中广核 CGN
中广核研究院有限公司
China Nuclear Power Technology Research Institute Co.,Ltd.

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EVT2204904-Technical Session 2.3:

Accident Analysis and Experimental Programs for LFR

Development of drift-flux correlations for vertical forward bubble column-type gas-liquid lead-bismuth two-phase flow

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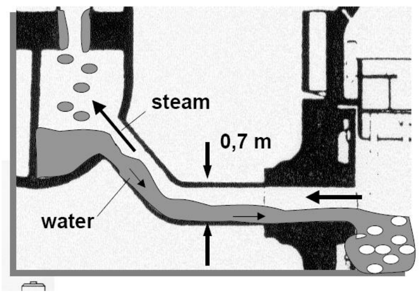
2023.03.13

Content

01.Introduction

- Gas-liquid two-phase flow is typical phenomenon in accident scenario in NPP



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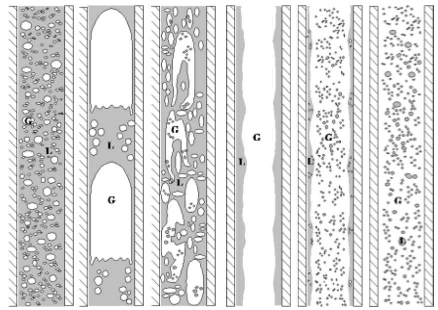
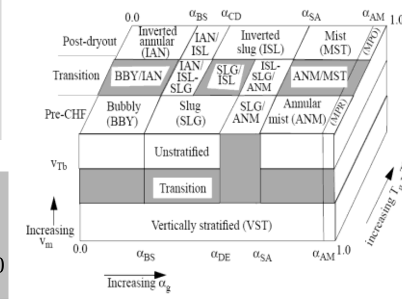


Flow regime in vertical tube

$$A\alpha\frac{\partial p}{\partial z}+\tau_{v0}L_v+\tau_iL_i+\rho_v g\alpha A\sin\theta+\frac{\partial}{\partial t}(\rho_v A\alpha u_v)+\frac{\partial(\rho_v A\alpha u_v^2)}{\partial z}-\delta M\cdot u_i=0$$

$$A(1-\alpha)\frac{\partial p}{\partial z}+\tau_{l0}L_l-\tau_iL_i+\rho_l g(1-\alpha)A\sin\theta+\frac{\partial}{\partial t}[\rho_l A(1-\alpha)u_l]+\frac{\partial}{\partial z}[\rho_l A(1-\alpha)u_l^2]+\delta Mu_i=0$$

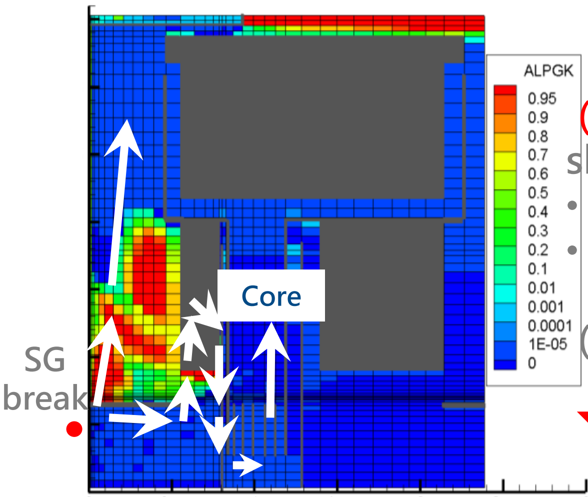
Momentum equation



Flow regime evaluation

Bubble column-type gas-liquid two-phase flow

- Extreme condition：Velocity of liquid phase is near zero and gas bubble is driven by buoyancy



Bubble transportation path

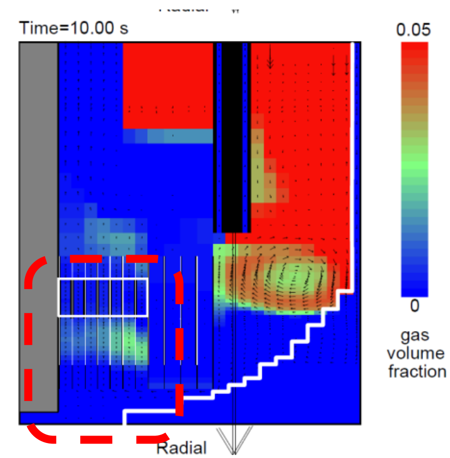
Typical Bubble Column Flow in LFR

（1）SGTR anlysis(The main pump is shutdown)

- Steam bubble may transport into the core
- Insert additional reactivity and threanten the safety of reactor

（2）FP transportation in LBE pool during DEC

void fraction prediction → reactivity calculation → evaluation of accident



SGTR analysis of EFIT
Several bubbles transport into the core channel，α=0.01

01.Introduction

- Prediction of void fraction：drift-flux model

$$\langle\langle v_g\rangle\rangle = \frac{\langle j_g\rangle}{\langle \alpha\rangle} = C_0\langle j\rangle + \langle\langle v_{gj}\rangle\rangle = C_0\left(\langle j_g\rangle + \langle j_f\rangle\right) + \langle\langle v_{gj}\rangle\rangle$$

- Predict the void fraction
- In code: calculate the drag force

Distribution parameter C_0: $$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_f}$$

Gas drift velocity v_{gj}: $$\langle\langle v_{gj}\rangle\rangle = \sqrt{2}\left(1-\langle\alpha\rangle\right)^{1.75}\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25}$$

Correlations based on gas-H2O two-phase flow

Problem of application：

1. Many correlations are based on the assumption of 1.2, which is applied in the gas-two phase flow with large liquid velocity.
2. Property of LBE is different with Water.
3. The distribution parameter depends on several effect factor, not only density ratio

The limitation of existing study on LBE two-phase flow

1. LBE is not transparent so the visual observation is difficult
2. Correlations applied to gas-LBE two-phase flow is lack

