Experimental Investigation of Rod Pitch Effect on Void Fraction in 5 x 5 Rod-bundle under Elevated Pressure Conditions

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Highlights
- Rod-bundle two-phase flow experiments were performed at prototypic BWR conditions.
- Test sections with different rod pitch lengths was used for the present experiment.
- 3D X-ray CT System was developed for the void fraction measurement
- The effect of the void fraction behaviors for different rod pitch-length is discussed.
- Drift-flux correlations applicable for rod-bundle test sections are discussed.

ABSTRACT
In the present study, void fraction distributions in 5x5 rod-bundle test sections were investigated. Two different rod-bundle test sections with different rod pitch lengths were constructed. Experiments were carried out using unheated rod-bundle test sections equipped with 10 mm rod diameter with rod-pitch lengths of 13 and 12 mm, respectively. The HUSTLE (Hitachi Utility Steam Test Leading Facility) facility supplied steam and water with an inlet mass flux (G) ranging from 75 to 500 kg/m²/s at 5.0 to 7.5 MPa system pressure. These inlet and boundary conditions simulate the prototypic BWR at natural circulation conditions. For the measurement of void fraction, the X-ray CT system was newly developed for the three-dimensional time-averaged void fraction measurement, and 3D void fraction distributions were successfully obtained for various pressure conditions. The volume-averaged void fraction was also measured using differential pressure transmitters. Based on the newly developed void fraction database, the assessment was carried out using state-of-the-art drift-flux correlations applicable for rod-bundle. Existing correlations tend to show good void fraction prediction at high mass flux conditions for both geometries, poorer performance was shown for the narrow rod test sections with low mass flux.
conditions. Furthermore, the effect of the rod-pitch lengths on void fraction distribution in rod-bundle flow field was assessed. It was observed that narrower rod bundle configuration tends to have higher void fraction at given mass flux. Narrowed pitch-length enhances wall-friction against two-phase flow, which likely suppress the central phase fraction peak tendency. This promotes lower distribution parameter values, results in increased area-averaged void fraction for narrower pitch test section. However, the present study revealed that no existing correlations could clearly capture the void fraction trend for the narrow rod test section.

**Keywords:** Rod bundle, Tight-lattice, Void fraction, Drift-flux model, X-ray CT system

1. Introduction

In case of the loss of coolant accident (LOCA) scenarios in boiling water reactor (BWR) facilities, near pool boiling conditions may occur within the fuel assembly due to the presence of decay heat. In order to assess the cooling capability and safety margin of the reactor core, the predictive capability of void fraction values at such conditions is crucial to determine critical parameters such as two-phase water mixture level and so on. However, the experimental database under low flow conditions is minimal for the rod-bundle geometry operated under steam-water two-phase flow.

Anklam and Miller performed boiling experiments in an 8 × 8 rod bundle under high-pressure conditions (3.9 - 8.1MPa) for pool conditions and low flow rate conditions [1]. In their study, the volume averaged void fraction was measured using a differential pressure transducer, and the mixture level-swell was quantitatively evaluated. It was reported that, at a condition of low heat and mass flux, constant drift-velocity without void fraction dependency was observed. However, in their analysis, thermal equilibrium assumptions were adopted to calculate the superficial gas and liquid velocities, and it may introduce non-negligible uncertainties in flow rate
measurements. Qazi et al. performed pool boiling experiments in a $2 \times 2$ rod bundle geometry embraced by a circular casing under atmospheric pressure condition [2]. Axial void fraction distribution was investigated using the heated rod bundle test section. It was shown that the existing drift-flux models, including Zuber-Findlay [3] and Chexal-Lellouche [4] correlations, could not predict the void distribution under pool conditions. Clark et al. investigated the rod-bundle two-phase flow under low pressure and low liquid flow conditions to assess the effect of recirculating flow patterns in the casing, which is considered as a large flow channel [5]. It was pointed out that the subchannel hydraulic diameter and rod-bundle casing width are the two key characteristic length scales. The two-phase flow experiment was carried out using $8 \times 8$ rod bundle test facility under atmospheric pressure conditions. The recirculating flow pattern was generated by both the downward mass flux at the periphery of the flow channel and the upward mass flux at the central region. From the obtained database, both the distribution parameter and drift velocity showed increasing trend under the recirculating flow condition. A new drift-flux correlation accounting for such effect was developed, which incorporates the drift velocity correlation by Hibiki and Ishii (2003) [6], and the distribution parameter, which newly includes the concept of a critical void fraction to account for the recirculation. Kinoshita et al. (2019)[17], later, extended the correlation developed by Clark et al. by taking account the pressure scaling effect for the $8 \times 8$ rod bundle test section at low pressure and low flow rate conditions.

Given the studies mentioned above and associated thermal-hydraulic issues in rod-bundle geometries, the present study aims to develop the database for steam-water two-phase flow in the $5 \times 5$ test section at prototypic BWR conditions simulating the boil-off phenomenon, which basically is a reactor core uncover via decrease in mixture level due to the small break loss-of-coolant-accident. An experiment was performed using multi-purpose steam-water test facility
called HUSTLE (Hitachi Utility Steam Test Leading facility) to measure void fraction distribution using the three-dimensional time-averaged X-ray CT system in two unheated $5 \times 5$ rod bundle test sections. These two rod-bundle test sections are comprised of 10 mm outer diameter at different pitch lengths of 12 mm and 13 mm, respectively. The steam and water were supplied at a total mass flux lower than 500 kg/m²/s, which simulates the natural circulation mass flux rate of BWRs. Operational pressure was set at a range of 5.0 to 7.5 MPa(abs), also simulating the prototypic conditions.

2. Experiment

2.1. Experimental Facility

The schematic of the experimental facility, including HUSTLE, is depicted in Fig. 1. As can be seen, the HUSTLE is equipped with a steam loop with a compressor, with a rated operation pressure of 7.2 MPa and maximum steam and water flow rates of 70 tons/hour and 160 tons/hour, respectively. By utilizing the steam condenser and the water inventory control line, steam dome pressure and pressure vessel water level can be maintained at the desired value.

The steam and water were separately injected to the test section from the HUSTLE loop. The steam-water two-phase flow was formed in the mixing section and then flowed upwardly through the test section. The two-phase mixture is then returned to the HUSTLE’s steam dome. In order to minimize the heat loss, water was supplied to the casing surrounding during the experiment, as shown in Fig. 2.

