Empirical correlations for predicting the self-leveling behavior of debris bed

CHENG Songbai[1,*] YAMANO Hidemasa[1] SUZUKI Tohru[1] TOBITA Yoshiharu[1] NAKAMURA Yuya[2] ZHANG Bin[2] MATSUMOTO Tatsuya[2] MORITA Koji[2]

[1]*Advanced Nuclear System R&D Directorate, Japan Atomic Energy Agency (JAEA), 4002 Narita, O-arai, Ibaraki, 311-1393, JAPAN*

[2]*Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka, 819-0395, JAPAN*

Abstract Studies on the self-leveling behavior of debris bed are crucial for the assessment of core-disruptive accident (CDA) occurred in sodium-cooled fast reactors (SFR). To clarify this behavior over a comparatively wider range of gas velocities, a series of experiments were performed by injecting nitrogen gas uniformly from a pool bottom. Current experiments were conducted in a cylindrical tank, in which water, nitrogen gas and different kinds of solid particles, simulate the coolant, vapor (generated by coolant boiling) and fuel debris, respectively. Based on the quantitative data obtained (mainly the time variation of bed inclination angle), with the help of dimensional analysis technique, a set of empirical correlations to predict the self-leveling development depending on particle size, particle density and gas injection velocity was proposed and discussed. It was seen that good agreement could be obtained between the calculated and experimental values. Rationality of the correlations was further confirmed through detailed analyses of the effects of experimental parameters such as particle size, particle density, gas flow rate and boiling mode. In order to facilitate future analyses and simulations of CDAs in SFRs, the obtained results in this work will be utilized for the validations of an advanced fast reactor safety analysis code.

Key words Sodium-cooled fast reactor, Core disruptive accident, Self-leveling, Debris bed, Gas injection, Empirical correlation

1 Introduction

The disaster in March 2011 at the Fukushima Dai-Ichi nuclear power plant in Japan makes more and more people to realize that severe accidents might occur, even if their probability is extremely low. In order to achieve In-Vessel Retention (IVR) for sodium-cooled fast reactors (SFR), the evaluation of core disruptive accident (CDA) has been one of the major concerns in the safety analyses during the past decades[1]. During a postulated CDA in a SFR, possibly as a consequence of rapid quenching and fragmentation of core materials, a multiphase flow system can form, which could be composed of a mixture of liquid sodium, molten fuel, molten structure, refrozen fuel, solid fuel pellets, fission gas, fuel vapor, and other materials[1]. Deposition of this system will lead to the formation of debris beds over the core-support structure and/or in the lower inlet plenum of the reactor vessel (as depicted in Fig.1)[2]. Typically, the debris bed will form conically-shaped mounds. However, coolant boiling caused by decay heat, might lead ultimately to leveling of the debris bed[3,4]. This mechanism, as illustrated in Fig.2, defines the term ‘debris-bed self-leveling’.

To prevent the penetration of the reactor vessel by molten fuel and distribute molten fuel or core debris formed in a CDA into non-critical configurations, in some SFR designs in-vessel retention devices are used[5]. Multi-layer debris tray installed in the bottom region of the vessel is one of such devices[6,7]. During a hypothetical CDA, discharged molten fuel after being quenched and

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* Corresponding author. *E-mail address:* cheng.songbai@jaea.go.jp

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fragmented into fuel debris in the lower plenum region, is expected to accumulate on the different layers of the debris tray[6,7]. To stably remove the decay heat generated from debris bed on the tray, the size, retention capability, and allocation of the tray should be carefully designed. Self-leveling is an important inducing factor to trigger molten fuel to transfer among the tray. Thus, the study on this behavior is of essential importance to the design of the tray. In addition, self-leveling behavior will greatly affect the heat removal capability of debris beds[2,8].

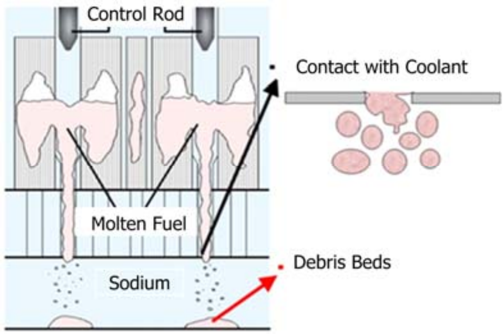

Fig.1 Debris bed profile.

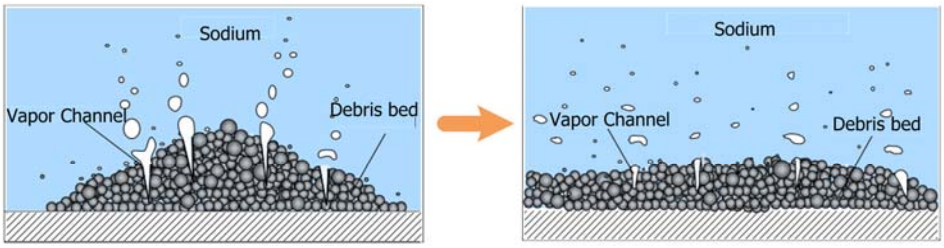

Fig.2 Self-leveling behavior.

