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DEM Analysis on Jamming Probability of Ball-type Secondary Shutdown System for a Small Modular Reactor

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1. Introduction

In the past, there have been attempts and studies on eliminating soluble boric acid in small modular reactors (SMRs). Soluble boron-free concepts can eliminate boric-acid-induced corrosion and simplify the large components related to Chemical and Volume Control System (CVCS). According to the US-NRC guide for Reactivity Control Systems, two completely independent and diverse reactivity control systems are required and therefore, some alternative concepts for replacing soluble boron control system have been proposed as the Secondary Shutdown System (SSS). Of the concepts, injecting solid neutron absorbers through independent guide tubes has been widely proposed in various studies [1-3], and the concept was actually employed in the actual nuclear power plant such as Hanford N-Reactor and B-Reactor under the name "Ball-3X Safety System"[4]. Moreover, for the liquid-metal and gas-cooled GEN IV reactors (such as LFR, GFR, and GFR) in which liquid boric acid cannot be used, the solid neutron absorber injection concept has been widely proposed and designed as the SSS [5]. Unlike liquid soluble boron system, the solid absorber injection concept should guarantee its operation reliability under any circumstances and therefore its jamming phenomena should be well understood and quantified to avoid serious accidents. Based on this background, this paper attempts to understand jamming phenomena and quantify its probability in terms of various physical variables based on experiment and simulation.

2. Discrete Element Method

Discrete Element Method (DEM) is the most commonly used numerical model for describing the mechanical behavior of granular material flow. The proposed SSS is a concept in which spherical neutron absorbers stored in hopper are injected into a guide tube through a door system, and it is a good example to interpret as DEM.

2.1 Physical Concept of DEM

The DEM is constructed by applying Newton's second law to the system containing the moving particles. At each time step, obtaining all the forces and moments acting on each particle and calculate the displacement to get the new position of each particle. DEM was firstly proposed by Cundall (1979) and basically consists of the following assumptions [6].

(1) Each particle included in the system is assumed to be inelastic.
(2) Forces due to the action of spring and damping occurs in the vertical and the horizontal direction at the collision point of particles.
(3) Each time step should be small enough to assume that the speed during the time step is constant.
(4) It is assumed that each particle is a rigid body, but a small overlap is allowed, and the impact force is calculated by the extent of overlap.

Then, the governing equations for the translational and rotational motion of particle i with mass m_i and moment of inertia I_i can be written as

$$\mathbf{F}_{i,total} = m_i \frac{d\mathbf{v}_i}{dt} = \sum_j (\mathbf{F}_{ij}^{\,n} + \mathbf{F}_{ij}^{\,t}) + \mathbf{F}_{i,g} \tag{1}$$

$$\boldsymbol{\tau}_{i,total} = I_i \frac{d\mathbf{w}_i}{dt} = \sum_j (\mathbf{R}_{con,i} \times \mathbf{F}_{ij}^{\,t} - \boldsymbol{\tau}_{ij}^{\,r}) \tag{2}$$

where $\mathbf{v}_i$ and $\mathbf{w}_i$ are the velocity and angular velocity of particle i, respectively, $\mathbf{F}_{ij}$ and $\boldsymbol{\tau}_{ij}$ are the contact force and torque acting on particle i by particle j or walls, $\mathbf{R}_{con}$ is the vector from the center of mass to contact point, and $\boldsymbol{\tau}_{con}$ is the torque due to friction.

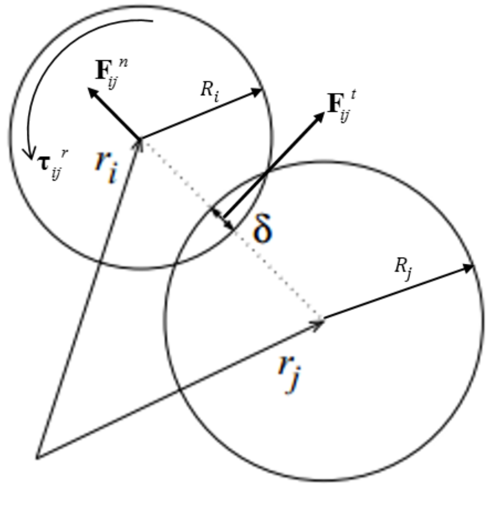

Fig. 1. Schematic illustration of the forces acting on particle i from contacting particle