2.2. Test section

Schematic and the specification of the reference and narrow pitch $5 \times 5$ rod-bundle test sections are shown in Fig. 2 and Table 1, respectively. Dimensions of these test sections were
determined from the actual 9x9 and 10x10 BWR fuel assemblies. The 10 mm outer diameter rod was utilized, and these rods were set at two different pitch lengths of 13 mm and 12 mm for reference and narrow pitch test sections. Hydraulic equivalent diameters are 12 mm, and 8 mm, respectively. The rod-bundle assembly is supported at the lower tie-plate and grid-spacers. The reference pitch test section's hydraulic equivalent diameter was set approximately equivalent to that of 10 x 10 BWR fuel assembly. For the grid-spacer, a ferrule-type spacer was utilized to minimize flow disturbances. Square channel boxes were designed as 68 mm x 68 mm, and 62 mm x 62 mm dimensions for reference-pitch and narrow-pitch test sections, respectively. Titanium was utilized for the test section material to minimize the X-ray attenuation for the void fraction distribution measurement.

2.3. Measurement method and accuracy

For the void fraction measurement, both the 3D time-averaged X-ray computed tomography (CT) system and differential pressure transducer were utilized in the present study. The CT is a non-intrusive method to measure the time-averaged phase distribution across a test section at a given axial coordinate. By modifying the medical X-ray CT scanners and adopting cone-beam tomography method for prototypic BWR thermal-hydraulic conditions, the 3D time-averaged X-ray CT system was successfully implemented at Hitachi [7-10]. Fig. 3 depicts the pictorial view and a schematic of the X-ray CT system, equipped with an X-ray tube and a flat panel detector (FPD). A detailed specification of the measurement system is tabulated in Table 2 [11].
On the rotational device, the X-ray tube and the FPD were mounted, and the rod-bundle test section was placed in between them. As the X-ray tube and the FPD rotates around the test section, the attenuated X-ray beam passing through the test section was detected by the FPD. As a result, the system is capable of measuring test section’s projection data from all angles. To account for the unsteady feature of two-phase flow, X-ray CT measurement was repeated multiple times to obtain averaged projection data [8-10]. This superposition technique also reduces the deviation in CT-value due to the X-ray energy variation. By reconstructing the projection data, the distribution of the linear attenuation coefficient was obtained. For reconstructing the projected data, the filtered back-projection technique, commonly utilized in the nuclear medicine field, was adopted in the present study.

The CT value of the reconstruction element \((i, j, k)\), \(CT_{ijk}\), was calculated by,

\[
CT_{ijk} = a \mu_{ijk} + b .
\]

(1)

Here, \(\mu_{ijk}\), \(a\), and \(b\) represent the attenuation coefficient \((i, j, k)\), and empirical constants, respectively. By utilizing the attenuation coefficient values of pure liquid \((\mu_f)\) and gas \((\mu_g)\), the attenuation coefficient of the two-phase mixture and void fraction can be expressed as,

\[
\mu_{ijk} = \left(1 - \alpha_{ijk}\right) \mu_f + \alpha_{ijk} \mu_g .
\]

(2)

By combining the above two relations, the void fraction can be obtained using \(CT_{ijk}\).

\[
\alpha_{ijk} = \frac{\mu_{ijk} - \mu_f}{\mu_g - \mu_f} = \frac{CT_{ijk} - CT_f}{CT_g - CT_f}
\]

(3)

Here, \(CT_f\) and \(CT_g\) represent the CT-values of water and steam, respectively. These values were evaluated through the CT images obtained under water-only and steam-only conditions. Thus, based on three different CT images of fully-liquid, fully-steam, and two-phase mixture, void fraction value in the rod-bundle geometry was calculated.
In addition, differential pressure transducer was utilized to measure the volume-averaged void fraction in the present study. The water taps were connected along the axis of the channel box, as shown in Fig. 2. From the measured differential pressure value ($\Delta P$), the volume-averaged void fraction ($<\alpha_{\text{DP}}>$) was evaluated using the following relation:

$$<\alpha_{\text{DP}}>_V = \frac{\Delta P - \Delta P_F - \Delta P_{\text{Spacer}}}{(\rho_f - \rho_g) g H}.$$  

Here, $\Delta P_F$, $\Delta P_{\text{Spacer}}$, $g$, $H$ are the frictional pressure drop, pressure loss due to spacer grid, gravitational acceleration, and the measurement length. Lockhart-Martinelli’s method was utilized to evaluate two-phase multiplier for the frictional pressure drop. For the pressure drop due to the spacer grid, $\Delta P_{\text{Spacer}}$, it was empirically determined from the single-phase flow experiment.

Comparisons of the volume-averaged void fraction measurement using the X-ray CT Scan ($<\alpha_{\text{X-CT}}>_V$) and the differential pressure transmitter ($<\alpha_{\text{DP}}>_V$) are depicted in Figs. 4 and 5 for both reference-pitch and narrow-pitch test sections. They were compared at 5.0, 7.0, and 7.5 MPa pressure values under stagnant water, natural circulation, and low flow rate conditions. The overall agreement between the two measurement methods is reasonable. However, a relatively larger deviation was observed at the low void fraction region ($\alpha < 0.2$). Since the accurate pressure drop measurement using the DP-transducer at low void fraction range involves relatively larger uncertainties, the larger scatters appear in Figs. 4 and 5. Due to the non-negligible uncertainties in void fraction measurement less than 20 % in the present system, only the data collected at the void fraction greater than 20 % will be considered for the present analysis. This treatment also eliminates possible uncertainties arise by the effect of subcooled boiling flow. As pointed out by Hibiki et al. [11], the distribution parameter in diabatic two-phase flow system is usually impacted by subcooled boiling effect in the void fraction range of $\alpha = 0 \sim 0.2$. Beyond this range, the wall
nucleation effect is suppressed, and overall flow characteristics of the saturated boiling flow resembles adiabatic two-phase flow characteristics, which has been validated by various database in the past [12]. In the present HUSTLE facility, the steam-water mixture was supplied to the test section externally under thermal-equilibrium state, which cannot simulate the subcooled boiling flow condition. Thus, consideration of void fraction data larger than 20 % is suitable to study the saturated boiling flow characteristics in tight-lattice rod-bundle geometry.

