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Assessment of an Ultrasonic Sensor and a Capacitance Probe for Measurement of Two-phase Mixture Level

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Abstract

We performed a comparison of two-phase mixture levels measured by an ultrasonic sensor and a two-wire type capacitance probe with visual data under the same experimental conditions. A series of experiments are performed with various combinations of airflow and initial water level using a test vessel with a height of 2m and an inner diameter of 0.3m. The ultrasonic sensor measured the two-phase mixture level with a maximum error of 1.77% with respect to the visual data. The capacitance probe severely under-predicted the level data in the high void fraction region. The cause of the error was identified as the change of the dielectric constant as the void fraction changes when the probe is applied to the measurement of the two-phase mixture levels. A correction method for the capacitance probe is proposed by correcting the change of the dielectric constant of the two-phase mixture. The correction method for the capacitance probe produces a r.m.s. error of 5.4%. The present experimental data are compared with the existing pool void fraction correlations based on drift-flux model. The Kataoka-Ishii correlation has the best agreement with the present experimental data with an r.m.s. error of 2.5%.

I. Introduction

Two-phase mixture level is one of the important parameters in the nuclear components where a large inventory of water is contained, such as reactor vessels, pressurizers, and steam generators. After the TMI-2 accident, accurate measurement of the two-phase mixture level has been emphasized in nuclear power plants. The measurement of liquid levels without surface fluctuation is a relatively simple process. Under the condition of surface fluctuation, however, it is very difficult to measure the two-phase mixture levels accurately [1, 2].

A capacitance probe is widely used for the measurement of two-phase mixture levels due to its simple measurement principle and easy maintenance. The capacitance probe has been used to measure two-phase mixture level swell in the reactor vessel of the Advanced Plant Experiment (APEX) facility of Oregon State University [3]. However, a measurement error could arise as a result of the variation of the dielectric constant of the material filled between the two tubes of the capacitance probe as the void fraction changes. Meanwhile, the capacitance probe is only slightly affected by the fluctuating surface conditions. The acoustic devices such as ultrasonic sensor have been applied to the measurement of two-phase mixture levels. The acoustic devices do not depend on the state of the filled material because they are not in contact with this material. However, they could be subject to errors caused by the loss of echo signal from a highly fluctuating surface. Recently, Lee and No [4] have developed an ultrasonic method for the measurement of a two-phase mixture level with surface fluctuation under conditions of high temperature and pressure. In addition, the ultrasonic method has been applied to measure two-phase mixture levels when the liquid entrainment and off-takes takes place from the two-phase mixture surface in a vessel [5].

In the present study the two-phase mixture levels from an ultrasonic sensor and a capacitance probe are compared against visual data under the same experimental conditions in order to assess possible measurement errors. A series of experiments are performed in a test vessel with various combinations of air flow rate and initial water level.

II. Experiment

1. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in **Fig. 1**. The test vessel is made of a 2m long transparent Pyrex pipe with an inner-diameter of 0.3m to enable visual observations of the flow pattern and the two-phase mixture level. Air is supplied to the bottom of the test vessel and discharged through an air discharge line at the top of the vessel. A bubbling device installed in the lower part of the vessel achieves uniform bubble generation. The bubbling device has a number of small holes 5mm in diameter. The air flow rate is measured in the air supply pipe by rotameters. Water is supplied by a water reservoir. Two-phase mixture levels are measured with various combinations of air flow rates and the collapsed liquid levels. The range of air flowrates is 300 – 1200 LPM, which corresponds to 0.07 – 0.32 m/s in terms of the superficial air velocity in the vessel (j_g). The range of the collapsed liquid level (L_c) is 0.8 – 1.2m (40% - 60% of the full height of the vessel).

