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An investigation on debris bed self-leveling behavior with non-spherical particles

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Studies on debris bed self-leveling behavior with non-spherical particles are crucial in the assessment of actual leveling behavior that could occur in core disruptive accident of sodium-cooled fast reactors. Although in our previous publications, a simple empirical model (based model), with its wide applicability confirmed over various experimental conditions, has been successfully advanced to predict the transient leveling behavior, up until now this model is restricted to calculations of debris bed of spherical particles. Focusing on this aspect, in this study a series of experiments using non-spherical particles was performed within a

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recently-developed comparatively larger-scale experimental facility. Based on the knowledge and data obtained, an extension scheme was suggested with the intention to extend the base model to cover the particle-shape influence. The proposed scheme principally consists of two parts-with one part for correcting the terminal velocity of a single non-spherical particle, which is the key parameter in our base model, and the other for representing the additional particle-particle interactions caused by the shape-related parameters. Through detailed analyses, it is found that by coupling this scheme, good agreement between experimental and predicted results can be achieved for both spherical and non-spherical particles given current range of experimental conditions.

Keywords; sodium-cooled fast reactor; core disruptive accident; debris bed; self-leveling; non-spherical particle; empirical model; extension scheme

1. Introduction

In a postulated core-disruptive accident (CDA) of a sodium-cooled fast reactor, core debris might settle on the core-support structure and/or in the lower inlet plenum of the reactor vessel (as illustrated in **Figure 1**) because of rapid quenching and fragmentation of molten core materials in the subcooled sodium plenum [1, 2]. Typically, the debris bed will form roughly conically-shaped mounds. However, coolant boiling caused by decay heat, might lead ultimately to leveling of the debris bed [2, 3]. This mechanism, as illustrated in **Figure 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-vessel retention devices are used in some SFR designs [1]. A multi-layered debris tray installed in the bottom region of the vessel is one of such devices [4]. During a hypothetical CDA, after being quenched and fragmented into fuel debris in the lower plenum region, discharged molten fuel is expected to accumulate on the different layers of the debris tray [4]. 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 trays. 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, 3].

Unfortunately, over the past decades very little work related to self-leveling has been performed. Most of the studies generally assume that the upper surface of debris bed is level. Noting the importance of self-leveling in the heat removal capability, Hesson et al. and Gabor began some pioneering experimental studies on this subject [5, 6]. 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 these studies, Alvare and Amblard used copper-water beds to further conclude that boiling even with low power promoted the leveling [7].

To clarify the mechanisms underlying this behavior, in recent years several series of experiments were elaborately designed and conducted under the collaboration between Japan Atomic Energy Agency (JAEA) and Kyushu University (Japan) [8]. Overall, as illustrated in **Figure 3**, those experiments can be generally divided into two categories, namely the macroscopic leveling experiments and microscopic flow-regime investigations. Due to the nontransparency of particle beds, the macroscopic leveling experiments were mainly performed to clarify the overall characteristics of leveling [2, 3, 8-10], namely the role of experimental parameters (such as particle properties and bubbling rate) on its onset and evolution. In those experiments, to simulate the coolant boiling during CDAs, various experimental methods, including depressurization boiling, bottom-heated boiling as well as gas-injection, have been employed. As for the microscopic flow-regime series [8, 11, 12], which also consists of several well-organized tests performed at various bubbling conditions (as shown in Figure 3), was specifically conducted to ascertain the flow characteristics within particle beds, thus providing convincible visual evidence (esp. bubble-particle interaction) for supporting the overall understandings. It has been confirmed that by combining the knowledge from flow-regime investigations the observed overall leveling characteristics can be understood more effectively [8].

On the other hand, aside from experimental investigations, modeling studies and numerical simulations are also progressing. For instance, SIMMER-III, an advanced fast reactor safety analysis code [13], is currently being developed by incorporating several computer models treating the particle–particle and particle-bubble interactions (e.g. the discrete element method) [14-17]. However, due to the extremely complex and uncertain nature of the three-phase flow involved in the leveling phenomenon [2, 9], empirical approach is still regarded as an attractive and indispensable option at present stage because of its distinct advantage in calculation efficiency. On one hand, with an effective empirical model, experimental database can be expanded (interpolated or extrapolated) with much lower cost. On the other hand, the derivation and analyses of empirical approach do provide useful knowledge for computer model improvement and verifications. Focusing on these aspects, originally by applying dimensional analysis technique, a simple empirical approach was successfully advanced based on the experimental data from the quasi-2D leveling test (shown in Figure 3) [9, 18]. Motivated by the potential of utilizing this approach at actual reactor accident conditions, recently its wide applicability has been further confirmed through several validation projects involving a great amount of experimental data from various conditions, including difference in bubbling mode (boiling or gas-injection), bed geometry and range of experimental parameters [9, 19-21].

However, it should be noticed that up until now, the developed empirical model (hereafter referred to as "base model") is restricted to calculations of debris beds composed of spherical particles [9, 19-21]. Recognizing that in actual reactor accident conditions debris mounds formed with irregularly-shaped particles are more commonly encountered, therefore there is a pressing need to check whether the base model is extendable to cover such complex situations. The current paper is dedicated to this issue. In Section 2, conditions of the experiments involved in this work, including the large-scale leveling experiment (see Figure 3) as well as a pressure-drop measurement facility developed for acquiring a shape-related parameter (sphericity ϕ), are presented, while in Section 3, after a brief description of the base model, an extension scheme is suggested with an aim to incorporate the particle-shape influence. Further, in Section 4, based on the latest experimental data available, incorporation results of the proposed scheme are analyzed.

2. Description of Experiments

2.1. Self-Leveling Experiment

Figure 4 shows the schematic diagram of the large-scale leveling experimental setup used in this work. Here, this setup is selected instead of others because a much larger range of gas velocities (presently up to around 300 L/min) can be accomplished at normal three-dimensional conditions [10].

To permit visual observation and video-recording, a transparent cylindrical tank, with the effective dimensions of 310 mm in inner diameter and 1000 mm in height, was utilized. 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 tank and water-depth was adjusted to a height of around 180 mm before commencing each experimental run. Nitrogen gas was released into the tank from the bottom. To ensure a comparatively uniform percolation of nitrogen gas, over the bottom of the test tank porous media 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 Figure 4).

In recent years, over this setup extensive experimental runs using various spherical particles have been conducted [8, 10] and based on the data obtained good applicability of the base model has been also confirmed [19, 20]. In the current study, similar to the runs using spheres, a fixed volume of non-spherical solid particles (7 L) was deposited into the tank to form a conically-shaped particle bed that simulates the debris beds generated during CDAs. Currently, particle beds were formed with two types of non-spherical particles (namely alumina and stainless steel) of varied sizes and shape characteristics. **Table 1** lists the physical properties of these particles.