2.4. Experimental conditions

With the void fraction measurement methods introduced in the previous section, the rod-bundle two-phase flow experiments were conducted for both reference-pitch and narrow-pitch test sections. The operating pressures were set to 7.0 MPa to simulate the prototypic BWR conditions. Three different mass fluxes \( G \), namely, 75, 150, and 500 kg/m\(^2\)/s, were selected for the inlet conditions. Fig. 6 depicts the present test conditions plotted on the \( \alpha - G \) flow regime map utilized in the reactor safety analysis code, TRACE. As can be seen, the present test conditions range from dispersed bubble, cap/slug bubble, and interpolation region, respectively. Majority of the present database falls into cap/slug bubble flow regime and the interpolation region of annular-mist flow, which can be considered as a churn-turbulent flow regime. Some narrow rod datasets are close to annular-mist flow regime. In case of the flow condition close to annular-mist two-phase flow, utilization of dispersed two-phase flow model may induce nonnegligible error. Thus, ideally, the void fraction prediction model in that flow regime should be treated with separated flow model. Additional experimental datasets were obtained for the pressure condition at 2.0 MPa for the comparison purpose, where its results will be introduced in a subsequent section.
3. Drift-flux correlations

The drift velocity concept, which considers the effect of the relative velocity between two-phases in the two-phase flow system, was first introduced by Zuber and Findlay [3]. Here, the drift velocity \( v_{\text{gj}} \) is expressed as,

\[
v_{\text{gj}} \equiv v_g - j,
\]

where \( v_g \) and \( j \) are the gas velocity and mixture volumetric flux given by the summation of superficial gas and liquid velocities \( j_g \) and \( j_l \), respectively. For the channel flow analysis, a common approach is to utilize it in an one-dimensional form by taking the area-average, which yields,

\[
\langle \langle v_g \rangle \rangle = \frac{\langle j_g \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + \langle \langle v_{\text{gj}} \rangle \rangle.
\]

Here, \( C_0 \) and \( \langle \langle v_{\text{gj}} \rangle \rangle \) are defined as the distribution parameter and void fraction weighted mean-drift velocity. They are defined as:

\[
C_0 \equiv \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle},
\]

\[
\langle \langle v_{\text{gj}} \rangle \rangle \equiv \frac{\langle \alpha v_{\text{gj}} \rangle}{\langle \alpha \rangle}.
\]

Hereafter, void fraction weighted mean-drift velocity will be called “drift velocity”, for simplicity. In order to close the Eq. (6), the constitutive equations for the distribution parameter and drift velocity need to be given. In practice, different drift-flux correlations are utilized in reactor safety codes [13]. Here, some of the existing drift-flux correlations, which model the distribution parameter and drift velocity, utilized in the nuclear thermal-hydraulics analysis, will be introduced in the following section.
3.1. Ishii correlation

By extending the original work for Zuber and Findlay [3], Ishii [14] developed a drift-flux correlation for two-phase flow in medium-size vertical channels. As shown in Eq. (9), the distribution parameter was formulated as a function of \( C_\infty \) and density ratio, and it was assumed that the \( C_0 \) approaches unity as \( \rho_g/\rho_f \) approaches unity as well.

\[
C_0 = C_\infty - (C_\infty - 1) \frac{\rho_g}{\rho_f} \tag{9}
\]

Here, \( C_\infty \) represents the asymptotic value of the distribution parameter. The \( C_0 \) is empirically determined for upward adiabatic two-phase flow in a circular pipe or rectangular channels using Eq. (10).

\[
C_0 = \begin{cases} 
1.20 - 0.20 \sqrt{\frac{\rho_g}{\rho_f}} & : \text{circular pipe,} \\
1.35 - 0.35 \sqrt{\frac{\rho_g}{\rho_f}} & : \text{rectangular channel.}
\end{cases} \tag{10}
\]

Ishii also developed a modified correlation to account for the void profile development in the subcooled boiling flow by including an exponential function.

\[
C_0 = \begin{cases} 
1.20 - 0.20 \left( \frac{\rho_g}{\rho_f} \right) \left( 1 - e^{-18(\alpha)} \right) & : \text{circular pipe,} \\
1.35 - 0.35 \left( \frac{\rho_g}{\rho_f} \right) \left( 1 - e^{-18(\alpha)} \right) & : \text{rectangular channel.}
\end{cases} \tag{11}
\]

As can be seen from the formulation, as the void fraction approaches zero, the distribution parameter also approaches zero, which is physically plausible.
For the drift velocity correlations, they are modeled by adopting the drag law. Depending on the flow regime of the flow channel, the unique drift velocity correlation is given.

Bubbly flow regime:

\[ \langle \langle v_g \rangle \rangle = \sqrt{2} \left( \frac{\sigma g \Delta \rho}{\rho_f} \right)^{0.25} (1-\langle \alpha \rangle)^{1.75}, \]  

(12)

Slug flow regime:

\[ \langle \langle v_g \rangle \rangle = 0.35 \left( \frac{\Delta \rho g D_h}{\rho_f^2} \right)^{0.5}, \]  

(13)

Churn flow regime:

\[ \langle \langle v_g \rangle \rangle = \sqrt{2} \left( \frac{\Delta \rho g \sigma}{\rho_f^2} \right)^{0.25} \]  

(14)

Annular flow regime:

\[ \overline{V_g} = \left\{ \langle \langle v_g \rangle \rangle + (C_0 - 1) \langle j \rangle \right\} \]

\[ = \frac{1 - \langle \alpha \rangle}{\langle \alpha \rangle + \left\{ \frac{1 + 75(1-\langle \alpha \rangle)}{\rho_e \sqrt{\langle \alpha \rangle}} \rho_f \right\}^{1/2}} \left\{ \langle j \rangle + \frac{\Delta \rho g D_h (1-\langle \alpha \rangle)}{0.015 \rho_f} \right\} \]  

(15)

Here, the relative velocity between the two phases is expressed by the mean transport drift velocity \( \overline{V_g} \). In the present analysis, Ishii’s churn flow regime model is utilized for the analysis.

3.2. Bestion correlation

A drift-flux correlation utilized for the thermal-hydraulic analysis code, CATHARE, was developed by Bestion [15]. It was developed from the experimental database obtained from various rod bundle test sections comprised of 12 and 24 mm hydraulic diameters. The correlation
utilizes the drift velocity term which includes the geometrical effect represented by the hydraulic diameter term. In the original literature, exact derivation of the distribution parameter was not mentioned. Still, the usage 1.0 showed the best results and is utilized as the recommended value in later studies. The Bestion’s correlation can be applied to a wide range of void fraction values.

\[ C_0 = 1.0 \] (16)

The drift velocity term is calculated as,

\[ \left\langle \frac{\nu_x}{g} \right\rangle = 0.188 \sqrt{\frac{gD_H \Delta \rho}{\rho_g}}. \] (17)

Here, \( D_H \) is the hydraulic diameter of the rod-bundle flow channel.

3.3. Rouhani correlation

Rouhani [16] proposed the correlation for the distribution parameter, which is now utilized in the reactor system analysis code, TRAC-BF1/ MOD1. The correlation is applicable for flow conditions ranging from bubbly to churn-turbulent flow. As can be seen from Eq. (18), it is expressed as a function of mass flow rate, instead of a density ratio.

\[ C_\infty = 1.0 + 0.2 \left( \frac{\rho_f}{G} \frac{\sqrt{gD_H}}{1/2} \right) \] (18)

The distribution parameter is then calculated by substituting it to the original definition of \( C_0 \).

\[ C_0 = C_\infty - (C_\infty - 1) \sqrt{\frac{\rho_g}{\rho_f}} \] (11)

For the drift velocity, Bestion’s correlation introduced in a previous section is utilized in the TRAC-BF1/ MOD1 code.