Unfortunately, over the past decades, although some information on debris bed hydrodynamics and heat transfer has been available[9], very little work related to self-leveling has been performed. Most of these studies generally assume that the upper surface of the debris bed is level. Noting the importance of self-leveling in the heat removal capability, Hesson *et al.*[10] and Gabor[11] began some pioneering experimental studies on this subject. In separate experiments, they validated the existence of self-leveling behavior respectively by introducing a bubbling airflow through a particle bed and by volume-heating of a particle bed composed of UO_2-salt water.

Following the lead from these predecessors, by using depressurized and bottom-heated boiling methods, Zhang *et al.* further investigated this behavior with a cylindrical test tank 605 mm in height and 300 mm in diameter[2-4,8]. Based on the experimental observations from an early subcooled boiling condition (q<0.43 W/cc), the overall behavior of self-leveling, namely the role of experimental parameters (such as particle size, particle density, particle shape and equivalent boiling intensity) on the development of self-leveling, was recognized.

Since the motion of bubbles inside particle beds has been proven to be of critical importance to the onset and evolution of self-leveling[2-4,8], to provide more direct evidence supporting these understandings, by use of gas injection, recently Cheng *et al.* initialed several series of visualization experiments to investigate the bubbling behavior inside particle beds[9,12]. Due to the different interaction mechanisms observed between solid particles and bubbles, three characteristic flow regimes, termed respectively as the bubble coalescing regime, the transitional regime and the bubble trapping regime, were identified. Furthermore, based on a set of quantitative data obtained from a small-scale quasi-2D rectangular set-up, by performing regression analysis, empirical correlations were successfully advanced to estimate the transient variation in the bed inclination angle during the leveling process[13,14]. These correlations yielded good statistical performance over the validity range (Q_g≤8 L·min^{-1}), which to some extent demonstrated the possibility of empirical predictors to the self-leveling behavior.

However, it should be noticed that compared to actual reactor accident conditions (with q possibly up to a scale of several W/cc), all the up-to-date experiments performed (regardless of what 'boiling' method they have employed) as well as the empirical formulas proposed are limited to a range of extremely lower gas velocities. Focusing on this aspect, in this study a series of experiments were conducted by percolating nitrogen gas uniformly through particle beds within a much wider range of gas flow rates (currently up to 300 L·min^{-1}). Moreover, by applying dimensional analysis technique, empirical correlation set to predict the self-leveling development depending on particle size, particle density and gas injection velocity was developed. In the near future it is expectable that these correlations will be employed for the verifications of SIMMER-III, an advanced fast reactor safety analysis code.

2 Experimental apparatus and procedures

A schematic diagram of the experimental set-up used for this work is shown in Fig.3. With the effective dimensions of 310 mm in inner diameter and 1000 mm in height, a cylindrical test tank made of transparent acrylic resin was utilized to permit visual observation and video-recording. Purified water and nitrogen gas were employed to simulate the coolant and vapor (generated by coolant boiling), respectively. Water was poured into the tank from the top of the viewing tank and water-depth was adjusted to be around 180 mm before commencing each experimental run. Nitrogen gas was released into the tank from the bottom. Here, gas percolation was chosen instead of more conventional boiling ways (such as bottom-heated and volume-heated) because in this way the gas phase could be adjusted and controlled more easily. Therefore, it becomes more viable completion of our experiments required at much larger range of gas velocities. To ensure a comparatively uniform percolation of nitrogen gas, over the bottom of the viewing tank porous media (Sumitomo Electric make) were utilized as gas distributor. To regulate and accomplish desired gas flow rates, along the pipelines a number of valves and gauges were elaborately designed and equipped (see Fig.3).

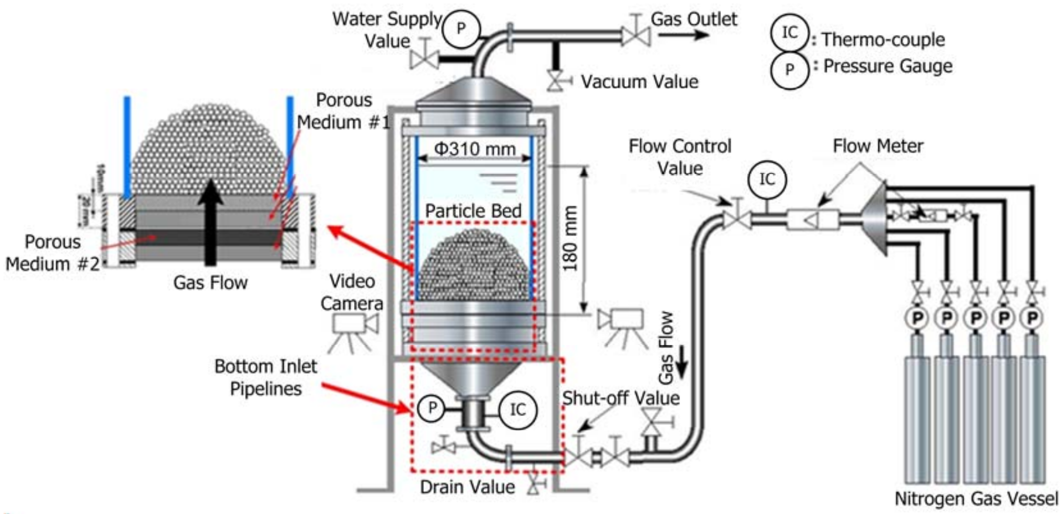

Fig. 3 Schematic diagram of experimental system.