✓ Based on theoretical analysis+experiment data, develop new model

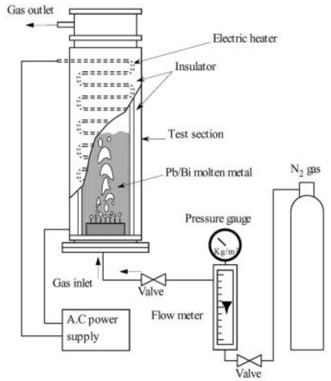
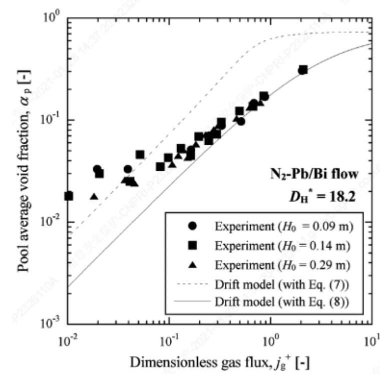
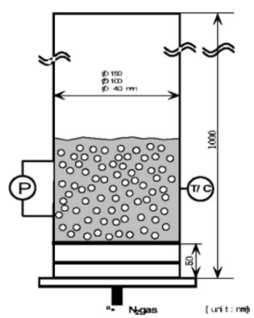
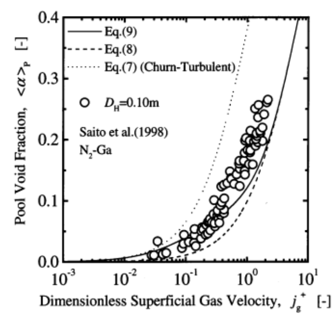
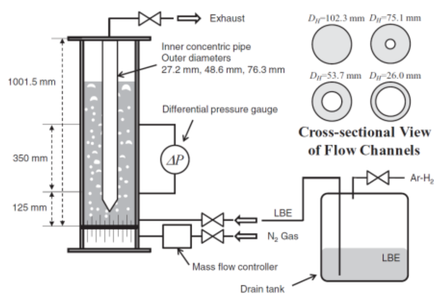
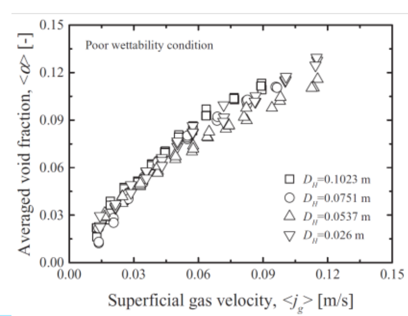
02.Evaluation of existing correlations

Developer	Correlations		Characteristics
1~3 Ishii	$C_0=1.2-0.2\sqrt{\rho_g/\rho_f}$ $C_0=1.35-0.35\sqrt{\rho_g/\rho_f}$	$\langle\langle v_{gj}\rangle\rangle=\sqrt{2}\left(1-\langle\alpha\rangle\right)^{1.75}\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25}$ Bubbly flow $\langle\langle v_{gj}\rangle\rangle=0.35\sqrt{gD_h\Delta\rho/\rho_f}$ Slug flow $\langle\langle v_{gj}\rangle\rangle=\sqrt{2}\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25}$ Churn flow	• Gas-H2O • for small/medium tube
4 Kataoka & Ishii	$\langle\langle v_{gj}\rangle\rangle=0.0019D_h^{*0.809}\left(\rho_g/\rho_f\right)^{-0.157}N_{\mu_f}^{-0.562}\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25},N_{\mu_f}\le 0.00225,D_h^*\le 30$		• Gas-H2O • for large tube
5 Kocamustafaogullari & Ishii	$\langle\langle v_{gj}\rangle\rangle=0.54\sqrt{gD_h\Delta\rho/\rho_f},D_h^*\le 30$ $\langle\langle v_{gj}\rangle\rangle=3.0\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25},D_h^*>30$		• Gas-H2O
6 Hibiki & Ishii correlations (for bubbly flow)	$C_0=\exp\left\{0.475\left(\frac{\langle j_g^+\rangle}{\langle j^+\rangle}\right)^{1.69}\right\}\left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)+\sqrt{\frac{\rho_g}{\rho_f}},0<\frac{\langle j_g^+\rangle}{\langle j^+\rangle}<0.9$ $C_0=\left[4.08-2.88\left(\frac{\langle j_g^+\rangle}{\langle j^+\rangle}\right)\right]\left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)+\sqrt{\frac{\rho_g}{\rho_f}},0.9<\frac{\langle j_g^+\rangle}{\langle j^+\rangle}$ $\langle\langle v_{gj}\rangle\rangle=\langle\langle v_{gj}\rangle\rangle_{Ishii}\exp\left(-1.39\langle j_g^+\rangle\right)+\langle\langle v_{gj}\rangle\rangle_{KI}\left[1-\exp\left(-1.39\langle j_g^+\rangle\right)\right]$		• Gas-H2O
7 Hibiki & Ishii correlations (for cap bubble)	$C_0=1.2\exp\left\{0.110\langle j^+\rangle^{2.22}\right\}\left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)+\sqrt{\frac{\rho_g}{\rho_f}},0<\langle j^+\rangle<1.8$ $C_0=0.6\exp\left\{-1.2\langle j^+\rangle-1.8\right\}\left(1-\sqrt{\frac{\rho_g}{\rho_f}}\right)+\sqrt{\frac{\rho_g}{\rho_f}},\langle j^+\rangle>1.8$ $\langle\langle v_{gj}\rangle\rangle=0.0019D_h^{*0.809}\left(\rho_g/\rho_f\right)^{-0.157}N_{\mu_f}^{-0.562}\left(\sigma g\Delta\rho/\rho_f^2\right)^{0.25}$		• Gas-H2O

02.Evaluation of existing correlations

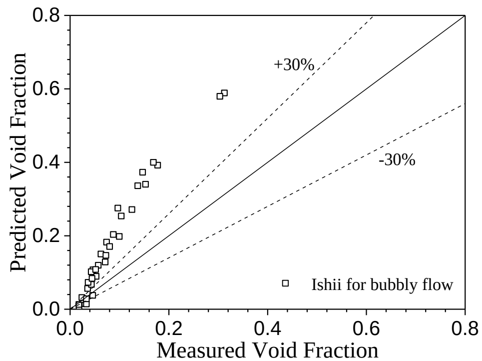
Developer	Correlations	Characteristics
8 Mikityuk(for pool)	$C_0 = 2.4 \quad \langle\langle v_{gj} \rangle\rangle = 0.61\sqrt{gD_h \Delta\rho / \rho_f}$	• Gas-Liquid metal
9 Mikityuk(for loop)	$C_0 = 0.9 \quad \langle\langle v_{gj} \rangle\rangle = 2.33\sqrt[4]{g\sigma\Delta\rho / \rho_f^2}$	• Gas-Liquid metal
10 Shi	$C_0 = 2.218 \quad \langle\langle v_{gj} \rangle\rangle = 14.22\, j_g^{1.104} \sqrt[4]{g\sigma\Delta\rho / \rho_f^2}$	• Gas-Liquid metal
11 Shen	$C_0 = \left(1 + \frac{\langle j_g^+ \rangle^{0.00102}}{0.0667\langle j_g^+ \rangle^{0.690} + 1.36\langle j_f^+ \rangle^{3.29}}\right)\left(1 + 4.82e^{-0.186D_h^*}\right)\left[1 - \left(\frac{\rho_g}{\rho_f}\right)^{0.0181}\right] + \left(\frac{\rho_g}{\rho_f}\right)^{0.0181}$ $\langle\langle v_{gj} \rangle\rangle = \begin{cases} 0.548\sqrt{D_h^*}\left(\sigma g\Delta\rho / \rho_f^2\right)^{0.25}, D_h^* \le 30 \\ 3.0\left(\sigma g\Delta\rho / \rho_f^2\right)^{0.25}, D_h^* > 30 \end{cases}$ high wettability wall $C_0 = \left(1 + \frac{\langle j_g^+ \rangle^{0.143}}{0.0853\langle j_g^+ \rangle^{0.719} + 0.115\langle j_f^+ \rangle^{1.08}}\right)\left(1 + 1.40e^{-0.0296D_h^*}\right)\left[1 - \left(\frac{\rho_g}{\rho_f}\right)^{0.0137}\right] + \left(\frac{\rho_g}{\rho_f}\right)^{0.0137}$ $\langle\langle v_{gj} \rangle\rangle = \begin{cases} 0.508\sqrt{D_h^*}\left(\sigma g\Delta\rho / \rho_f^2\right)^{0.25}, D_h^* \le 30 \\ 2.78\left(\sigma g\Delta\rho / \rho_f^2\right)^{0.25}, D_h^* > 30 \end{cases}$ low wettability wall	• Gas-Liquid metal

