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A STUDY OF THE EFFECT OF LIQUID-INDUCED FORCES ON GAS-SOLID FLOW BY A COMBINED CONTINUUM AND DISCRETE MODEL

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ABSTRACT

Numerical experiments are carried out to simulate the gas-solid flow in a packed bed with lateral gas blasting by a combined continuum and discrete model. The liquid-induced forces between neighbor particles are considered to be composed of two components: capillary and viscous. The results are analyzed in terms of gas-solid flow pattern, pressure drop fluctuation and microdynamic force distribution. It is shown that with the addition of water, the motion of particles is significantly suppressed either under raceway or fluidization conditions. In particular, particles tend to form agglomerates, which results in an enlarged stagnant zone and an increased fluctuation of bed pressure drop. The results suggest that the viscous component should be taken into account for gas-solid flow systems with high relative velocities between particles.

INTRODUCTION

The presence of liquid on the surface of particulate materials can change their behavior significantly. In practice, the liquid may come from the moisture condensation in a humid atmosphere, chemical reaction or thermal fusion in a reactor, or addition of binding liquid in a granulation process. Generally speaking, a cohesive force arises between particles due to the presence of liquid, which often causes particles to agglomerate, leading to the alteration of powder flowability in a process.

When the amount of liquid in the bulk solid is small, the liquid can form discrete pendular bridges between particles as long as their separation distance is smaller than a so-called rupture distance for a given liquid volume. The evaluation of the cohesive force between two spheres or a sphere and a wall has been the subject of research for many years (Hotta et al, 1974; Adams and Perchard, 1985; Hwang et al, 1986; Simons et al, 1994; Lian at al, 1993). The bulk behavior, however, cannot simply be inferred from the information obtained from isolated particles because the liquid bridges form a complex network amongst particles, and the situation can be further complicated by the presence of other competing forces such as fluid drag force in a system. While useful in understanding the bulk behavior of the system of interest (Wright and Raper, 1998), at present experimental studies are difficult in generating information related to the dynamics of individual particles. Computer simulation, therefore, provides an effective way to bridge the gap between bulk and individual particle behaviors.

There are few simulation studies of this kind in the literature where the cohesive forces due to the liquid bridge are considered at the individual particle level. Lian et al (1998) studied the impact coalescence of two agglomerates formed by wet primary particles using the Discrete Element Method (DEM). Muguruma et al (1998) applied the DEM to simulate the solid flow in a centrifugal tumbling granulator where the liquid bridge force was introduced as a result of adding the binding liquid. In gas-solid two-phase flow systems, the DEM needs to be combined with Computational Fluid Dynamics (CFD) to provide a full description of the dynamics of discrete particles and continuum fluid (Xu and Yu, 1997). Such a model can be generally referred to as the Combined Continuum and Discrete Model (CCDM). Using the CCDM, Mikami et al (1998) investigated the behavior of wet particles in a two-dimensional fluidized bed.

As discussed by Xu et al. (1999), the raceway and fluidization are two manifestations of the gas-solid and solid-solid interactions in a fluid bed reactor. A liquid phase can often be found in such a reactor, e.g. liquid iron or slag in a blast furnace or pre-reduction fluidized bed in ironmaking. The present work extends that work of Xu et al. (1999) by incorporating liquid-induced forces into their CCDM to study the effect of cohesive force on the raceway and fluidization. The behavior of wet particles subjected to lateral gas blasting is examined in terms of gas-solid flow patterns, pressure drop fluctuation and microdynamic force distribution.

COMBINED CONTINUUM AND DISCRETE MODEL

In the CCDM, Newton's second law of motion is used to describe the motion of individual particles and the Navier-Stokes equation to describe fluid flow. The translational and rotational motions of a particle at any time, t, can be written as

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_i \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \mathbf{T}_i \tag{2}$$

where m_i, I_i, $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are, respectively, the mass, moment of inertia, translational and rotational velocities of particle i. The resultant force acting on particle i, $\mathbf{f}_i$, includes the fluid drag force, gravity, inter-particle and cohesive forces. The inter-particle forces at contact points can generate a torque, $\mathbf{T}_i$, causing the particle to rotate.

