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Experimental Study of Liquid Holdup in Pressurizer in Case of Loss-of-Residual-Heat-Removal during Mid-loop Operation

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Abstract

A separate effect test facility consisting of hot-leg, surge line and pressurizer is installed to investigate the gas flow into the pressurizer and the entrained water holdup in the pressurizer. The collapsed and mixture levels are measured with changes of gas flow rate during the liquid holdup process. Onset of liquid collapse, CCFL and frictional drop in the surge line are examined during the water collapse process. Scaling analysis is performed to have scale similarities between test facility and real plant. CCFL and velocity similitude are applied to geometric scale parameters in the test facility. Scale similarity for the collapsed and mixture levels are examined. The collapsed level has a similarity from the present scaling methodologies. The mixture level also has a similarity in case that the void fraction is preserved. Preliminary experimental results are obtained for the liquid holdup process. The collapsed level becomes a control parameter instead of the water level in hot-leg together with the gas flow rate.

1. Introduction

In case of the pressurizer manway opening after the loss of residual heat removal during a mid-loop operation, the steam generated by the decay heat entrains the coolant at the inlet of surge line. The entrained coolant flows into the pressurizer via the surge line and builds up a collapsed level in the pressurizer. Because of the steam up-flow toward a manway opening, the accumulated water in the pressurizer not only has a collapsed water level, but also a mixture water level. A liquid holdup phenomenon is closely related to the off-take at T-junction with vertical surge line that is performed by the same authors[1]. The liquid holdup in the pressurizer is dominantly affected by the discharge quality at the T-junction that varies with the conditions of the water level in hot-leg and the gas up-flow rate, and is directly related to the collapsed level. The mixture level in the pressurizer is affected by the gas flow rate and the collapsed level accumulated for a given elapsed time, and is not affected by the hot-leg conditions (e.g. water level in hot-leg) any more.

When the coolant is accumulated in the pressurizer to the extent that the gas flow does not penetrate the liquid holdup and is not discharged through the manway opening, the RCS pressure rises and, as a results, the decrease of gas flow rate occurs, which causes the collapse of liquid from the pressurizer to the hot-leg. Afterwards, the hydraulic head of liquid in the pressurizer decreases and the off-take and coolant discharge restart. In such a process the counter-current flow and flooding also occurs in the surge line. A behavior of the insurge and collapse of the coolant water in the pressurizer gives rise to the oscillation, which has an important effect on the core stability by the re-distribution of the coolant inventory.

The current study is in progress and especially, the experimental work has been comprehensively performed till now. The objectives and contents of the present study are as follows:

- To design the test facility, the scaling analysis for geometric and level parameters are performed, which enables to minimize the distortion by a scale-down and to have the scale similarity between the experimental results and the actual phenomena in real plant.
- To obtain data of the separate effect test (SET), the experiments are performed for the collapsed and mixture levels in the pressurizer, for the onset of the water collapse, and for water oscillation and CCFL in surge line. From the results of experiment, new empirical correlations are developed.
- Using the thermal-hydraulic code, RELAP5/MOD3.x, code assessment is performed for better predictability. If needed, models or correlations are modified or improved.

2. Scaling Analysis for Test Facility Design

Prior to the detailed design of test facility, the scaling analysis has been performed, which results in the proper scaling methodologies to apply to the test facility. The

Korea standard nuclear power plants (KSNP, UCN units 3&4) are selected as a prototype plant. Firstly, to determine an overall scale of the test facility, the scale ratios of a gas flow rate (Q_g) and an area (a) are determined as 1/25 scale if the gas velocity (v) ratio is preserved. Such a value of scaled-down ratio is larger than that of the existing integral test facilities for mid-loop operation. Therefore, the test section of pressurizer relatively has a large scale.

