Void fraction and pressure gradient measurement of two-phase flow in packed bed

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1. Introduction

During severe accident progress, if reactor vessel failure occurs at water flooded reactor cavity condition, the core melt materials are relocated and form debris bed on the bottom of containment building due to fuel coolant interaction (FCI). In order to ensure the integrity of containment building possibly threatened by molten core concreate interaction (MCCI), the cooling limitation of debris bed should be precisely analyzed.

Dryout heat flux (DHF) is one of the key parameters to represent cooling limitation of debris bed and it means the minimum heat flux occurring dryout inside particle bed. It is also well known that the dominant physical factor to occur dryout is the high flow resistance of debris bed as it is a porous medium.

Although there are several experimental reports on two-phase flow pressure gradient through particle bed, all the test conditions were restricted at below about 0.6 of void fraction value. As a result, none of previous models were able to predict two-phase flow pressure gradient at high void fraction condition as reported in our previous work[1]. However, due to the lack of void fraction measurement in our previous work, modeling of interfacial friction was unavailable. In this work, therefore, the void fraction measurement is additionally proceeded to produce experimental database for two-phase friction force modeling in particle bed.

2. Methods and Results

2.1 PICASSO V2 facility

The PICASSO V2 (Pressure drop Investigation and Coolability ASSessment through Observation Version 2) facility, shown in Fig. 1, is used to measure both two-phase pressure loss and void fraction through particle bed. The most features of this facility is similar to the previous version[1] but with reduced inner dimeter from 100 mm to 90 mm and height of test section from 700 mm to 500 mm. In addition to this, several measurement sensors are installed to either reduce uncertainty and gather void fraction data. The two thermocouples are located at side of test section for calculating air density. Air injection is controlled by mass flow controller instead of needle valve which used in the previous one. Finally, the void fraction is measured by capacitance probe CS-616 by Campbell Scientific.

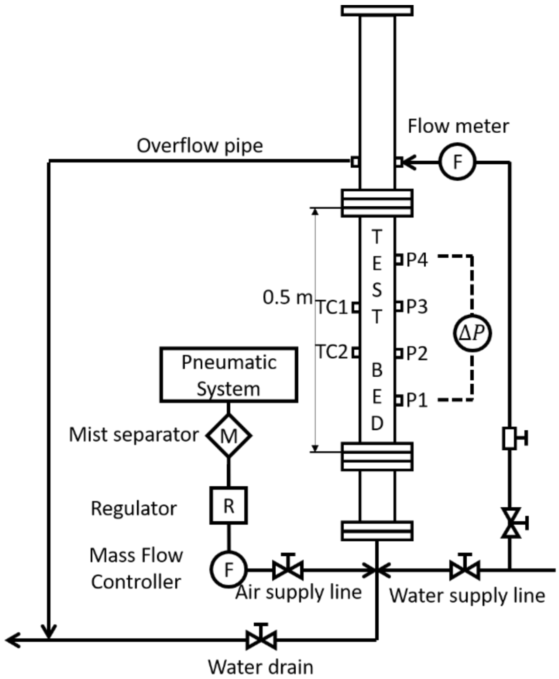

Fig. 1. Schematic diagram of the experimental facility

2.2 Calibration of void fraction sensor

The capacitance probe gives wave signal whose frequency is proportional to the dielectric permittivity of the medium in which the sensor is inserted. By assuming solid matrix is fixed, the relation between frequency of capacitance probe and void fraction of particle bed can be expressed as[2]:

$$\alpha = \frac{f^{-2a} - f_0^{-2a}}{f_1^{-2a} - f_0^{-2a}} \quad (1)$$

where f_0 and f_1 are frequency at $(\alpha = 0)$ and $(\alpha = 1)$, respectively. The a is empirical constant to be between -1 and 1 except 0. In order to determine the constant a, the weighting method[3] is applied to measure void fraction inside test bed prior to pressure gradient measurement.

For the calibration of the capacitance probe, the particles are partially filled up to P4 port, which is blue square in Fig. 2(a). The frequency of signals at $(\alpha = 0)$ and $(\alpha = 1)$ is then measured as illustrated in Fig. 2(a)-(b). Later, the air is injected from below (Fig. 2(c)) and the relocated water due to air volume inside particle bed and pipe below test section is extracted through the P4 port as illustrated in Fig. 2(d). When the weight of the extracted water (w) and frequency from the sensor converge certain values, the air valve is suddenly closed.

As very fine mesh is installed below test bed to prevent air escape from the lower pipe as illustrated in Fig. 2(e). By the measurement of the height (h) of extracted water from the lower pipe, the void fraction of test section can be estimated by calculate volume of water from the test section as:

$$\alpha = \frac{\frac{w}{\rho} - hA}{\varepsilon V_{bed}} \qquad (2)$$

where ρ, A, ε and V_{bed} are the density of water, cross section area of test section, porosity of test bed and total volume of test bed, respectively.