In all experimental runs, a fixed amount of solid particles (7 L) was deposited into the tank to form a conically-shaped particle bed that simulates debris beds generated during CDAs. Currently, particle beds were formed with three types of particles (namely alumina, zirconia and stainless steel beads) of varying sizes ranging from 2.0 mm to 6.0 mm. Table 1 summarizes the physical properties of these particles.

Table 1 Physical properties of particle beads used

Material	d_p / mm	ρ_p/ kg·m^{-3}	ε_s / %	V_T /10^{-1} m·s^{-1}
Alumina sphere	2.0	3600	61.2	3.69
	4.0		62.7	5.89
	6.0		59.1	7.32
Zirconia sphere	2.0	6000	62.1	5.34
	4.0		61.5	8.29
	6.0		59.3	10.07
Stainless steel sphere	2.0	7800	61.8	6.35

During experiments, two video cameras, both capable of recording tens of frames per second, were used to record the movements of the particle bed through two perpendicular directions. By using image analysis software, still frames extracted afterwards from the video recordings were used for quantitative measurement and analyses. Figure 4 demonstrates the definition of measured inclination angle of the mound used for following analyses. Clearly, the tangent of the inclination angle equals the ratio of the maximum height of the apex to the radius of the viewing tank. Thus, the inclination angle describes the overall average shape of the particle bed rather than its local periphery shape. To quantify the transient behavior associated with self-leveling, we further define:

$$R(t)=\frac{\text{Inclination angle at time } t}{A_0} \quad (1)$$

where A_0 (degree) denotes the initial inclination angle (0 s).

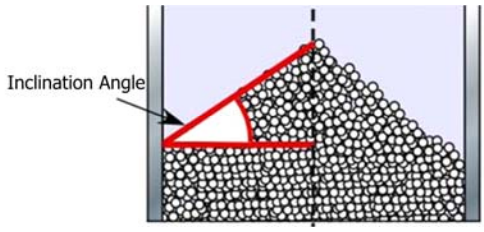

Fig.4 Diagram of measured inclination angle.

To obtain the general characteristics of self-leveling with various kinds of particles, different gas flow rates were used. Table 2 lists the experimental parameter settings currently used, including particle size (d_p), particle density (ρ_p), as well as gas flow rate (Q_g) or gas velocity (U_g).

Table 2 Experimental parameters

Case No.	Material	d_p / mm	Initial inclination angle / (°)	Q_g /L·min^{-1}	U_g / ×10^{-3} m·s^{-1}
1	Alumina	2	18.8	9.2	2.02
2			18.9	20.4	4.50
3			18.8	27.8	6.13
4			19.5	40.2	8.88
5			17.7	48.2	10.65
6		4	18.4	9.2	2.03
7			18.8	28.8	6.36
8			18.1	54.6	12.05
9			18.9	110.4	24.38
10		6	19.0	50.1	11.07
11			18.6	100.0	22.09
12			18.9	212.5	46.95
13	Zirconia	2	18.4	37.3	8.24
14			18.4	102.8	22.71
15		4	19.5	98.1	21.67
16			19.2	205.8	45.46
17		6	18.4	109.8	24.26
18			18.3	222.7	49.19
19			17.5	305.7	67.55
20	Stainless steel	2	17.7	51.7	11.42
21			18.4	100.8	22.27

3 Development of empirical correlations

In the self-leveling experiments, we observed that the particles at the surface of the debris bed are pushed up by the flow inside the bed (caused by gas percolation) and detach from the debris bed to cascade down the slope to rest at the base of the particle-bed mound. Cascading is influenced by convective flows in the water pool. Fig.5 schematically shows this movement which underpins particle bed leveling. Although in the past, numerous experimental and model-based studies have been conducted in an attempt to clarify the fluidization behavior in multi-phase systems[14], these findings might not be directly applicable as in the current system the particle bed is far from fluidized.

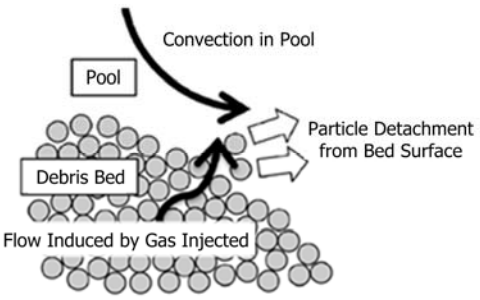

Fig.5 Schematic view of self-leveling mechanism.

Noting this distinct difference, attention was focused on previous literatures regarding the analysis of packed bed movement. Koide *et al.*[15,16] and Abraham *et al.*[17] have both experimentally studied the critical gas velocity (U_{gc}) required for the suspension of solid particles (or particle aggregates) in three-phase columns. From these studies, column dimensions and shape, sparger design and properties of the liquid and solid particles were observed to have a strong influence on U_{gc}. Furthermore, they proposed some rational empirical correlations to estimate U_{gc}. Since there are obvious similarities between those investigations and the self-leveling behavior currently studied, as aforementioned, attempts were successfully made to advance empirical formulas for previous investigations at relatively lower gas velocities[14]. In this section, we will develop new correlations using the current experimental data set.