It is observed that due to the gravity as well as voids existing within particle beds and porous media, liquids poured into the test tank could immediately penetrate and fill up the bottom inlet pipelines (see Figure 4), even prior to the start-up of each experimental run. These accumulated liquids, with a sudden triggering from the gas flow injected afterwards, will flood upwards and collapse the particle mounds within split seconds. To alleviate the disturbance from accumulated liquids, a pressure-adjustment method, which aims on eliminating all accumulated liquids out of the bottom inlet pipelines by creating and keeping a comparatively lower pressure within the test tank, was utilized [10]. In addition, it has been also noticed that the comparatively larger gas flow rate in the current system would lead to extremely dense distribution of bubbles within water pool, as a result making particle beds even invisible. Therefore, an intermittent gas delivery method is employed for measuring. Reasonability of these treatments has been well verified in our previous publications [10].

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 different directions. By using image analysis software, still frames extracted afterwards from the video recordings were used for quantitative measurement and analyses. Since the spatial configuration of debris beds is a critical parameter for its coolability, e.g. tall mound shape debris bed is hardly coolable, as demonstrated in **Figure 5**, an overall bed inclination angle rather than local periphery shape is measured for the following analyses. To quantify the transient behavior associated with the leveling, we further introduce $R(t)$:

$$R(t) = \frac{\text{Inclination angle at time } t}{\text{Initial inclination angle } A_0 (t = 0\text{s})} \quad (1)$$

Evidently, the initial bed angle A_0 is also an important parameter that may impair the accuracy of the following analyses. Here, to achieve a purer analysis of the particle-shape influence on the leveling evolution, aside from pilling-up of the initial bed mound carefully, based on the knowledge from previous analyses [10, 21], the experimental data is further calibrated ensuring that for all the runs performed the A_0 used for analyses is varied within a rather limited range (e.g. around 18~20 degree).

To obtain the general characteristics of self-leveling with non-spherical particles, different gas flow rates were used. A summary of the gas flow rates employed for each particle is given in Table 1.

2.2. Pressure-Drop Measurement Experiment

It has been well-known that under actual reactor conditions, instead of a few fixed shapes, there is the possibility for debris to be formed with a variety of irregular shapes [23]. Therefore, it might be not practicable to estimate the shape-related parameters directly from microscopic measurement. Since the Ergun equation has been utilized extensively by numerous investigators over the past years for the estimation of packed bed pressure drops [24-26], in this work a method by back-calculation of pressure drop using this equation is recommended for estimating the particle sphericity ϕ:

$$\frac{\Delta P}{H_{\mathrm{pb}}} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_{\mathrm{f}}}{(\phi d_{\mathrm{v}})^2}U_{\mathrm{f}} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_{\mathrm{f}}}{\phi d_{\mathrm{v}}}U_{\mathrm{f}}^{\ 2} \tag{2}$$

It is instructive to note that, although the numerical value of ϕ does not describe the accurate shape of a particle, for most engineering purposes this limitation does not matter because it can represent the overall effect of shape on hydrodynamic behavior which is of interest [25].

The experimental setup used to measure pressure drops is illustrated in **Figure 6**. A cylindrical column, with the effective dimensions of 54.5mm in inner diameter and 200mm in length, is utilized for holding particle beds. At the ends of both sides, two knit meshes of negligible resistance are installed to prevent the particles from leaving as well as for the uniform distribution of nitrogen gas which is used as working fluid. The bed pressure drop is measured by means of a precise differential pressure transducer. The gas flow rate, measured by a volumetric flow meter with accuracy up to 0.1L/min, is adjusted over a comparatively wider range for experimental measurements (up to several hundreds of L/min). Temperatures and pressures at the inlet and outlet of the column are monitored as well.

Prior to any measurement for non-spherical particles, the developed facility and its measurement system are qualified by a series of validity tests using spheres. As shown in

Figure 7, although some uncertainties are present possibly due to the potential parameters (e.g. particle roughness) that have not been considered in the Ergun equation, the comparatively good agreement to some extent justifies to the quality of our experimentation and instrumentation.

Using the validated experimentation and by back-calculation of Equation (2), the sphericity of our non-spherical particles becomes estimable and the obtained results are shown in Table 1 as well.

3. Modeling Studies

3.1. Base Model

Considering the characteristics of the leveling behavior observed [9, 19-21], based on extensive testing and error analyses, the following dependency is assumed for the transient variation of $R(t)$:

$$\frac{1-R(t)}{1-R(t_0)} = (\frac{t}{t_0})^n \tag{3}$$

Where n is a characteristic exponent defined to express the average leveling rate, and $R(t_0)$ is the ratio of inclination angle at a specific time t_0 to the initial angle A_0.

To estimate $R(t_0)$ and n, we notice that when a particle is in a force balance state (gravity force, drag force and buoyancy force), particles in the medium have reached terminal velocity. Though self-leveling behavior is quite different from the force balance state, the terminal velocity of the particle or its transformative form might be effective in characterizing the leveling [2, 9, 19]. This thought is confirmable by several prior studies regarding the analysis of packed bed movement. For instance, Koide et al. and Abraham et al. experimentally studied the critical gas velocity (U_{gc}) required for the suspension of solid particles (or particle aggregates) in three-phase columns [27-29]. In their 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}. Using the transformative form of particle terminal velocity, they successfully proposed some rational empirical correlations to estimate U_{gc}. Considering the obvious similarities between their investigations and the self-leveling behavior, in the past years the following dimensionless functions have been proposed and validated [9, 19-21]:

$$R(t_0) = K_1 (\frac{U_g}{V_T})^{A_1} (\frac{\mu_l V_T}{\sigma_l})^{A_2} (\frac{\rho_p - \rho_l}{\rho_l})^{A_3} \quad (4)$$

$$n = K_2 (\frac{U_g}{V_T})^{B_1} (\frac{\mu_l V_T}{\sigma_l})^{B_2} (\frac{\rho_p - \rho_l}{\rho_l})^{B_3} \quad (5)$$

By performing statistical analysis, the empirical constants K_i (i =1~2), A_j (j =1~3) and B_k (k =1~3) could be evaluated. Thus, by combining Equations (3) ~ (5), $R(t)$ becomes calculable. The obtained constant values as well as detailed comparison between experimental and predicted values of $R(t)$ for the large-scale leveling system are shown in **Figure 8**. It seems that the base model describes relatively well all experimental points using spherical particles, even for two testing cases that have not been used as a base for statistical derivation.

3.2. Extension Scheme

Since the particle terminal velocity is a critical parameter in the base model, it is natural that this term should be corrected as accurate as possible when we consider the modeling extension. Fortunately, we noticed that in the past decades, many empirical correlations relating the terminal velocity of a non-spherical particle to some shape-related parameters (esp. the sphericity ϕ) were developed. Here, after comprehensive evaluation, we finally choose the Geldart's method because compared to other investigators Geldart has explicitly pointed out that the sphericity used in his equations is estimated from macroscopic measurement [25], namely in a way similar to us (see Section 2.2), thereby to some extent providing us more confidence for its utilization and accuracy.

Geldart believed that the terminal velocity V_{T} of a non-spherical particle can be calculated as following [25, 30]:

$$V_{\mathrm{T}} = K_{\mathrm{T}} V_{\mathrm{TS}} \tag{6}$$

Where K_{T} is a correction factor based on particle sphericity ϕ, and V_{TS} is the terminal velocity of a sphere having the same volume (d_{v}).