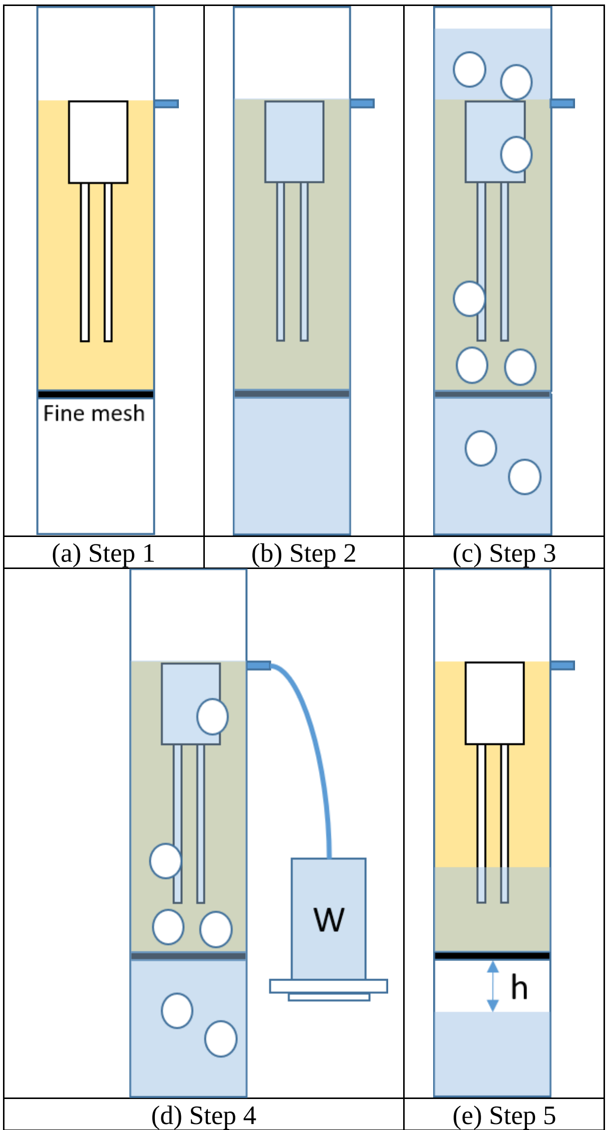

Fig. 2. Calibration of the capacitance probe by using weighting method

In the calibration, the alumina ball whose average diameter is 4.22 mm is filled in test section with 0.386 of porosity. As a result, the constant a is determined to be 0.14 by non-linear least square method. As can be seen in Fig. 3, the error of measured void fraction between weighting method and capacitance probe is within 10 % of error (blue line in Fig. 3).

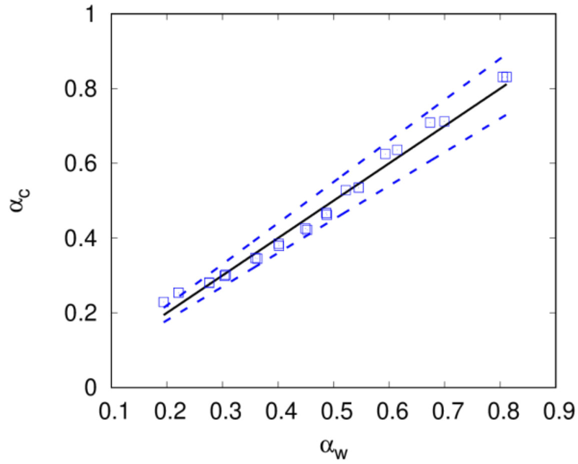

Fig. 3. Comparison of measured void fractions between weighting method and capacitance probe

2.3 Experimental results

In the measurement of two-phase pressure gradient and void fraction is conducted with alumina particle packed bed whose porosity is 0.391. The permeability ($K = 1.22e^{-8}$) and passability ($\eta = 2.35e^{-4}$) of the test bed are obtained from the air single phase pressure gradient data by non-linear least squares curve fitting as shown in Fig. 4. The measured values are slightly higher than the estimated value by Ergun model[4]. The y axis of Fig. 4 is the nondimensional pressure gradient which can be obtained by:

$$P^* = -\nabla P / (\rho_l g) \qquad (3)$$

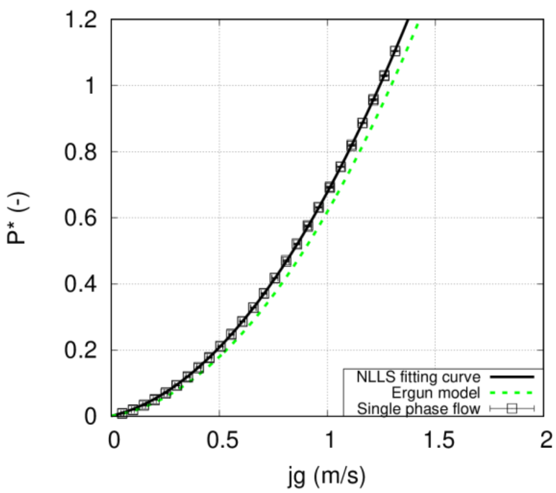

Fig. 4. Single phase pressure gradient

The measured two-phase pressure gradient through the test bed is plotted in the Fig. 5. In the figure, the predicted values by previous two-phase pressure drop models which are suggested by Tung & Dhir (TD) [5], Schmidt

(S) [6], Taherzadeh & Saidi (TS) [7] and Park et al. (P) [8] are also compared. From the comparison, it is obvious that there is no appropriate model to predict two phase pressure loss at high void fraction condition where pressure gradient suddenly decreases to be single phase flow at about 0.8 m/s of air velocity.