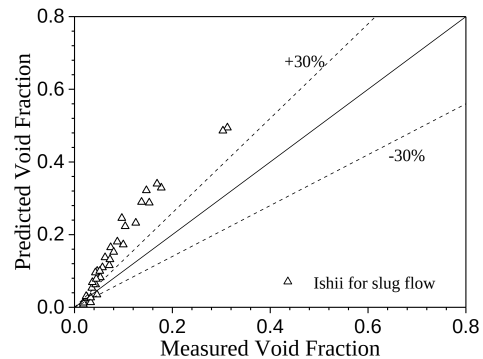
02.Evaluation of existing correlations

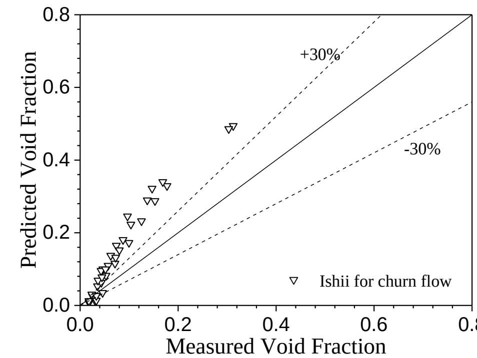
Developer	Test facility	Characteristics
1 JNC & Kyoto University Experiment	 	• void fraction is measured by neutron radiography • N2-LBE • for evaluation and verification of correlations
2 Saito Experiment	 	• void fraction is measured by pressure difference gauge • N2-Gallium & N2-H2O • for evaluation and verification of correlations
3 Ariyoshi Experiment	 	• void fraction is measured by conductivity probe • N2-LBE • for development of correlations

02.Evaluation of existing correlations

1~3







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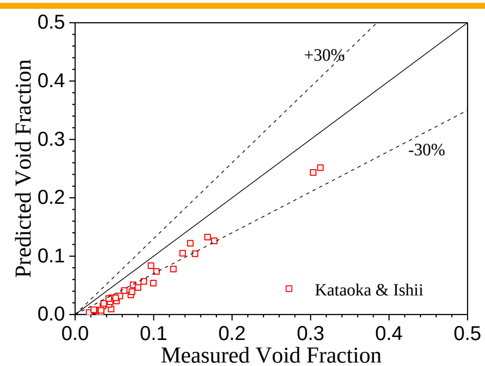

Obvious deviation is observed for void fraction prediction by most correlations based on gas-water two-phase flow

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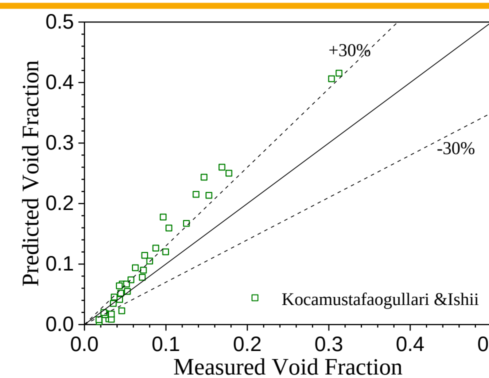

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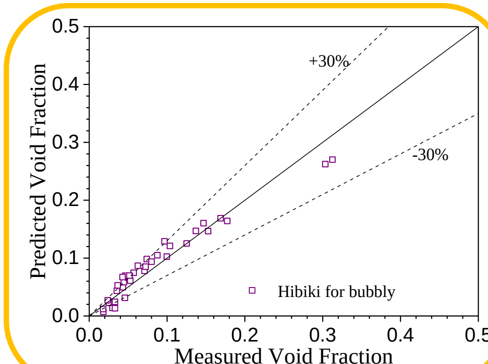
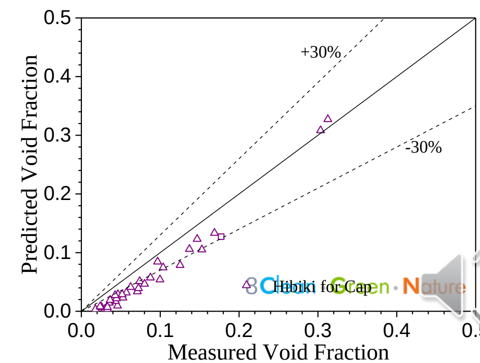
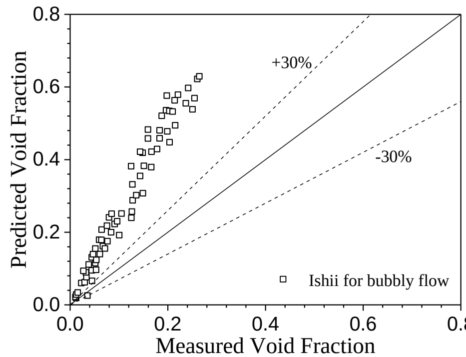
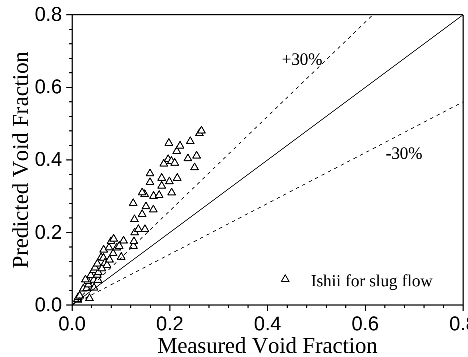


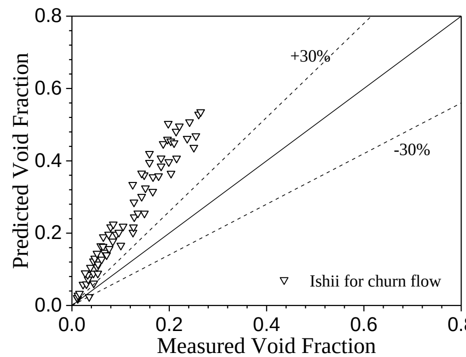


02.Evaluation of existing correlations

1~3







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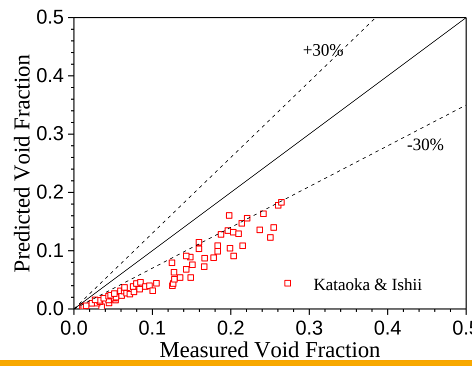