The continuity and momentum equations of the fluid field expressed in terms of the local mean variables over a computational cell are given by

$$\frac{\partial \varepsilon}{\partial t}+\nabla\cdot(\varepsilon\mathbf{u})=0 \tag{3}$$

$$\frac{\partial(\rho_f\varepsilon\mathbf{u})}{\partial t}+\nabla\cdot(\rho_f\varepsilon\mathbf{uu})=-\nabla p-F+\nabla\cdot(\varepsilon\boldsymbol{\tau})+\rho_f\varepsilon\mathbf{g} \tag{4}$$

where $\mathbf{u}$, ρ_f, p and ε are, respectively, the fluid velocity, density, pressure and porosity; $\mathbf{F}$, $\boldsymbol{\tau}$ and $\mathbf{g}$ are the volumetric fluid-particle interaction force, fluid viscous stress tensor and gravitational acceleration.

Detailed theoretical treatments, such as the calculation of inter-particle forces, fluid-particle interaction forces, and the coupling between the discrete and continuum models, can be found elsewhere (Xu and Yu, 1997, 1998; Xu et al., 1999). As such, the following only details the calculation of the cohesive forces resulting from the addition of liquid.

Cohesive Forces

The actual state of interstitial liquid amongst particles depends upon the amount of liquid added into the bulk solids. When only a small amount of liquid is introduced, the liquid can form discrete pendular bridges between particles, producing a cohesive force between particles. This force is both capillary and viscous in nature. The capillary component arises from the pressure deficiency in the bridge and surface tension of the liquid whilst the viscous component from the flow of liquid in the bridge. The viscous force can be significant when liquid viscosity is high or particles are approaching each other at high relative velocities (Adams and Perchard, 1985).

The difficulty in calculating the capillary force comes from the determination of the actual surface profile of a liquid bridge between two particles, which is a function of the contact angle, particle size, and liquid volume. The analytical solution is quite formidable even for a simple case. Usually, the surface profile of a liquid bridge is treated approximately as a toroid (Fisher, 1926; Hotta et al, 1974) or solved numerically as a nodoid (Hwang et al, 1987; Lian at al, 1993). Lian et al. (1993) has shown that the error caused by the approximate method is less than 10% for all stable separations and a wide range of liquid bridge volumes. Simon et al. (1994) also pointed out that the approximate solution underestimates the exact values by less than 14 % for two equally sized spheres with zero contact angle. Therefore, the toroid approximate method is widely used in the literature.

On the other hand, to calculate the capillary force in the DEM or CCDM, the distribution of liquid amongst particles has to be specified. Strictly speaking, there is no easy way to predict this distribution; and the numerical simulation has to be based on simplified conditions. Muguruma et al (1998) assumed that the liquid added into the centrifugal tumbling granulator is uniformly distributed among all gaps in which the formation of a stable liquid bridge is possible. Lian et al (1998) and Mikami et al (1998) treated the liquid bridge volume as constant in the simulation of impact coalescence of two agglomerates and wet particle fluidization by assuming sufficient water storage on the surface of particles in the form of liquid film. The importance of the viscous force on the energy dissipation, which was ignored by Muguruma et al. (1998) and Mikami et al. (1998), has been emphasised by Lian et al (1998).

In this work, a constant liquid bridge volume is assumed. The liquid-induced force $\mathbf{f}_L$ is the sum of the capillary force, $\mathbf{f}_c$, and viscous force, $\mathbf{f}_v$, i.e.

$$\mathbf{f}_L=\mathbf{f}_c+\mathbf{f}_v \tag{5}$$

which provides a cohesive force in the normal direction between two particles. For convenience, the capillary force is evaluated using the regression equation given by Mikami et al (1998), so that

$$f_c=\pi R_i\gamma\left[\exp\left(a_1\frac{S_i}{R_i}+a_2\right)+a_3\right] \tag{6}$$

where γ, R_i and S_i are, respectively, liquid surface tension, particle radius and separation distance between particles; a_1, a_2 and a_3 are, respectively, regression coefficients as a function of contact angle and liquid bridge volume (Mikami et al., 1998). The latter, V^*, is defined as $V^*=V/(R_i)^3$, where V is the liquid bridge volume.