3.4. Ozaki-Hibiki correlation
The drift-flux correlation developed by Ozaki and Hibiki [17] is based on the experimental data collected under prototypic pressure and temperature conditions for upward boiling two-phase flow in an 8×8 rod bundle. The correlation is validated up to the void fraction value of 0.87 using the existing experimental database obtained at FRIGG and NUPEC test facilities. In Ozaki-Hibiki correlation, the drift flux correlations are defined as:

\[
C_0 = 1.1 - 0.1 \sqrt{\frac{\rho_g}{\rho_f}}, \quad (19)
\]

\[
V_{gj}^+ = V_{gj,B}^+ \exp(-1.39 \langle j_g^+ \rangle) + V_{gj,P}^+ \{1 - \exp(-1.39 \langle j_g^+ \rangle)\}. \quad (20)
\]

Here, + sign indicates non-dimensional variables, and the dimensionless drift velocity and superficial gas velocity are defined as follows.

\[
V_{gj}^+ = \left( \frac{\langle v_g \rangle}{\Delta \rho g \sigma / \rho_f^2} \right)^{0.25}, \quad (21)
\]

\[
\langle j_g^+ \rangle = \left( \frac{\langle j_g \rangle}{\Delta \rho g \sigma / \rho_f^2} \right)^{0.25}. \quad (22)
\]

The subscripts \(B\) represents the drift velocity correlation for bubbly flow regime proposed by Ishii [14]. The dimensionless form of the drift velocity in bubbly flows is given by:

\[
V_{gj,B}^+ = \sqrt{2} \left(1 - \langle \alpha \rangle \right)^{1.75}. \quad (23)
\]

Likewise, the subscript \(P\) represents the drift velocity correlations proposed by Kataoka-Ishii [18], which is applicable to a large-diameter channel at pool conditions. The correlation is divided into two formulations depending on the channel size.
\[ V_{gj,p}^+ = 0.0019 \left( D_H^* \right)^{0.809} \left( \frac{\rho_g}{\rho_f} \right)^{-0.157} N_{\mu_f}^{-0.562} \quad \text{for} \quad D_H^* \leq 30, \quad (24) \]

\[ V_{gj,p}^+ = 0.030 \left( \frac{\rho_g}{\rho_f} \right)^{-0.157} N_{\mu_f}^{-0.562} \quad \text{for} \quad D_H^* \geq 30. \quad (25) \]

The above correlations are valid for low viscous flow conditions, characterized by the viscous number defined in the following relation.

\[ N_{\mu_f} = \frac{\mu_f}{\rho_f \sigma \sqrt{\frac{\sigma}{g\Delta\rho}}}^{0.5}. \quad (26) \]

The dimensionless hydraulic equivalent diameter is expressed as:

\[ D_H^* = \frac{D_H}{\sqrt{\frac{\sigma}{g\Delta\rho}}}. \quad (27) \]

For the high viscous fluid case \((N_{\mu} > 2.25 \times 10^{-3})\), Kataoka-Ishii gives the dimensionless drift velocity as,

\[ V_{gj,p}^+ = 0.92 \left( \frac{\rho_g}{\rho_f} \right)^{-0.157} \quad \text{for} \quad D_H^* \geq 30 \quad (28) \]

3.5. Clark correlation

Clark et al [5]. conducted an experiment with adiabatic pressure at low flow rate conditions using an 8 x 8 rod-bundle test facility. The new drift-flux correlation was developed to bridge the conditions considered by high pressure and low-pressure pool flow conditions [19]. High distribution parameter values were observed at low flow conditions due to the recirculation effect. Such trend was included in their newly defined \(C_{\infty}\) as,
\[ C_\infty = \begin{cases} C_{\infty L} & \text{for } \langle j^+ \rangle \leq \langle j^+ \rangle_{C_{\infty \max}}, \\ C_{\infty H} & \text{for } \langle j^+ \rangle > \langle j^+ \rangle_{C_{\infty \max}}, \end{cases} \]

(29)

where \( C_{\infty H} \) and \( C_{\infty L} \) are given by:

\[ C_{\infty H} = 1.1 + 1.84 \exp(-0.1 \langle j^+ \rangle), \]

(30)

\[ C_{\infty L} = \frac{C_{\infty H} \left( \frac{\langle j^+ \rangle}{\langle j^+ \rangle_{C_{\infty \max}}} \right)^{-1} - 1}{\langle j^+ \rangle_{C_{\infty \max}} - \langle j_f \rangle} \langle j^+_g \rangle + 1, \]

(31)

\[ \langle j^+ \rangle_{C_{\infty \max}} = m \langle j_f^+ \rangle + b, \]

(32)

\[ m = \frac{1}{1 - \langle \alpha \rangle_{\text{crit}} C_0}, \]

(33)

\[ b = \frac{\langle V^+ \rangle_{\text{crit}} \langle \alpha \rangle_{\text{crit}}}{1 - \langle \alpha \rangle_{\text{crit}} C_0}, \]

(34)

\[ \langle \alpha \rangle_{\text{crit}} = \min \left(0.0284 \langle j_f^+ \rangle + 0.125, 0.52\right), \]

(35)

3.6. INSS correlation

Kinoshita et al. [20] extended Clark et al.’s drift-flux correlation using the pressure scaling methodology. It therefore bridges between the Clark et al. correlation at low pressure conditions and the high-pressure correlation by Ozaki-Hibiki. The \( C_{\infty H} \) was modified by multiplying the pressure scaling factor, \( F \), which is defined follows:

\[ C_{\infty H} = 1.1 + \left(1.84 \exp(-0.1 \langle j^+ \rangle)\right) \cdot F, \]

(36)

\[ F = \min \left\{ 
\begin{array}{c}
1 \\
\frac{1.70 - 582 \left( \frac{\rho_g}{\rho_f} \right)}{\max}
\end{array}
\right\}. \]

(37)
For the drift velocity, the Eq. (20) is used. The validity of the modified pressure scaling has been confirmed by benchmarking the database collected at Purdue University and ORNL. For the present analysis, this correlation will be referred as an INSS correlation.