In an analogous manner, for a specific time t_0 we assume that the following dimensionless form may be advanced[13,14]:

$$R(t_0)=\mathrm{f}\left(\frac{U_\mathrm{g}}{V_\mathrm{T}},\frac{\mu V_\mathrm{T}}{\sigma},\frac{\rho_\mathrm{p}-\rho_\mathrm{l}}{\rho_\mathrm{l}}\right) \quad (2)$$

where μ (Pa·s) is the liquid viscosity, σ ($\mathrm{N\cdot m^{-1}}$) is the liquid surface tension, ρ_p ($\mathrm{kg\cdot m^{-3}}$) and ρ_l ($\mathrm{kg\cdot m^{-3}}$) are the particle and liquid densities, respectively. U_g ($\mathrm{m\cdot s^{-1}}$) is the gas velocity based on cross-sectional area, and V_T ($\mathrm{m\cdot s^{-1}}$) is the particle terminal velocity approximated by Stokes' law for small particles (Reynolds number≤0.2) and the Heywood tables for larger particles (0.2<Reynolds number≤10^5)[18]. Eq.(2) can be rewritten in functional form as

$$R(t_0)=K\left(\frac{U_\mathrm{g}}{V_\mathrm{T}}\right)^\mathrm{a}\left(\frac{\mu V_\mathrm{T}}{\sigma}\right)^\mathrm{b}\left(\frac{\rho_\mathrm{p}-\rho_\mathrm{l}}{\rho_\mathrm{l}}\right)^\mathrm{c} \quad (3)$$

or in logarithmic form

$$\ln R(t_0)=\ln K+a\ln\left(\frac{U_\mathrm{g}}{V_\mathrm{T}}\right)+b\ln\left(\frac{\mu V_\mathrm{T}}{\sigma}\right)+c\ln\left(\frac{\rho_\mathrm{p}-\rho_\mathrm{l}}{\rho_\mathrm{l}}\right) \quad (4)$$

where K, a, b and c are empirical constants.

Based on the experimental parameters and inclination angles measured for the 21 experimental runs in this study, the dimensionless terms in Eq.(4) ($\ln R(t_0)$, $\ln K$, $\ln(U_\mathrm{g}/V_\mathrm{t})$ and $\ln((\rho_\mathrm{p}-\rho_\mathrm{l})/\rho_\mathrm{l})$) were calculated. Further, by performing linear regression analysis, constants K, a, b and c could be evaluated. The following dimensionless correlation was obtained for the final experimental state (t_0=180 s) with a correlation coefficient of 0.979:

$$\ln R(180\mathrm{s})=0.671-0.100\ln\left(\frac{U_\mathrm{g}}{V_\mathrm{T}}\right)+ 0.635\ln\left(\frac{\mu V_\mathrm{T}}{\sigma}\right)+0.465\ln\left(\frac{\rho_\mathrm{p}-\rho_\mathrm{l}}{\rho_\mathrm{l}}\right) \quad (5)$$

where

$$0.0034\le\frac{U_\mathrm{g}}{V_\mathrm{T}}\le 0.067$$

$$0.369\ \mathrm{m\cdot s^{-1}}\le V_\mathrm{T}\le 1.007\ \mathrm{m\cdot s^{-1}}$$

$$2\ \mathrm{mm}\le d_\mathrm{p}\le 6\ \mathrm{mm}$$

$$2.6\le\frac{\rho_\mathrm{p}-\rho_\mathrm{l}}{\rho_\mathrm{l}}\le 6.8\ \text{(with water as liquid phase)}$$

Figure 6 shows the comparison of experimental values with predicted values for $R(t_0)$ according to Eq.(5). It can be seen that the agreement between the predicted and experimental values is fairly good with RMS error of 3.72%.

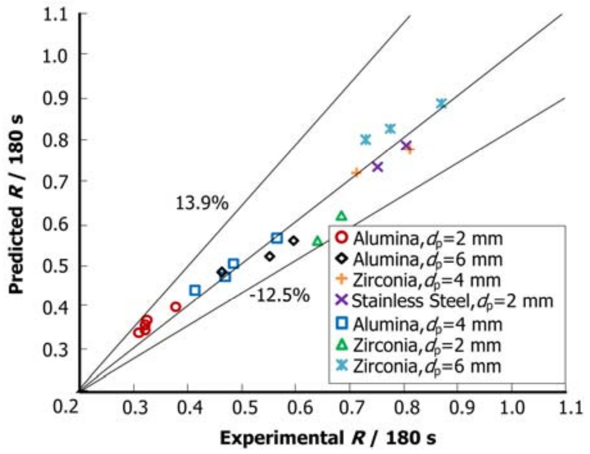

Fig.6 Comparison of experimental values with predicted values of R (180 s), RMS error=3.72%.