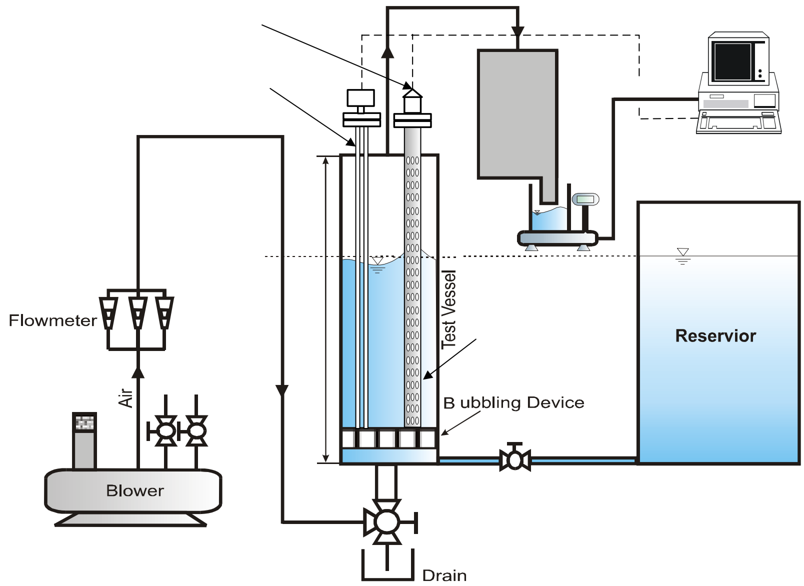

Fig. 1 Schematic diagram of the experimental apparatus.

2. Two-Phase Mixture Level Measurements

The ultrasonic sensor employed in the present experiment is a XCT-8 made by Miltronics Co. (Canada). The ranges of measurable distance and temperature are 0.45 – 8m and -40 – 150°C, respectively. A signal processor (Multiranger plus by Miltronics) is used to process the signal. The attenuation of echo signals increases due to diffused reflection when the two-phase mixture surface fluctuates. As the diffused reflection from the surface increases further, the echo signal becomes much smaller and, as a result, can be lost. This phenomenon is called loss of echo. To avoid this problem, a waveguide, which has a number of small holes, is designed to reduce attenuation and echo loss of the ultrasonic wave. The effectiveness of the waveguide has been investigated with various hole diameters [4]. In the present study, a waveguide having a number of small holes with a diameter of 20mm with a vertical interval of 100mm is used.

A two-wire type capacitance level transmitter is used because the test vessel material is not electrically conductive. The probe is manufactured by HITROL Co. LTD (Korea). The ranges of measurable level and temperature are 0 – 2.0m and -20 – 60°C, respectively. The diameter and spacing of the two-wires are 13mm and 30mm, respectively.

The visual levels are obtained from the averaged values, which are determined from still images of motion pictures recorded by a video camera and an external scale attached on the wall of the test vessel.

III. Results and Discussion

The measured two-phase mixture levels from the capacitance probe and the ultrasonic sensor are compared with the visual levels for three different collapsed water levels, as shown in **Fig. 2**. The relative two-phase mixture level is defined as the ratio of the measured level to the collapsed water level. The results of the ultrasonic sensor show good agreement with the visual data. The capacitance probe agrees well with the visual data in the low air flow region. However, as the gas flow is increased further, the capacitance probe begins to under-predict the level data and the differences become larger.

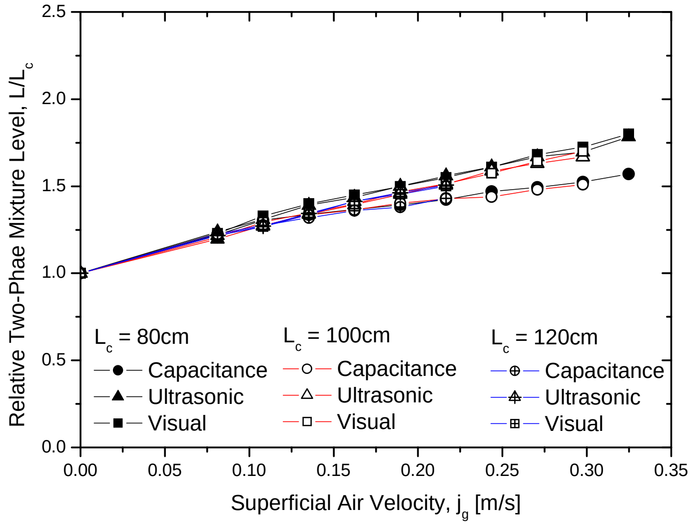

Fig.2 Measured two-phase mixture levels given superficial air velocity of the test vessel.

Figure 3 shows a comparison of the measured void fractions by the capacitance probe with the visual void fractions. When the visual void fraction is 0.44, as an example, the relative error reaches approximately 12.8%. **Figure 4** shows the void fraction measured by the ultrasonic sensor with respect to the visual void fraction. The ultrasonic sensor measured the two-phase mixture level with a maximum error of 1.77% with respect to the visual level data. These results demonstrate that the ultrasonic device could be applied to the measurement of two-phase mixture levels with surface fluctuation provided that a well-designed waveguide is used.