4. Results and discussions

4.1. Three-dimensional void fraction distribution

Three-dimensional time-averaged void distributions in the 5x5 rod bundle test section measured by the X-ray CT system ranging from atmospheric pressure to 7.5 MPa are depicted in Figs. 7 and 8. It can be observed from the plot that the higher void region was concentrated in the test sections’ central area in all the experimental conditions. The lowest void fraction was observed at the channel-box corners and near-wall regions. As the total mass flux increases, void fraction difference between central region and near-wall region tends to be more prominent. Effect of the system pressure change on void fraction distributions in the reference-pitch geometry at a fixed steam mass flux of 20 kg/m²/s, is depicted in Fig. 7. No notable differences in the distribution were observed in between 5.0 to 7.5 MPa, and a similar trend was observed for the narrow-pitch rod test section (Fig. 8). Compared to the reference-pitch test section though, the void fraction difference between the central and channel-corner region is slightly diminished with narrower pitch-length and elevated pressure. From this point of view, a narrow rod-pitch design may distribute the gas void evenly across the channel at high pressure conditions ($P > 5.0$ MPa).

In order to analyze the trend, local void fraction distributions measured by the X-ray CT system for both reference-pitch and narrow-pitch test sections were compared in axial direction and the results are illustrated in Fig. 9. As can be seen, void fraction distributions at subchannels tends to differ for narrower pitch, where flatter void distribution is observed. This may be due to
the influence of the narrowed wall boundary, which acts as frictional resistance against upward flow. When more bubbles are concentrated in the subchannel center, cross-sectional averaged void fraction of the flow channel tends to be larger, as was the case for the narrow pitch-length test section. In contrast, the steam flowed upward easily at the sub-channel center region at the reference-pitch rod bundle because the distance between the rods was much larger. Steam gathers at the center part of the flow channel and flows upward at higher velocity, which reduces the cross-sectional averaged void fraction of the flow path. Due to these factors, void fractions in a narrow-pitch rod bundle were found to be larger than those in the reference-pitch geometry.

4.2. Evaluation of existing drift-flux correlations with data

The six drift-flux correlations introduced in a previous section are assessed with datasets obtained for reference-pitch and narrow-pitch test sections for three different mass flux. Change in void fraction with respect to the quality value for both test sections at operating pressures 2.0 MPa and 7.0 MPa are depicted in Figs. 10 and 11, respectively. Here, results from reference-pitch test section are shown on the left-hand side column with solid circle data points, and narrow-pitch test section on the right-hand side with open circle data points. As can be seen, increasing trend of void fraction tends to differ for different mass fluxes and rod pitch lengths.

For the prototypic pressure condition of 7.0 MPa, existing correlations tend to capture the trend well especially by Ozaki and Hibiki [17] and INSS [20] correlations for reference-pitch test section. These correlations were validated with NUPEC 8x8 square-array rod-bundle test data under prototypic operating conditions with the upper limit of the void fraction of 0.87. As was mentioned in Section 3.6, since these two correlations tend to overlap with one another with respect to pressure, lines representing these two correlations in Fig. 10 are overlapping as quality reaches 0.1 or above. INSS [20] correlation is an extended version of Clark et al. (2014) with pressure scaling
factor, and it can be observed that it is applicable for prototypic pressure condition of 7.0 MPa. However, for narrow rod experimental results, some data points tend to divert from the correlation. Thus, one of the possible conclusions could be that, narrow pitch-length in rod-bundle geometry tends to induce difference in flow characteristics at lower mass flux conditions \((G = 75, 150 \text{ kg/m}^2/\text{s})\). Such characteristics become prominent with lower pressure, as can be confirmed from Fig. 11. To fully understand details, more detailed local two-phase flow parameters analysis including subchannel void fraction and interfacial area concentration should be conducted, which can serve as a future study.

To assess the predictive capability of the drift-flux correlations at a prototypic operation condition of 7.0 MPa, four statistical parameters, namely, mean error, \(m_d\), standard deviation, \(s_d\), mean relative deviation, \(m_{rel}\), and mean absolute relative deviation, \(m_{rel, ab}\), are utilized for evaluating bias and random uncertainty. The bias and random uncertainty of correlations are indicated by the mean error and standard deviation, respectively.

\[
m_d = \frac{1}{N} \sum_{i=1}^{N} \left( \langle \alpha(i)_{cal} \rangle - \langle \alpha(i)_{exp} \rangle \right),
\]

\[
s_d = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( \langle \alpha(i)_{cal} \rangle - \langle \alpha(i)_{exp} \rangle \right)^2 - m_d^2},
\]

\[
m_{rel} = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{\langle \alpha(i)_{cal} \rangle}{\langle \alpha(i)_{exp} \rangle} \right] \times 100\%,
\]

\[
m_{rel, ab} = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{\langle \alpha(i)_{cal} \rangle}{\langle \alpha(i)_{exp} \rangle} \right] \times 100\%,
\]

Here, \(N, \alpha_{cal}, \alpha_{exp}\), are the number of datasets, calculated void fraction, and measured void fraction, respectively.

Table 3 summarizes the performance evaluations of six drift-flux correlations for all databases including both reference and narrow pitch test sections at low, intermediate, and high
mass flux values at 7.0 MPa. In view of $m_d$, and $m_{rel}$ values, INSS correlation showed the best performance. Clark et al. [19] underestimated the dataset, since it was developed for low pressure and low flow rate conditions. This implies that the pressure scaling method introduced in INSS correlation with inclusion of Eq. (36) is effective for the present experimental conditions. Table 4 shows statistical performance of these correlations with respect to mass flux, $G$. As also can be confirmed from Fig. 10 void fraction prediction at intermediate to lower mass flux tends to decrease compared to $G = 500$ kg/m$^2$/s case.

For the reference-pitch geometry of low mass flux (75 kg/m$^2$/s) at 2.0 MPa pressure conditions, majority of existing drift-flux correlations tend to overestimate the data. For the narrow-pitch geometry, two correlations, namely, Ozaki and Hibiki (2015) and INSS correlations show reasonable predictive capabilities. As was mentioned in Section 3.6, since these two correlations tend to overlap with one another with respect to pressure, lines representing these two correlations in Fig. 11 are overlapping as quality reaches 0.1 or above. The INSS [20] correlation is an extended version of Clark et al. (2014) with pressure scaling factor, however, according to the results shown in Fig. 13, the pressure scaling is not quite effective to represent the 2.0 MPa pressure conditions. Further investigation may be necessary to improve the pressure scaling term represented by Eq. (37). The Clark et al. [19] correlation, which was developed for the low pressure and low flow rate flow conditions, considers the recirculatory flow pattern in the channel box. Such phenomenon induces high $C_0$ value, which results in lower averaged void fraction value. Thus, the correlation serves as a minimum averaged void fraction for the given flow rate. This was the case for both reference-pitch and narrow-pitch test sections until $G = 150$ kg/m$^2$/s. At high mass flux conditions exceeding $G = 150$ kg/m$^2$/s, existing correlations show improved performance predicting void fraction trend. This is likely that high mass flux diminishes multi-
dimensional flow behaviors caused by the presence of large-scale channel effect of the casing width. Although, further improvement in existing correlations may be necessary for 2.0 MPa condition, in case of boil-off and/or abnormally low pressure conditions, it can be concluded that Clark et al.’s correlation serves as a lower bound. For the upper bound, Ozaki and Hibiki serves as a reasonable representation, as majority of datasets are within the region bounded by these two correlations.

