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## ABSTRACT

Similarities have been developed in this paper to decrease computation load of CFD-DEM simulation. By applying the similarities, the computation time was greatly decreased. The results were verified by both the numerical simulations and experiments.

## 1. INTRODUCTION

Fluidized bed has been widely used in industry. Fluidization is complex solid-gas two phase phenomenon, and it is essential to simulate it numerically to comprehend it. Tsuji et al (1) first employed CFD-DEM (Discrete Element Method) to simulate fluidized bed. CFD-DEM has been widely used to simulate fluidized bed in recent decades, because its assumptions were simple and it was easy to model the complex phenomena on the particle level. But CFD-DEM was difficult to apply to large scale fluidized beds, due to the problem of huge computation. One effort to decrease computing time was to employ the parallel computation. The other effort to decrease computation load was to use large particles to represent small real particles, so that, the number of particles in bed was decreased and then the calculation load was decreased. There were several methods to realize this goal. One method was to apply similarity (2),(3), in which the physical properties of fluid and particle were adjusted. The other method was to change drag acted on particles (4).

In this paper, the similarities were developed based on (3). Imaginary large particles, each of which represented a group of small real particles, were employed to decrease computation load. In order to make the movement of imaginary particles similar to that of real particles, similarities were deduced as explained below. The physical meaning of the similarities was discussed. Both numerical and experimental verifications were made. It was shown by validation that the similarities were correct and the calculation load can be greatly decreased. CFD-DEM could simulate a large scale fluidized bed by applying the similarities.

## 2. SIMILARITY FOR CFD-DEM SIMULATION

### 2.1 DEM Model of Fluidized Bed

DEM (Discrete Element Method) applied Newtonian dynamical equations to compute motion of each particle. The forces acting on a particle in a fluidized bed were gravity, drag and contact force (equ. (1)). The contact force was modeled as spring dashpot (Fig.1,(1)).

$$m\ddot{\vec{X}} = m\vec{g} + \vec{F}_D + \vec{F}_C \tag{1}$$

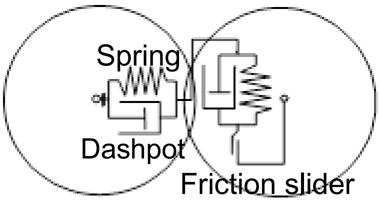



Fig.1 Model of contact force of DEM

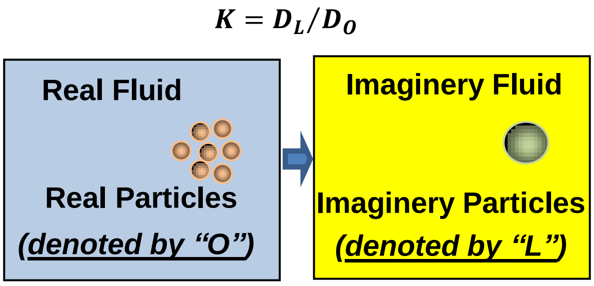



Fig.2 Real bed and magimary bed

### 2.2 Deduction of Similarities

The imaginary large particle was K-fold enlarged (equ.(2)) and represented the group of real particles (The number of real particles in the group was $K^3$, refer to Fig.2). The density of imagery particle kept the same with real particle (equ.(3)).

$$\mathrm{K} \equiv D_{p,L}/D_{p,O} \tag{2}$$

$$\rho_{P,L} = \rho_{P,O} \tag{3}$$

Our job was to find an imaginary fluid to make the movement of imaginary particles similar to that of real particles. If the movement of particles in fluidized bed was similar, the Reynolds Number Re and Archimedes Number Ar would be the same for both real particles and imaginary particles. Those were

$$\mathrm{Re} = \frac{|V_L - U_L|\,\rho_{f,L}\varepsilon_L D_{p,L}}{\mu_{f,L}} = \frac{|V_O - U_O|\,\rho_{f,O}\varepsilon_O D_{p,O}}{\mu_{f,O}} \tag{4}$$

$$Ar = \frac{D_{P,L}{}^3 \rho_{f,L}(\rho_{P,L} - \rho_{f,L})g}{\mu_{f,L}{}^2} = \frac{D_{P,O}{}^3 \rho_{f,O}(\rho_{P,O} - \rho_{f,O})g}{\mu_{f,O}{}^2} \tag{5}$$