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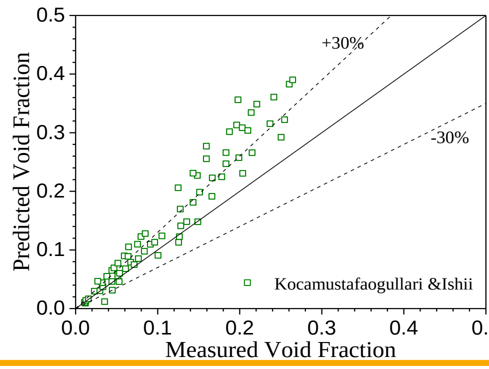

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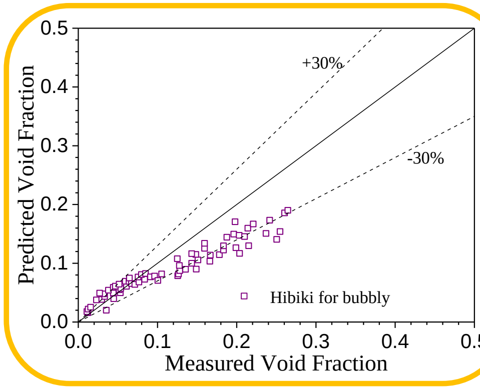
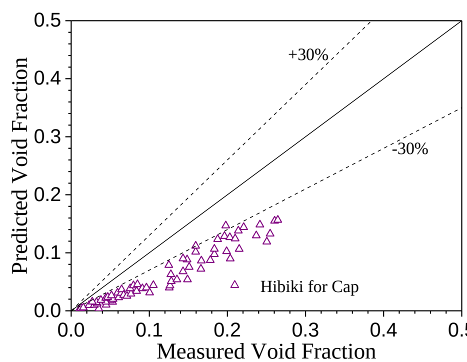
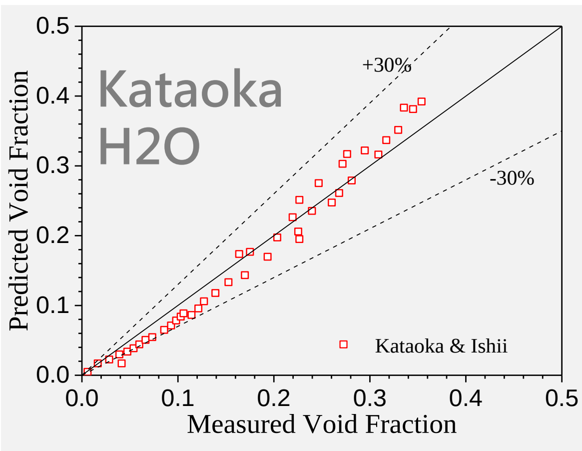
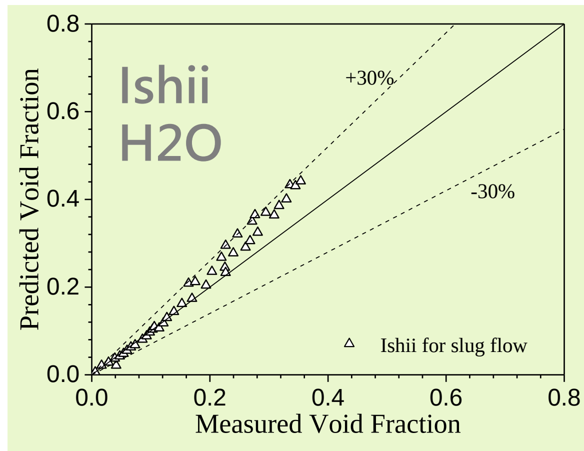


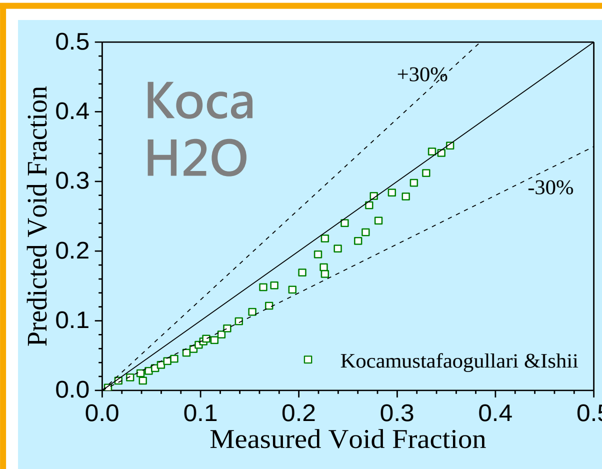
The void fraction prediction in Saito-Ga test is consistent with it in N2-LBE test