Another possible source of discrepancy in void fraction prediction is the difference in flow structure at given experimental conditions. Fig. 6 illustrates the present experimental conditions plotted on the $\alpha$-$G$ flow regime map utilized in TRACE code. Although, the validity of the TRACE code flow regime map for tight-lattice rod-bundle test sections hasn’t been confirmed by any previous research, the possibly reason for the large diversion from the trend at $G = 75$ kg/m$^2$/s for narrow rod test section may be due to the possible change in flow regime transition boundaries. As Liu and Hibiki (2017)[21] pointed out, several flow regime transition criteria for rod-bundle geometries are dependent on the hydraulic diameter $D_H$, which is expressed as a function of rod diameter $D_0$ and pitch length, $P$.

$$D_H = \frac{4\left(P^2 - \pi / 4D_0^2\right)}{\pi D_0}$$

Thus, slight change in $P$ value contributes to reduction in $D_H$ value, such that flow regime transitions such as churn flow to annular flow, and cap turbulent flow to churn flow can be highly affected from the regular pitch-length. In order to verify its hypothesis, proper flow regime identification methodology for narrow rod test section should be developed through experiments as a future study.

In order to analyze the present dataset in view of the one-dimensional drift-flux model, drift-flux plane, also known as $\langle j \rangle$ - $\langle v_g \rangle$ plane, is considered. This is a commonly utilized
approach to evaluate drift-flux parameters from the experimental data. Figs. 12 and 13 depict the comparison of existing drift-flux correlations with the present experimental data on drift-flux plane using dimensionless gas velocity $<<v_g^+>>$ and mixture volumetric flux, $<j^+>$. In order to evaluate $<j^+>$ from the given $G$ value, following approach was taken. First, with a given mass flux and quality values of $G$ and $x$, both $j_g$ and $j_f$ were calculated using following relation (Eqs. (43) and (44)):

$$j_g = \frac{Gx}{\rho_g}$$  \hspace{1cm} (43)

$$j_f = \frac{G(1-x)}{\rho_f}$$  \hspace{1cm} (44)

Then, minimum and maximum $j_f$ values, which corresponds to the minimum and maximum $x$ values for the inlet, were calculated using Eq. (44). Based on these lower and upper bounded $j_f$ values, $<j^+>$ ($=<j_g^+> + <j_f^+>$) was obtained to utilize Eq. (6) in dimensionless form. Hereafter, assessment of existing correlations will be performed in three folds.

In view of (1) pressure scaling effect, the overall trend in a reference-pitch test section is not captured well for the 2.0 MPa cases for both reference-pitch and narrow-pitch. However, the predictive capabilities tend to improve as pressure elevates. The Ozaki-Hibiki’s correlation reasonably captures the trend well for 7.0 MPa cases. The INSS correlation ultimately merges with Ozaki-Hibiki correlation but it tends to underestimate the gas velocity at low mixture volumetric flux region of $<j^+>$ below 10 in 7.0 MPa case. For $P=7.0$ MPa, Rouhani’s correlation shows similar trend as Ozaki-Hibiki for the given conditions of present dataset, but it tends to overestimate as $<j^+>$ value surpasses 15.
In view of (2) mass flux effect, overall, prediction gets better at higher mass flux for both geometries and pressure conditions. Rouhani’s correlation shows good agreement at low mass flux condition \((G=75 \text{ kg/m}^2\text{/s})\) at \(P=2.0 \text{ MPa}\), but it tends to diverge from datasets as mass flux increases. In 7.0 MPa cases, Bestion and Ishii’s correlations tend to underestimate the dataset at 75 and 150 kg/m\(^2\)/s, but Ishii’s correlation shows suitable agreement at 500 kg/m\(^2\)/s. Clark et al.’s correlation, which provides maximum possible \(C_0\) value due to recirculation effect, obviously overestimates dataset, except for the very low flow rate conditions. For the narrow rod conditions, no correlations could capture the experimental trend at given \(G\) value, and existing correlations may need to be reconsidered with additional analysis on pitch-length effect.

Finally in view of (3) pitch-length effect, by comparing left-hand side and right-hand side columns of Figs. 12 and 13, narrower flow channel slightly decreases the slope of datasets in the drift-flux plane, which is identical to the \(C_0\) value. Existing correlations including Ozaki-Hibiki and INSS tend to capture the trend reasonably for high-pressure and high-mass flux conditions. However, the none of the correlations could satisfactorily represent the datasets for 2.0 MPa conditions. The change in \(C_0\) due to the pitch-length is one of the notable characteristics of tight-lattice rod-bundle geometry, and further analysis will be carried out in a following section.

4.3. Effect of rod pitch on three-dimensional void fraction distribution

From the experimental results presented in the previous section, assessment of the pitch length effect on volume averaged void fraction values is considered. It can be seen from Fig. 14 (a) that the void fractions in narrow-rod-pitch tends to be higher than reference-pitch design. Such trend is more prominent at a lower total mass flux condition, circle datapoints representing \(G = 75 \text{ kg/m}^2\text{/s}\) conditions. In order to investigate it further, best-fit lines were obtained for reference-
pitch void fraction data in Fig. 14(a), and the void fraction values were compared with identical steam mass flux \(G_g\) inlet conditions for narrow rod data. The results are depicted in Fig. 14(b). The vertical axis represents the void fraction ratio of narrow and reference-pitch data defined as \(\langle \alpha_{\text{Narrow}} \rangle / \langle \alpha_{\text{Reference}} \rangle\), and is plotted with respect to steam mass flux, \(G_g\). In general, void fraction tends to increase in a range of 20% when the pitch-length is narrowed. The largest void fraction ratio value was observed at the lowest mass flux condition of \(G = 75 \text{ kg/m}^2/\text{s}\) at its highest \(G_g\) value. For the low mass flux condition, increase in void fraction ratio was observed with respect to \(G_g\). As can be observed from the TRACE’s flow regime map in Fig. 6, narrow rod test data at higher void fraction range approaches close to annular flow regime, while experimental conditions at high void fraction values for reference-pitch remain in interpolation region, or churn flow regime. Thus, possible difference in flow regime transition criteria due to the change characteristic length (hydraulic diameter) caused by the pitch length effect needs to be investigated. For the intermediate mass flux condition of \(G = 150 \text{ kg/m}^2/\text{s}\), it overall showed void fraction ratio >1 , but the increase is not as considerable as was the case for \(G = 75 \text{ kg/m}^2/\text{s}\). For the highest mass flux condition of \(G = 500 \text{ kg/m}^2/\text{s}\), it shows decreasing behavior of the void fraction ratio and gradually approaches to 1 as the \(G_g\) value increases.