The equation proposed by Adams and Perchard (1985) is used to evaluate the normal component of the viscous force, f_{vn}, i.e.

$$f_{vn}=\frac{3}{2}\pi\mu_L v_{rn}\frac{R_i^2}{S_i} \tag{7}$$

where μ_L and v_{rn} are, respectively, liquid viscosity and relative approaching velocity between two particles in the normal direction. To avoid singularity in Eq. 7, a very small minimum separation distance of 0.03 μm is set as suggested by Lian et al (1998). The tangential component of the viscous force has been ignored due to the lack of a rigorous analytical solution for its evaluation and the preliminary nature of the present work.

SOLID PHASE	
Number of particles	10,000
Particle diameter	0.004 m
Particle density	2,440 kgm^{-3}
Spring constant	40,000 Nm^{-1}
Friction coefficient	0.3
Viscous damping coefficient	0.12
GAS PHASE	
Viscosity	1.8×10^{-5} $kgm^{-1}s^{-1}$
Density	1.205 kgm^{-3}
Bed width× height×thickness	0.3×1.0×0.004 m
Jet opening	0.020 m
Cell width×height	0.01×0.02 m
LIQUID PHASE	
Liquid viscosity	1.01×10^{-3} $kgm^{-1}s^{-1}$
Surface tension	0.073 Nm^{-1}
Contact angle	0 rad

Table 1: Parameters used for the present simulation.

Solution Schemes

The explicit time integration method is used to solve the translational and rotational motions of a system of discrete particles in the discrete model. The conventional SIMPLE method is used to solve the equations for the fluid phase in the continuum model. The discretization schemes, and treatments on initial and boundary conditions are the same as those used in the previous work (Xu and Yu, 1997; Xu et al., 1999). Table 1 summarizes the parameters used in the present simulations. Note that the bed is only one diameter in thickness. In this case, if the effect of the front and back walls is ignored, the motion of both solid and fluid phases is two-dimensional although the calculation porosity is three dimensional as described elsewhere (Xu and Yu, 1997).

RESULTS AND DISCUSSION

Depending on the gas velocity, a packed bed can transform from a fixed to a fluidized state or vice versa. As discussed by Xu et al. (1999), for such a bed with dry particles, two zones can be identified: a stagnant zone in which particles largely remain in their initial positions, and a mobile zone in which particles can move in various flow patterns. If the gas velocity is in a certain range, the mobile zone is confined in front of the gas inlet, forming the so-called raceway in which particles can circulate. If the gas velocity is higher than a critical value, gas escapes from the bed in the form of bubbles and slugs and fluidisation results, with the mobile zone growing as a result of the combined effect of bubble penetration and shearing between moving and static particles until a stable state where the boundary separating the mobile and stagnant zones is unchanged. Such phenomena can also be found in the present study with wet particles.

Figure 1 shows the effect of water addition on the cavity formation. The particles on the roof of the cavity slide down along the wall in the form of agglomerates due to cohesion. Such an agglomerate is soon broken down into primary particles which are dragged by gas and impact on the cavity wall. The particles move along the cavity wall and finally paste onto the wall under the joint effect of fluid drag and cohesive forces. The cavity continues to grow with occasionally dropping down of an agglomerate until a stable macroscopic state. Compared with the raceway phenomena for dry particles (Xu et al., 1999), the circulation of particles inside the cavity or raceway is greatly suppressed by the presence of cohesive forces.