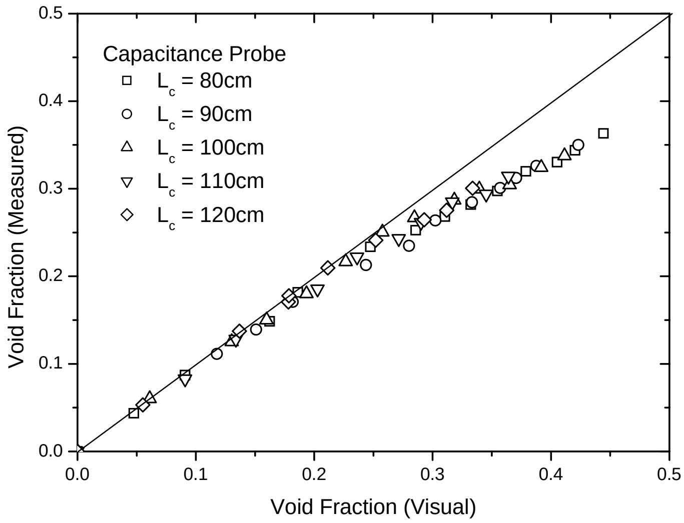

Fig.3 Comparison of the void fraction measured by the capacitance probe with the visual data.

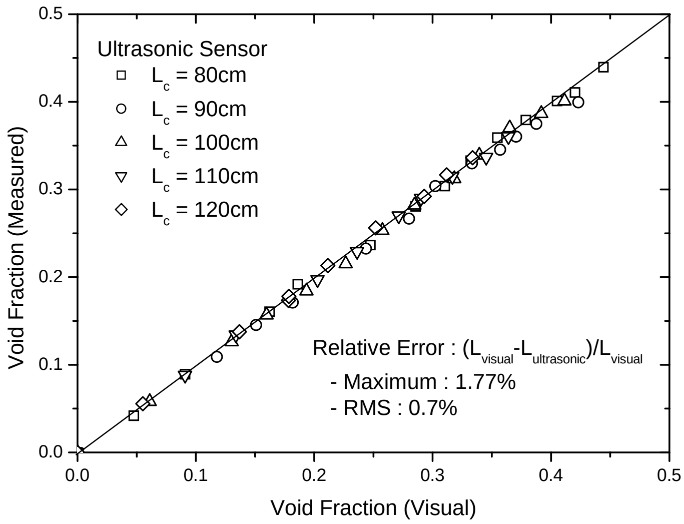

Fig.4 Comparison of the void fraction measured by the ultrasonic sensor with the visual data.

The relative two-phase mixture levels are plotted with visual void fraction as shown in **Fig. 5**. The two-phase mixture levels by the capacitance probe are not affected by the collapsed water level and are proportional to the visual void fractions. This indicates that the dielectric constant of the two-phase mixture should not be the same with that of the single-phase water and must be varied with the void fraction.

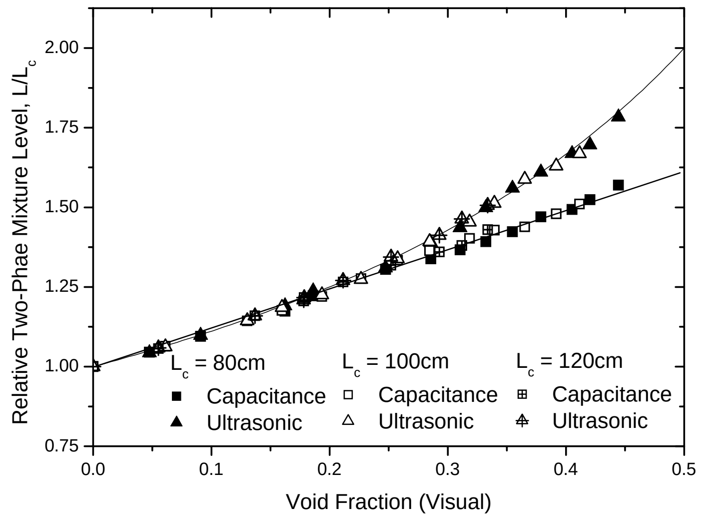

Fig.5 Measured two-phase mixture levels vs. the visual void fraction.