$$[Q_g]_R = [v\ a]_R = a_R \tag{1}$$

2.1. Diameter and Length of Horizontal Pipe (Hot-leg)

According to a value of scale ratio of gas flow rate, other scale ratios are determined. The hot-leg is simulated as the horizontal pipe. The CCFL similitude is applied to the scaling of the horizontal pipe diameter (D) as the following:

$$[j_g^*]_R = 1 \quad \rightarrow \quad [D]_R = [Q_g^{2/5}]_R. \tag{2}$$

From the above result, D is scaled down from 1.067m to 0.295m. This scale is closer to the real plant geometry than that of previous experimental scales. The length (L) of the horizontal pipe is scaled as the same value with the D-scale ratio ($[D]_R$) of 0.276, which is on the basis of experimental results [2] for CCFL in the hot-leg.

$$[L/D]_R = 1 \quad \rightarrow \quad [L]_R = [Q_g^{2/5}]_R \tag{3}$$

2.2. Diameter and Length of Surge Line

In the surge line, the gas-water mixture co-currently flows into the pressurizer during a liquid holdup process. Also, the mixture may counter-currently flows during a collapse of accumulated water in pressurizer and its oscillation (a water collapse process). Therefore, during a mid-loop condition the scaling methodologies that can be applied to the scaling of the surge line diameter (d) may be one or more. As the current study has more focus on the liquid holdup process rather than the post-holdup process, the velocity similitude ($[v]_R = 1$) is applied to the scaling of the surge line diameter likewise the hot-leg diameter.

$$[Q_g]_R = [a\ v]_R = [a]_R = [d^2]_R \quad \rightarrow \quad [d]_R = [Q_g^{1/2}]_R \tag{4}$$

From the above result, the diameter of surge line is determined as 0.0514m, which is actually changed into 0.05m in manufacturing process of the test facility. Therefore, the surge line to hot-leg diameter ratio (d/D) of the test facility is 0.169, on the other hand, that of real plant is 0.241.

In a real plant, the surge line geometry has a three-dimensionally complex shape because of the existence of other components. The surge line is composed of 9 branches (horizontal or vertical) and 8 elbows (45 or 90 degree). The gas velocity in surge line is higher than that in hot-leg because of its small diameter. For these reasons, it is expected that the pressure drop becomes more prominent. Therefore, the pressure drop similitude is applied to the scaling of the surge line length.

$$\Delta p = f(L/D)\frac{1}{2}\rho_g v_g^2 \rightarrow [\Delta p]_R = 1 \rightarrow [L/D]_R = 1 \tag{5}$$

The above scaling methodology is the same result as that of hot-leg length. Therefore, the $[L/D]_R = 1$ scaling satisfies the pressure drop similarity together with the empirical similarity [2] for stratified flow regime on a horizontal pipe.

2.3. Diameter and Height of Pressurizer

The pressurizer diameter (D_p) is determined by the velocity similitude as the same that of surge line. This similitude resultantly satisfies the collapsed level preservation as description subsequently.

$$[D_p]_R = [Q_g^{1/2}]_R \tag{6}$$

In the pressurizer height (H), the scale ratio to be 1/1 is suggested because of the importance of the hydraulic head caused by an accumulated liquid in the pressurizer. However, the height is inevitably scaled down by a limitation of experimental environment. According to the ratio of $[H]_R = 1/6$, the pressurizer height is scaled down from 12.944m to 2.157m.

The manway diameter (d_M) on the top of pressurizer is also scaled, which is the opening occurring discharge flow in this study. The velocity similitude is also applied to the manway diameter, which results in d_M=0.0812m.

2.4. Collapsed and Mixture Levels in Pressurizer

The scaling similarities of the collapsed and mixture levels of water in the pressurizer are examined from the above analyses for geometric scaling parameters.

