbach equation.

$$\left.\frac{dP}{dz}\right|_{\text{total}} = \Phi_l^2 \left.\frac{dP}{dz}\right|_l = \Phi_g^2 \left.\frac{dP}{dz}\right|_g \tag{19}$$

$$\left.\frac{dP}{dz}\right| = \frac{1}{2D_h}\left\{\begin{array}{l} f_l\rho_l(\alpha_l v_l)^2 + \\ C\left[f_l\rho_l(\alpha_l v_l)^2 f_g\rho_g(\alpha_g v_g)^2\right]^{1/2} + f_g\rho_g(\alpha_g v_g)^2 \end{array}\right\} \tag{20}$$

After then, liquid and vapor phasic pressure drops have to be divided from total pressure drop. It is defined as in equations (21) & (22) by the phasic momentum equation. The theoretical basis is following the work of Chisholm.

$$\left.\frac{dP}{dz}\right|_l = \left.\frac{dP}{dz}\right|_{\text{total}} \left(\frac{Z^2}{\alpha + (1-\alpha)Z^2}\right) \tag{21}$$

$$\left.\frac{dP}{dz}\right|_g = \left.\frac{dP}{dz}\right|_{\text{total}} \left(\frac{1}{\alpha + (1-\alpha)Z^2}\right) \tag{22}$$

$$Z^2 = \frac{f_l\rho_l v_l^2 \alpha_{fw} / \alpha_l}{f_g\rho_g v_g^2 \alpha_{fg} / \alpha_g} \tag{23}$$

$$\alpha_{kw} = \frac{p_k}{p} \tag{24}$$

Parameter Z^2 is determined with liquid or vapor wetted parameter. A new variable phasic fraction on the wall (24) is defined and this value is evaluated depending on flow regime. It is summarized in Table I. In the case of post-CHF, phasic fraction on the wall is calculated by interpolation between value in pre-CHF and post-CHF considering the degree of dry-out. Additional information can be found in MARS-KS theory manual chapter 3.1.3.8.5 [2].

Table I: summary of phasic fraction on the wall in MARS-KS

Flow Regime	Bubbly	Slug	Annular	Mist pre-CHF
α_{fw}	$1-\alpha_g$	$1-\alpha_{BS}$	$\alpha_{bubble}^{0.25}$	$1-\alpha_g$
α_{gw}	α_g	α_{BS}	$1-\alpha_{bubble}^{0.25}$	α_g
Flow Regime	Inverted Annular	Inverted Slug	Mist	Mist post-CHF
α_{fw}	$1-\alpha_{bubble}^{0.5}$	$1-\alpha_{bubble}^{0.5}$ $\alpha_{droplet}$	$1-\alpha_g$	$1-\alpha_g$
α_{gw}	$\alpha_{bubble}^{0.5}$	$\alpha_{bubble}^{0.5}$ $1-\alpha_{droplet}$	α_g	α_g

3. Methods

The in-house code, developed based on the above summary, is used to compare both wall friction packages quantitatively under the same thermal hydraulic conditions. In-house code was developed by using MATLAB and REFPROP v.8 for the properties, and the code results were validated against the original codes TRACE 5.482 and MARS-KS 1.5.

Under the selected hydraulic conditions, a comparison was performed. In the previous sections, both MARS-KS and TRACE depend on the flow regime to determine wall drag. Thus, it is confirmed how the deviation graph differ with respect to flow regime by changing flow direction and heat flux in test 1. In the same way, deviation graphs are checked with changing slip ratio in test 2 and pressure in test 3. It is summarized in Table I.

It will be intuitive to view deviation graphs based on changing void fraction and mass flux, so all graphs are express value of formula (25) in three dimensions, with the x-axis in void faction and y-axis in mass flux. It is emphasized that all the comparisons are based on the default models only. Both codes have substantial flexibility of choosing correlations and evaluating these options are left as future works.

$$\text{derivation} = \ln\left[\left(\left.\frac{dP}{dz}\right|_{wall}\right)_{\text{TRACE}} \Big/ \left(\left.\frac{dP}{dz}\right|_{wall}\right)_{\text{MARS-KS}}\right] \tag{25}$$

Table I: Selected thermal hydraulic conditions

	Flow direction	Heat flux [Kw/m²]	P [MPa]	Slip ratio	G [kg/m²-sec]	Void fraction
Base	horizontal	0	15.5	1	[500, 600, 700, ⋮ 4400, 4500]	[0, 0.05, 0.1 ⋮ 0.95, 1]
test I -1	**vertical**	**0**	15.5	1		
test I -2	**vertical**	**2000**				
test II -1	horizontal	0	15.5	**3**		
test II -2				**5**		
test III -1	horizontal	0	**7**	1		
test III -2			**0.15**			
	Tl [K]	Tg [K]	Dh [m]	Roughness		
Common Condition	T_{sat}	$T_{sat}+2$	0.012	0		