Figure 6 shows a case where a material is filled in the lower part of the vessel and air exists in the above the material. When the two conductors insulated are located form the bottom to the top of the vessel, the change in capacitance is expressed as follows:

$$\Delta C = A_{cp}(\varepsilon_2 - \varepsilon_1)L\,, \quad (1)$$

where ε_2 and ε_1 are dielectric constants of the material and air, respectively. The constant *A* is a geometric constant determined by the type of capacitance probe. Since *A* and (ε_2 - ε_1) are constant, the change in capacitance (ΔC) is a function of the material level (L) only. Therefore, the material level (L) can be obtained through measurement of ΔC.

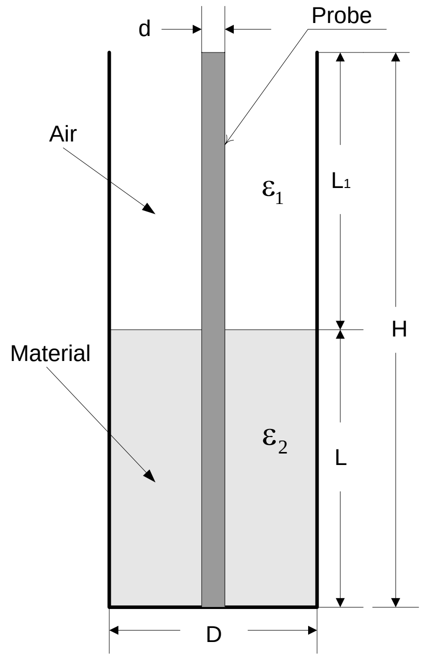

Fig.6 Measurement principle of the capacitance probe.

For the case where the material filled between the two tubes of the capacitance probe in the lower part of the vessel is a two-phase mixture of air and water, the dielectric constant of the two-phase mixture is dependent on the void fraction and will be lower than that of single-phase water. However, the dielectric constant of single-phase water is used in the two-phase mixture level measurements because the capacitance probe is calibrated in the single-phase condition. This may explain why the capacitance probe under-predicts the visual data in the high void fraction region. As the dielectric constant of the water is much larger than that of air, the variation of the dielectric constant is small and negligible in the low void fraction region. However, the variation of the dielectric constant cannot be negligible in the high void fraction region. **Figure 7** shows the variation of the ratio of the dielectric constants of the two-phase mixture to those of the single-phase water. The ratio is not unity and decreases as the void fraction becomes larger.

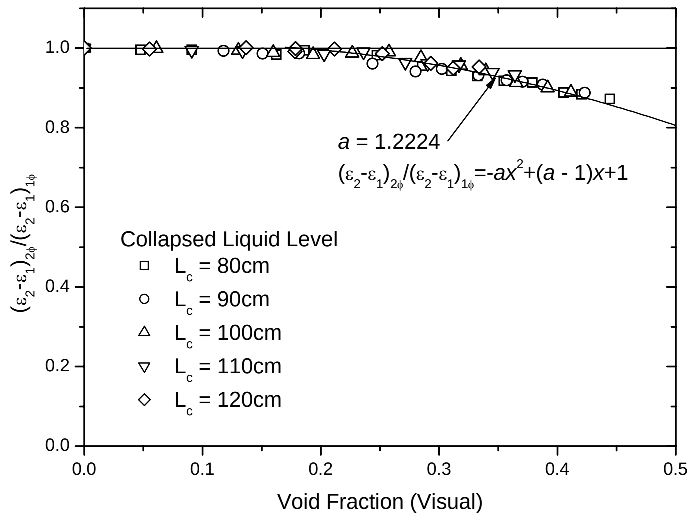

Fig.7 The ratio of the dielectric constants of two-phase mixture to those of single-phase water.

We need to correct the dielectric constant of the two-phase mixture when a capacitance probe calibrated in a single-phase liquid is used in the measurement of the two-phase mixture level. Therfore, the dielectric constant of a two-phase mixture and air, $(\varepsilon_2 - \varepsilon_1)_{2\phi}$, should be adjusted such that L_{cp} is the same as the real two-phase level, $L_{2\phi}$:

$$(\varepsilon_2 - \varepsilon_1)_{2\phi} = f(\alpha)(\varepsilon_2 - \varepsilon_1)_{1\phi} \tag{2}$$

where

$$\Delta C = A_{cp} f(\alpha)(\varepsilon_2 - \varepsilon_1)_{1\phi} L_{cp} = A_{cp}(\varepsilon_2 - \varepsilon_1)_{2\phi} L_{2\phi}\,. \tag{3}$$