As described previously, the ratio of gas flow rate is the same as that of area. The branch quality (x) at the inlet of surge line is preserved if the hot-leg diameter is scaled by the CCFL similitude[1]. Therefore, the entrained water flow rate (Q_{LE}) has the same scaled-down ratio.

$$[Q_{LE}]_R = a_R \ \& \ [x]_R = 1 \rightarrow [W_{LE}]_R = a_R \tag{7}$$

The liquid volume (V_{hold}) accumulated in the pressurizer is calculated from the elapsed time for level buildup (τ) multiplied by the entrained liquid flow rate (W_{LE}), which can be also expressed as the sectional area (A_p) of the pressurizer multiplied by the collapsed level (z_c).

$$[Q_{LE}\,\tau]_R = [V_{hold}]_R = [A_p]_R[z_c]_R \tag{8}$$

The pressurizer area (A_p) has the same scaled-down ratio with a_R by the velocity similitude to the pressurizer diameter. The time to build up the same relative revel is the same as the scaled-down ratio of pressurizer height.

$$[A_p]_R = a_R\ ,\ [\tau]_R = [H]_R \tag{9}$$

Therefore, the pressurizer height ratio is the same as the collapsed level ratio and the ratio of nondimensionalized collapsed level is preserved as 1.

$$[H]_R = [z_c]_R \rightarrow [z_c/H]_R = [z_c^*]_R = 1 \tag{10}$$

The ratio of nondimensonalized mixture level (z_m^*) is able to be preserved in case of several conditions are satisfied. z_m^* can be expressed as a function of the nondimensional numbers of inlet velocity (N_{ui}) and density (N_ρ)[3].

$$z_m^* = z_m^*(N_{vi}, N_\rho) = z_m/H \tag{11}$$

where, N_{vi} is j_0/v_{gj}. Excluding the nondimensional number of density to preserve the z_m^*, the result is as

$$[z_m^*]_R = 1 \rightarrow [N_{vi}]_R = 1 \rightarrow [v_{g,in}\,\alpha/v_{gj}]_R = 1 \tag{12}$$

where $v_{g,in}$ is the inlet gas velocity into the pressurizer. $[v_{g,in}]_R$ can be preserved with the bases that the hot-leg area ratio is equal to the gas flow rate and that the ratio of surge line area is equal to the ratio of pressurizer area:

$$a_R = [W_g]_R \ \&\ [A_s/A_p]_R = 1 \ \rightarrow\ [v_{g,in}]_R = 1 \tag{13}$$

where A_s is the surge line area. To satisfy $[z_m^*]_R = 1$ from Equation (12), the following two parameters should be preserved:

$$[v_{gj}]_R = 1 \ \&\ [\alpha]_R = 1 \quad For \quad [z_m^*]_R = 1 \tag{14}$$

where α is the local void fraction in pressurizer and its averaged property is expressed as $\overline{\alpha}$. α is defined as

$$\alpha = \frac{j_g}{C_0 j_0 + v_{gj}} \cong \frac{1}{C_0 + \frac{v_{gj}}{v_{g,in}} \frac{A_p}{A_s}} \tag{15}$$

where C_0 is the flow distribution parameter. Equation (15) represents that the flow distribution parameter and the inlet gas velocity into the pressurizer should be preserved for the void fraction preservation.

$$[C_0]_R = 1\ ,\ [v_{gj}]_R = 1 \quad \text{For } [\alpha]_R = 1\ (\cong [\overline{\alpha}]_R = 1) \tag{16}$$

Using average void fraction, the relation between the collapsed level and the mixture level can be expressed by the amount of the accumulated liquid volume:

$$z_m (1 - \overline{\alpha}) A_p \ = \ z_c A_p \tag{17}$$

Therefore, if the ratio of the average void fraction is preserved, the nondimensionalized mixture level is capable of being preserved because the ratio of collapsed level is already preserved.

$$[z_m^*]_R = [z_c^*]_R = 1 \quad (\text{ if } [\overline{\alpha}]_{\mathrm{R}} = 1) \tag{18}$$

Table 1 summarizes the results of scaled-down ratio and applied methodologies for scaling parameters. All geometric scales except for hot-leg diameter and pressurizer height are scaled down as ratio of 1/5.