In the case that imaginary bed was similar to real bed, the followings would be satisfied

$$\vec{V}_L = \vec{V}_O, \vec{U}_L = \vec{U}_O,\ \varepsilon_L = \varepsilon_O,\ p_L = p_0 \tag{6}$$

and due to $\rho_{P,L} >> \rho_{f,L}, \rho_{P,O} >> \rho_{f,O}$, the following could be deduced

$$\mu_{f,L}/\mu_{f,O} = K^2 \tag{7}$$

$$\rho_{f,L}/\rho_{f,O} = K \tag{8}$$

If (3), (7) and (8) were satisfied, the imaginary particles would move similarly to real particles. We would validate it numerically and experimentally. Before the validation, the meaning of dynamic similarities was discussed in the following section.

### 2.3 Meaning of similarities

A particle in a fluidized bed was acted on by three kinds of forces, gravity, drag and contact forces (equ.(1)). If the forces acting on an imaginary particle were equal to the sum of forces acting on the group of real particles which were presented by imaginary particle, the movement in imaginary bed would similar to that of real bed. The gravity, drag and contact force would be checked in the following. The minimum fluidization velocity was also checked.

**Gravity**

$$Gravity\_force\big|_L = \rho_{P,L}\frac{\pi}{6}D_{P,L}^3 g = K^3(\rho_{P,O}\frac{\pi}{6}D_{P,O}^3 g) = K^3 Gravity\_force\big|_O \tag{9}$$

**Drag**

$$\vec{F}_{D,L} = (\frac{\beta}{1-\varepsilon_L}(\vec{V}_L - \vec{U}_L) - \nabla p_L)\frac{\pi D_{P,L}^3}{6} \tag{10}$$

where

$$\beta = \frac{\mu_{f,L}}{D_{p,L}^2} f(\varepsilon_L, \mathrm{Re}_L) \tag{11}$$

substituting(3), (7) and (8) into(10),(11), the following could be obtained

$$\vec{F}_{D,L} = K^3\vec{F}_{D,O} \tag{12}$$

**Minimum fluidization velocity $V_{mf}$**

$$V_{mf,L} = \frac{\mu_{f,L}}{\rho_{f,L}D_{P,L}} f(Ar_L) = \frac{\mu_{f,O}}{\rho_{f,O}D_{P,O}} f(Ar_O) = V_{mf,O} \tag{13}$$

The gravity and drag acted on the imaginary particle equated to the sum of gravity and drag acted on the group of real particles respectively (refer to equ.(9),(12)). As the result, imaginary particle and real particle had the same minimum fluidization velocity $V_{mf}$ (refer to equ.(13)).

**<u>Contact force</u>**

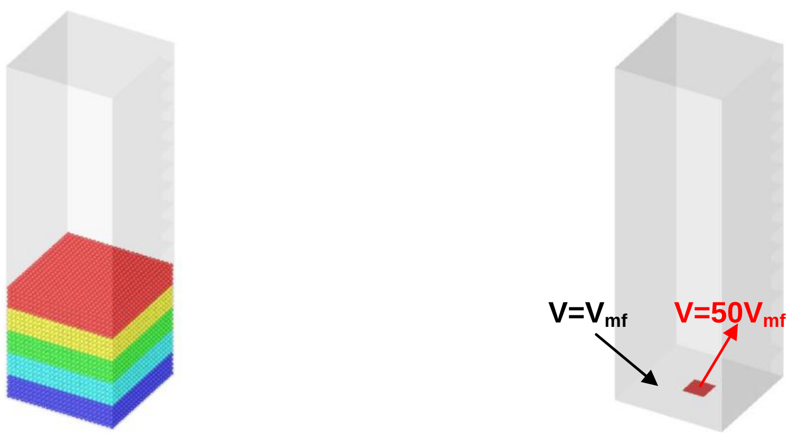
It was difficult to equate the contact force acing on imaginary particle with the contact force acting on real particles, because the real particles in the same group moved in different directions. Fortunately, it was implied in (<u>1</u>) that the magnitude of coefficient of spring in the spring/dashpot model (Fig.1) of DEM did not greatly affect the behavior of particles. The coefficients of spring and friction used for imaginary particles were the same with that of the real particles; we hoped that the contact force would be roughly similar for imaginary and real bed.