Table 1
DEM force and torque models

Force models	Normal force	Tangential force	References
Linear spring-dashpot model	$\mathbf{F}_{ij}^{\ n} = k_n \delta_n \mathbf{n} - c_n (\mathbf{v}_{ij} \cdot \mathbf{n})\mathbf{n}$ $k_n = \frac{4}{3} E_{ij} \sqrt{R_{ij}},\ c_n = 2\sqrt{m_{ij} k_n}$	$\mathbf{F}_{ij}^{\ t} = k_t \delta_t + c_t (\mathbf{v}_{ij} \times \mathbf{n}) \times \mathbf{n}$ $k_t = 8G_{ij}\sqrt{R_{ij}\delta_n},\ c_t = 2\sqrt{m_{ij} k_t}$	Cundall and Strack (1979)
Hertz-Mindlin contact force model	$\mathbf{F}_{ij}^{\ n} = k_n \delta_n^{3/2} \mathbf{n} - \eta_n (\mathbf{v}_{ij} \cdot \mathbf{n})\mathbf{n}$ $\eta_n = \sqrt{\frac{10}{3}} \gamma \sqrt{m_{ij} k_n},\ \gamma = \frac{\ln(e)}{\sqrt{\ln^2 e + \pi^2}}$	$\mathbf{F}_{ij}^{\ t} = -\min\left[k_t \delta_t + \eta_t (\mathbf{v}_{ij} \cdot \mathbf{t}) \mu_s \left\lvert \mathbf{F}_{ij}^{\ n} \right\rvert \right] \mathbf{t}$ $\eta_t = \sqrt{\frac{10}{3}} \gamma \sqrt{m_{ij} k_t},\ \gamma = \frac{\ln(e)}{\sqrt{\ln^2 e + \pi^2}}$	Zhou et al.(1999) [9], and Zhu and Yu (2002) [10]

Torque models	Rolling friction torque	Torque from tangential forces	References
	$\boldsymbol{\tau}_{ij}^{\ r} = \eta_r R_{con,i} \left\lvert \mathbf{F}_{n,s} \right\rvert \widehat{\mathbf{w}}_i$	$\boldsymbol{\tau}_{ij}^{\ t} = \mathbf{R}_{con,i} \times \mathbf{F}_t$	Zhou et al.(1999), and Zhu and Yu (2002)

2.2. DEM Force Model

In general, the contact between two particles is not at a single point but on a finite area, because the contact of two rigid bodies are allowed to overlap slightly in the DEM. Then, the contact force over this area can be decomposed into a component in the contact plane (or tangential plane) and one normal to the plane. Fig. 1 schematically shows the typical forces and torques involved in a DEM simulation. DEM generally uses a simplified force model to determine the forces and torques due to the contact between particles, and there are many approach have been proposed for this purpose. Generally, linear spring model is the simplest model. "Linear spring–dashpot model" proposed by Cundall and Strack (1979) is the most common linear spring model, where the spring accounts for the elastic deformation and the dashpot is used for for the viscous dissipation[6]. More theoretically model, Hertz–Mindlin and Deresiewicz model, has also been developed. Hertz (1882) proposed a theory to describe the elastic contact between two spheres in the normal direction and he proved that the relationship between the normal force and normal displacement was nonlinear [7]. Mindlin and Deresiewicz (1953) proposed a tangential force model in a similar way [8]. This Hertz-Mindlin and Deresiewicz theory-based model is the most commonly used model in DEM and it is used in this study as well. Table 1 shows the equations for some commonly used force models for spherical particles, including the linear spring–dashpot model and the simplified Hertz–Mindlin and Deresiewicz model.

2.3. DEM Simulation Results

Many studies in laboratory experiments [11] and computer simulations [12] showed that jamming is due to arch formation at the hopper opening. However, jamming is still a complicated phenomenon in which various parameters act simultaneously. We selected the particle diameter, the hopper opening size, the friction coefficient between the wall and particles, and the number of particles as the significant parameters through some preliminary experiments. We confirmed the effect of each parameter on jamming through DEM.