3. Test Facility for Pressurizer Experiment

The test facility is designed and manufactured based on the results of scaling analysis. Figure 1 shows the overall schematic diagram of the test facility, which consists of air-water supply tank, horizontal pipe (hot-leg), surge line, pressurizer. Air blowing system including an air blower and the control panel of air flow control is also installed to supply large amount of an air flow. Overall geometry of the test section has a large scale compared to the previous test facility, accordingly, which is why the air is used for this study instead of a steam. The air blower is a ring type without pulsation and has a power of 27kW to generate maximally 22,000lpm at 1atm.

Slugging impact occurring in the horizontal pipe with large diameter of nearly 30cm is a severe problem on experimental works, which needs the structural reinforcement. Thus, the materials of the horizontal pipe and the T-junction are substituted an acryl with a steel after the visual observation. The surge line and the pressurizer are made using the transparent acryl, which enables to observe a hydraulic behavior. Surge line is designed as a simplified shape compared to that of real plant. It has designed 6 branches and 5 elbows with large radius of curvature. Differential pressure is measured from both ends of surge line. Pressurizer has a shape of cylindrical tank. The diameter and height of the pressurizer are 48.9cm and 2.157m, respectively. The outlet of surge line is connected to the center of pressurizer bottom. To measure the collapsed and mixture levels, the DP transmitter and the electro-probe are installed. On the top of pressurizer, there is a manway hole with 8.12cm diameter. Table 2 represents the scale of the pressurizer test facility compared to the reference plant, UCN Unit 3&4. In Table 2, the gas flow rate, 4.3kg/s, is calculated in condition of 0.5% of normal power (approximately, 48hrs after reactor shutdown).

4. Preliminary Results of Pressurizer Test

Preliminary results of the pressurizer experiment are obtained, especially, for the collapsed and mixture levels of water in pressurizer. Experimental work can be divided into two categories; the liquid holdup process in pressurizer, the water collapse and oscillation process in surge line. Preliminary results include data limited to the former work, and both of two works are in progress. In the experiment of liquid holdup process, the water level in horizontal pipe (h) is not a control parameter to govern the levels any more because the current experiment is performed in condition of the steady state. Therefore, the collapsed level instead of h and the gas flow rate are control parameters to affect the mixture level.

Total 38 data for the mixture level in liquid holdup process are obtained till now. The collapsed level ranges from 110mm to 763mm and the air velocity in surge line ranges from 18.3m/s to 55.9m/s. Figures 2 and 3 show the mixing behavior of accumulated water and gas flow in the pressurizer. The mixture level interface becomes more unstable as the collapsed level decreases at a given gas flow rate. Also, the mixture level increases and becomes more unstable as an increase of gas flow rate at a given collapsed level. As the cross-sectional area is suddenly expanded when the gas flows into the pressurizer, the region of bubbly mixing over the entire area widely exists. Also, the region that the single liquid phase and the developing gas flow phase coexist is observed near the bottom of pressurizer as shown by Figure 4. In Figure 5, the result of the measurements of two levels are represented as a stepwise increase of gas flow rate. The data of mixture level are obtained by an average for steady period that the collapsed level and the gas flow rate remain consistently. Additionally, to quantify the dispersion of the mixture level oscillation, the standard deviation is also obtained, which is subsequently calculated for the average value of mixture level. As a gas flow increases, the mixture level increases together with the increase of its standard deviation. Such a tendency is represented in Figure 6. The vertical red lines in Figure 6 means the standard deviation. Therefore, the oscillation of level interface becomes larger as the mixture level increases. Figure 7 shows the relative level ratio, z_m/z_c. In case that the collapsed levels are within 30cm, z_m/z_c values are higher than those in case over 30cm. Such a separate distribution may give an information of the range that is inadequate for discussing the buildup of a mixture level because of its excessive oscillation at low value of z_c. In the RELAP5/MOD3.2 code, the Kataoka-Ishii correlation is correlated for the prediction of void fraction in conditions of large diameter (D>0.08m) and churn-turbulent bubbly flow regime, which is capable of being using the comparison of void fraction with the present data as shown in Figure 8. The Kataoka-Ishii correlation relatively predicts well the present data except for data within 30cm of z_c.