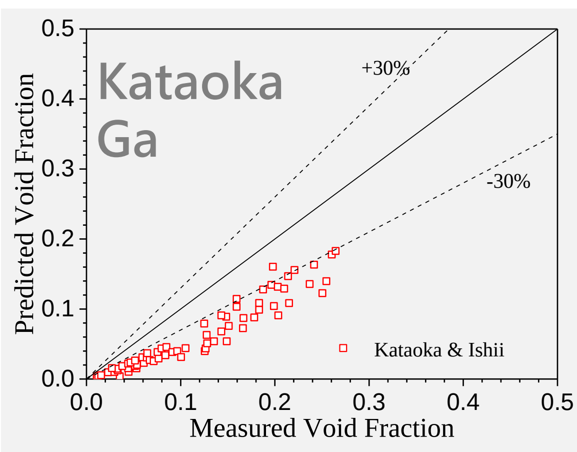


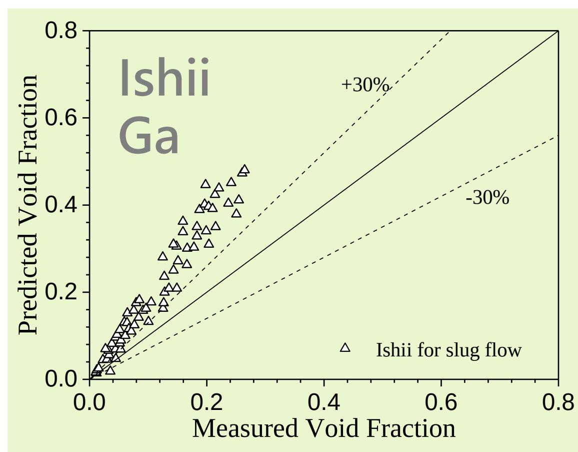
02.Evaluation of existing correlations

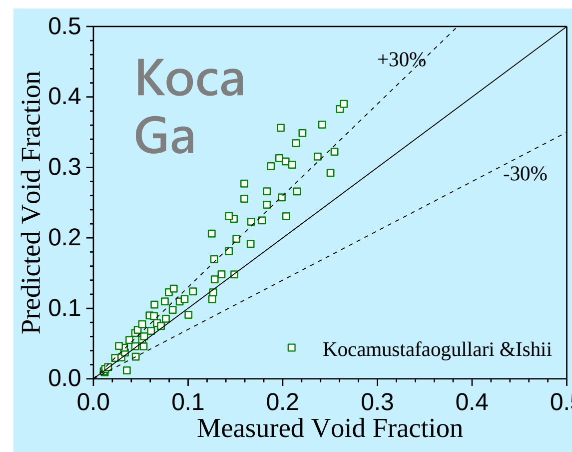








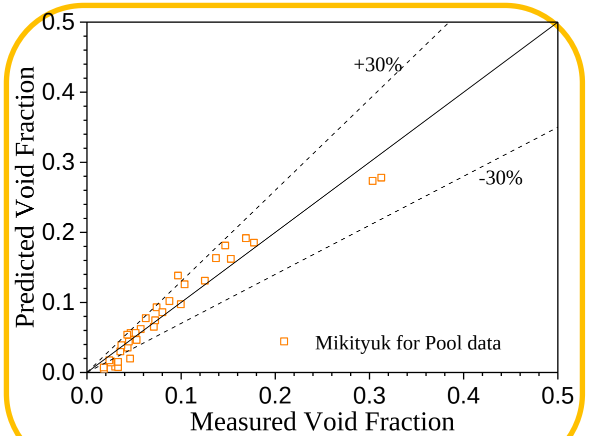


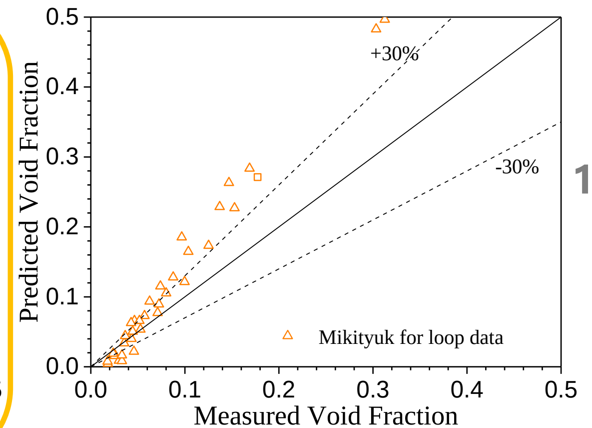


- The correlations based on gas-water two-phase flow data give better prediction in Saito-H2O test

02.Evaluation of existing correlations

8~9





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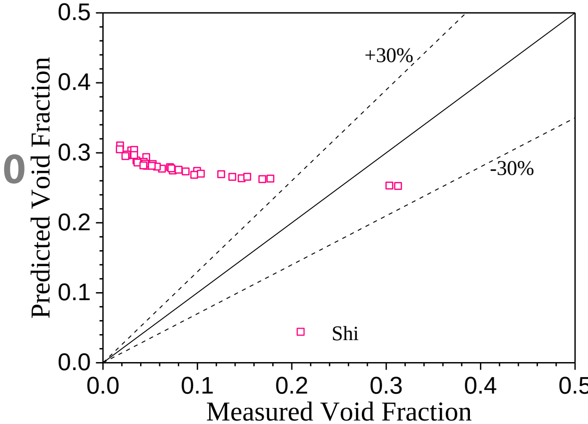

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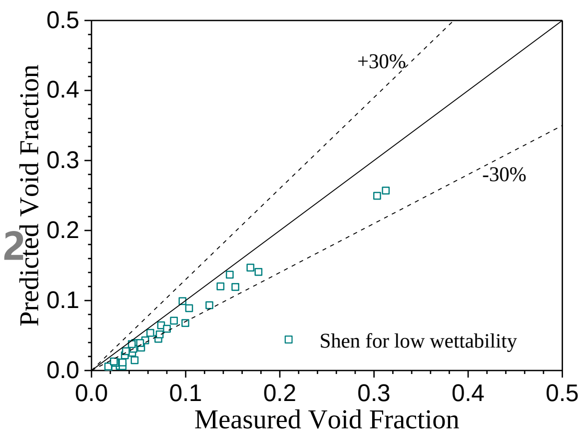
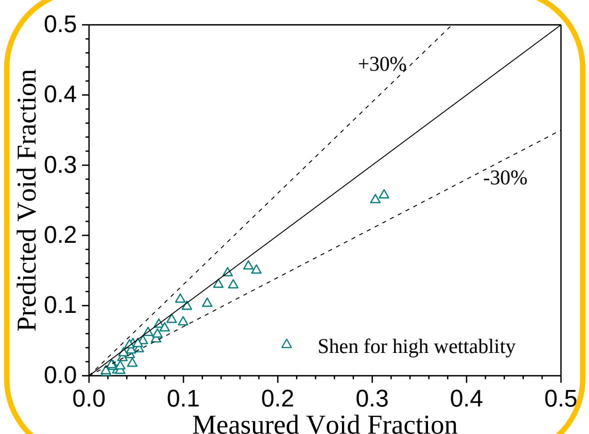
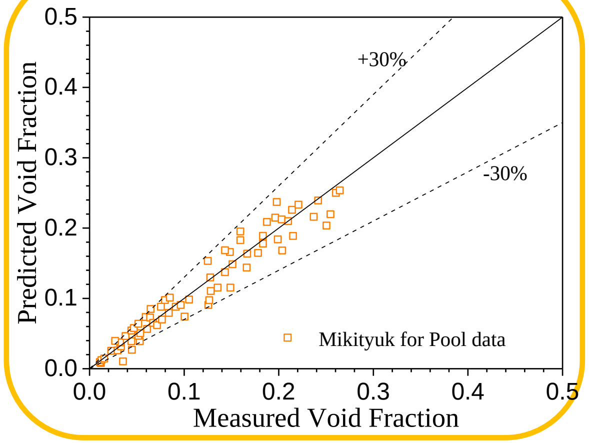