In the ideal case, the ratio $(\varepsilon_2 - \varepsilon_1)_{2\phi}/(\varepsilon_2 - \varepsilon_1)_{1\phi}$ should be 1 and 0 when $\alpha_{2\phi}$ = 0.0 and 1.0, respectively. Also, we assume that the ratio depends only on the void fraction:

$$\frac{(\varepsilon_2 - \varepsilon_1)_{2\phi}}{(\varepsilon_2 - \varepsilon_1)_{1\phi}} = f(\alpha) = -a\alpha^2 + (a-1)\alpha + 1\,. \tag{4}$$

In the present experiment, the ratio $(\varepsilon_2 - \varepsilon_1)_{2\phi}/(\varepsilon_2 - \varepsilon_1)_{1\phi}$ is best fitted with the experimental data when a = 1.2224, as shown in **Fig. 7**. These values are considered reasonable as we cannot find detailed information about the design parameters of a commercial capacitance level transmitter. **Figure 8** shows a comparison of the corrected void fractions with the visual void fractions. The corrected void fractions agree with the visual data with a r.m.s error of 5.4%.

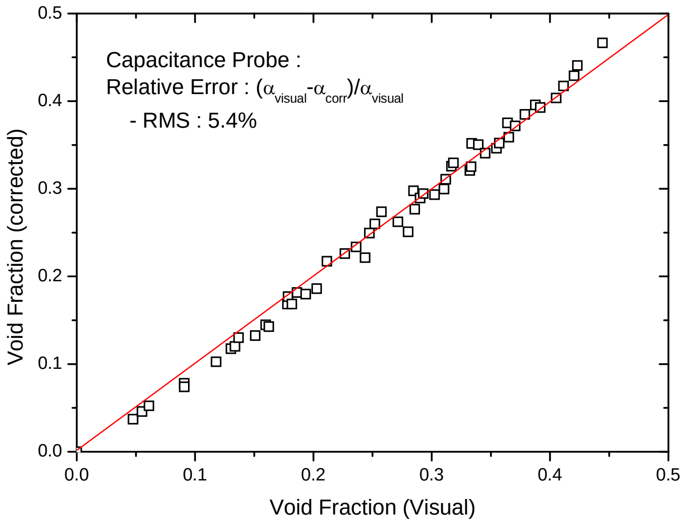

Fig.8 Comparison of the corrected void fraction with the visual void fraction.

Table 1. The existing pool void fraction correlations based on drift flux model

Authors	C_0	C_1
Zuber-Findlay [6]	1.2	1.41
Kataoka-Ishii [7]	$1.2-0.2\sqrt{\frac{\rho_g}{\rho_f}}$	$0.030\left(\frac{\rho_g}{\rho_f}\right)^{-0.157} N_{\mu f}^{-0.562}$ $(D^* > 30)$
Boesmans-Berghmans [8]	1.2	$F_{ci}\left[1.373+0.177\left(\frac{\rho_g}{\rho_f}\right)^{-0.25}\right]$
Rouhani [9] (RELAP5/MOD3.3 and MARS 2.1)	$C_\infty-(C_\infty-1)\sqrt{\frac{\rho_g}{\rho_f}}$ where $C_\infty=1+0.2\sqrt{\frac{\rho_f(gD)^{1/2}}{\lvert G\rvert+0.001}}$	- For $j_g^+ < 0.5$, Use Zuber-Findaly - For $j_g^+ > 1.768$, Use Kataoka-Ishii - For $0.5 < j_g^+ < 1.768$, linear interpolation between is used between the two correlations

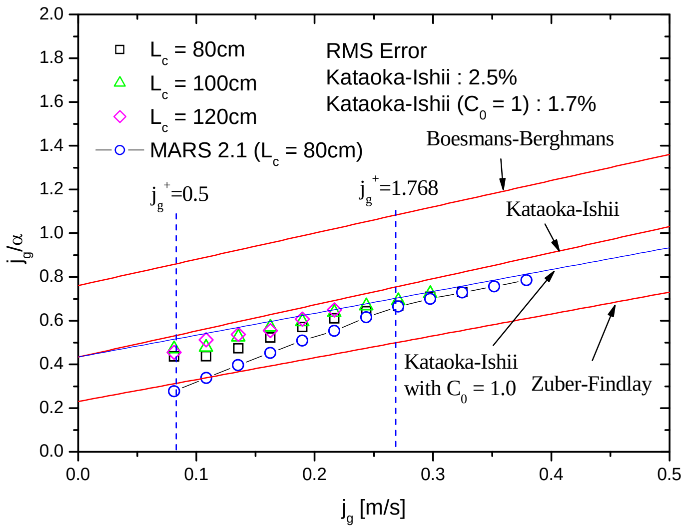

Fig.9 Comparison of the experimental data with the existing pool void fraction correlations.