## 3. VERIFICATION OF SIMILARITY BY NUMERICAL SIMULATION

In order to validate the similarity, numerical simulations of various K (K=1, 2,4,8,16) were made. It was assumed that the simulation for real particles (K=1) was correct. The bubble shapes were compared to those of the real bubble to check whether the similarities were correct or not. The sizes of bed were listed in Table1. The boundary conditions and initial condition were shown in Fig.3. The parameters of various K were list in Table 2.

Table1 The sizes of bed for numerical validation calculation

| bed length [m] | bed width [m] | bed height [m] | static bed height [m] |
|---|---|---|---|
| 0.32 | 0.32 | 0.96 | 0.32 |

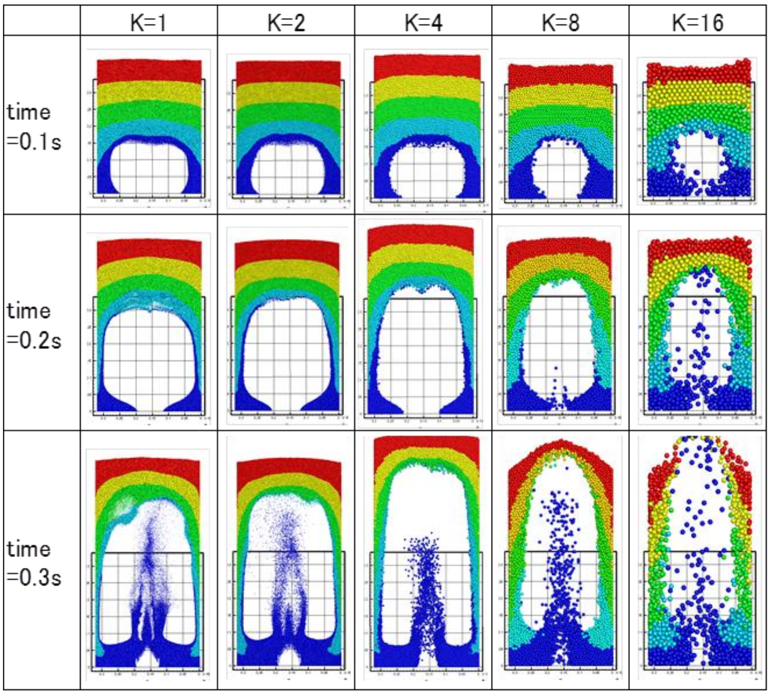



(a) Initial position of particles (b) Inlet gas velocity

Fig.3 Boundary condition and Initial condition

Table 2 The parameters for validation calculations

| multiple K [-] | 1 | 2 | 4 | 8 | 16 |
|---|---|---|---|---|---|
| diameter of particle [m] | 0.001 | 0.002 | 0.004 | 0.008 | 0.016 |
| particle density [kg/m$^3$] | 2700 | 2700 | 2700 | 2700 | 2700 |
| fluid density [kg/m$^3$] | 1.161 | 2.322 | 4.644 | 9.288 | 18.576 |
| fluid viscosity [pa/s] | 1.86E-05 | 7.45E-05 | 2.98E-04 | 1.19E-03 | 4.77E-03 |
| spring constant [N/m] | 800 | 800 | 800 | 800 | 800 |
| mesh size [m] | 0.002 | 0.004 | 0.008 | 0.016 | 0.032 |
| number of particles [-] | 40,000,000 | 5,000,000 | 625,000 | 78,125 | 9,765 |
| time step [s] | 2.00E-05 | 5.00E-05 | 1.00E-04 | 4.00E-04 | 8.00E-04 |
| CPU cores used in parallel calculation | 80 | 40 | 20 | 10 | 5 |




(Central slice of 3D simulation)
Fig.4 The bubble shapes of various K

The bubble shapes for various K were shown in Fig.4. It was found that the bubbles for K=2~16 agreed reasonably with the bubble of K=1. The smaller the K, the better the result. The comparison of bubbles showed that the movement of particles was similar if the equ.(3), (7) and (8) were satisfied. Calculation load was defined as (14) and magnification of load was defined as (15). It was found in Fig.5 that calculation load could be reduced by the factor of $K^{-4.3}$.