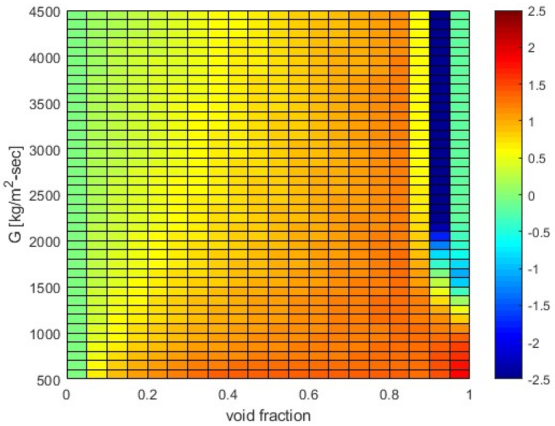
4. Results and Discussion

4.1. Tendency of deviation graph regarding changing Flow Regime, slip ratio or pressure.

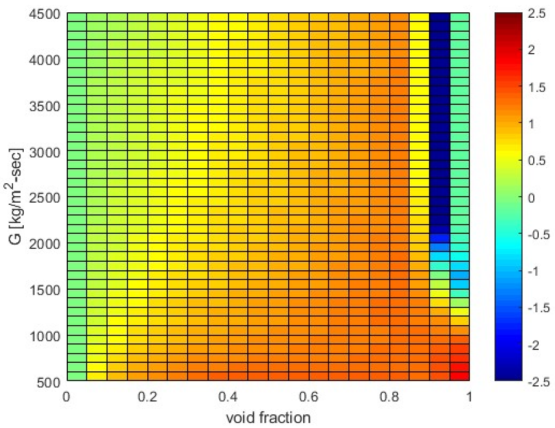
Fig. 2 (a), (b), and (c) are deviation graphs, when hydraulic condition is base, test I-1, and test I-2, respectively. It is found that regardless of flow regime, deviation graphs are almost the same. The selected flow regime is also almost the same between base and test I-1. Although the selected flow regime in test I-2 differs from that in base, the calculated wall pressure drops have just small difference. It is because that degree of dry-out is small. Further analysis will be made later on case of having large degree of dry-out.

These results show that flow direction does not have much effect on the deviation between two codes and if the degree of dry-out is small, there is no difference despite selecting flow regime as post-CHF regime in both codes.

(a) base case



(b) test I-1 (vertical, zero heat flux)



(c) test I-2 (vertical non zero heat flux)

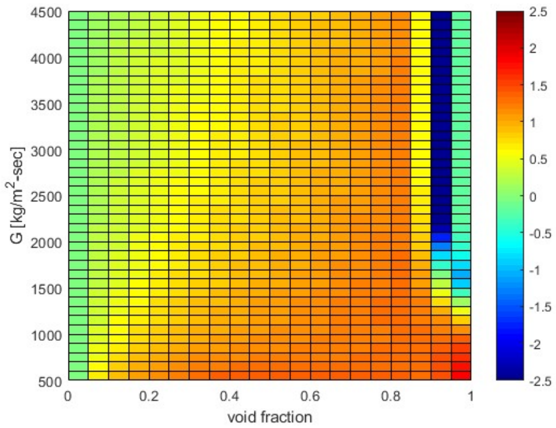
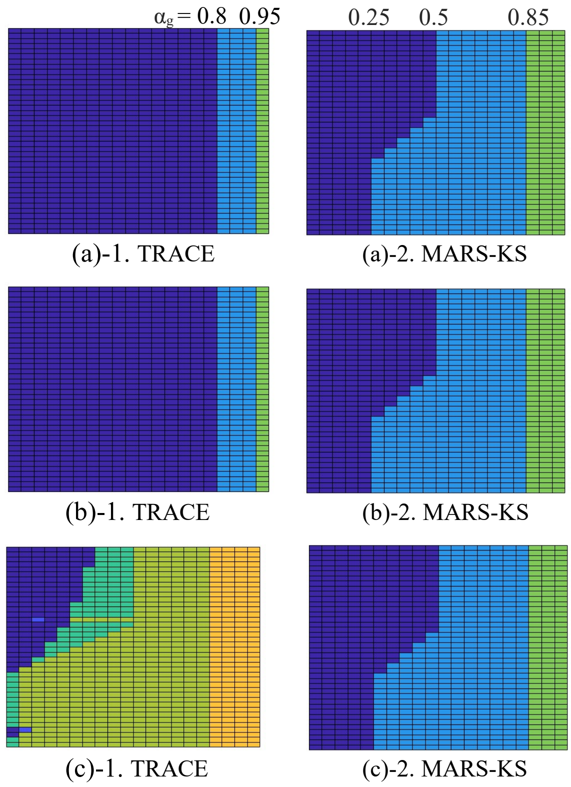