The present void fraction data are compared with the exiting pool void fraction correlations based on the drift flux model as shown in **Fig.9**. The drift flux formulation for the void fraction can be represented as the following form

$$\alpha = \frac{j_g}{C_0 j_g + u_{gj}}, \tag{5}$$

where

$$u_{gj} = C_1 \left[\frac{\sigma g \Delta\rho}{\rho_f^2} \right]^{1/4} \tag{6}$$

and the coefficients of C_0 and C_1 are dependent upon the flow pattern and determined experimentally.as summarized in **Table 1**. The experimental data and the existing correlations are plotted in a domain of j_g/α and j_g as shown in **Fig.9**. The Kataoka-Ishii correlation [7] shows the best agreement with the present experimental data with an r.m.s. error of 2.5%. The Boesmans-Berghmans [8] correlation, which considered the liquid circulation effect, does not agree with the present data. Therefore, it can be considered that the liquid circulation effect should be not dominant in the present experimental conditions. The radial air flow distribution could be considered as nearly uniform because the Kataoka-Ishii correlation with C_0 = 1.0 shows better agreement with the present data than the original Kataoka-Ishii correlation in which C_0 is slightly lower than 1.2 in the present experimental conditions. According to MARS 2.1 code, almost present experimental data belong to the intermediate regime between the churn-turbulent bubbly flow and the churn-turbulent flow. The MARS results are very similar to the present experimental data when j_g^+ is higher than 1.768. However, MARS code over-predicts the present void fraction data when j_g^+ is lower than 1.768 since linear interpolation is used between Zuber-Findlay [6] and Kataoka-Ishii [7] correlations with the coefficients proposed by Rouhani [9].

IV. Conclusions

We performed a comparison of two-phase mixture levels measured by an ultrasonic sensor and a two-wire type capacitance probe with visual data under the same experimental conditions. A series of experiments are performed with various combinations of airflow and initial water level using a test vessel with a height of 2m and an inner diameter of 0.3m. From the present experimental studies, the following conclusions can be drawn.

First, the ultrasonic sensor measured the two-phase mixture level with a maximum error of 1.77% with respect to the visual level data in the present experiment. The ultrasonic method measures the two-phase mixture level more accurately than the conventional methods under conditions of surface fluctuation provided that a well-designed waveguide is applied.

Second, the capacitance probe severely under-predicted the level data in the high void fraction region. The cause of the error is identified as the change of the dielectric constant when the probe is applied to the measurement of the two-phase mixture levels. A correction method for the capacitance probe is proposed by correcting the change of the dielectric constant of the two-phase mixture. The correction method for the capacitance probe produces a r.m.s. error of 5.4%.

Third, the present experimental data are compared with the existing pool void fraction correlations based on drift-flux model. The Kataoka-Ishii correlation has the best agreement with the present experimental data with an r.m.s. error of 2.5%.

Nomenclature

C_0	distribution parameter
ΔC	change in capacitance in the capacitance probe
D	inner diameter of the test vessel
D^*	Bond number, $D\left[\dfrac{g\Delta\rho}{\sigma}\right]^{1/2}$
F_{ci}	liquid circulation factor (The authors recommended F_{ci} = 2.0.)
H	height of the test vessel
j_g	superficial velocity of air
j_g^+	non-dimensional superficial velocity, $j_g \Big/ \left[\dfrac{\sigma g\Delta\rho}{\rho_f^2}\right]^{1/4}$
L	level
$N_{\mu f}$	viscosity number, $\mu_f \Big/ \sqrt{\rho_f \sigma \left[\dfrac{\sigma}{g\Delta\rho}\right]^{1/2}}$
u_{gj}	drift velocity

Greek

α	void fraction
ε	dielectric constant of a material

Subscript

1	a material of which level is to be measured
2	air
1ϕ	single-phase
2ϕ	two-phase
cp	capacitance probe
c	collapsed liquid

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