In Fig. 6, the measured void fraction during experiment is also compared to other data in literature. The test bed of Chikhi et al.[2] is composed of 4 mm particles and the one of Tutu et al.[3] is composed of 3.18 mm which are similar to our test bed.

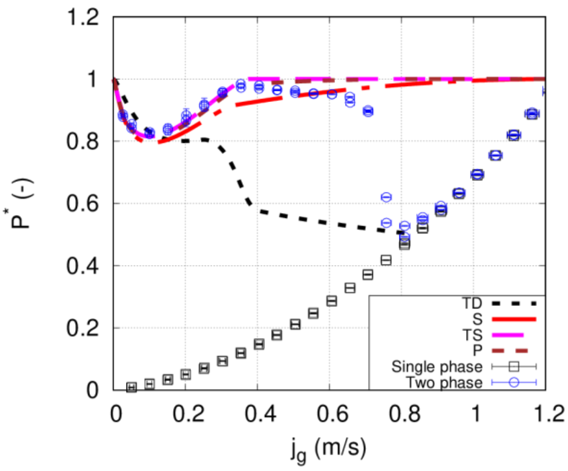

Fig. 5. Two phase pressure gradient

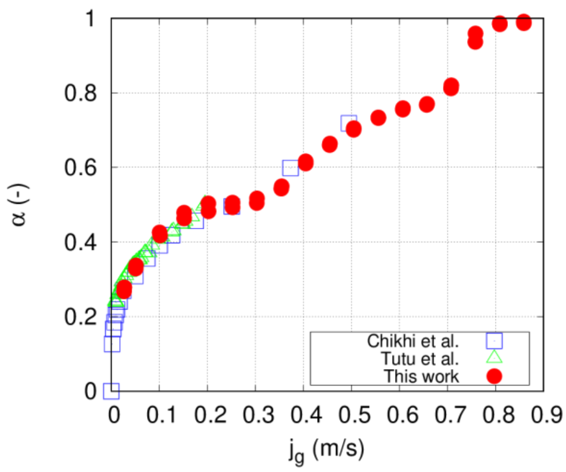

Fig. 6. Void fraction data

By the measurement of void fraction, the interfacial friction between water and air phase can also be deduced from the relationship between interfacial friction and pressure gradient[9] as :

$$-\nabla P = \rho_l g - \frac{F_i}{1-\alpha} \qquad (4)$$

where F_i is the interfacial friction (N/m^3) between fluid phases.

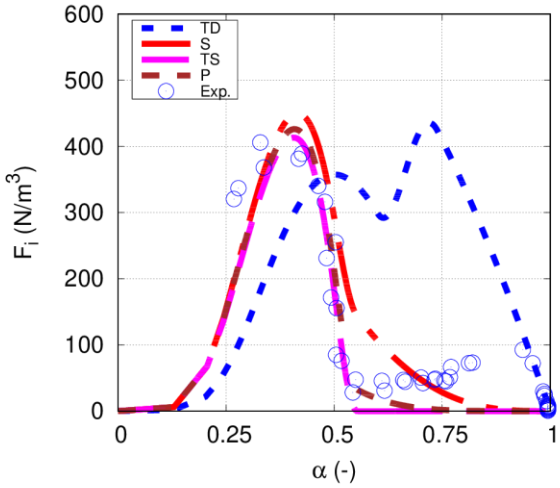

Fig. 7. Interfacial friction

From the Fig. 7, the prediction of interfacial friction at high void fraction above about 0.6 is not available from previous models. As the dryout would occur at such high void fraction condition, this result implies that the necessity of further developments at two-phase pressure models for precise prediction of DHF.

3. Conclusions

As reported in our previous work[1], the previous two-phase pressure drop models are not able to predict the pressure gradient trend at high air velocity range. Therefore, the measurement of not only two-phase pressure drop through packed bed but also void fraction have been conducted to analyze the factors needed to be modified.

For measurement of void fraction, the capacitance probe has been adopted and calibrated with the weighting method prior to the pressure loss test. Owing to additional measurement of void fraction, it is confirmed that the major reason of this discrepancy comes from poor prediction of interfacial friction at high void fraction at those models.

Therefore, additional consideration of interfacial friction behavior at high void fraction seems to be necessary to development of hydrodynamic models predicting debris bed coolability.

Acknowledgements

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