Fig. 2. Deviation graphs in case of base and compared test I-1 and I-2. (vertical pre-CHF and vertical post-CHF)

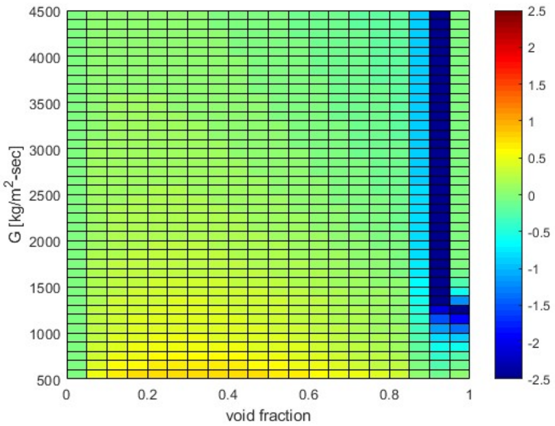


TRACE			
Flow Regime	Bubbly/Slug	Transient	Annular /Mist
MARS-KS			
Flow Regime	Bubbly	Slug	Annular
MARS-KS			
Flow Regime	Inverted annular	Inverted slug	Dispersed

Fig. 3. Selected flow regime in TRACE and MARS-KS code. (a) base case (b) in test I-1 (c) in test I-2

By comparing Fig. 4. and base case in Fig. 2 (a), effect on the slip ratio can be evaluated. Fig. 4 (a) and (b) shows deviation graphs, when slip ratio is 3 and 5. While the slip ratio become 3, some positive deviation in Fig. 2 (a) is to be close to zero. And then, when the slip ratio reaches 5, some deviations is more negative. Flow regime of test II-1 and II-2 is same with base case.

(a) test II-1 (slip ratio = 3)



(b) test II-2 (slip ratio = 5)

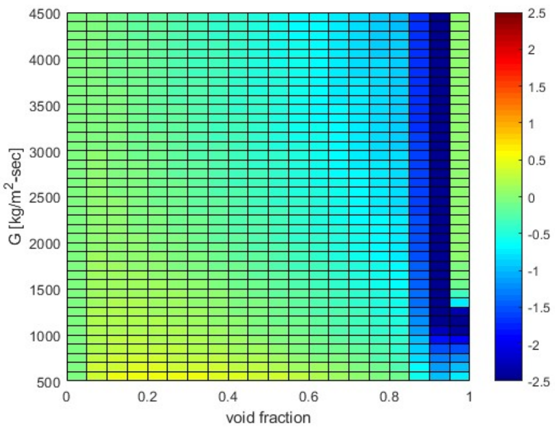


Fig. 4. Deviation graphs in case of test II-1 and II-2. (slip ratio = 3 or 5)

Fig. 5. is drawn for further analysis. Fig. 5. shows pressure drop calculated in MARS-KS and TRACE, when total mass flux is 3500kg/m^2-sec. In MARS-KS, wall friction increases as the slip ratio increase, while wall friction decreases in TRACE. What makes this difference will be analyzed later, and evaluation using experimental data will be done.

To check effect by changing pressure, graphs are shown in Fig. 6. (a) and (b) is graph, when pressure is 7 and 0.15 MPa, respectively. While the graph looks similar with base case in Fig. 2 (a), it can be seen that the positive value of deviation is increasing. It means that the smaller pressure, greater the deviation.

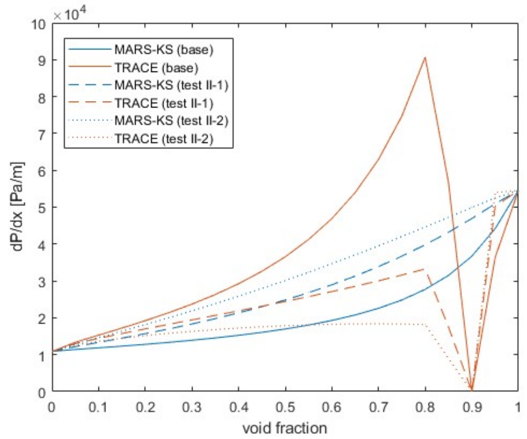
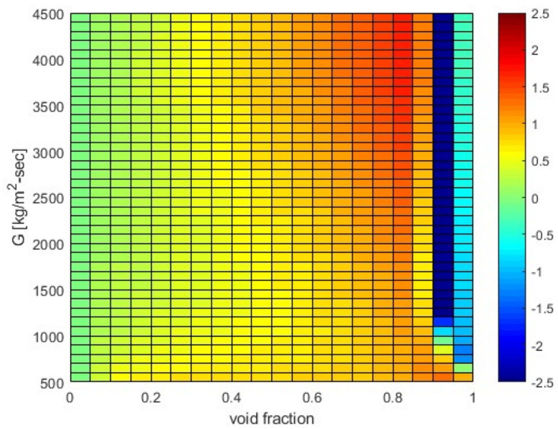


