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# Analysis of interparticle forces and particle-wall interactions by powder bed pressure drops at incipient fluidization

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ABSTRACT

A novel method is proposed to evaluate the interparticle forces and particle-wall interactions based on the pressure drop measurements at incipient fluidization. In the first experiment, we used the liquid bridge force as the model interparticle force of the glass ballotini (53 μm–105 μm). The theoretical relationship between the model liquid bridge force and the liquid addition volume was successfully presented. In the second part of experiment, the interparticle forces and the particle-wall interaction of cornstarch powders in a Perspex cylinder are determined. While the particle-wall interaction shows a linear relationship with the apparent bed-wall contact area, the interparticle force follows a logarithm relation with the bed mass for the Warren-Spring-type cornstarch powders. The results were also compared to the cohesion values obtained by a conventional shear tester. The results conclude that our method serves as an economically and accurate alternative to conventional shear testers.

## 1. Introduction

The interparticle force of a particle assembly is the summation of the van der Waals force, the liquid bridge force, the electrostatic force and other physical/chemical interactions and is difficult to be measured since a particle assembly typically consists of a number of particles with different sizes and/or other physical/chemical properties. However, the interparticle force strongly affects the flowability and other bulk behavior of the particle assembly, the measurement of the interparticle force of a particle assembly has been a subject of interest for both physicists and engineers [1]. Although models and methods have been developed to predict or measure the van der Waals force [2], the liquid bridge force [3–4], the electrostatic force [5–6], between two particles, the theoretical prediction or measurement of the interparticle forces of a particle assembly remains challenging. Although the discrete element method (DEM) based computational simulations show the possibility of approaching the local interparticle forces between particles [7–8], the contact mechanics used in the DEM simulation are usually with many assumptions, for example, the spring and dash-pot contact model assumption [9].

The measurement of the particle assembly cohesion is largely based on the shear testers [10–11]. The powder bed stress yield loci are used to extrapolate the powder bed cohesion under a zero normal stress condition. One of the problems for using the shear tester for the powder bed cohesion determination is the destruction of the powder bed caused by the application of the normal stress to the powder bed during the stress yield loci determination. The method for the measurement of the interparticle force of a powder bed with minor destructions is still under development. Here, a method is proposed to effectively and economically measure the interparticle force and the particle-wall interaction for the cohesive powders based on the non-destructive gas-solid interactions.

When the gas flows through a fixed powder bed, it experiences a pressure loss by friction. The Darcy's law and Ergun equation are used for the calculation of pressure drops through a randomly packed bed of spheres in both laminar and turbulent flows [12]. When increasing of the superficial gas velocity gradually, the gas-solid drag force finally balances with the buoyancy weight of the particles and the pressure drop across the bed reaches is approximately the buoyancy weight of the bed divided by the bed cross-sectional area at incipient fluidization [13]. Moreover, the pressure drop *overshoot*, which is the extra pressure drop above the pressure drop across the normal fluidized bed at incipient fluidization, has been reported in cohesive particle fluidization studies [14]. Although using the pressure drop overshoot to evaluate the interparticle forces had been proposed in one earlier study [15], the measured interparticle force from only one condition was reported without comparing to the interparticle forces obtained by other methods or theoretical predictions. Here, we systematically determine the liquid bridge force based interparticle forces by the pressure drop overshoots under well controlled liquid additions. Also, we initially apply the stage-wise pressure drops at incipient fluidization for the evaluation of the powder bed cohesions with different loading and of the tensile strengths between the powder bed and the container wall.