By extending the work of Pettyjohn and Christiansen [31], Geldart proposed the following set of formulas for calculating the correction factor K_{T} [25, 30]:

For Re_{T} <0.2, $$K_{\mathrm{T}} = 0.843 \times \log_{10}(\phi / 0.065) \tag{7}$$

For Re_{T} >1000, $$K_{\mathrm{T}} = (0.43/(5.31 - 4.88\phi))^{1/2} \tag{8}$$

For 0.2 < Re_{T} <1000,

$$K_{\mathrm{T}} = [0.843 \times \log_{10}(\phi / 0.065) - (0.43/(5.31 - 4.88\phi))^{1/2}] \frac{1000 - Re_{\mathrm{T}}}{1000 - 0.2} + (0.43/(5.31 - 4.88\phi))^{1/2} \tag{9}$$

Where Re_{T} is the particle Reynolds number based on d_{v} at its terminal velocity.

On the other hand, from previous analyses regarding the macroscopic leveling experiments, we also observed that [2, 8, 10], possibly due to the additional particle-particle collisions and frictions caused by the shape-related parameters (such as roughness or eccentricity), particle shape is confirmable to have a suppressing role on the leveling, i.e. for the runs using non-spherical particles, the leveling proceeds more slowly or less likely to occur (see **Figure 9**). To account for this influence, two correction functions (K_3, K_4), with their form discussed later in the next Section, are being considered for correcting Equations (4) and (5), respectively:

$$R(t_0) = K_3 [K_1 (\frac{U_{\mathrm{g}}}{V_{\mathrm{T}}})^{A_1} (\frac{\mu_1 V_{\mathrm{T}}}{\sigma_1})^{A_2} (\frac{\rho_{\mathrm{p}} - \rho_1}{\rho_1})^{A_3}] \tag{10}$$

$$n = K_4 [K_2 (\frac{U_{\mathrm{g}}}{V_{\mathrm{T}}})^{B_1} (\frac{\mu_1 V_{\mathrm{T}}}{\sigma_1})^{B_2} (\frac{\rho_{\mathrm{p}} - \rho_1}{\rho_1})^{B_3}] \tag{11}$$

4. Result of Analysis

Substituting the measured sphericity (see Table 1) into Equations (6)~(9), we can calculate V_T for non-spherical particles. **Figure 10** depicts the parity plot of $R(t)$ for the experimental runs using non-spherical particles at varied gas flow rates (~300L/min) using the base model but with V_T corrected for the shape influence. It is evident that the base model, even with particle terminal velocity corrected using the Geldart's equations, tends to predict a faster leveling for the runs using non-spherical particles, which to some extent provides confirmation of our judgment in Section 3.2 that the additional correction functions (K_3, K_4) should be incorporated.

Substituting experimental $R(t_0)$ and n values as well as their predictive results using the base model with only V_T corrected into Equations (10)~(11), the additional correction factors (K_3, K_4) could be obtained. Since the fluid Reynolds number has been proven to be effective by many authors in their studies regarding developing empirical correlations for characterizing flow regimes in gas-liquid flow through packed beds [32, 33], here the variation of K_3 versus gas Reynolds number is tentatively plotted (see **Figure 11**). It seems that whatever the non-spherical particle is, as gas Reynolds number increases, K_3 tends to be decreasing. Extremely, when Re_g is large enough, K_3 seems to approach 1.0, the value for spherical particles. This might be because higher Re_g means a larger gas flow rate and further a greater impetus for lifting solid particles, as confirmable in our flow-regime investigations[8, 11-12], as a result making the additional particle-particle resistance less prominent. On the other hand, from Figure 10 it also seems that a noticeable difference is observable for those particles, indicating that aside from Re_g, the differences encountered in the particle properties (e.g. d_v, ρ_p, ε, ϕ) might be also influential to the correction functions. Since through the extensive validations performed in the past, the base model has proven itself to be comparatively applicable to represent the influence of particle size and density [9, 19-21], therefore it seems reasonable to infer that the difference in ε and ϕ

might be the potential primary contributors. Furthermore, we notice that although in general, ε is a bed parameter relating to several factors, especially the particle shape (ϕ) and packing method (loosely or tightly) [34], in our experimental conditions it should be approximately governed by ϕ since a consistent packing method (namely random-close-packing) has been employed for all the runs performed, even including the runs using spherical particles. Therefore, we believe the measured effective ϕ might be sufficient to represent those differences in particle properties.

Based on the above analyses, here a functional form for estimating K_3 is suggested:

$$K_3 = 1 + s\frac{(1-\phi)^q}{(Re_{\mathrm{g}})^p} \tag{12}$$

Obviously, when ϕ=1 or $Re_{\mathrm{g}} \to \infty$, K_3 approaches to 1. Thus, it seems that its reasonability can be well ensured.

By making regression analyses for the current dataset, constants s, p and q in Equation (12) can be evaluated and the following correlation was found with a correlation coefficient of 0.984 :

$$K_3 = 1 + 3.419 \times \frac{(1-\phi)^{1.171}}{(Re_{\mathrm{g}})^{0.527}} \tag{13}$$

In a similar way, a predictive function for K_4 is obtained with correlation coefficient of 0.952:

$$K_4 = 1 + 8.062 \times \frac{(1-\phi)^{1.317}}{(Re_{\mathrm{g}})^{0.572}} \tag{14}$$

By combining the base model with the extension scheme, an estimation of $R(t)$ for both spherical and non-spherical particles is achievable. The parity plot, shown in **Figure 12**, demonstrates that the estimated values of $R(t)$ agree reasonably well with experimentally observed values, even for non-spherical particles. Therefore, although further analyses and verifications, e.g. those investigating the interpolation/extrapolation capability of the proposed scheme (esp. Equations (13) and (14)), might be needed, to some extent the potential extension capability of our base model to predict the debris bed self-leveling behavior at more realistic bed conditions has been displayed.

Finally, we have to point out that although in reactor accident conditions debris bed is possibly formed with high temperature, in our leveling studies we have focused our attention primarily on its overall hydrodynamic motion. In addition, we have to also stress that, as aforementioned, apart from empirical model investigations, owing to the experimental knowledge that the self-leveling behavior might be dominated by the solid phase [8, 12, 19], currently several computer models treating the particle–particle and particle-bubble interactions are being developed and incorporating into SIMMER-III, an advanced fast reactor safety analysis code [14-17]. Therefore, aside from further empirical-approach investigations at various situations that may be encountered under reactor accident conditions, knowledge and expanded database from this work might be also utilized for the improved verifications of those computer models [19]. We believe some of the potential issues (e.g. the difference of thermo-physical properties between water and sodium) might be also solvable by the well-verified SIMMER-III code in the near future.

5. Concluding remarks

Motivated to provide some insight for a better understanding and an improved estimation of CDAs in SFRs, a series of experiments was carried out to investigate the characteristics of debris bed self-leveling behavior using non-spherical particles. Owing to the knowledge and data obtained, an extension scheme has been advanced to incorporate the particle-shape influence into a base model which is restricted to calculations of debris beds composed of spherical particles. The proposed scheme mainly consists of two parts-with one part for correcting the terminal velocity of a single non-spherical particle, which is the key parameter in the base model, and the other part for representing the additional particle-particle interactions caused by the shape-related parameters. It is found that by coupling this scheme, a good agreement between experimental and predicted results can be achieved for both spherical and non-spherical particles given the current range of experimental conditions. Although further investigations might be necessary, the current study to some extent has confirmed the potential extension capability of our base model for estimation of debris bed self-leveling behavior at more realistic bed conditions.