To further predict the transient behavior, characteristics of the time variation of inclination angle was analyzed. It is noticeable that $R(t)$ should be a decreasing function with the following boundary conditions:

$$\text{at } t=0,\ R(t)=1 \tag{6}$$

at $t=t_0$,

$$R(t)=R(t_0) \text{ (as predicted by Eq.(3))} \tag{7}$$

Also, according to the definition, its domain should be

$$R(t)\geq 0 \quad \text{(for any } t\text{)} \tag{8}$$

To satisfy Eqs.(6)−(8), the following dependency is assumed as

$$\frac{1-R(t)}{1-R(t_0)}=(\frac{t}{t_0})^{\mathrm{n}} \tag{9}$$

where n is a characteristic exponent defined to express the average leveling rate[14]. Overall, the faster the leveling process is, the smaller the n value is. Similarly, for the current experimental data, the following correlation can be found with a correlation coefficient of 0.954:

$$\ln n=0.55-0.105\ln(\frac{U_g}{V_{\mathrm{T}}})+0.745\ln(\frac{\mu V_{\mathrm{T}}}{\sigma})+0.445\ln(\frac{\rho_{\mathrm{p}}-\rho_{\mathrm{l}}}{\rho_{\mathrm{l}}}) \tag{10}$$

Equation(10) has the same validity range as Eq.(5). The parity plot for Eq.(10) is shown in Fig.7. The maximum relative error is approximately 29.8 %, indicating a respectable agreement existing between the n values predicted by Eq.(10) and its counterparts estimated from experimental fittings.

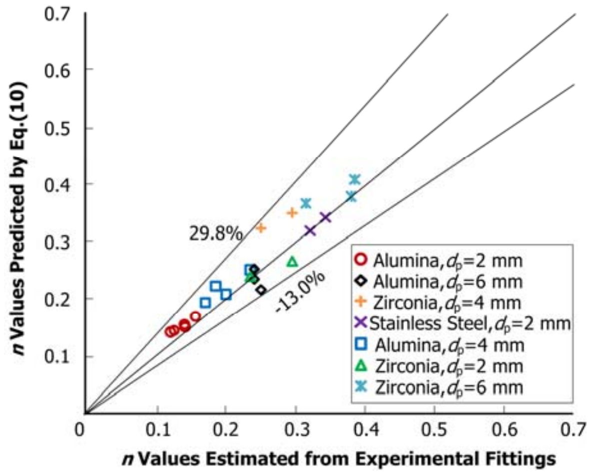

Fig.7 Comparison between values estimated from experimental fittings and its calculated counterparts according to Eq.(10), RMS error=2.46%.

Substituting the values of $R(t_0)$ and n given by Eqs.(5) and (10), respectively, into Eq.(9), we can calculate $R(t)$. The detailed comparison between experimental and predicted values of $R(t)$ is shown in Fig.8. Although uncertainties may be present in Eqs.(5) and (10) (see Figs.6 and 7), the current set of correlations seems to describe relatively well all 21 experimental runs in this study with an average RMS error of 10.04 %.

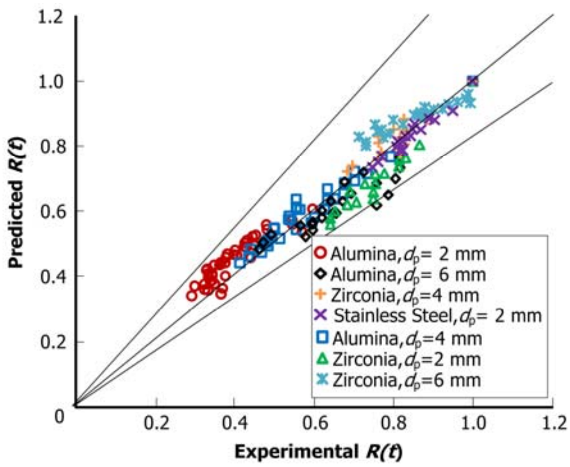

Fig.8 Parity plot for $R(t)$.

Figure 9 depicts the transient variation of particle bed with gas flow rate for several typical experimental runs using different particles. Overall, it seems that higher gas flow rate facilitates the leveling, and results in faster decrease in $R(t)$. In our previous studies performed at lower range of gas velocities[2-4,8,13,14], a similar influence of gas flow rate or its analogous role, the equivalent power density in bottom-heating and depressurized boiling experiments, was also recognized. This might be explained by the facts that as already verified in the related flow regime studies[9,12], gas velocity does have influence on the regime transition, i.e. as gas velocity increases, a greater impetus for lifting solid particles is attained, thereby leading to the transition of bubbling behaviors, even from the trapping regime to the coalescing regime. The influence of gas flow rate can be well represented by the current set of equations, thereby demonstrating to some degree its ability in predicting self-leveling behavior.