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## 2. Experimental

Two different particles are used in the experiments. The particle size distributions were measured by the laser diffraction sizing technique using Mastersizer 2000 (Malvern, UK). Glass ballotini (diam, $d_p$ = 53–105 μm; volume mean diam, 85.32 μm; density; 2476 kg/cm$^3$) are used as the sample particles in the first part of experiment using the liquid bridge force as the model interparticle force. The silicone fluid (viscosity, 315 cp; surface tension, γ = 21.94 dyne/cm) was homogeneously mixed to the glass ballotini as the binding bridge using a high shear mixer (supermixer YS-MG-1, INORA Inora Machinery, Taiwan) rotating at 120 rpm for 3 min. The amount of the silicone fluid added is represented by the dimensionless liquid volume $V^* = \frac{liquid\ volume}{liquid\ volume + particle\ volume}$. The amounts of fluid addition were 0, 8.84 × 10$^{-4}$, 1.32 × 10$^{-3}$, or 1.77 × 10$^{-3}$. For the glass particles within this size range, the small amount of liquid addition allows the liquid bridge force as the major interparticle force [16]. In the second part of experiments, cohesive cornstarch powders (volume mean diam, 15.6 μm; density; 1494 kg/cm$^3$) stored in a 50°C, RH = 65% environment for 24 h were used as the sample particles.

The schematic drawing of the experimental setup is shown in Fig. 1. An acrylic cylinder with an inner diameter of 3.0 cm was used to carry out the fluidization experiments for both particles. A screen printing cloth (mesh 200) was used as the gas distributor and 3 mm glass beads were used to uniformly distribute air in the windbox. In a typical experiment, the silicon oil-mixed glass ballotini or cornstarch powders were weighted and loaded on top of the gas distributor. Air from the compressor was dried and introduced to the system as the fluidizing gas. The inlet air velocity $u_0$ (volumetric rate/cylinder cross-sectional area) was controlled by a controller (MCH-50SLPM-D, Alicat Scientific, USA). The pressure drop across the bed (including the pressure drop across the gas distributor) at steady state, $\Delta P$, was measured by a differential pressure transmitter (FCO352, Furness Controls, precision = ±0.25%). The cyclic operation began with a packed bed condition, followed by increasing $u_0$ until reaching the full fluidization condition, and finalized by decreasing $u_0$ until reaching the pack bed condition again. $\Delta P$ as a function of the inlet air velocity for this cyclic operation was recorded. The reproducibility tests were carried out and each experimental condition run 2 times. The average $\Delta P$ values were used for further analyses and the corresponding statistic error bars are provided in the following figures.

