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Formulation of two-phase flow patterns in porous media at high air velocity

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1. Introduction

If a severe accident occurs with a severe core degradation and progresses into reactor vessel failure, the core materials are relocated to the bottom of containment building and form debris bed in a LWR (Light Water Reactor). Under the circumstance, the cooling limitation of debris bed should be reliably assessed for analyzing its possibility of progressing into to MCCI (Molten Core Concrete Interaction) threatening containment integrity. In this research, the cooling limitation of particulate debris bed which can be formed due to FCI (Fuel Coolant Interaction) under wet cavity strategy was considered.

One of key parameters to represent the debris bed cooling limit is Dryout Heat Flux (DHF), defined as the maximum heat flux through the bed without dryout. The dominant phenomenological factor of dryout occurrence is the flow resistance resulting experimental studies and model developments in literature[1, 2]. However, there has been rarely conducted to observe two-phase flow characteristics in the packed bed at high void fraction. Therefore, in this work, the characteristics of two-phase flow have been experimentally studied from low to high void fraction conditions to extend predictability of previous models into wider range of particle sizes which will be used to predict DHF of ex-vessel debris bed in severe accident.

2. Methods and Results

2.1 PICASSO facility & Test cases

The PICASSO (Pressure drop Investigation and Coolability ASSessment through Observation), shown in Fig. 1, is an experimental device designed to measure the pressure loss of single-phase and two-phase flows in a packed bed.

The PICASSO facility consists of three acrylic flange pipes. The bottom pipe was filled with the diameter of 8mm stainless steel balls so that the velocity of gas is evenly distributed in the radial direction. The flange pipe at the center, filled with experimental particles, is 0.7 m in height and 0.1 m in inner diameter. In the upper and lower parts of the middle flange, an acrylic plate with 841 holes having a diameter of 2 mm was placed to prevent the change of the internal structure of the bed. The upper flange pipe was additionally installed to prevent water overflow.

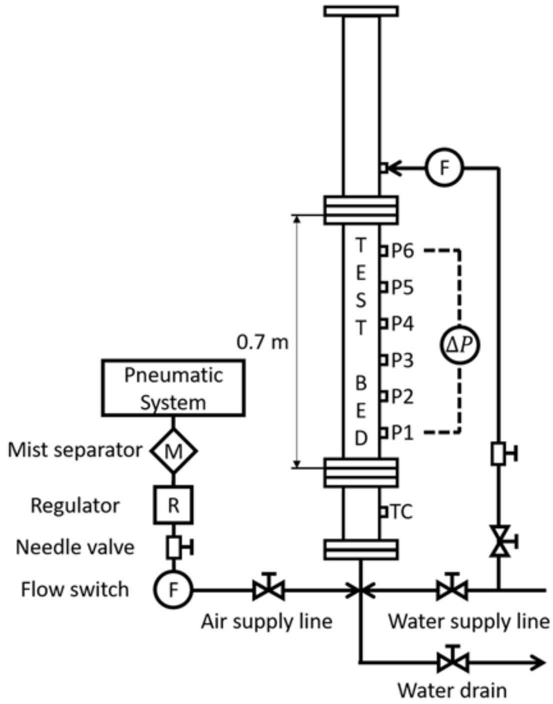

Fig. 1. Schematic diagram of the experimental facility

In the test section, six pressure measurement ports are located at 100 mm intervals. Three differential pressure transmitters were used in the two-phase flow experiment, and one was used to measure the differential pressure in the single phase cases. In addition, a static pressure measurement was additionally conducted to calculate the internal air density. Details of the location of the measuring points and the pressure sensors are listed in Table 1.

Table 1. Detail information of pressure sensors

	Range (kPa)	Location	Error (kPa)
Two-phase	- 62 ~ 62	P1-P6 (DP16)	0.03
	0.0 ~ 100	P1-P3 (DP13)	0.04
	0.0 ~ 100	P4-P6 (DP46)	0.04
	-6.2 ~ 6.2	P3-P4 (DP34)	0.003
	17	P5	0.02
Single - phase	0.0 ~ 10	P1-P6 (DP16)	0.004
	17	P5	0.02

The air supplied in the pneumatic system was filtered through the mist eliminator and then used in the experiment. The flow rate of air was controlled by a pressure regulator and needle valve. The flow rate was measured using PFMB flow switches (2 ~ 200LPM, 5 ~

500LPM and 10 ~ 1000LPM) manufactured by SMC. All data measured during the experiment was collected with a data acquisition system manufactured by National Instruments at a time interval of 2.5 seconds.

The test bed was packed with spherical stainless steel particles whose diameter is 4.05 mm according to the manufacturer's specification. The mean diameter of the particles measured in 31 random samples was 4.035 mm and the distribution of the population's diameters was estimated to be ± 0.028 mm with a probability of 95%.