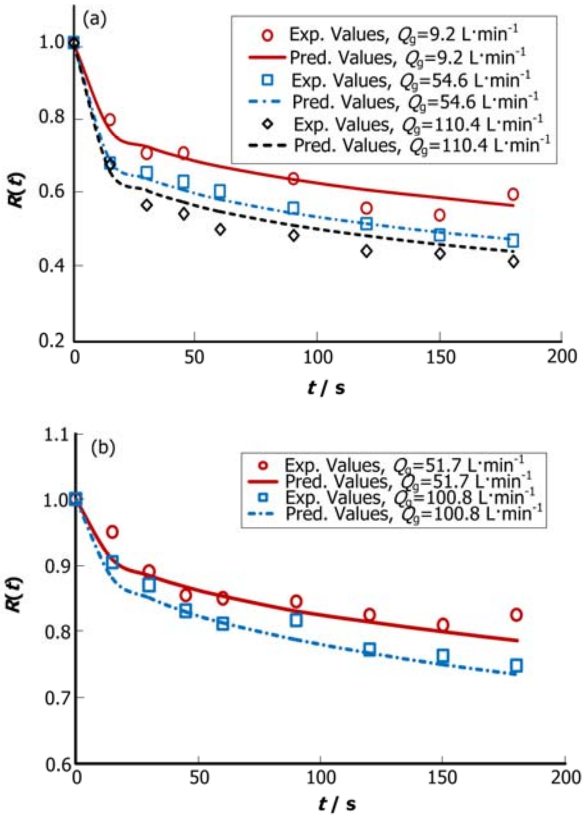

Fig.9 Effects of gas flow rates on Alumina, d_p=4 mm (a) and stainless steel, d_p=2 mm (b).

Figures 10 and 11 respectively plot the transient variation of particle bed with particle size and density for several typical experimental runs at different gas flow rates. Similar to former investigations at lower gas velocities[2-4,8,13,14], a slower decrease in $R(t)$ can be observed as particle diameter or density increases. This is because whatever the gas flow rate is, with the increase in particle size or density, particle becomes heavier and tends to be more difficult to be moved by the gas flow inside the bed, as confirmed in our earlier studies regarding flow regime investigations[9,12]. Again, the good agreement between the experimental and model predicted data on the influence of particle size and density provides confirmation of our proposed empirical equations.

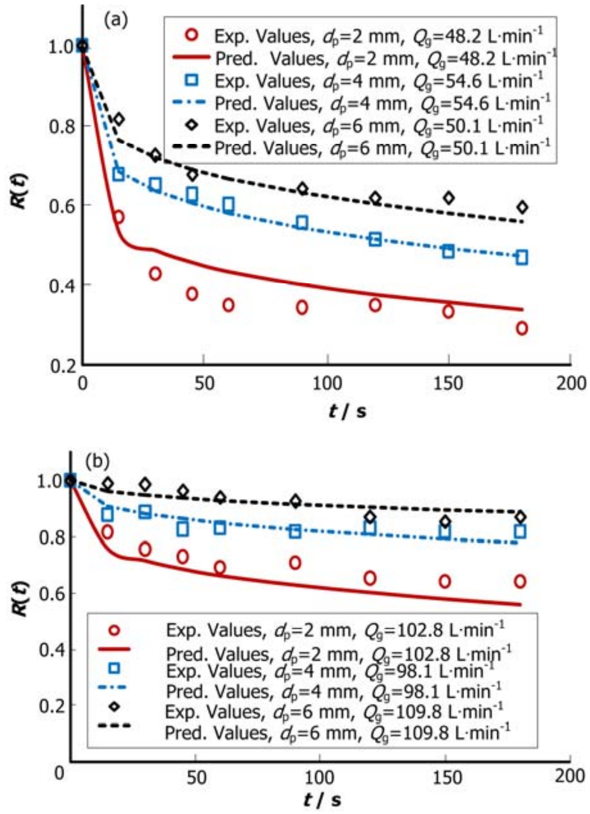

Fig.10 Effects of particle sizes on $R(t)$, Alumina particle, Q_g=50 L·min^{-1} (a) and Zirconia, Q_g= 100 L·min^{-1} (b).

Finally, as stated-above, to clarify the overall mechanisms of self-leveling behavior, several series of experiments have been previously performed by employing depressurization and bottom-heating boiling methods[2,8]. By making quantitative analyses, it was even confirmed that the self-leveling behavior under the two different boiling modes proceeded in almost the same way. To further check the influence of boiling mode on the leveling, comparative analyses were made between experimental data of several typical runs performed using the depressurization boiling and the corresponding predicative results of current empirical equations (as plotted in Fig.12). It seems that although current set of equations can predict leveling behavior under gas-injection conditions over comparatively wider range of gas velocities (see Fig.8). It tends to generally predict faster leveling development under the employed boiling conditions, especially during the initial periods.

This should be primarily due to the difference in 'boiling' or 'gas percolation' patterns of the two systems. The previous depressurization and bottom-heating experiments were focused on an early subcooled boiling periods, in which the steam condensation occurs and boiling intensity is not constant but increasing as the water subcooling decreases, while in the current system the simulated 'boiling' by 'gas percolation' to some extent resembles quasi-steady bulk boiling more in characteristics. As a result, relatively larger intensity of gas flows in the beds under the present gas-injection conditions might lead to much faster development of the self-leveling. The present comparison suggests that coolant vapor condensation in the bed and the subcooled pool would significantly changes the characteristics of the self-leveling dynamics.