The knowledge and fundamental data obtained from this work might be also utilized for future analyses and verifications of some particle-based models developed for SIMMER-III, an advanced fast reactor safety analysis code.

Nomenclature

A_0	Initial bed angle [degree]
A_j, B_k (j, k =1~3)	Empirical constants defined in Equations (4)~(5)
d_p	Particle diameter [mm] or [m]
d_v	Volume-equivalent diameter of non-spherical particle [mm] or [m]
K_1, K_2	Empirical constants defined in Equations (4)~(5)
K_3, K_4	Correction functions representing additional shape-induced particle-particle interaction [-]
K_T	A correction factor for estimating V_T of a non-sphere [-]
m	Total mass of the weighed particles [kg]
N	Total number of the weighed particles [-]
n	A characteristic exponent defined to express the average leveling rate [-]
ΔP	Pressure drop [Pa]
H_{pb}	Bed height [m]
Q_g	Gas flow rate [L/min] or [ml/min]
$R(t)$	Ratio of inclination angle at time t to the initial angle (0 s) [-]
Re_g	Gas Reynolds number ($\rho_g U_g d_v / \mu_g$), [-]

Re_T	Particle Reynolds number based on d_v at its terminal velocity[-]
t	Time [s]
t_0	A given or specific time [s]
U_g (or U_f)	Superficial velocity of gas (or fluid)[m/s]
U_{gc}	Critical gas velocity [m/s]
V_T	Terminal velocity of a single particle (sphere or non-sphere) in stagnant liquid [m/s]
V_{TS}	Terminal velocity of a sphere having the same volume (d_v)[m/s]
s, p, q	Empirical constants defined in Equation (12)

Greek Letters

ε	Bed voidge [-]
ϕ	Particle sphericity [-]
ρ_g	Gas density [kg/m^3]
ρ_l (or ρ_f)	Liquid (or fluid) density [kg/m^3]
ρ_p	Particle density [kg/m^3]
μ_g	Gas viscosity [Pa·s]
μ_l (or μ_f)	Liquid (or fluid) viscosity [Pa·s]
σ_l	Liquid surface tension [N/m]

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Figure captions

Figure 1. Debris bed formation.

Figure 2. Self-leveling behavior.

Figure 3. Constitution of performed leveling-related experiments.

Figure 4. Schematic diagram of experimental setup.

Figure 5. Diagram of measured bed inclination angle.

Figure 6. Schematic view of experimental setup for pressure-drop measurement.

Figure 7. Comparisons between predicted and measured pressure drops using the test spheres.

Figure 8. Parity plot comparing predicted $R(t)$ with experimental data using the base model (spherical particle).

Figure 9. Effect of particle shape on the leveling behavior.

Figure 10. Parity plot comparing predicted $R(t)$ with experimental data using the base model with only V_T corrected (non-spherical particle).

Figure 11. Characteristics of K_3 with different Re_g.

Figure 12. Parity plot of $R(t)$ for both spherical and non-spherical particles with the extension scheme coupled.

Table 1. Physical properties of non-spherical particles and the gas flow rates employed.

Material	d_v [a](mm)	ρ_p (kg/m^3)	ϕ [b](-)	V_{TS} [c](m/s)	Q_g (L/min)
Alumina	1.58	3600	0.411	0.31	20.1, 49.2, 103.5
	2.01		0.429	0.37	22.7, 57.8, 99.4
	2.72		0.386	0.46	21.9, 55.7, 111.6
Stainless	1.14	7800	0.826	0.43	56.0, 104.8
steel	2.26		0.737	0.69	55.0, 106.5, 215.3, 296.2

[a] Volume-equivalent diameter estimated by weighing a known number (N) of particles: $d_v = (\frac{6m}{\pi N \rho_p})^{1/3}$.

[b] Estimated by back-calculation of Ergun equation using the method described in Section 2.2.

[c] Estimated in water based on d_v using Stokes's law for small particles, and Heywood tables for larger particles [22].

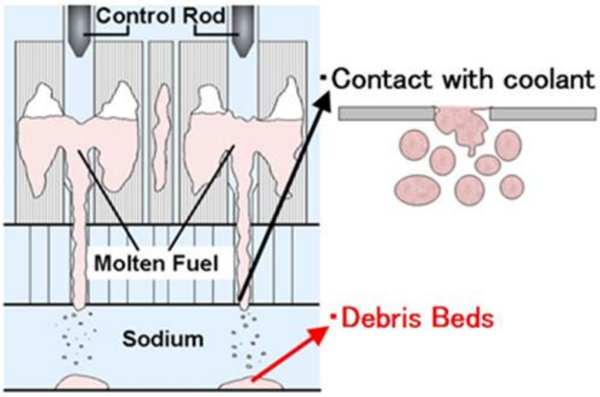

Figure 1. Debris bed formation.

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An investigation on debris bed self-leveling behavior with non-spherical particles

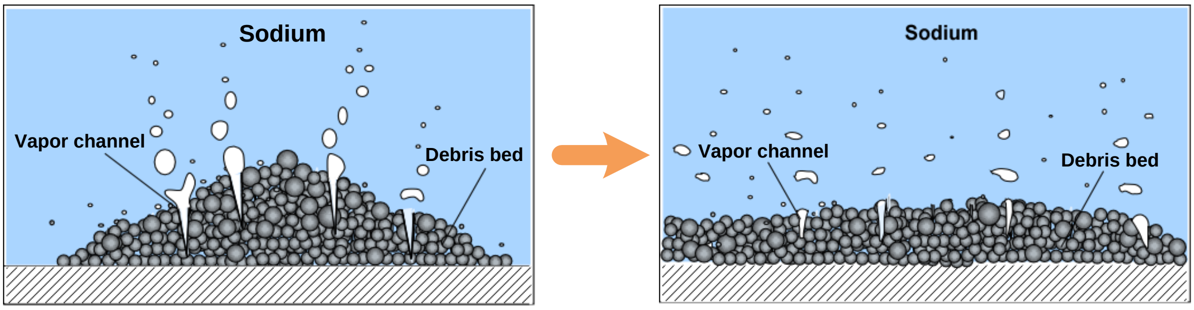

Figure 2. Self-leveling behavior.