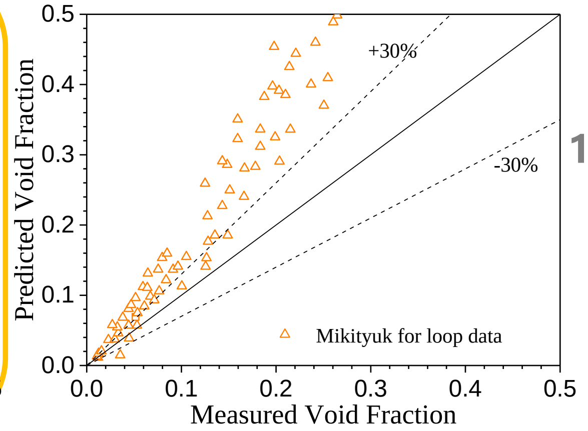


Mikityuk (pool) and Shen correlations can give good agreement with test data

02.Evaluation of existing correlations

8~9





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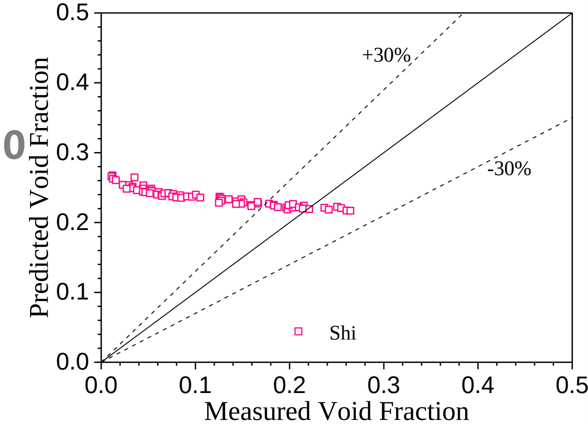

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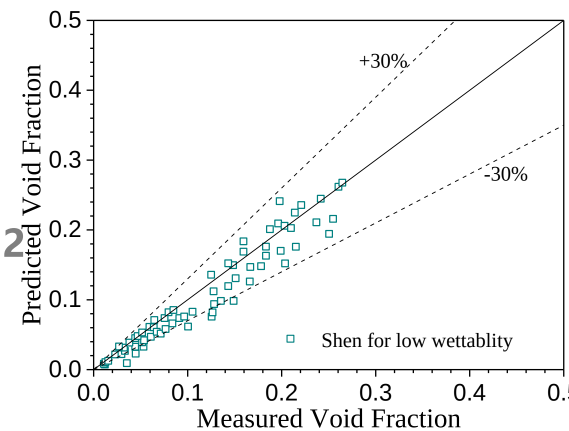
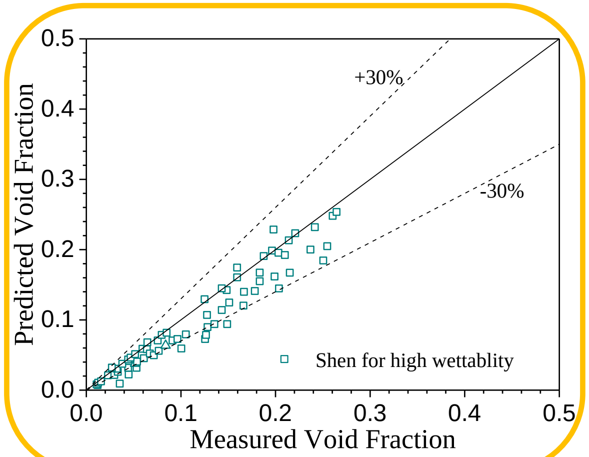




Summary：

Among 12 correlations

- **Only Hibiki's correlations, Mikityuk, and Shen correlations can give good prediction**

03.Theoretical analysis of drift-flux parameter

Step1:Theoretical model
- Get the α and velocity distribution along radius
- Calculate C0 by definition

Step2：Influence factor
- Change input parameter in theoretical model
- Analysis the influence

Step3：new correlation
- quantify the effect by fitting
- get new correlation

Clark’ s theoretical model for bubble column

$$\alpha(r)=\alpha_c\left[1-(r/R)^p\right]$$

$$\rho(r)=\rho_f\left(1-\alpha(r)\right)+\rho_g\alpha(r)$$

$$\rho(r)=\rho_f\left[1-\alpha_c+\alpha_c(r/R)^p\right]$$

$$\bar{\rho}-\rho_i(r)=\rho_f\left(\frac{2\alpha_c}{p+2}\right)\left[1-\left(\frac{r}{R}\right)^p\right]$$

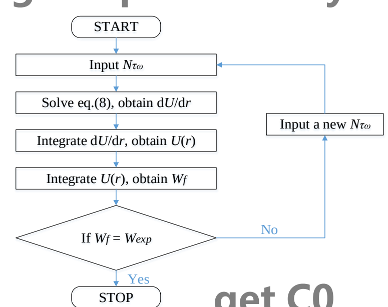
$$\frac{l}{R}=0.14-0.08\left(\frac{r}{R}\right)^2-0.06\left(\frac{r}{R}\right)^4$$

$$\tau(r)=-\mu\left(\frac{dU}{dr}\right)-l^2\rho\left|\frac{dU}{dr}\right|\left(\frac{dU}{dr}\right)$$

$$\tau(r)=\tau_w\left(\frac{r}{R}\right)+\frac{1}{2}rg\left[\bar{\rho}-\rho_i(r)\right]$$

$$0=\left[N_{\tau_w}+\frac{Ga}{2}\frac{\alpha}{p+2}\right]r'+2\frac{du'}{dr'}+\left(\frac{l}{R}\right)^2(1-\alpha)Ga\left(\frac{du'}{dr'}\right)\left|\frac{du'}{dr'}\right|$$

get liquid velocity



get C0

$$C_0=\frac{\int_0^1\left[\alpha u'+\frac{\alpha^2}{1-\alpha}Fr\right]r'dr'}{\alpha_c\left(1-\frac{2}{p+2}\right)\int_0^1\left[u'+\frac{\alpha}{1-\alpha}Fr\right]r'dr'}$$

03.Theoretical analysis of drift-flux parameter

Step1:Theoretical model
- Get the α and velocity distribution along radius
- Calculate C0 by definition

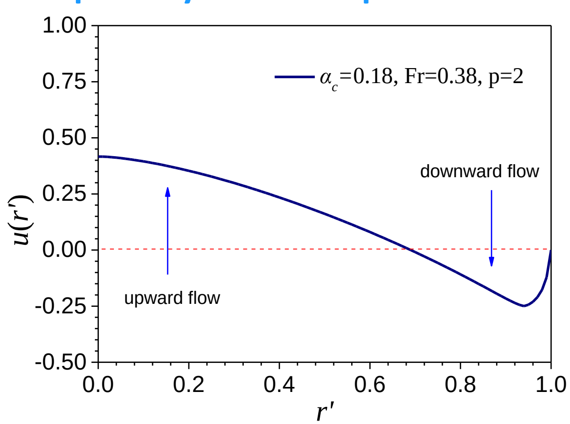
Step2：Influence factor
- Change input parameter in theoretical model
- Analysis the influence

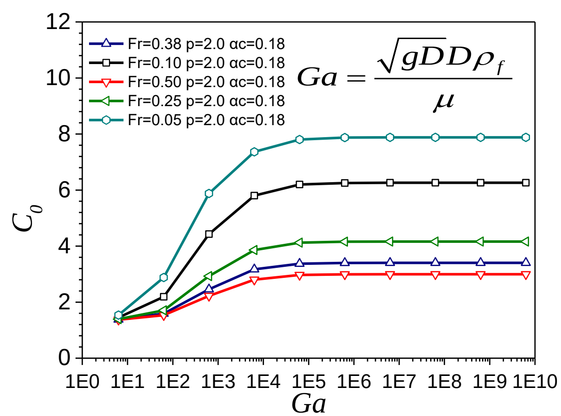
Step3：new correlation
- quantify the effect by fitting
- get new correlation

In the center of the flow channel, the liquid metal is entrained by rising bubbles and flows upward. Correspondingly, liquid metal near the wall flows downward to fill the vacancy after the fluid in center area leaves.