5. Conclusions

A separate effect test facility consisting of hot-leg, surge line and pressurizer is installed to study the holdup and collapse of entrained water in the pressurizer. The scaling analysis for test facility and the preliminary experimental results for the pressurizer experiment are described on this paper. Conclusions are summarized as follows:

• The velocity similitude is applied to the diameters of the surge line and the pressurizer. In the surge line, the L/D similarity by an experimental basis is applied to length scale, which results in the pressure drop similarity together with the velocity similitude. In the pressurizer, it satisfies the collapsed level similarity because the branch quality has a similarity, which is obtained by the CCFL similitude to the hot-leg. In case of the void fraction in pressurizer is preserved, the mixture level can additionally have a similarity.

• In a liquid holdup in pressurizer, the water level in hot-leg is not an important control parameter any more. Instead, the collapsed level and the gas flow rate are main control parameters. At a given collapsed level, the mixture level and its oscillation increase with an increase in gas flow. The ratio of z_m to z_c in case that collapsed levels are above 30cm are little affected by the change of collapsed level. The present data of void fraction agree with the prediction of Kataoka-Ishii correlation used in RELAP5/MOD3.2.

References

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Table 1. Scaling methodologies and results for pressurizer test facility

Scaling parameter			Scaling results	Scailng methodology
Hot-leg	Diameter	D	$[D]_R = [W_g^{2/5}]_R$ =0.276	CCFL similitude
	Length	L	$[L]_R = [D]_R = [W_g^{2/5}]_R$ =0.276	Experimental experience([2])
Surge line	Diameter	d	$[d]_R = [W_g^{1/2}]_R$ =1/5	Velocity similitude
	Length	l	$[l]_R = [d]_R$ =1/5	Pressure drop similitude
Pressurizer	Diameter	D_p	$[D_p]_R = [W_g^{1/2}]_R$ =1/5	Velocity similitude
	Height	H	$H_R = 1/6$	-
	Manway diameter	d_M	$[d_M]_R = [W_g^{1/2}]_R$ =1/5	Velocity similitude
	Collapsed level	z_c	$[z_c]_R = 1/6$, $[z_c^*]_R = 1$	Liquid mass similarity
	Mixture level	z_m	$[z_m^*]_R = 1$ (If $[\overline{\alpha}]_R = 1$)	Mixture mass similarity