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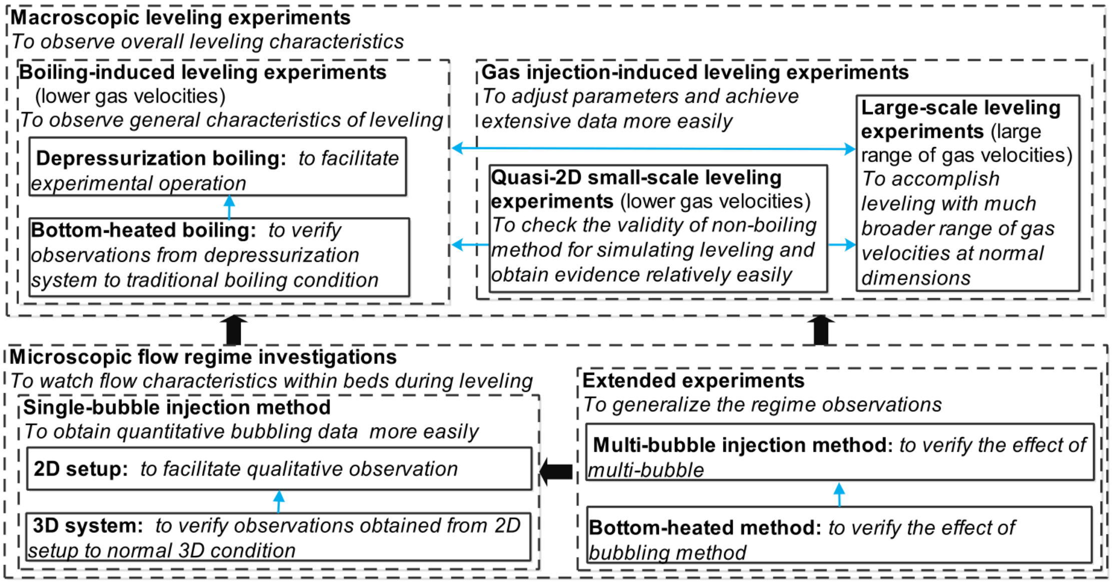

Figure 3. Constitution of performed leveling-related experiments.

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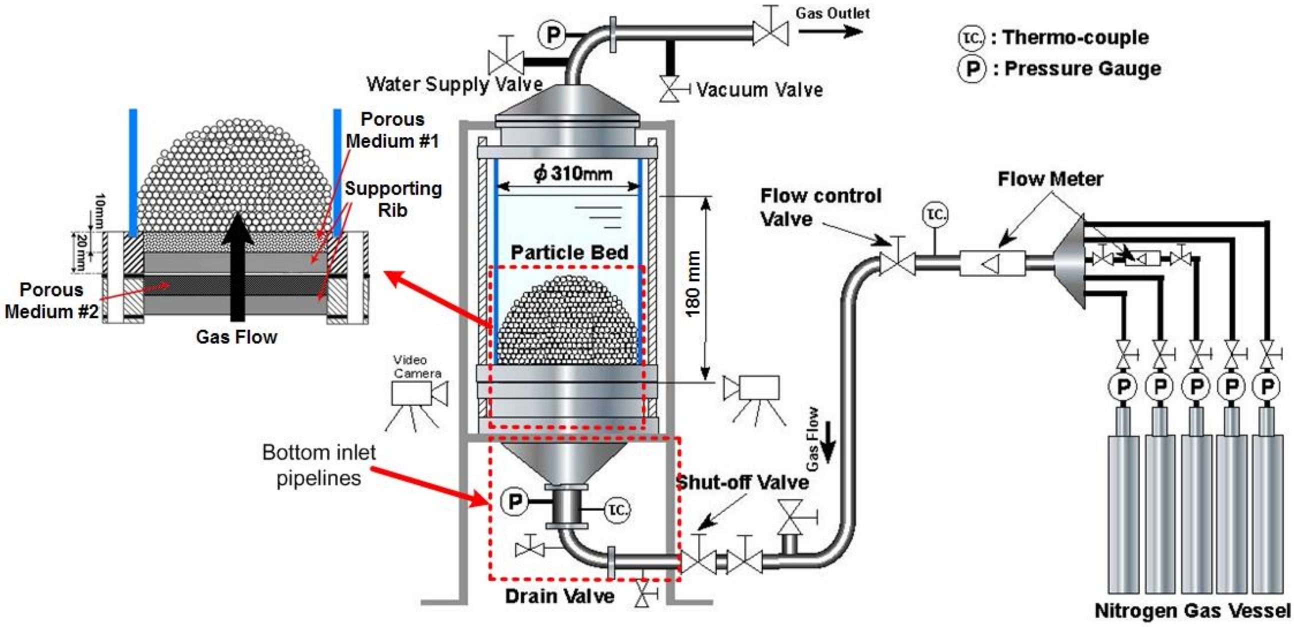

Figure 4. Schematic diagram of experimental setup.

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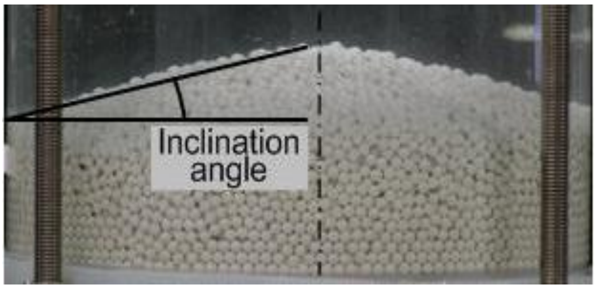

Figure 5. Diagram of measured bed inclination angle.

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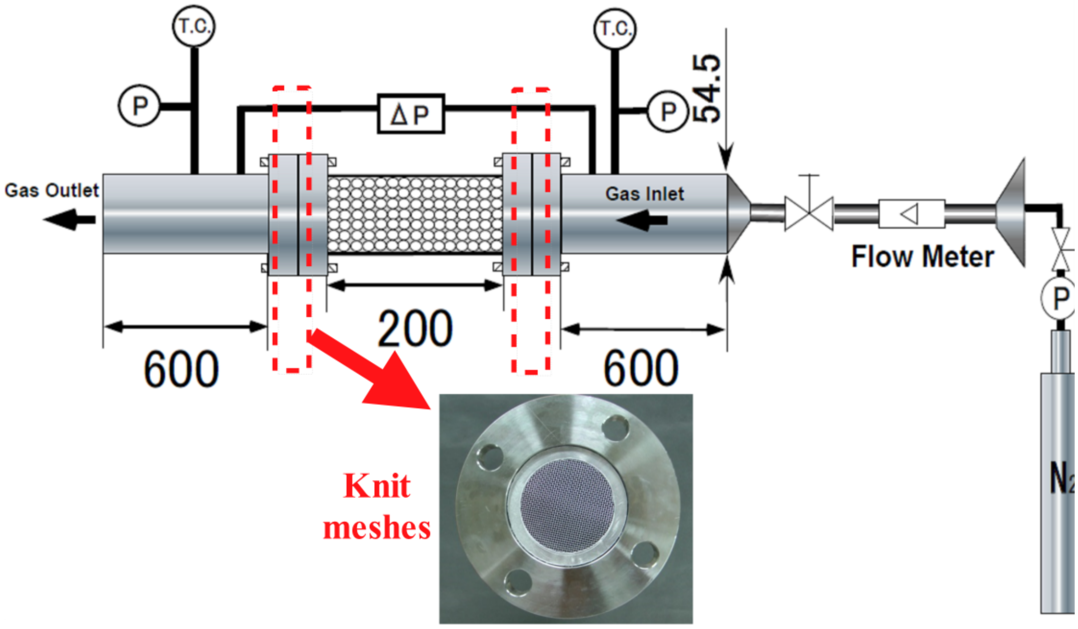