Such suppression becomes more obvious when examining the size of the stagnant zone or mobile zone in fluidization formed from a fixed bed. Figure 2 shows solid mixing patterns at a specified time instance when the stable boundary separating mobile and stagnant zones is formed for three different amounts of water addition. In the figure, the particles in the initial fixed bed are marked alternatively black and white in order to visualise the solid displacement. Both experimental and numerical observations indicate that such a stable state can be achieved within a few seconds (Xu et al., 1999). Inspection of the distortion of the stripes shown in Fig. 2 suggests that the presence of water can change the "mixing" between black and white spheres considerably. When the water amount is large, solid motion in the mobile zone is significantly retarded, giving a larger stagnant zone.

The motion of a wet particle is governed by the fluid drag, inter-particle forces and liquid-induced cohesive forces, in addition to gravity. These forces vary spatially and temporally. Figures 3 and 4 show the distributions of the sum of inter-particle and cohesive forces, and fluid drag forces under comparable gas-solid flow patterns with and without water addition. The results shown in these figures suggest that there are similar distribution patterns for dry and wet fluidizations. Large inter-particle and cohesive forces are mainly found along the boundary separating the mobile and stagnant zones, propagating into the bed; and large fluid drag forces at or above the bubble roof.

The cohesive forces must be the major factor responsible for different behaviour between dry and wet particles. Because of the cohesive nature of the forces, it is difficult for particles to transit from a static to moving state, giving a larger stagnant zone (Fig. 2). Comparing Fig. 3b and Fig. 4b also indicates a steeper boundary separating the mobile and stagnant zones for wet fluidization. At the same time, particles in the mobile zone do not always act as individuals due to the formation of agglomerates. In fact, as obvious from Fig. 4, a most striking difference here is that particles rain down from the solid-slug roof in the form of agglomerates for the wet fluidization. Consequently, the formation and break-up of a solid-slug are not so gradual, which may result in a large fluctuation in operation. Figure 5 shows the fluctuation of bed pressure drop between the jet inlet and the bed exit along the wall with gas inlet. It appears that the addition of water gives larger fluctuations, although the difference in the mean pressure drops is not significant.

As mentioned above, the addition of a liquid induces two forces: capillary and viscous. The latter, however, was not considered in the simulation of wet fluidization by Mikami et al. (1998). As implied by Eq. (7), this force depends on the relative velocity between particles, in addition to parameters such as liquid viscosity, particle size and separation distance. The rigorous motion of particles in a fluidized bed can generate localised high relative velocities and hence large viscous forces. Therefore, the viscous force may also play an important role in controlling micro- and macroscopic behaviour. In fact, although a similar gas-solid flow pattern is observed, a larger bed pressure fluctuation results with the incorporation of the viscous force in the present CCDM simulation as shown in Fig. 6. This larger pressure fluctuation confirms the role of viscous forces in the energy dissipation as found by Lian et al. (1998).

CONCLUSION

Addition of a liquid into a particulate system can have a significant effect on its bulk behaviour. The present CCDM simulations indicate that when water is added to a bed packed with glass beads subjected to lateral gas blasting, the motion of particles is significantly suppressed either under raceway or fluidisation conditions. In particular, particles tend to form agglomerates, which results in an enlarged stagnant zone and an increased bed pressure drop fluctuation. While more detailed studies are necessary in order to develop a better understanding of the role played by the liquid-induced forces, the results suggest that for gas-solid flow systems with high relative velocities between particles, the viscous effect should be taken into account.