Fig. 15(a) illustrates the dependency of \(G_g\) with respect to \(C_{\infty}\) for both geometrical conditions. As can be seen, \(C_{\infty}\) tends to approach asymptotic values , indicating that central peak void fraction profile is changing to a flatter profile, or a uniform distribution with higher mass flux. It is clear from the figure that the narrower pitch-length tends to show lower values than reference-pitch length. One of the possible reasonings is that the narrowed pitch-length may enhance wall-friction against two-phase flow, which likely alters the typically observed phase fraction peak tendency in reference-pitch. At a same \(G_g\) condition, distribution parameter tends to be lower for
the narrow pitch test section. The distribution parameter ratio, defined as $C_{0, \text{Narrow}} / C_{0, \text{Reference}}$ is plotted in Fig. 15(b). Except for one data point in $G = 150/\text{kg/m}^2/\text{s}$, $C_0$ in narrow pitch test section is lower than the reference-pitch. As indicated in the definition Eq. (6), lower $C_0$ results in higher void fraction, which explains the trend observed in Fig. 14(a).

5. Conclusions

Accurate prediction of void fraction in rod-bundle geometry is important in view of accident analysis and improved reactor safety design. In the present study, two sets of rod-bundle experiments using reference-pitch (13 mm) and narrow-pitch (12 mm) test sections were conducted under prototypic BWR operating conditions. For the void fraction measurement, three-dimensional time-averaged X-ray CT system was utilized to measure void fraction distributions. The system is comprised of an X-ray tube and a flat panel detector (FPD). A channel box (68 mm × 68 mm or 62 mm × 62 mm) was placed in the simulated pressure vessel and 5 × 5 simulated rod bundles with 10 mm OD for both reference-pitch and narrow-pitch test sections were designed and installed. As the X-ray tube and the FPD rotate around the test section, the X-ray beam was attenuated by the test section and the attenuated beam was measured by the detector. In order to minimize the X-ray attenuation by the structural materials, all parts of the test sections were made of titanium. The two-phase mixture consists of steam and water were supplied from the multipurpose steam-water test facility known as HUSTLE (Hitachi Utility Steam Test Leading Facility). Total mass flux was set lower than 500 kg/m$^2$/s, which corresponds to the natural circulation mass flux rate of BWRs, and the operating pressure was set ranging from 2.0 to 7.5 MPa(abs). Conclusions from the present study can be summarized as follows:
• The volume-averaged void fractions measured by the X-ray CT system well agreed with the differential pressure transducer measurement for $\alpha > 0.2$.

• A comparison of the void fractions evaluated experimentally with those proposed by previous drift-flux correlations showed good agreement at high total mass fluxes and reference rod test section. On the other hand, for the narrow rod test section at low total mass fluxes (less than 150 kg/m$^2$/s), the void fractions evaluated by the existing drift-flux correlations tend to perform poorer.

• The void fraction distribution in the region between the rods varied according to the distance between the rods. As a result, the void fractions in a narrow-rod-pitch-type rod bundle became larger than those in a reference-rod-pitch-type rod bundle.

• Narrowed pitch-length may enhance wall-friction against two-phase flow, which likely suppress the central phase fraction peak tendency. This likely promotes lower distribution parameter values, results in increased area-averaged void fraction for narrower pitch test section.

• Existing correlations showed good performance at prototypic pressure condition of 7.0 MPa.

• For narrow-rod conditions, no correlations could capture the experimental trend at a given mass flux value. As a future task, existing correlations may need to be improved with addition of pitch-length information.

Acknowledgements:
Part of this research was conducted as the Infrastructure Development Project for Enhancement of Safety Measures at Nuclear Power Plants: “Advanced Models for Thermal-hydraulic Analysis during Nuclear Fuel Boil-off Process” sponsored by the Ministry of Economy, Trade and Industry, Japan.
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Distribution parameter</td>
</tr>
<tr>
<td>$C_\infty$</td>
<td>Asymptotic value of distribution parameter</td>
</tr>
<tr>
<td>$CT$</td>
<td>Values measured by X-ray CT</td>
</tr>
<tr>
<td>$D_H$</td>
<td>Hydraulic equivalent channel diameter</td>
</tr>
<tr>
<td>$D_H^*$</td>
<td>Non-dimensional hydraulic equivalent channel diameter</td>
</tr>
<tr>
<td>$D_0$</td>
<td>Rod diameter</td>
</tr>
<tr>
<td>$D_{Sm}$</td>
<td>Bubble Sauter mean diameter</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration</td>
</tr>
<tr>
<td>$G$</td>
<td>Mass flux</td>
</tr>
<tr>
<td>$j$</td>
<td>Mixture volumetric flux</td>
</tr>
<tr>
<td>$j_g$</td>
<td>Superficial gas velocity</td>
</tr>
<tr>
<td>$j_f$</td>
<td>Superficial liquid velocity</td>
</tr>
<tr>
<td>$j_f^*$</td>
<td>Non-dimensional superficial liquid velocity</td>
</tr>
<tr>
<td>$L$</td>
<td>Chexal-Lellouche fluid parameter</td>
</tr>
<tr>
<td>$m_d$</td>
<td>Mean absolute error</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Generalized interfacial force</td>
</tr>
<tr>
<td>$m_{rel}$</td>
<td>Mean relative error</td>
</tr>
<tr>
<td>$m_{rel,ab}$</td>
<td>Mean absolute relative error</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of samples</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Viscous number</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$s_d$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$\nu_{gd}$</td>
<td>Drift velocity</td>
</tr>
<tr>
<td>$\bar{V}_{gd}$</td>
<td>Mean transport drift velocity</td>
</tr>
</tbody>
</table>
**Relative velocity**

---

**Greek symbol**
- $\alpha$: Void fraction
- $\Delta \rho$: Density difference between two phases
- $\mu$: Dynamic viscosity
- $\mu_{ijk}$: Attenuation coefficient
- $\rho$: Density
- $\sigma$: Surface tension

---

**Subscripts**
- $\text{crit}$: Critical value
- $f$: Liquid phase
- $g$: Gas phase
- $m$: Mixture

---

**Superscripts**
- $D$: Drag force

---

**Mathematical symbol**
- $\langle \rangle$: Area averaged quantity
- $\langle\langle\rangle\rangle$: Void-weighted averaged quantity

---

**Acronyms**
- BWR: Boiling water reactor
- FPD: Flat panel detector
- HUSTLE: Hitachi Utility Steam Test Leading Facility
REFERENCES:


**Figure Captions:**

Fig. 1: Schematic of the Experimental Facility [8]

Fig. 2: Schematic of the Rod-bundle Test Section [8]