$$\mathrm{cal.\,load} \equiv (\text{calculation time for 1s physical time}) \times (\text{number of CPU cores}) \quad (14)$$

$$\text{magnification of load} \equiv (cal.\ load(\ K))/(cal.\ load(K=1)) \quad (15)$$

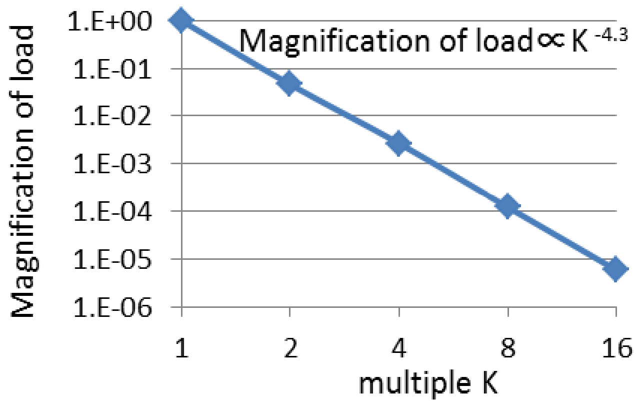



Fig.5 Reduce of calculation load by similarities

## 4. VERIFICATION OF SIMILARITIES BY EXPERIMENTS

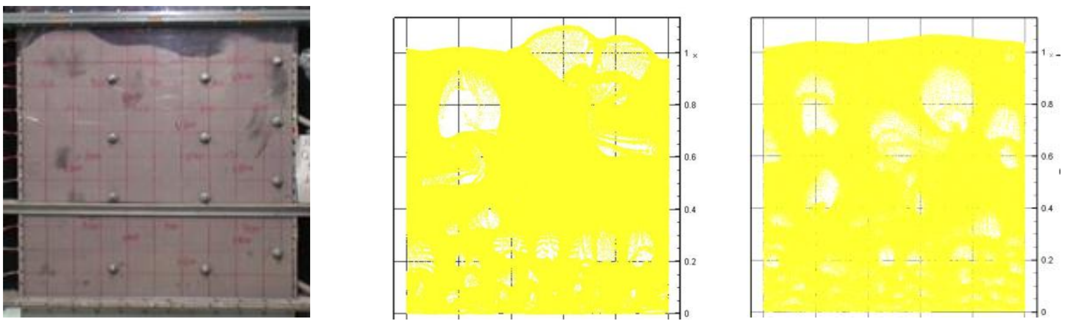
The experiments were also done to validate the similarities. A large fluidized bed was employed to carry out the experiments. The conditions of experiment were listed in table 3. In order to evaluate the simulation quantitatively, the bubble size, bubble ascending velocity and bubble frequency were measured at height of Z=0.8m. Only large bubbles (diameter larger than 0.15m) were taken count of, because the boundary of small bubble was indecisive. The experiment results were shown at table 4.

Table 3 The conditions of experiments

| bed lengh | bed height | bed width | mean particle diameter | particle density | superficial velocity V0 | V0/Vmf |
|---|---|---|---|---|---|---|
| [m] | [m] | [m] | [mm] | [kg/m$^3$] | [m/s] | [-] |
| 1 | 1 | 0.037 | 0.29 | 2610 | 0.322 | 4 |

Table 4 The results of experiments at height Z=0.8m
(only bubbles which were larger than 0.15m were taken count)

| mean bubble size [m] | mean bubble ascending velocity[m/s] | bubble frequency[-/(s·m)] |
|---|---|---|
| 0.163 | 1.09 | 2.5 |



(a) Experiment (b) Simulation (K=4) (c) Simulation (K=16)

Fig.6 Snapshot of Bubble

The number of particles in the bed was too much in this case (more than one billion particles) to use CFD-DEM simulation. Similarities (K=4 and K=16) were applied to simulate the particle movement in the bed and compared with experiments. The snapshots of bubble for experiments and simulations were show in Fig.6. The comparison of simulation and experiment was shown in Fig.7. It could be found that the simulation, in which the similarities were applied, agreed with experiment well. The bubbling sizes of simulations were little smaller than that of experiment, while the bubble ascending velocity and bubble frequency of simulation were a little larger than those of experiments.