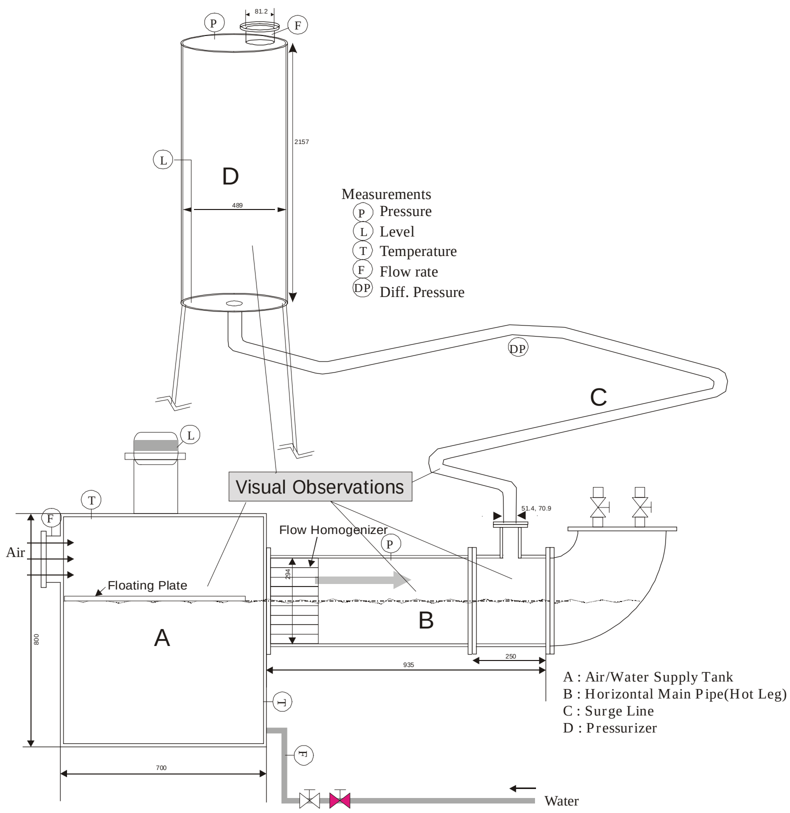

Figure 1. Overall schematic of pressurizer test facility

Table 2. Scale comparison of test facility and reference plant

Components		KSNP	KAIST SET	Scaled-down ratio
hot-leg diameter	[m]	1.067	0.295	0.276
surge line diameter	[m]	0.257	0.05	0.2
gas flow rate	[kg/s]	4.3	0.217	0.04
hot-leg length	[m]	3.388	0.935	0.276
surge line length	[m]	23.405	4.681	0.2
pressurizer diameter	[m]	2.445	0.489	0.2
pressurizer height	[m]	12.944	2.157	0.167
manway diameter	[m]	0.406	0.0812	0.2

