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Drift-flux model of sub-channel in vertical rod bundles with spacer grids

Quan-yao Ren [a,b], Liang-ming Pan [a,*], Wen-xiong Zhou [a], Hang Liu [a,b], Ting-pu Ye [a]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems (Chongqing University), Ministry of Education, Chongqing 400044, China
[b] Science and Technology on Reactor System Design Technology Laboratory, NPIC, Chengdu 610041, China

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ABSTRACT

Drift-flux model has been one of the most popular models predicting two phase flow parameters in nuclear reactor and other industrial equipment since proposed. Most of researches are based on the void fraction measurement on the whole cross-section of the void fraction, which is under the influence of casing tube and might be unfit for sub-channel. Therefore, experiments have been performed to measure the void fraction in sub-channels with the newly designed impedance void meter, based on which the existing drift-flux correlations have been evaluated. However, few correlations have good performance in bubbly and cap bubbly flow. In order to improve the accuracy and consider the physical significance, the new correlation of distribution parameter is proposed by adopting Julia's drift velocity correlation. The proposed correlation could predict the present data, Yang's data and Clark's data with the mean relative error of 13.96%, 16.23% and 24.9% respectively. Furthermore, the *L*/*D* effect on distribution parameter has been analyzed with different spacer grids. The mixing vane spacer grid (MVSG) results in a larger value of distribution parameter than simplified spacer grid in low void fraction region for the stronger recirculating flow.

1. Introduction

It is of great significance to conduct proper thermal-hydraulic analysis and predict the two phase flow parameter accurately in the chemical industry, petroleum and nuclear power plants etc. On the purpose of predicting the thermal-hydraulic parameters easily, some system codes (such as RELAP5 and TRAC) and sub-channel codes (such as COBRA, ATHAS, WOSUB, FLICA-4) have been developed. As an important parameter related to all two phase flow phenomena, void fraction deserves full considerations, especially the related theoretical models and empirical correlations, which is of great significance for the safety of nuclear reactor.

As an effective and simple method, drift-flux model has been adopted widely to calculate the void fraction and evaluate phase distribution characteristics since proposed by Zuber and Findlay [1]. In RELAP5-3D and RELAP5/MOD3, Chexal-Lellouche's empirical drift-flux correlations [2] were adopted in vertical bubbly-slug flow in rod bundles [3,4]. And the Bestion correlation for drift velocity [5] was implemented in CATHAR and TRAC-BWR [6]. As for thermal-hydraulic sub-channel codes COBRA-IV [7,8], the void fraction in sub-channels was calculated based on the options among three correlations: homogenous model, modified Armand model and Chexal-Lellouche model [2]. Moreover, WOSUB, ATHAS and FLICA-4 also adopted drift flux model to deal with the two phase flow problems in sub-channel [9].

In the past decades, many drift-flux models have been proposed for two phase flow in rod bundles, such as Chexal-Lellouche [2], Kataoka-Suzuki [10], Kamei-Tomiyama [11] and Chen-Ishii [12] correlations etc. These drift-flux correlations developed or adopted for rod bundles are summarized in Table 1 and would be discussed in Section 3. Most of drift-flux correlations [2,12–14] for rod bundles are similar to those for circular pipe but with different coefficients. The features of rod bundles channel are not considered and analyzed in the drift-flux parameters, such as the differences in different sub-channels, the effects of spacer grid and casing tube, etc. Furthermore, most of them were empirical correlations for rod bundles and developed based on the void fraction measured on the whole cross-section of the rod bundle channel with different measuring devices, which is under the influence of casing tube. However, the casing tube does not exist in actual PWRs, evaporator and other industrial equipment. Thus errors might be introduced when these correlations are applied to calculate the void fraction in the sub-channels. Therefore, it is necessary to perform an assessment on the applicability of the existing models in sub-channel and propose more accurate drift-flux correlation based on void fraction in sub-channel.

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* Corresponding author.
E-mail address: cneng@cqu.edu.cn (L.-m. Pan).