Through DEM simulation, we could confirm the clear relation between jamming probability and some parameters. We obtained jamming probability for different the number of particle from the DEM simulation and the results are shown in Fig. 2. The curves in the graph show that the smaller diameter of the Particles, the smaller the jamming occur probability before N number particles pass. Also, jamming grows

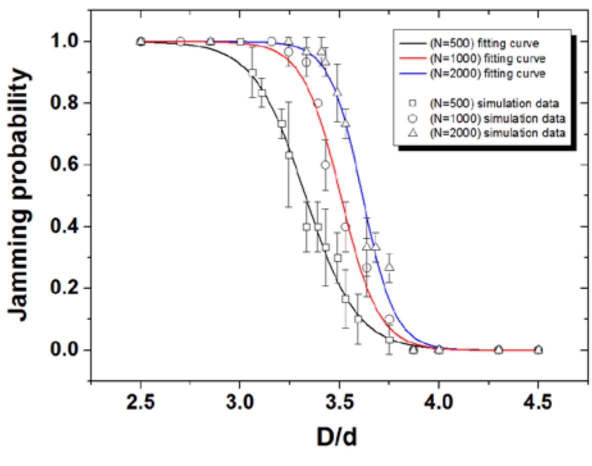

Fig. 2. Jamming probability as a function of D/d, where d is the particle size, D is the hopper opening size. Each graph corresponds to the probability of the hopper getting jammed before N particles pass through it. From left to right, correspond to N=500, 1000, 2000. The fitting curves are hyperbolic tangent function with two parameters α , R_0 : $J(D/d) = \{1-\tanh[\alpha (D/d-R_0)]\}/2$.

with N for fixed D/d. These data are consistent with those found in a two dimensional hopper [13], obtained with a fixed number of grains.

We also confirmed the relation between jamming probability and the wall-particle friction coefficient. We obtained jamming probability for different values of friction coefficient from the DEM simulation and the results are shown in Fig. 3. The curves in the graph show that the more jamming occurs when higher friction forces between particles and walls. This phenomenon is interpreted as a result of increasing the probability of forming an arch (known to cause jamming) at the entrance of the hopper as the friction coefficient increases. These data are consistent with those found in a two dimensional hopper [14], obtained with different shape.

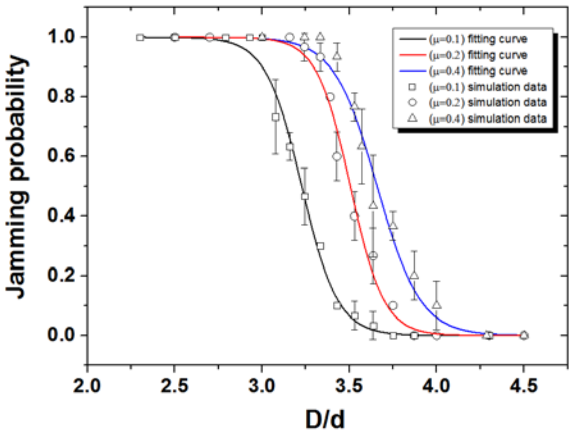

Fig. 3. Jamming probability according to friction coefficient, where μ is the wall-particle friction coefficient. From left to right, correspond to μ = 0.1, 0.2, 0.4. In this case, the number of particle N is 1000.

3. Experiment

We have confirmed the relationship between jamming and various parameters through DEM for the new SSS. However, it does not mean that we found a condition that the actual SSS work well without jamming. Therefore, it is essential to verify the relationship between jamming and parameters through experiments.

3.1. Experimental Setup and Procedure

Fig. 4. is a conceptual diagram of our experimental setup. We fabricated a 3D hopper with D = 12 mm opening diameter of acrylic material. The wall of this hopper is 3 mm thick acrylic geometry having an angle of 60 degrees with respect to the ground. We proceeded to experiment in the way of putting N = 500, 1000, 2000 monodisperse stainless steel spheres of d =2.5, 3, 3.5, 4, 5 mm in diameter. For each condition, we counted the number of jamming events N_J and obtained the jamming probability J which is defined as N_J/N_t, where N_t is the number of the total trial for each condition.