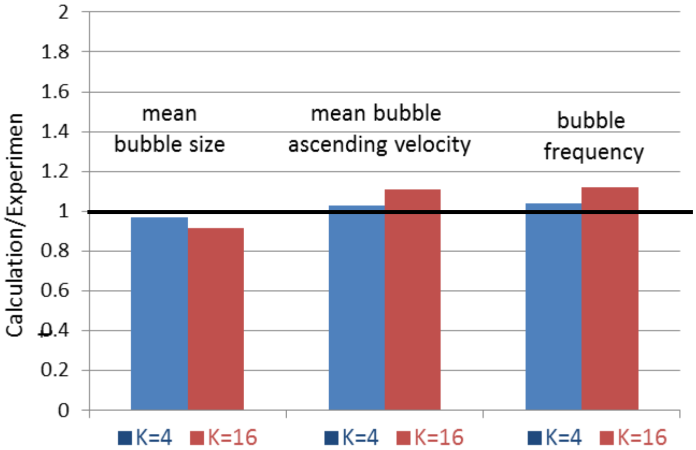
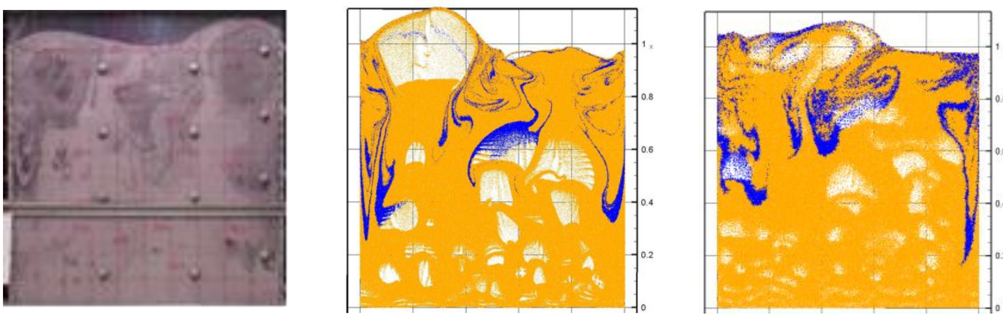



Fig.7 Comparison of experiment and simulation



(a) Experiment (b) Simulation (K=4) (c) Simulation (K=16)

Fig.8 Flow pattern in the fluidized bed

The flow pattern in the bed was also observed. At a certain time ($t=t_0$), the particles at top of bed were marked by black color. The black marked particle went downward along walls and central line of bed. Fig.8 showed the snapshot of $t= t_0+5s$. The comparison on flow pattern between simulations and experiment showed that the similarities-applied CFD-DEM were able to solve the flow pattern correctly.

## 5. CONCLUSIONS

The similarities were developed by employed imaginary particles and imaginary fluid. The diameter of imaginary particle was K-fold larger than real particle. If equations (3), (7) and (8) were satisfied, movement of imaginary particles was similar to that of real particles. The similarities were validated by both numerical simulation and experiment. The calculation load was greatly decreased by applying the similarities.

## SYMBOLS AND SUBSCRIPT

Ar Archimedes number
$D_p$ diameter of particle [m]
$\vec{F}_C$ contact force [N]
$\vec{F}_D$ drag [N]
g gravity accretion
K diameter ratio, define as equ.(2) [-]
m mass of particle [kg]
p pressure [pa]
Re Reynolds number
U velocity of particle [m/s]
V velocity of fluid [m/s]
$V_0$ superficial velocity of fluid [m/s]
$V_{mf}$ minimum fluidization velocity [m/s]
$\vec{X}$ position vector of the particle center
β inter-phase momentum transfer coefficient [kg/m$^2$ s]
ε volume fraction of fluid
$\rho_f$ density of fluid [kg/m$^3$]
$\rho_p$ density of particle [kg/m$^3$]
$\mu_f$ viscosity of fluid [pa•s]

**Subscript**
*f* fluid
L enlarged imaginary particle or imaginary field
O real particle or real field
P particle

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