A flow circulation over radius forms. Because the liquid metal is contained in a static pool during experiment, the overall volume flux over channel cross section and the liquid Reynolds number based on average velocity are zero.

Input Ariyoshi's test parameter





- With Ga increasing, C0 increases
- Ga>100000， C0 keeps constant
- Ga number of liquid heavy metal is larger than water

03.Theoretical analysis of drift-flux parameter

Step1:Theoretical model

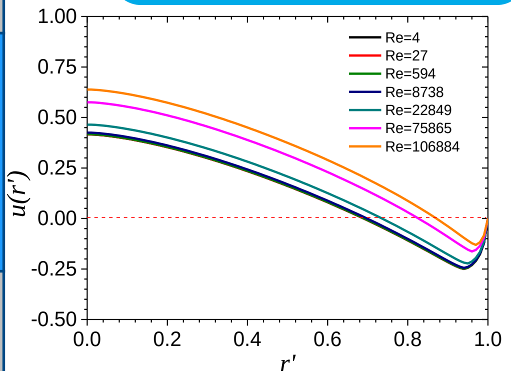
- Get the α and velocity distribution along radius
- Calculate C0 by definition

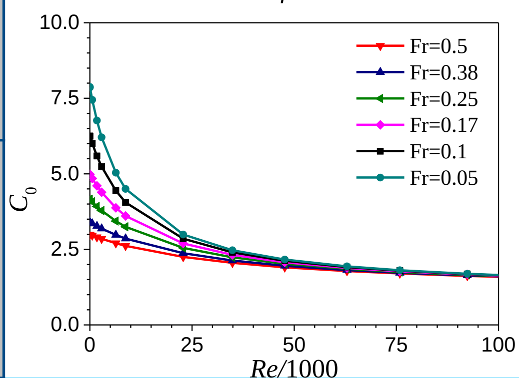
Step2：Influence factor

- Change input parameter in theoretical model
- Analysis the influence

Step3：new correlation

- quantify the effect by fitting
- get new correlation





- **With Re decreasing（to Bubble Column）,C0 increase greatly**
- **With Frincreasing，C0 decrease**

$$Fr = \frac{\langle\langle v_{gj} \rangle\rangle}{\sqrt{gD_h}} = \langle\langle v_{gj}^{+} \rangle\rangle \left(\frac{\sigma g \Delta\rho}{\rho_f^2} \right)^{0.25} / \sqrt{gD_h}$$

- For Saito or JNC&KU's pool-type test，Re of liquid metal nears 0，C0>>1
- For loop-type test， C0 is smaller than it in pool-type test

03.Theoretical analysis of drift-flux parameter

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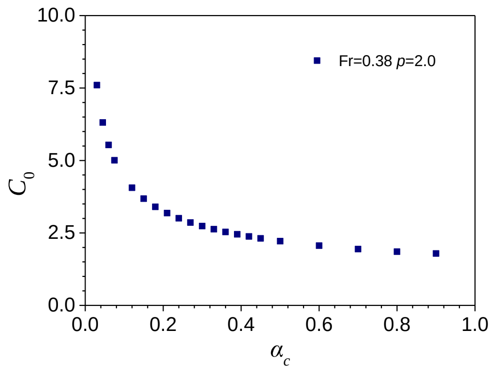

- With averaged void fraction increasing，C0 decrease

In summary, the influence factor include
- **Reynolds number（liquid velocity, channel diameter）**
- **Froude number（channel diameter）**
- **Void fraction（gas superficial velocity）**

03.Theoretical analysis of drift-flux parameter

Step1:Theoretical model
- Get the α and velocity distribution along radius
- Calculate C0 by definition

Step2：Influence factor
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Step3：new correlation
- quantify the effect by fitting
- get new correlation

$$C_0 = f(\mathrm{Re}) - \left[f(\mathrm{Re}) - 1\right]\sqrt{\frac{\rho_g}{\rho_f}}$$

$$f(\mathrm{Re}) = 1.39 - 0.0155\ln(\mathrm{Re})$$

Ishii correlation

$$f(\mathrm{Re}) = \begin{cases} X_1 g_1(Fr), \lg(\mathrm{Re}) < 3.26 \\ X_2 g_2(Fr) - X_3 g_3(Fr)\lg(\mathrm{Re}), 3.26 \le \lg(\mathrm{Re}) \le 5 \end{cases}$$

$$g_1 = 0.391 - 0.632\ln(Fr)$$
$$g_2 = 0.449 - 0.58\ln(Fr)$$
$$g_3 = -0.286 + 0.755\ln(Fr)$$

1、Introduce new relation about Re and Fr

$$C_0 = 1.82 - 0.62\lg(\alpha_c) + 2.03\left[\lg(\alpha_c)\right]^2$$

$$\langle \alpha \rangle = \frac{j_g^+}{2.74 j^+ + 3.77}$$

Fitting with Ariyoshi's test data

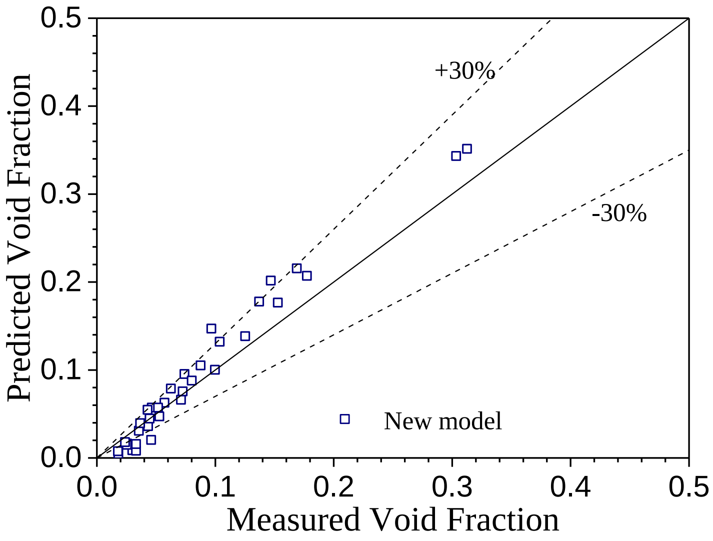
$$\langle\langle v_{gj}^+ \rangle\rangle = \begin{cases} 0.54\sqrt{gD_h^*}, D_h^* \le 30 \\ 3.0, D_h^* > 30 \end{cases}$$