Figure 2. Mixture level at z_c=0.24m

Figure 3. Mixture level at z_c=0.54m

Figure 4. Gas flow into the liquid in pressurizer

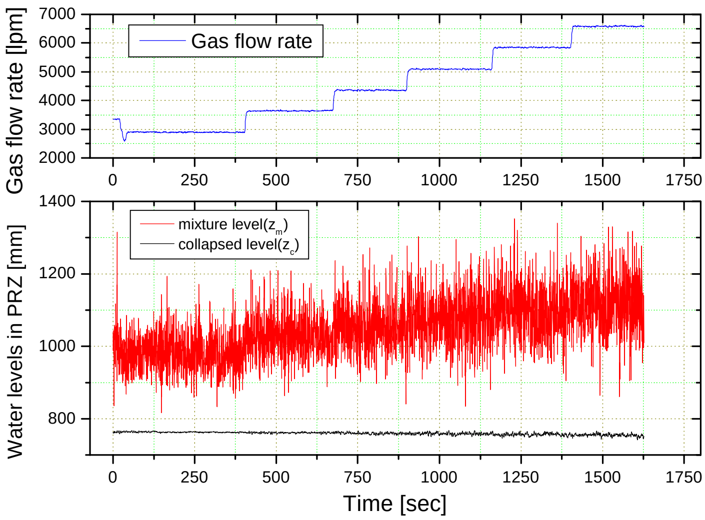

Figure 5. Mixture level distribution as increase of gas flow

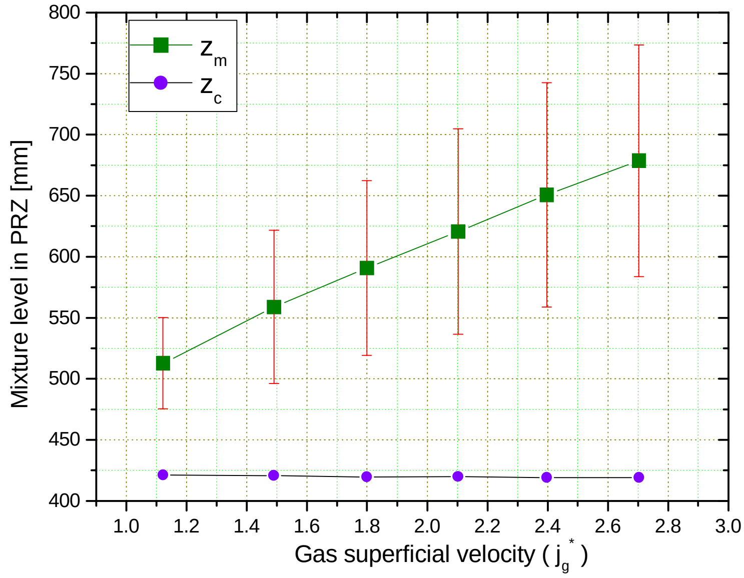

Figure 6. Mixture level and its dispersion

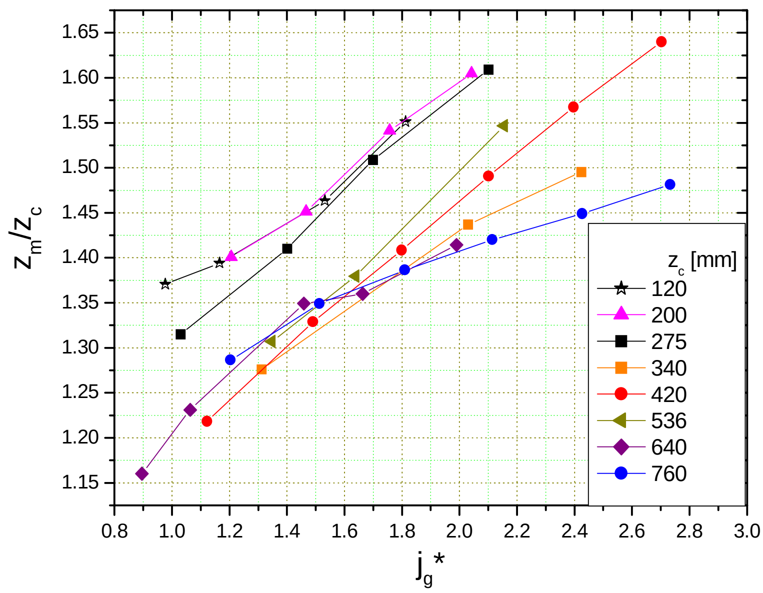

Figure 7. Relative mixture level

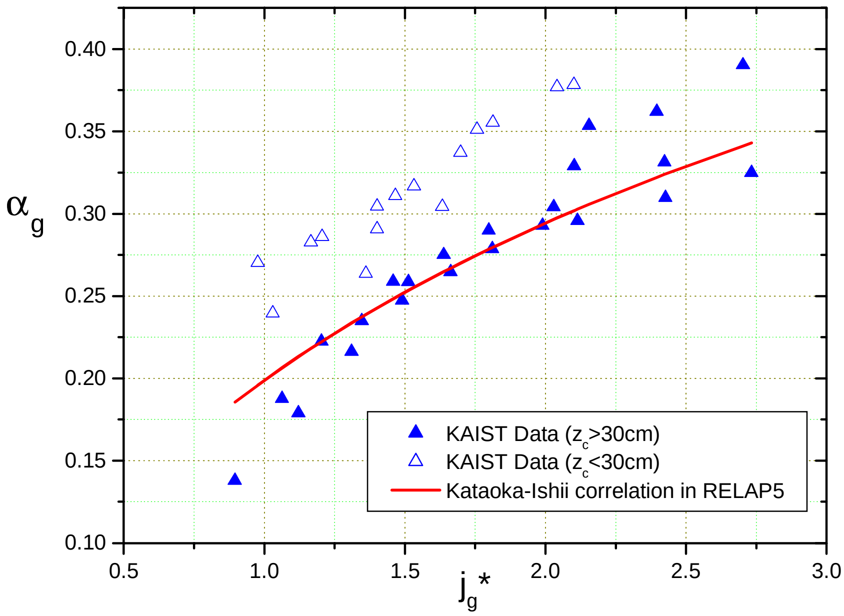

Figure 8. Comparison of void fraction with Kataoka-Ishii Correlation