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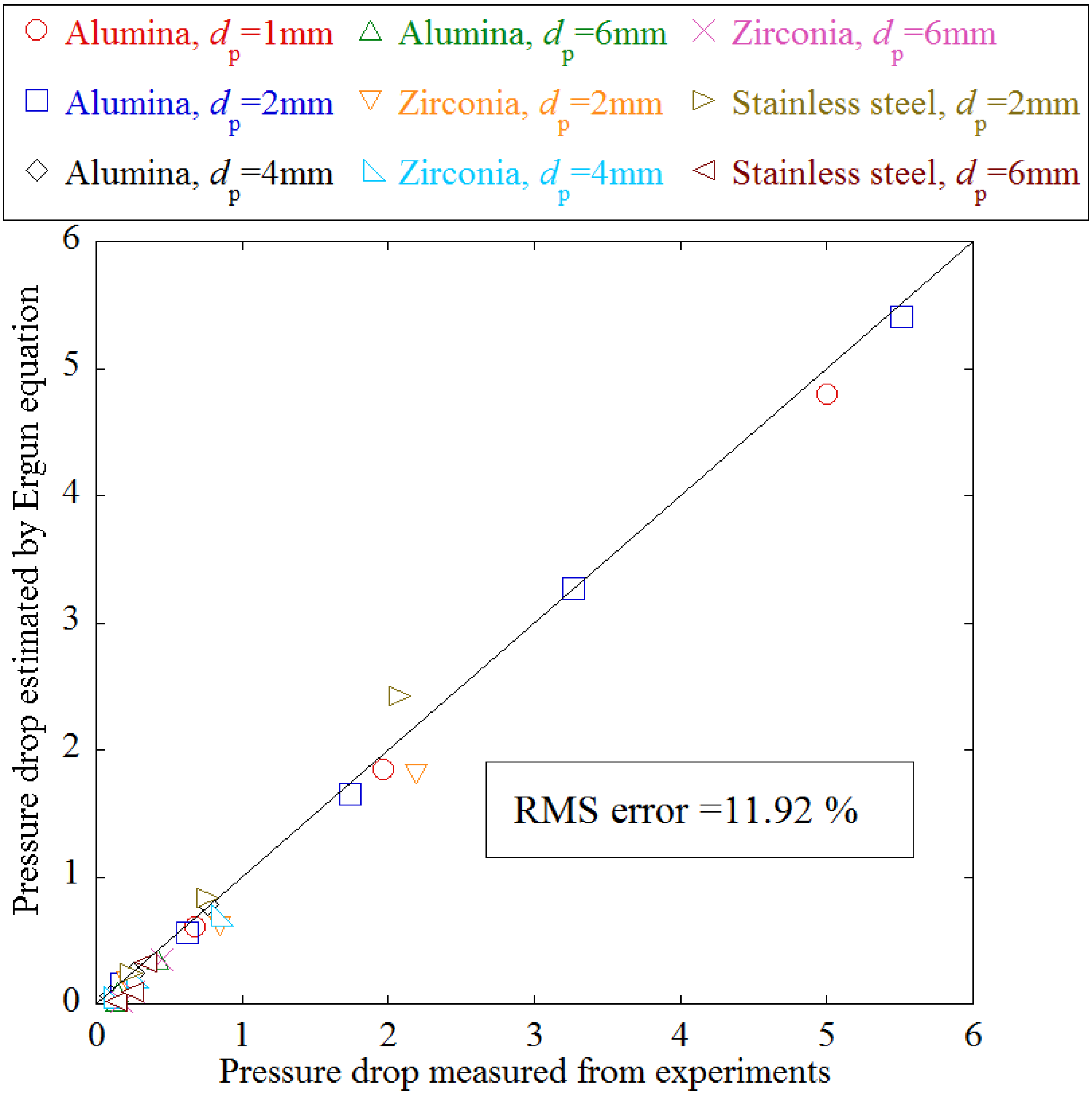

Figure 7. Comparisons between predicted and measured pressure drops using the test spheres.

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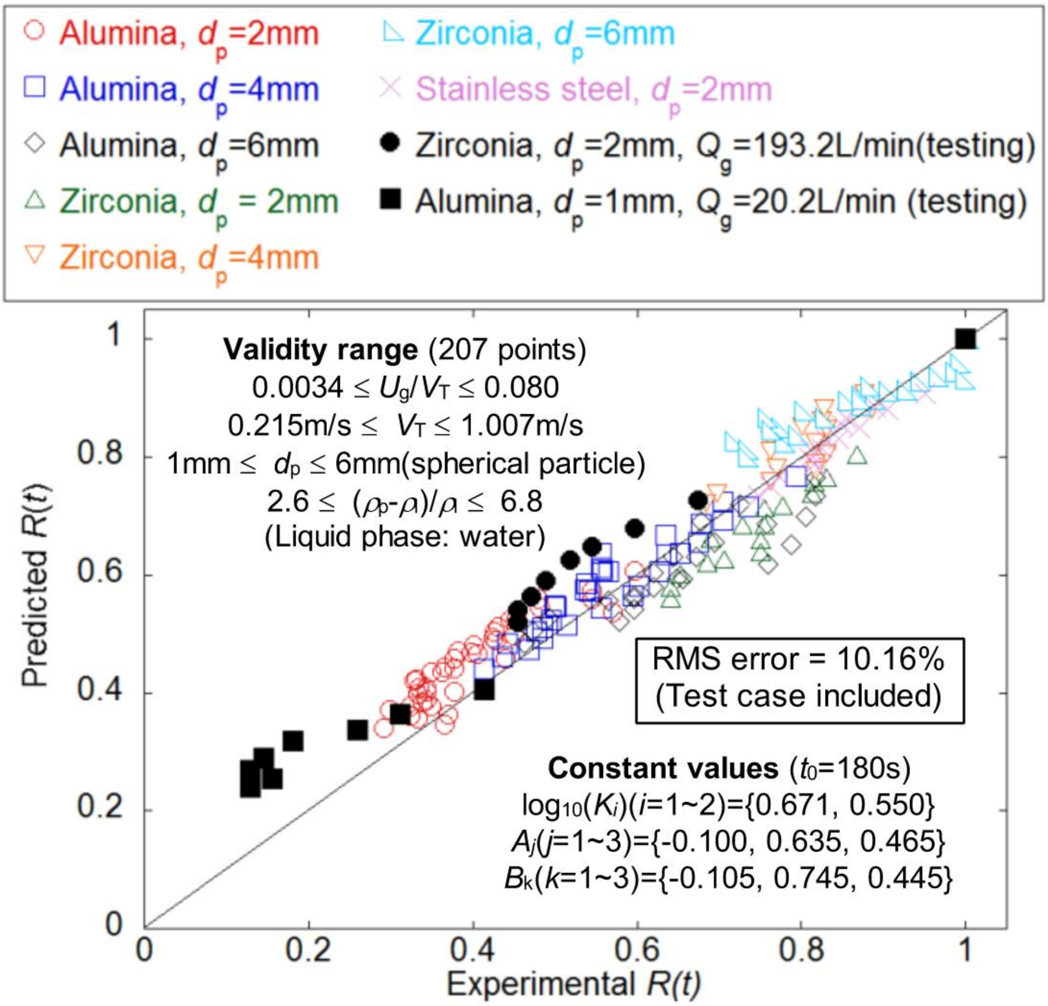

Figure 8. Parity plot comparing predicted $R(t)$ with experimental data using the base model (spherical particle).