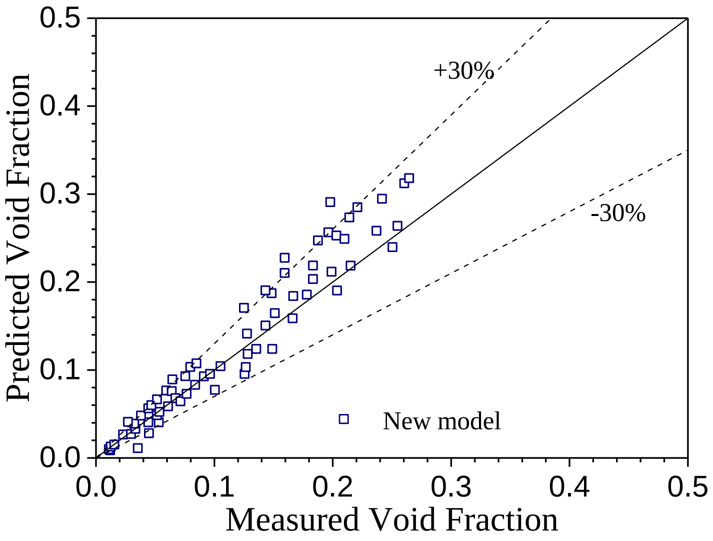
2、Introduce the modification of α

3、Compound with Vgj to get new correlations

04.Development of new correlation

Comparing with test data (left : JNC right : Saito-Ga)



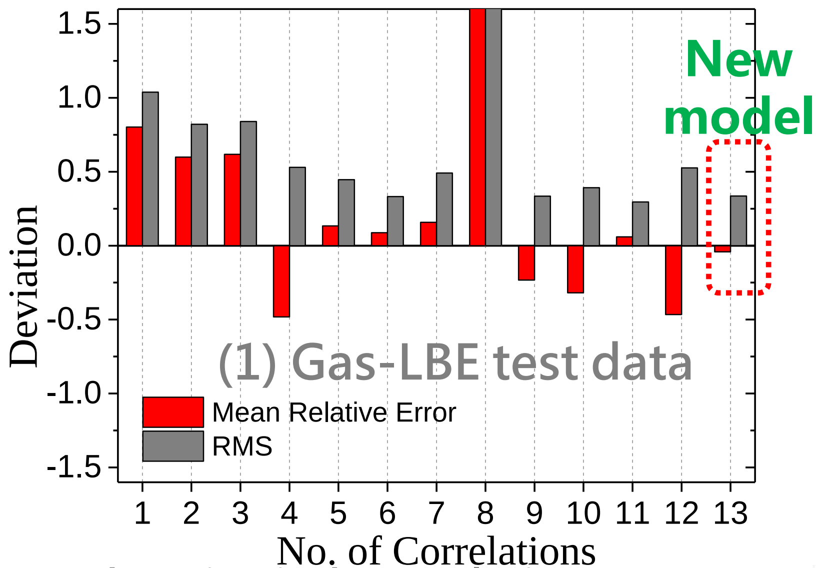


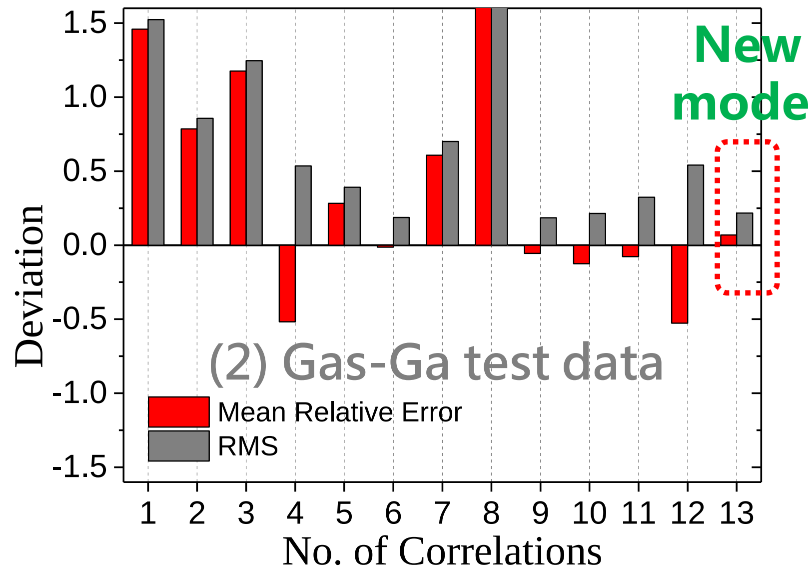
- void fraction predicted by the new correlations agrees well with test data

04.Development of new correlation

Statistical evaluation

(1-Ishii for bubbly, 2-Ishii for slug, 3-Ishii for churn, 4-Kataoka & Ishii, 5-Koca & Ishii, 6-Mikityuk for pool 7-Mikityuk for loop, 8-Shi, 9-Shen(high wettability), 10-Shen(low wettability), 11-Hibiki for bubbly, 12-Hibiki for cap, 13-New developed model)





Comprehensive index：relative error+RMS

$$\xi_j = 0.5\left[\frac{\min_j |\varepsilon_j|}{|\varepsilon_j|} + \frac{\min_j \varepsilon_{RMSj}}{\varepsilon_{RMSj}}\right]$$

From 0 to 1，the larger value means the better prediction

Correlations number, j	ξ_j for gas-LBE test	ξ_j for gas-Ga test
1	0.168	0.066
2	0.215	0.117
3	0.210	0.080
4	0.322	0.186
5	0.489	0.261
6	0.685	**0.995**
7	0.433	0.144
8	0.027	0.018
9	0.530	0.625
10	0.442	0.488
11	0.856	0.376
12	0.325	0.184
13	**0.939**	0.528

New correlations：

- ✓ The prediction is better than other correlations for LBE

05.Conclusion

Based on one-dimensional modified theory analysis, the distribution parameter is estimated and the effect on which is quantitatively discussed, then a new correlation considering is developed. The obtained conclusions and prospects are as follows:

- **Analysis result based on modified Clark's theoretical model shows that distribution parameter is assuming very high values at low Re number. Besides, with Froude number increase, distribution parameter tends to decrease. At lower void factions, distribution parameter is also assumed to be high values. It indicates that the pipe size, flow rate and void fraction can all influence distribution parameter.**

- **Considering the quantitative laws of above influence factors obtained by theoretical analysis and fitting the data of Ariyoshi's test, a new correlation for gas-LBE two-phase flow is developed and evaluated with JNC & KyotoU and Saito's test. The new correlation gives the good prediction for gas-LBE two-phase flow in the void fraction range of 0~30%.**

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Thank you!