Fig. 3: 3D X-ray CT System [8]

Fig. 4: Comparison of Volume-averaged Void Fraction for Reference-pitch Test Section

Fig. 5: Comparison of Volume-averaged Void Fraction for Narrow-pitch Test Section

Fig. 6: Present Test Conditions on the TRACE code Flow Regime Map

Fig. 7: 3D Void Fraction Distribution Measured by X-ray CT System for Reference-rod Test Section

Fig. 8: 3D Void Fraction Distribution Measured by X-ray CT System for Narrow-rod Test Section

Fig. 9: Void Fraction Distribution for (Top) Reference-pitch and (Bottom) Narrow-pitch Test Sections

Fig. 10: Comparison of Existing Drift-flux Correlations with Present Experimental Data at $P = 7.0$ MPa

Fig. 11: Comparison of Existing Drift-flux Correlations with Present Experimental Data at $P = 2.0$ MPa

Fig. 12: Comparison of Existing Drift-flux Correlations with Reference and Narrow Rods Experimental Data using Drift-flux Plane for $P = 7.0$ MPa

Fig. 13: Comparison of Existing Drift-flux Correlations with Reference and Narrow Rods Experimental Data using Drift-flux Plane for $P = 2.0$ MPa

Fig. 14: (a) Dependency of Steam Mass Flux on Void Fraction, and (b) Effect on Rod-Pitch

Fig. 15: (a) Dependency of Steam Mass Flux on $C_0$, and (b) Effect on Rod-Pitch
### Table Captions:

Table 1: Test Section Specifications

Table 2: 3D X-ray CT System Specifications [11]

Table 3: Performance Evaluations of Drift-flux Correlations for $P = 7.0$ MPa

Table 4: Performance Evaluations of Drift-flux Correlations with respect to Total Mass Flux Values at $P = 7.0$ MPa
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Fig. 2: Schematic of the Rod-bundle Test Section [8]
Fig. 3: 3D X-ray CT System [8]
Fig. 4: Comparison of Volume-averaged Void Fraction for Reference-pitch Test Section

Reference Rod-bundle

$G < 500 \text{ kg/m}^2/\text{s}$

$\sigma = 0.018$
Fig. 5: Comparison of Volume-averaged Void Fraction for Narrow-pitch Test Section
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Fig. 15: (a) Dependency of Steam Mass Flux on $C_0$, and (b) Effect on Rod-Pitch
### Table 1: Test Section Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference-Rod</th>
<th>Narrow-Rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod outer diameter</td>
<td>10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Rod pitch</td>
<td>13 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td>Hydraulic diameter</td>
<td>12 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>Channel box width</td>
<td>68 mm × 68 mm</td>
<td>62 mm × 62 mm</td>
</tr>
<tr>
<td>Diameter/pitch</td>
<td>0.77</td>
<td>0.83</td>
</tr>
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</table>

### Table 2: 3D X-ray CT System Specifications

<table>
<thead>
<tr>
<th>Type of X-ray beam</th>
<th>Cone beam of the radiation angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage of X-ray tube</td>
<td>Max. 450 kV</td>
</tr>
<tr>
<td>Current</td>
<td>Max. 1.6 mA</td>
</tr>
<tr>
<td>Imaging region</td>
<td>250 mm in diameter</td>
</tr>
<tr>
<td></td>
<td>80 mm in height</td>
</tr>
<tr>
<td>Dimensions of each reconstruction element</td>
<td>0.3 × 0.3 × 0.3 mm³</td>
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<tr>
<td>Detection system</td>
<td>2D detector array</td>
</tr>
<tr>
<td></td>
<td>1024 × 512 pixels, 0.4 × 0.4 mm² pixel size</td>
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### Table 3: Performance Evaluations of Drift-flux Correlations for $P = 7.0$ MPa

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Reference &amp; Narrow Rod Test Sections</th>
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<tr>
<td></td>
<td>$m_d$</td>
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<tr>
<td>Ishii (1977)</td>
<td>0.06</td>
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<td>Bestion (1990)</td>
<td>0.09</td>
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<tr>
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<td>0.02</td>
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<tr>
<td>Ozaki and Hibiki (2015)</td>
<td>-0.01</td>
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<td>-0.14</td>
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<tr>
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Table 4: Performance Evaluations of Drift-flux Correlations with respect to Total Mass Flux Values at $P = 7.0$ MPa

<table>
<thead>
<tr>
<th>Correlations</th>
<th>$G = 75$ kg/m²/s</th>
<th>$m_d$</th>
<th>$s_d$</th>
<th>$m_{rel}$</th>
<th>$m_{rel,abs}$</th>
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<tr>
<td>Ishii (1977)</td>
<td>0.09</td>
<td>0.06</td>
<td>21.8%</td>
<td>22.4%</td>
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<tr>
<td>Bestion (1990)</td>
<td>0.11</td>
<td>0.04</td>
<td>25.8%</td>
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<td></td>
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<tr>
<td>Rouhani (1969)</td>
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<td>0.06</td>
<td>6.6%</td>
<td>11.8%</td>
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<td>0.05</td>
<td>0.7%</td>
<td>6.5%</td>
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<table>
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<th>$G = 150$ kg/m²/s</th>
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<tr>
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<td>0.05</td>
<td>-28.8%</td>
<td>28.8%</td>
<td></td>
</tr>
<tr>
<td>INSS (2019)</td>
<td>0.02</td>
<td>0.03</td>
<td>5.9%</td>
<td>8.1%</td>
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</table>

<table>
<thead>
<tr>
<th>Correlations</th>
<th>$G = 500$ kg/m²/s</th>
<th>$m_d$</th>
<th>$s_d$</th>
<th>$m_{rel}$</th>
<th>$m_{rel,abs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ishii (1977)</td>
<td>-0.01</td>
<td>0.01</td>
<td>-4.8%</td>
<td>5.1%</td>
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<tr>
<td>Bestion (1990)</td>
<td>0.02</td>
<td>0.02</td>
<td>4.6%</td>
<td>6.5%</td>
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<tr>
<td>Rouhani (1969)</td>
<td>-0.01</td>
<td>0.02</td>
<td>-4.2%</td>
<td>4.8%</td>
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<tr>
<td>Ozaki and Hibiki (2015)</td>
<td>-0.03</td>
<td>0.01</td>
<td>-10.0%</td>
<td>10.0%</td>
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<tr>
<td>Clark et al. (2014)</td>
<td>-0.12</td>
<td>0.01</td>
<td>-32.3%</td>
<td>32.3%</td>
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</tr>
<tr>
<td>INSS (2019)</td>
<td>-0.03</td>
<td>0.01</td>
<td>-10.2%</td>
<td>10.2%</td>
<td></td>
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</tbody>
</table>