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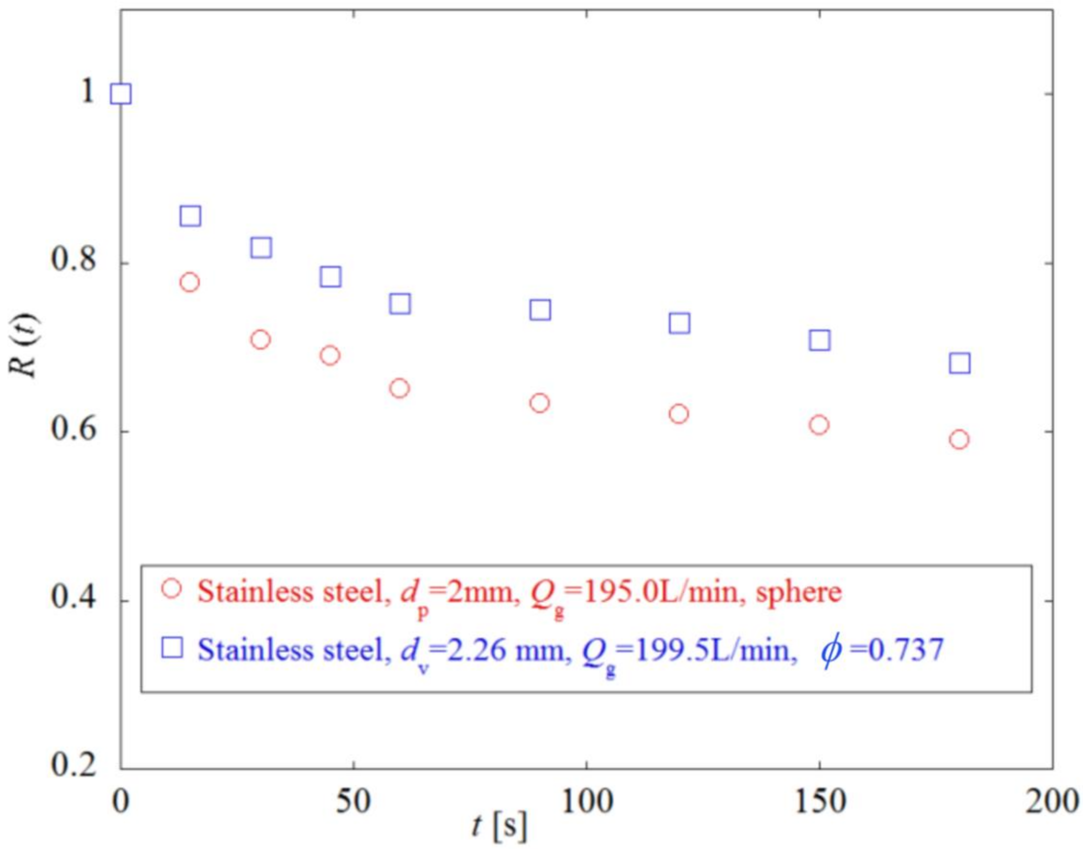

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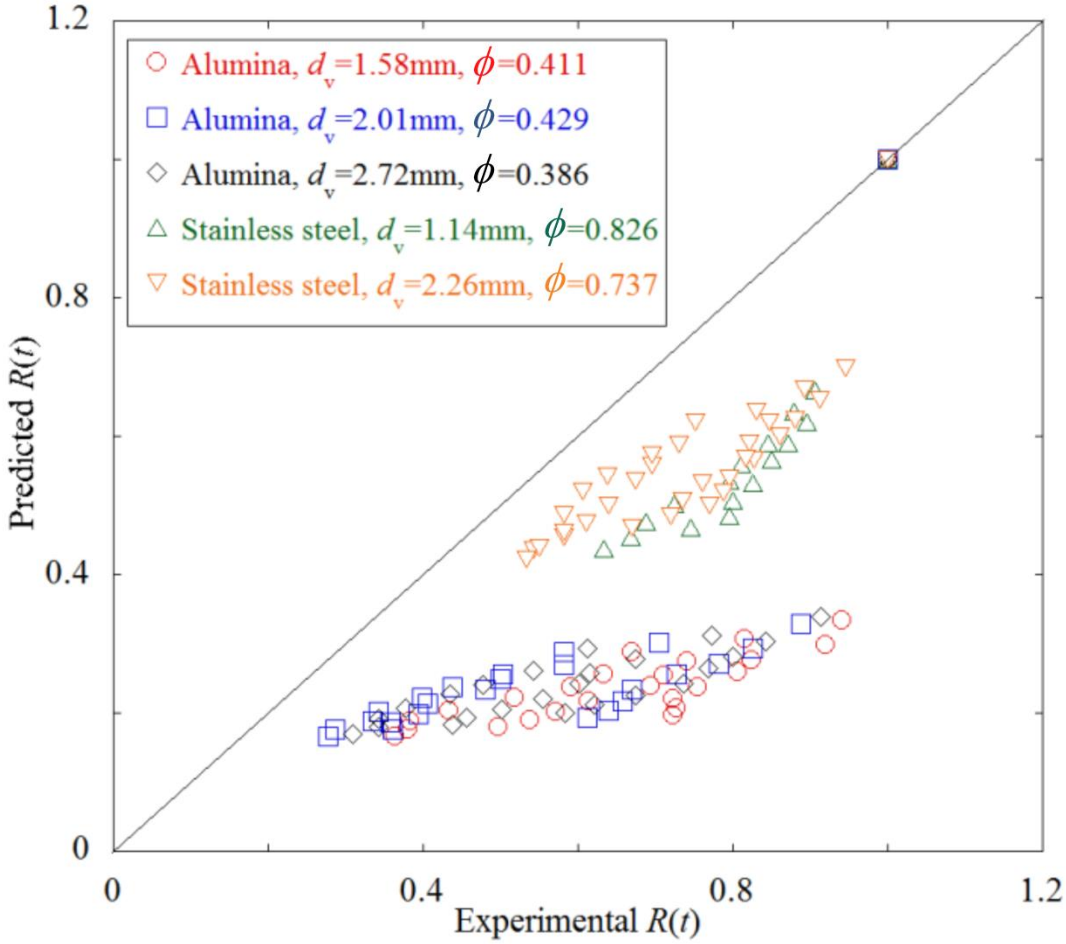