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Nomenclature

a	constant
b	constant
B_{sf}	reduction factor
Bo	Bond number
C	coefficient
C_0	distribution parameter
C_∞	limit value of distribution parameter
D	hydraulic diameter of test section (m)
D_0	rod diameter (m)
D_b	critical bubble size (m)
D_H	hydraulic diameter of test section (m)
E	error
g	gravitational acceleration ($m \cdot s^{-2}$)
G	mass flow rate ($kg/(m^2 \cdot s)$)
j	superficial velocity (m/s)
K_0	coefficient
L	axial length of test section (m) or coefficient
N	Number
$N_{\mu f}$	Viscosity number
p	pressure (Pa)
P_0	rod pitch (m)
V	voltage (V)
v	actual velocity (m/s)
v_{gj}	drift velocity (m/s)
V_{gj}^*	dimensionless drift velocity
< >	area averaged
<< >>	void-weighted averaged

Greek symbols

α	void fraction
γ	coefficient
ρ	density (kg/m^3)
$\Delta\rho$	density difference(kg/m^3)
σ	surface tension (N/m)

Subscripts

ab	absolute
B	bubbly flow
C	cap bubbly flow
cal	calculated
exp	experimental
H	high
g	gas phase
l	liquid phase
L	low
max	maximum value
min	minimum value
re	relative
wf	weighting factor

Subscripts

*	dimensionless

In present study, a sub-channel impedance void meter [15,16] has been designed to measure the void fraction in the inner sub-channel, which is beyond the influence of casing tube. And a large amount of experiment has been carried out to acquire the void fraction in different sub-channels for all flow regimes. Based on the measured data, the existing drift-flux correlations for rod bundles are evaluated, which ignore their original application range. However, no correlations could predict void fraction in all flow regimes with a good accuracy. Therefore, a flow regime independent drift-flux correlation is proposed for sub-channel, which is related to void fraction. Additionally, the effects of axial development and different spacer grids on distribution parameter have been analyzed.

2. Experimental facilities and instruments

2.1. Experimental setup

In order to obtain the void fraction of sub-channels, the test loop with 5 × 5 rod bundles has been constructed as shown in Fig. 1. The water flow rate is measured by HONEYWELL electromagnetic flow meters with an accuracy of ±0.5%. Compressed air is measured by OMEGA gas mass flow meters with an accuracy of ±(0.8% reading +0.2% full scale). Detailed information on this experimental setup could be referred to Ren et al. [15].

In order to simulate the bubble coalescence and break-up process in the two phase flow development at axial direction, the uniform phase distribution with small bubbles is essential at the inlet of test section. The air-water mixer has been designed to produce small and uniformly distributed bubbles, which contains four bubble injection elements similar to Yang et al. [14]. It has been demonstrated by the local measurement result with four-sensor conductivity probe [17] that the small and uniformly distributed bubbles with the chord length of 1–3 mm could be produced at 10.7 L/D of test section.

The test section is shown in Fig. 2. The axial locations of spacer grids and sub-channel impedance meters are shown in Fig. 2(a), in which L and D denote the length and hydraulic diameter of the test section respectively. The sub-channel impedance void meters are located in the 1# corner, 2# inner and 3# side sub-channel at 76.9 L/D and the 4# corner sub-channel at 64.2 L/D respectively as shown in Fig. 2. The length of the test section is 1500 mm while the other geometrical parameters are shown in Fig. 2(b). It should be noted the pressure and differential pressures are measured with YOKOGAWA transmitters with an accuracy of 0.065%. As introduced in Ren et al. [15], two kinds of spacer grids are adopted: the simplified spacer grid (SSG) shown in Fig. 3 and the prototypical mixing vane spacer grid (MVSG) consisting of dimples, springs and slit mixing vanes, which is the same as that adopted by Chen et al. [18]. Moreover, the experiments cover a wide range of flow conditions with the superficial gas velocity ranging from about 0.014 to 10.5 m/s and the superficial liquid velocity ranging from about 0.066 to 2.50 m/s, which contain 78 points of bubbly (B), 41 points of cap bubbly (CB), 49 points of cap turbulent (CT), 50 points of churn turbulent (C) and 7 points of annular (A) flow conditions referred to the inner sub-channel flow regime map with SSG acquired by Ren et al. [15].

2.2. Sub-channel impedance void meter

The sub-channel impedance void meter [15,16] has been designed to measure the time series void fraction in sub-channel, whose principle is similar to that in circular pipe [19]. As the void fraction changes in the sub-channel, the impedance and conductance of two phase flow would also change due to the different electrical parameters between air and water. As shown in Fig. 4, the impedance meter consists of 12 electric strip electrodes