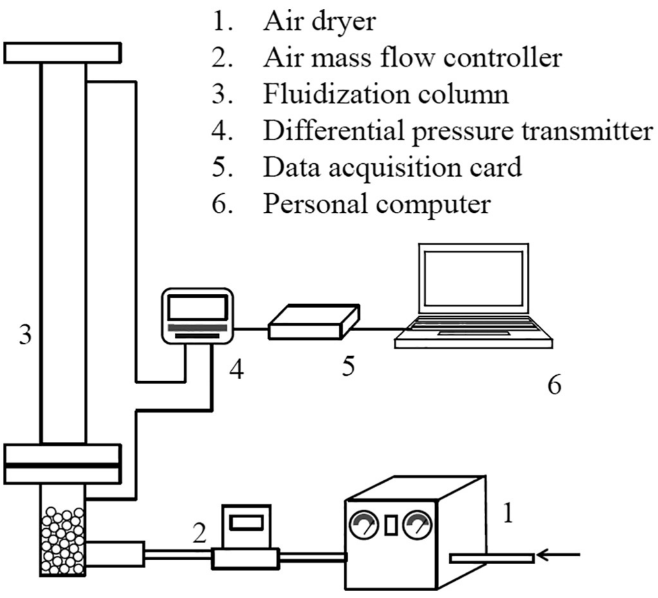

**Fig. 1.** The schematic drawing of the experimental setup.

## 3. Results and discussion

Fig. 2 shows a representative plot of $\Delta P$ as a function of the inlet air velocity ($u_0$) when gradually increasing $u_0$ ($u^+$) and decreasing $u_0$ ($u^-$). The pressure drop overshoot refers to the extra pressure drop caused by particle interaction at incipient fluidization. We proposed a method to determine the pressure drop overshoot, $\Delta P_{over}$, based on the difference of $\Delta P$ between Point A and Point B in Fig. 2. Ideally, Points A and B should be determined at *incipient fluidization*. When gradually increasing the inlet air velocity from a zero value, $\Delta P$ gradually increases and follows a linear relationship according to the Ergun equation. While the inlet air velocity reaching a certain value, $\Delta P$ suddenly decreases to Point C. Here, the bed is assumed at its incipient fluidization state at Point C. Since the bed has already been (partially/fully) fluidized at Point C and the original bed structure has been damaged, $\Delta P$ of an undamaged bed at Point A is determined by extrapolating the linear Ergun equation to Point C's inlet air velocity. Point B represents the fully fluidized $\Delta P$ at incipient fluidization. Since the fully fluidized bed is obtained between Point D and Point E, Point B is determined by extrapolating the linear fully fluidized bed $\Delta P$ prediction to Point C's inlet air velocity. Following this methodology, $\Delta P_{over}$ was determined at incipient fluidization for each bed loading study.

Fig. 3 shows the representative results of $\Delta P$ as a function of $u_0$ when gradually increasing $u_0$ ($u^+$) and decreasing $u_0$ ($u^-$) in the first part of the experiment with different glass ballotini loadings. In all cases, $\Delta P$ initially increases linearly with the increasing of $u_0$ as a fixed bed state. After $u_0$ increasing to a certain value, $\Delta P$ suddenly drops at incipient fluidization. With a further increasing of $u_0$, $\Delta P$ gradually increases to a steady value as a fully fluidized state. $\Delta P_{over}$ was determined for each case using the previous mentioned method. The results show that $\Delta P_{over}$ increases with the increasing of $V^*$. Since the fixed bed is instantaneously fluidized at incipient fluidization and the majority of particles moves freely without any contacts or with the particle contact coordination number less than 2 at fully fluidization [17], $\Delta P_{over}$ approximately equals the tensile yield stress to *tear apart* the powder bed held by pair-wise interparticle forces. Since $\Delta P_{over}$ is determined by the difference of the pressure drop between the Ergun equation prediction (fixed bed) and at fully fluidization, $\Delta P_{over}$ may relate to the pair-wise interparticle force as [18–19]:

$$\Delta P_{over} \approx tensile\ yield\ stress = \frac{(1 - bed\ voidage)(interparticle\ force)(coordination\ number)}{(particle\ diameter)^2 \pi} \tag{1}$$

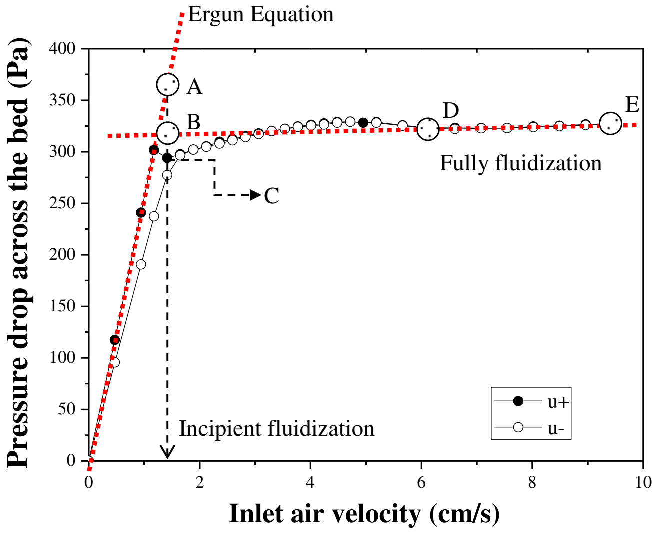

**Fig. 2.** An example of $\Delta P_{over}$ determination. (25.00 g glass ballotini with V* = 0).