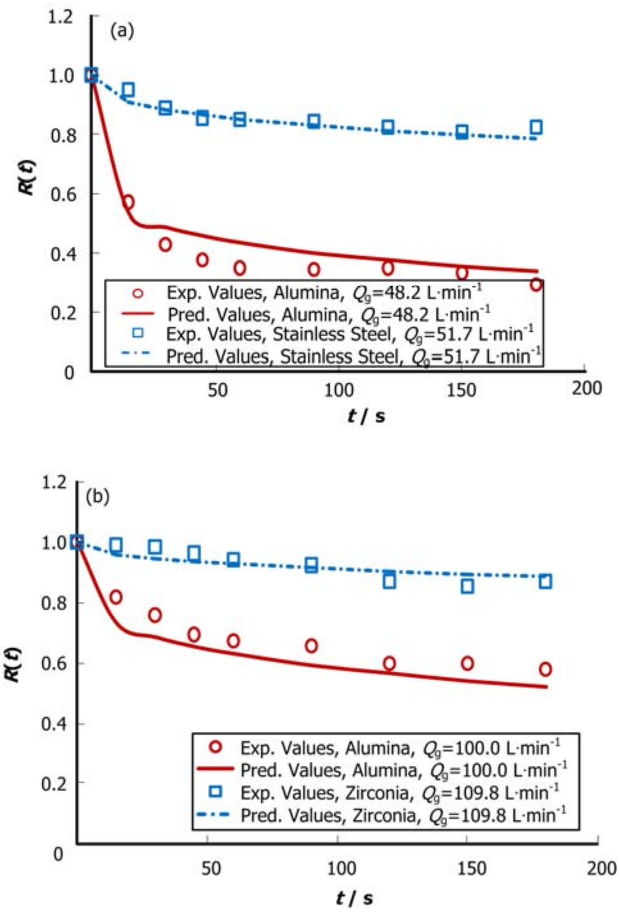

Fig.11 Effects of particle density on $R(t)$ with d_p=2 mm, Q_g=50 L·min^{-1} (a) and d_p=6 mm, Q_g =100 L·min^{-1} (b).

The above analysis can be further confirmed by comparing experimental runs with different boiling intensities. As also shown in Fig.12, the prediction error seems much diminished under higher boiling conditions. This might be due to the fact that highly-increased boiling intensity perhaps leads to a rapid increase of gas velocities, particularly for the early boiling periods, as a result making the difference between boiling and gas-injection comparatively narrowed.

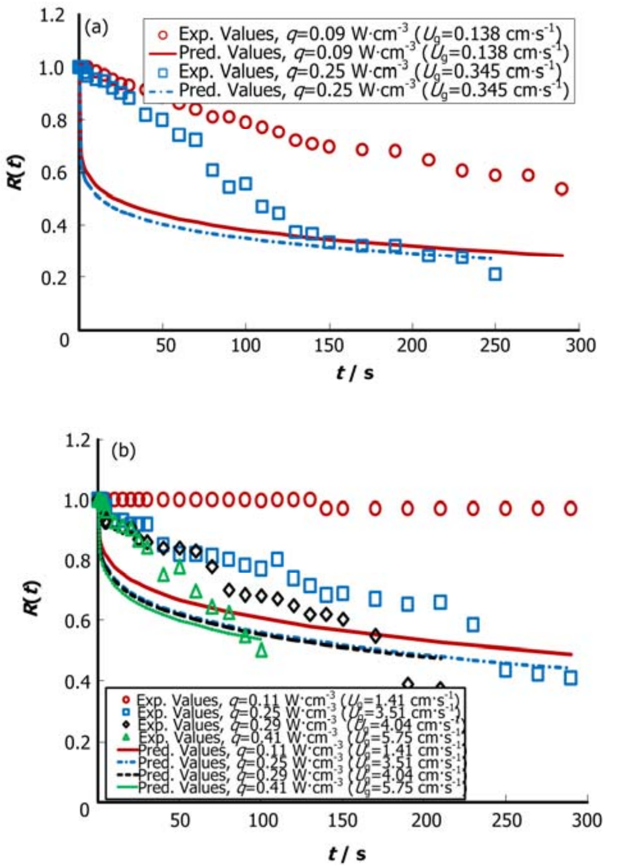

Fig.12 Predictability of current equation set to previous boiling experiments.

However, we need to point out that the difference in 'boiling' patterns should not impair the applicability of current findings obtained from gas-injection conditions. This is because, as already concluded from the related flow regime investigations[9,12], the observed bubbling behaviors, dominated by the different interaction mechanisms between solid particles and bubbles, are common characteristics over a wide range of conditions, regardless of 'boiling' method. To facilitate the numerical simulation of self-leveling, currently several mechanism models treating the particle-particle and particle-bubble interactions are being developed and incorporating into SIMMER-III, an advanced fast reactor safety analysis code[19]. The extensive experimental data as well as empirical correlations developed in this work, although not covering the entire range of physical properties of fuel debris and coolant, provides critical evidence and insight for the verifications of those models.

4 Conclusion

Debris bed self-leveling behavior is of essential importance to the heat removal capability as well as recriticality for fast reactors during CDAs. To further clarify the mechanisms of this phenomenon, a series of experiments were performed by percolating nitrogen gas uniformly through particle beds at much wider range of gas flow rates (up to around 300 $L \cdot min^{-1}$).