The porosity of the packed bed was calculated from the total volume of the middle flange pipe and the total weight of the particles used. The uncertainty of the porosity is also derived from the measurement error of particle weight and test volume. Detail information of the porosity characteristics are given in Table. 2.

Table 2. Porous characteristics of the test bed

Particle size (mm)	4.035 ± 0.028
Porosity (%)	38.67 ± 0.61
Permeability (m^2)	1.669 ± 0.115e-8
Passability (m)	2.174 ± 0.126e-4

After packing the particles in the test section, the test section and the pressure impulse line were filled with air for single-phase flow and water for two-phase flow experiments. In the case of the two-phase flow experiment, two different air injection methods were used whether the air velocity increases from zero (promptly) or from previous target value (gradually) to present target velocity as listed in Table 3.

Table 3. Experimental series

Test #	Phase	Increase of air velocity	Abbreviation
1	Single-Phase	-	SP
2	Two-Phase	Promptly	TPP
3	Two-Phase	Gradually	TPG

2.2 Experimental results

2.2.1 Single-phase flow test (SP)

Before the two-phase flow experiment, the single phase flow test was conducted to check the validity of measured porous characteristics and experimental facility. The measured pressure gradient at single phase flow is plotted in Fig. 2. In the figure, the y axis was converted to non-dimensional pressure gradient form (P^*) defined as

$$P^* = (-dP/dz)/(\rho_l g) \quad (1)$$

where $\rho_l g$ is the hydrostatic pressure. As can be seen, the measured data show good agreement to the Ergun's single phase flow model[3].

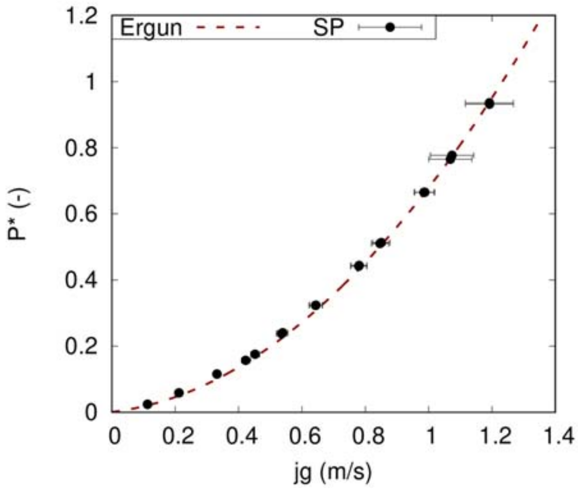

Fig. 2. Results of single phase flow test compared with Ergun's model

2.2.2 Two-phase flow test (TPP, TPG)

In the two-phase flow test, the two different experimental methods for increase of air velocity were implemented as previously mentioned in the section 2.1. The first method is to increase air velocity from zero to target velocity at every measuring points which will be remarked as TPP (Two-Phase Promptly increased velocity). In the other case, the air velocity was increased from the previous experimental points which will be noted as TPG (Two-Phase Gradually increased velocity).

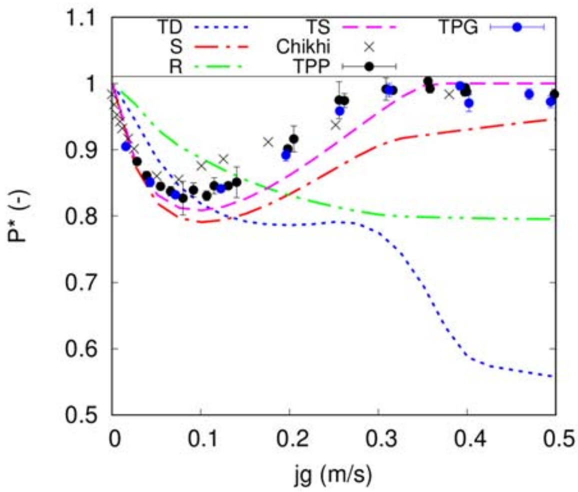

Fig. 3. Results of two-phase flow test at lower velocity region

2.2.2.1 Low velocity region (up to 0.5 m/s)

In the lower velocity region, the measured pressure gradient was compared with the previous experimental data conducted by Chikhi et al.[4] and models which are suggested by Tung & Dhir (TD)[5], Rahman (R)[6], Taherzadeh & Saidi (TS)[7] and Schmidt (S)[8] shown in Fig. 3.

As can be seen in the figure, there was no noticeable difference between TPP & TPG cases. In addition, the overall trends of both cases are similar to the data reported by Chikhi et al. In the comparison with model predictions, the Schmidt and Taherzadeh & Saidi models show relatively good agreement with the global trend of experimental data. The distinguishing point of these models are the consideration of channel flow formulation at about 0.3 ~ 0.4 m/s where interfacial friction diminishes which results pressure gradients converges to the hydrostatic head level.