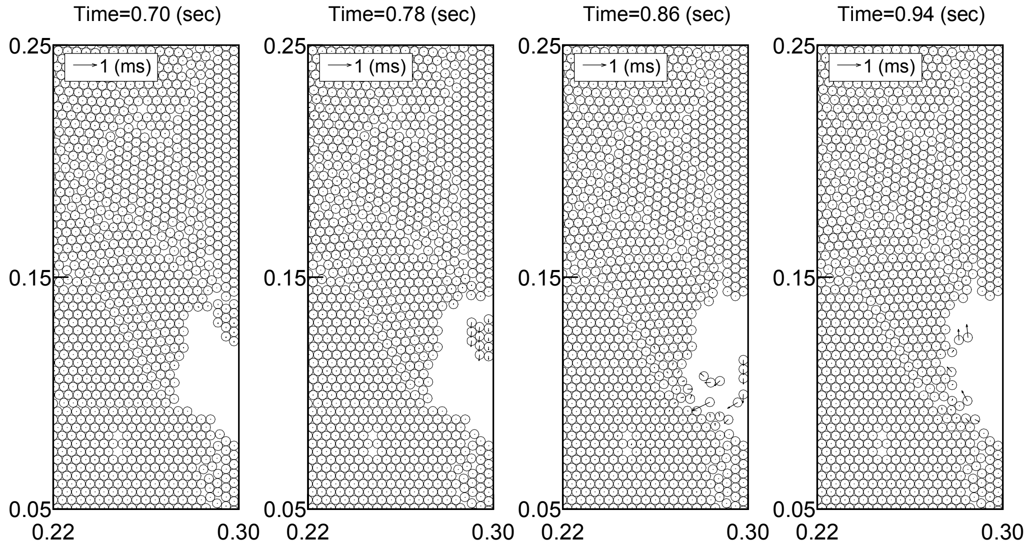
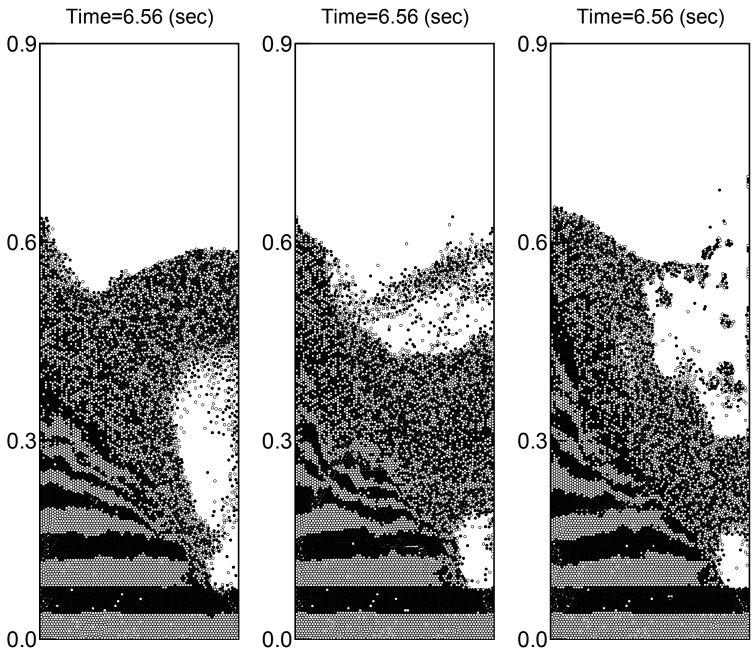
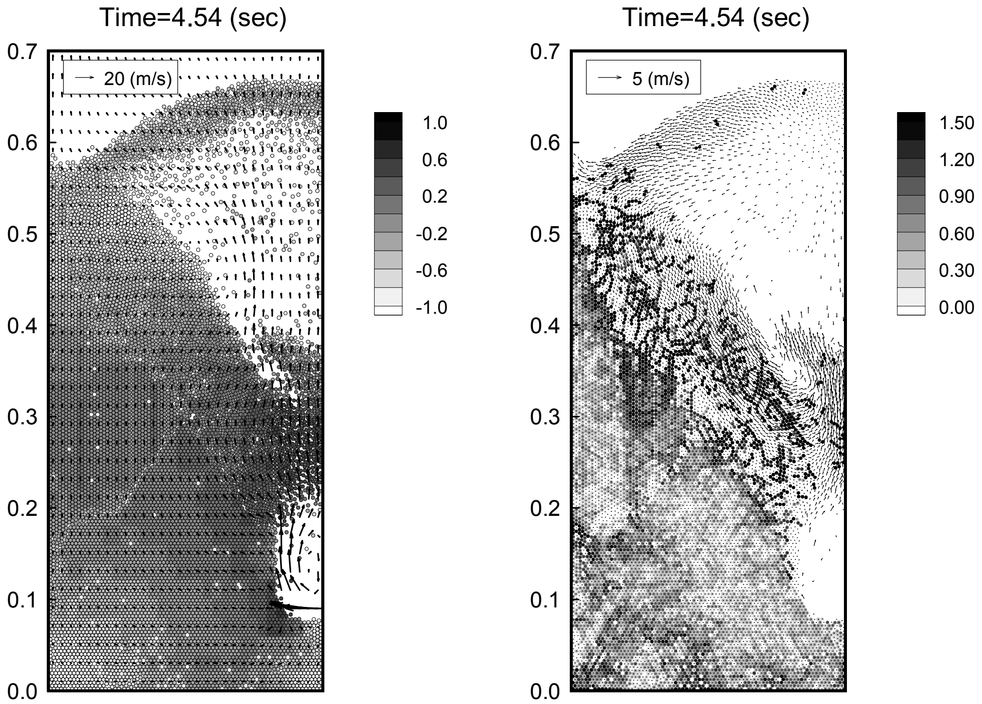