Based on the experimental observations and data obtained for different particle sizes, particle densities and gas flow rates, with the help of dimensional analysis technique, a set of empirical correlations was successfully developed for evaluating the transient variation in the bed inclination angle during the leveling process. Estimations of values yielded respectable results within a fair degree of accuracy given the current range of experimental conditions (with RMS error of 10.04 %). In addition, the followed analysis of the influence of particle size, particle density, gas flow rate as well as boiling mode further guarantees its rationality,which to some extent confirms the applicability of empirical predictors to the self-leveling behavior under current conditions. In order to benefit future simulation and analysis of CDAs in FBRs, the developed equations will be employed for the validations of SIMMER-III, an advanced fast reactor safety analysis codes.

Acknowledgments

The experiments involved were mainly performed using the facilities in Kyushu University.

Nomenclatures

Q_g / $L \cdot min^{-1}$ Volumetric gas flow rate

U_g / $cm \cdot s^{-1}$ Gas velocity based on cross-section of particle bed

U_{gc} / $m \cdot s^{-1}$ Critical gas velocity

d_p / mm Particle diameter

V_T / 10^{-1} m/s Terminal velocity of a single particle in stagnant liquid

t / s Time

t_0 / s A specific time

q / $W \cdot cc^{-1}$ Power density of debris bed

$R(t)$ Ratio of inclination angle at time t to the initial angle (0 s)

A_0 / (°) Initial inclination angle (0 s)

ε_s / % Solid holdup

ρ_p / $kg \cdot m^{-3}$ Particle density

ρ_l / $kg \cdot m^{-3}$ Liquid density

μ / $Pa \cdot s$ Liquid viscosity

σ / $N \cdot m^{-1}$ Liquid surface tension

References

1 Tentner A M, Parma E, Wei T. ANL-GENIV-128: Evaluation of Design Measures for Severe Accident Prevention and Consequence Mitigation, Argonne National Laboratory, Argonne, USA, 2010.

2 Zhang B, Harada T, Hirahara D. Nucl Eng Des, 2011, **241:** 366−377.

3 Zhang B, Harada T, Hirahara D. N6P1042: Experimental Study of Self-Leveling Behavior in Debris Bed, the Sixth Japan-Korea Symposium on Nuclear Thermal Hydraulics and Safety (NTHAS6), Okinawa, Japan, Nov.24−27, 2008.

4 Zhang B, Harada T, Hirahara D. N13P1212: Criteria for Occurrence of Self-Leveling in the Debris Bed, 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-13), Kanazawa, Japan, Sept.27−Oct.2, 2009.

5 Waltar A E, Reynolds A B. Fast breeder reactors. New York (USA): Pergamon Press, 1981, 671−677.

6 Nakai R, Suzuki T, Yamano H. Paper9117: Development of Severe Accident Evaluation Technology (Level 2 PSA) for Sodium-cooled Fast Reactors (1) Overview of Evaluation Methodology Development, 2009 International Congress on Advances in Nuclear Power Plants (ICAPP '09), Tokyo, Japan, May 10−14, 2009.

7 Nakai R, Suzuki T, Yamano H. N8P0095: Development of Level 2 PSA Methodology for Sodium-Cooled Fast Reactors (1 Overview of Evaluation Technology Development, the 8th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-8), Shanghai, China, Oct. 10−14, 2010.

8 Zhang B, Harada T, Hirahara D. J Nucl Sci Technol, 2010, **47:** 384−395.

9 Cheng S, Hirahara D, Tanaka Y. ICONE18-29710: Experimental study of bubble behavior in a two-dimensional particle bed with high solid holdup, 18th International Conference on Nuclear Engineering (ICONE-18), Xi'an, China, May 17–21, 2010.

10 Hesson J C, Sevy R H, Marciniak T J. ANL-7859: Post-Accident Heat Removal in LMFBRs: In-Vessel Considerations, Argonne National Laboratory, Argonne, USA, 1971.

11 Gabor J D. ANL-RDP-32: Simulation Experiments for Internal Heat Generation, Argonne National Laboratory, Argonne, USA, 1974.

12 Cheng S, Hirahara D, Tanaka Y. Exp Therm Fluid Sci, 2011, **35:** 405−415.

13 Cheng S, Tanaka Y, Gondai Y. N7P0009: Experimental Investigation on Self-leveling Behavior in Debris Bed, 7th Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety (NTHAS7), Chuncheon, Korea, Nov.14−17, 2010.

14 Cheng S, Tanaka Y, Gondai Y. J Nucl Sci Technol, 2011, **48:** 1327−1336.

15 Koide K, Yasuda T, Iwamoto S. J Chem Eng Jpn, 1983, **16:** 7−12.

16 Koide K, Horibe K, Kawabata H J. Chem Eng Jpn, 1984, **17:** 368−374.

17 Abraham M, Khare A S, Sawant S B. Ind Eng Chem Res, 1992, **31:** 1136−1147.

18 Holdich R G. Fundamentals of Particle Technology. Nottingham (UK): Midland Information Technology & Publishing, 2002, 45−54.

19 Tagami H, Tobita Y. N8P1049: Application of a large deformation method for self-leveling behavior, 8th Japan-Korea Symposium on Nuclear Thermal Hydraulics and Safety (NTHAS8), Beppu, Japan, Dec. 9−12, 2012.