The slight mismatch of the data at the velocity region between 0.1 and 0.3 m/s with Chikhi's might be caused by different permeability and a height effect. The height effect does act in the two different ways. The first is to decrease pressure gradient with height elevation due to less dense of packing at higher location. The other is to increase pressure gradient at higher location due to merge of slugs which reduce interfacial friction. As a result, the local pressure gradient can vary as shown in Fig. 4.

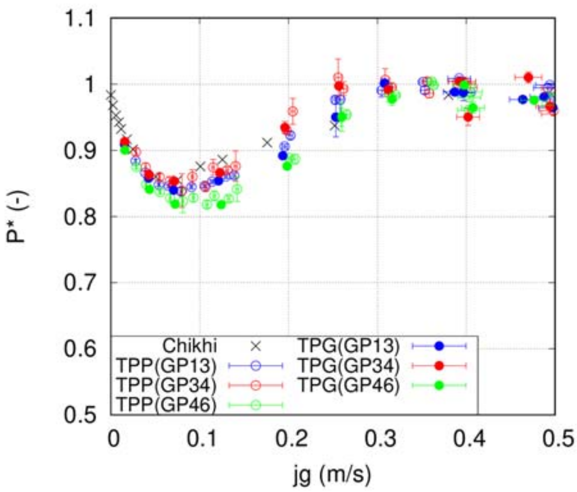

Fig. 4. Local pressure gradient measurement at low velocity region

2.2.2.2 High velocity region (above 0.5 m/s)

At the higher velocity region, the measured data between TPP and TPG show different behavior as shown in Fig. 5. In the case of TPP experiment, the pressure gradient starts to decrease as low as the black empty circles in Fig. 5. After then, the pressure gradient suddenly increases to about hydrostatic head level. The time to be the steady-state increase dramatically in this case[9] from few minutes to hours as the velocity increases from 0.6 m/s to about 0.9 m/s. Above 0.9 m/s, the pressure gradient becomes to be same as the single phase flow experimental results which implies the formulation of single phase flow. The final steady-state data of TPP experiments are plotted as black filled circles in Fig. 5. As one can see, the experimental results show good agreement to the Schmidt and Taherzadeh & Saidi models, which insist negligible interfacial friction due to channel flow formulation at high velocity region.

On the other hand, in the TPG experimental series, the time to be the steady-state condition was similar to the TPP cases, although the pressure gradient does not increase again. In this case, none of model predict the trend of pressure gradient to decrease suddenly from 0.7 m/s which means that the interfacial friction inside the bed increases at this region.

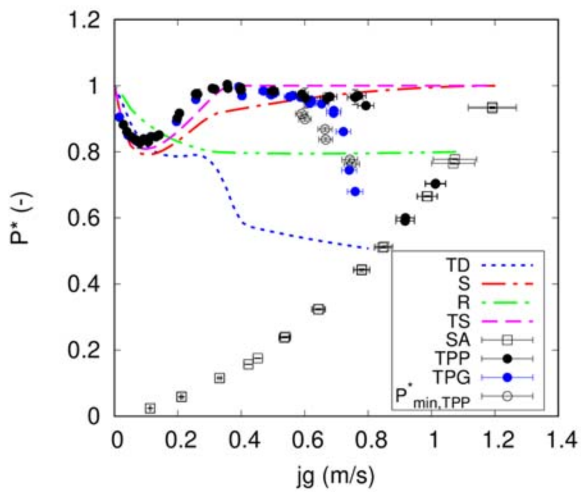

Fig. 5. Two-phase flow results at higher velocity region

The different behavior between TPP and TPG experiments implies that the formulation of two-phase flow pattern at high velocity region might be sensitively affected by the development of flow path.

3. Conclusions

The two-phase pressure drop experiment in the spherical particles (Ø 4.035 mm) packed bed with stagnant water is conducted from with the air superficial velocities ranged from 0 to 1.2 m/s. The trend of the two-phase flow pressure gradients is suddenly changed when the air velocity exceeds 0.6 m/s. At the low velocity region, the measured pressure gradients show good agreement with the preceding research. On the other hand, above 0.6 m/s of air velocity, the pressure gradients are sensitively affected by the experimental method whether the velocity increases promptly or gradually. Especially, in the case of gradual increase of air velocity, the measured pressure gradient decreases from 0.7 m/s which was not predictable from previous models. This different behavior depending on velocity increase method implies that the formulation of two-phase flow pattern at high velocity region might be sensitively affected by development of flow path. Therefore, additional consideration of these phenomena seems to be necessary to development of hydrodynamic models predicting debris bed coolability.

Acknowledgements

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