Fig. 5. frictional pressure drop calculated in MARS-KS and TRACE.

(a) test III-1



(b) test III-2

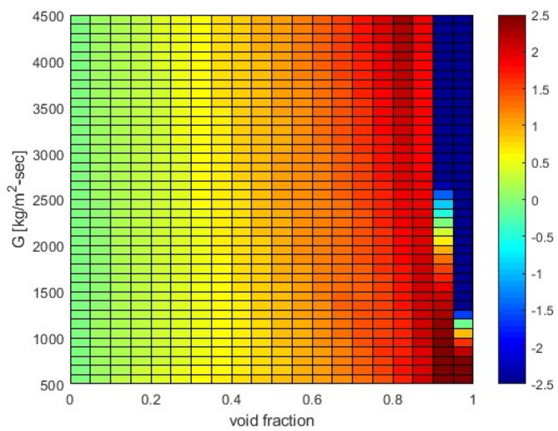


Fig. 6. Deviation graphs in case of test III-1 and III-2. (pressure = 7 or 0.15 MPa)

4.2. Analyzing of deviation graph

In Fig. 2 (a), the largest deviation is shown when hydraulic condition is that mass flux > 2000 and void fraction is close to 0.9. Additionally, even when mass flux is small (<2000), it has quite a big deviation. In Fig. 2 (a), scale is 2.5. It means equation (25) is 2.5, and likewise friction ratio of TRACE and MARS-KS is 12.1825(=$e^{2.5}$) times different.

To analyze the difference in more detail, Fig. 7. is presented. Fig. 7. shows frictional pressure drop, in which mass flux is 3500 or 1000 kg/m^2-sec.

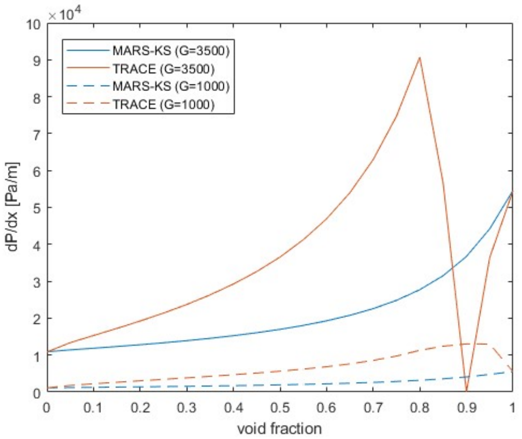


Fig. 7. frictional pressure drop calculated in TRACE and MARS-KS.

While MARS-KS uses Lockhart-Martinelli models, which calculates total pressure drop and distribute to liquid or vapor pressure drop, TRACE uses different models for different flow regimes. It leads to a graph shape of total pressure drop. Frictional pressure drop of MARS-KS is linear between flow regimes, but that of TRACE is discrete.

When flow regime is selected as bubbly/ slug in TRACE, i.e. $\alpha < 0.8$, difference of wall drag grows as the void fraction increases. It is because of considering enhancement term by nucleation. In TRACE, enhancement term due to nucleation is added by equation (10), but TRACE does not, so frictional pressure drop calculated in TRACE increases more rapidly than that of MARS-KS. It makes red color regime in Fig. 2 (a), in which red color means TRACE has larger friction pressure drop than MARS-KS.

When flow regime is selected as transition in TRACE, i.e. $0.8 < \alpha < 0.9$, wall drag of TRACE is drop sharply, when G = 3500 kg/m^2-sec, but increase steadily when G = 1000 kg/m^2-sec. It is because of wetted fraction in equation (14). When mass flux is small, wetted fraction is measured greatly, whereas, the larger the mass flux, the wetness of the wall is closer to zero. When G = 3500 kg/m^2-sec, wetted fraction is close to zero, and it makes a sharp reduction in the graph.

As flow regime of TRACE becomes annular, i.e. $\alpha > 0.9$, vapor frictional pressure drop is considered, which is evaluated by equation (18), so total pressure drop come to be increase and has similar value of MARS-KS.

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