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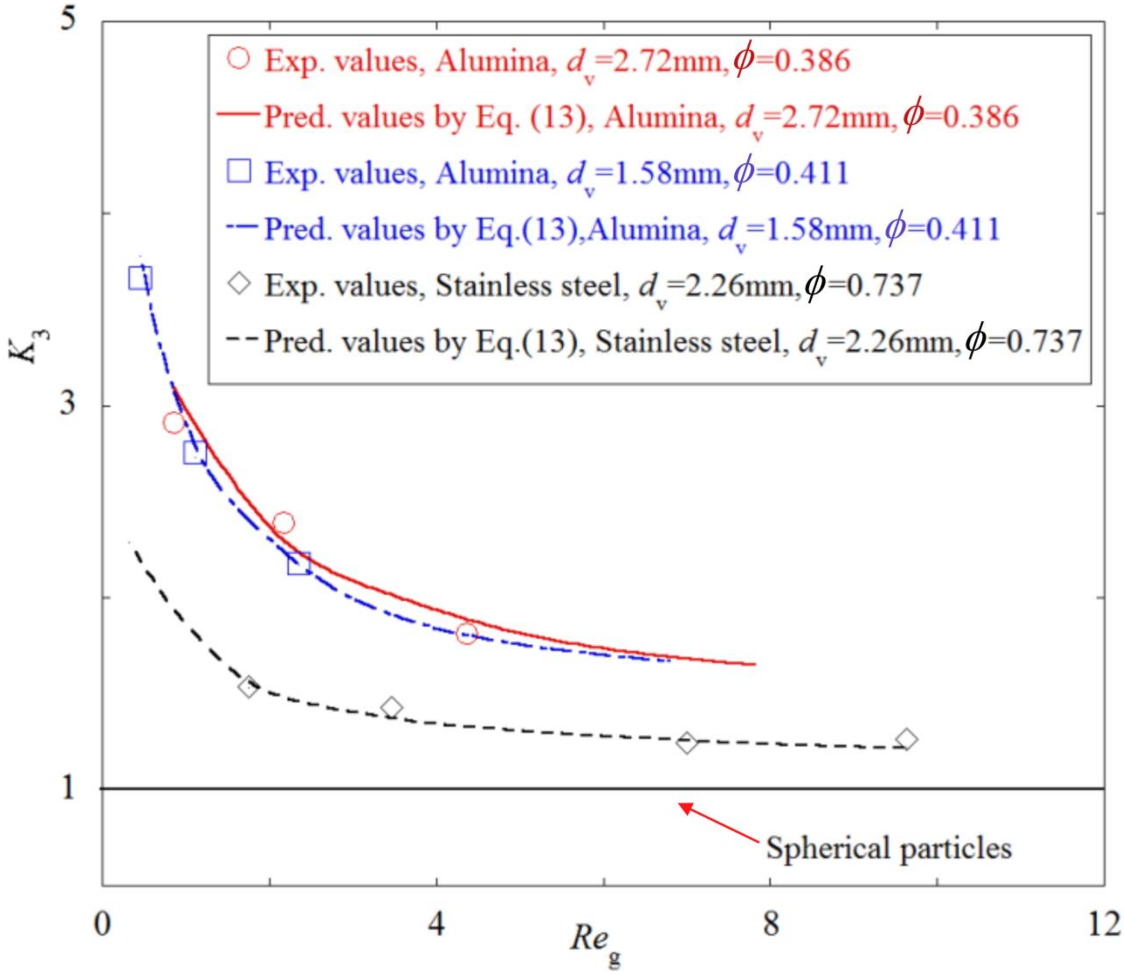
An investigation on debris bed self-leveling behavior with non-spherical particles



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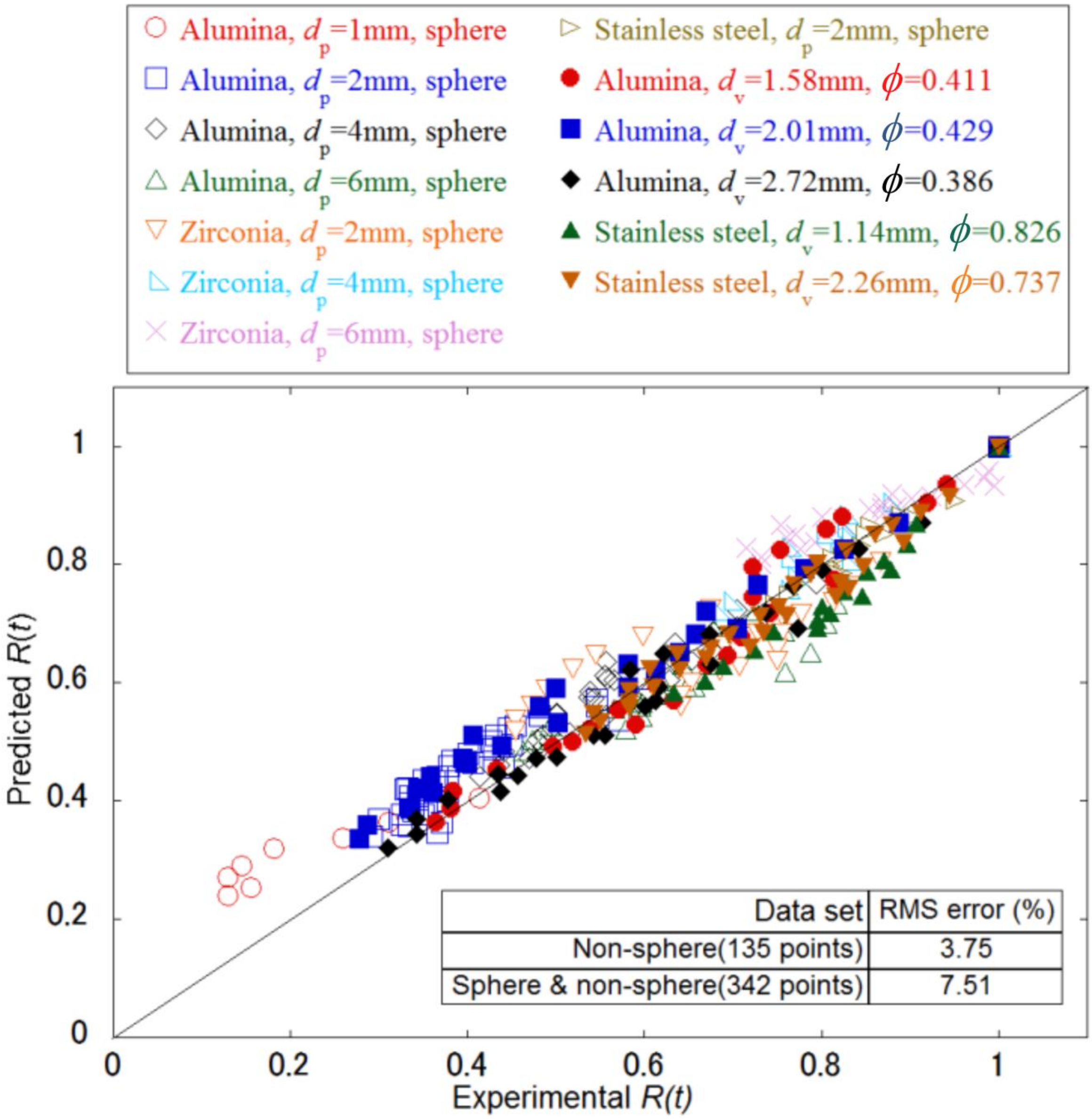

Figure 12. Parity plot of $R(t)$ for both spherical and non-spherical particles with extension scheme coupled.

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