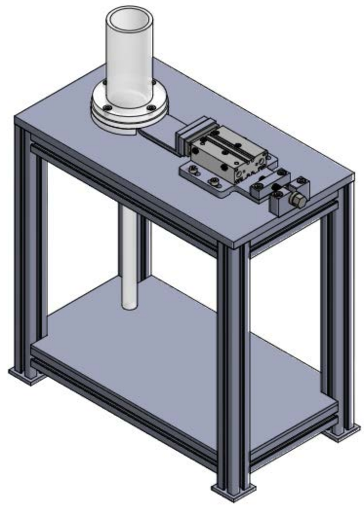

Fig. 4. Conceptual diagram of experimental setup

3.2. Experimental Results

We were able to observe a lot of jamming conditions as the experiment proceeded. Fig. 5. shows an image of a typical jamming event captured in the experiment. In our experiments, the first thing we checked is the relationship between jamming and the number of particles. We confirmed that the relationship between the number of particles and jamming probability is acting in real physics by comparing the N = 1000 and N = 2000 experimental results. Especially, we could find that the passing probability (i.e. 1 - J) is proportional to the square of the number of particles also, as in the simulation. It is shown in Fig. 6. Next, we were able to confirm that the simulation implement the real situation well by comparing experiment and simulations in similar condition. Regardless of the particle number

Fig. 5. Image of a typical jamming event

condition, the simulation results obtained by setting the wall-particle friction coefficient μ to 0.1 tend to be a slightly larger than experiment data. These results are shown in Fig. 7.

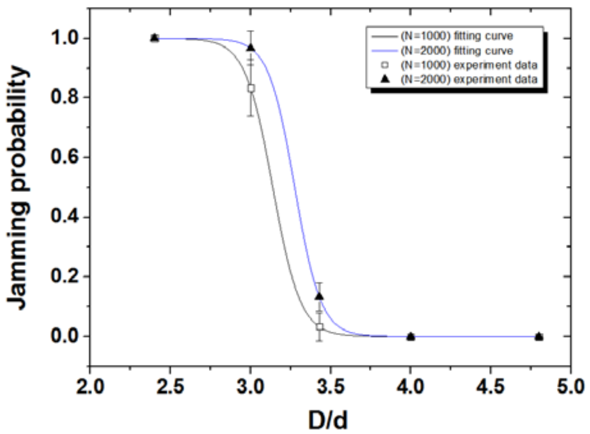

Fig. 6. Comparison of jamming probability by the number of particles

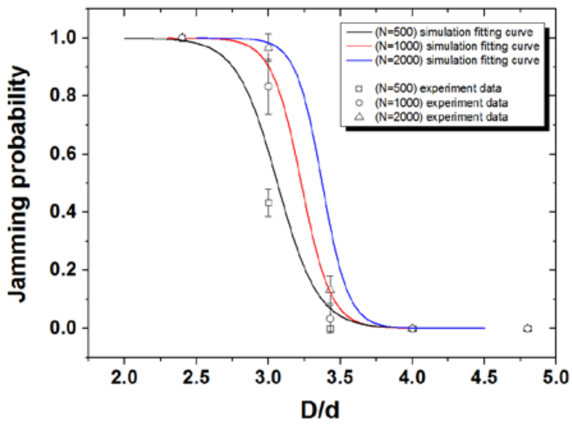

Fig. 7. Jamming probability graph comparing experiments and simulations

4. Conclusions

In this paper, we have performed analysis on the jamming phenomenon of the granular system of monodisperse balls in 3D hoppers to validate the ball-type SSS for soluble boron free small modular reactor. We showed that DEM can be effective in interpreting this SSS through comparison with previous well-known experimental results. Moreover, we compared with our own experiment results to verify the DEM simulation results. As further works, the following tasks are on-going and will be performed.

(1) We are undergoing a theoretical interpretation to understand the Jamming phenomenon.

(2) We will perform a comparison of the experiment and the simulation under more various conditions through more experiments.

(3) We are proceeding an experiment to verify that the new SSS can work well in complex reactor geometries.

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