Figure 1: Particle velocity showing the formation of cavity when the gas velocity is 26 m/s and V^*=0.01.



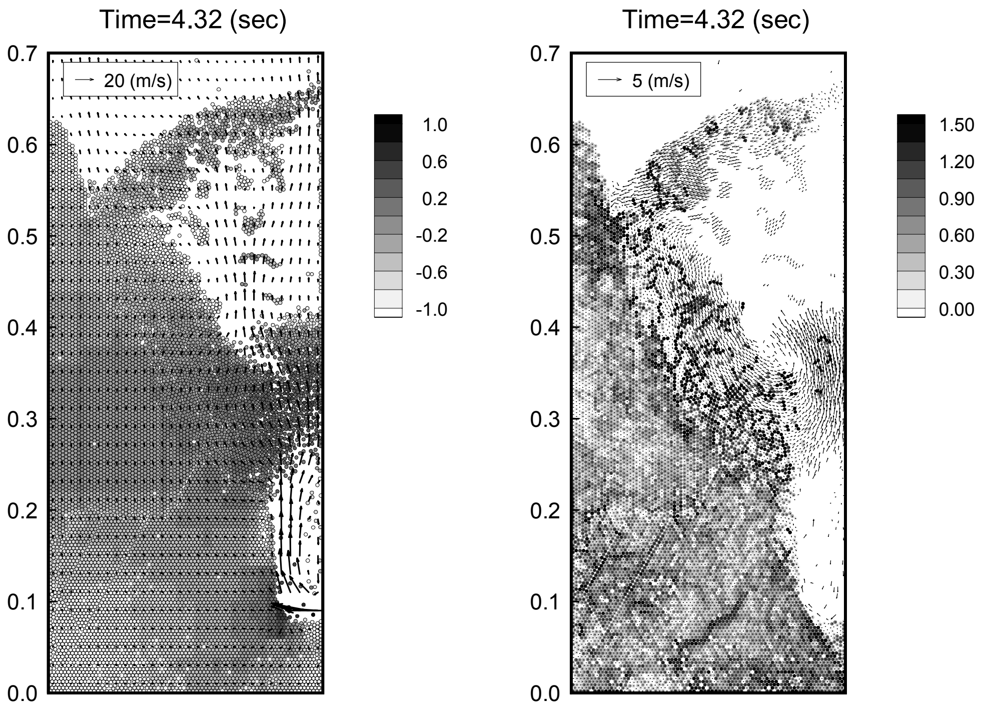
(a) (b) (c)

Figure 2: Solid mixing patterns at a specific instance for three different V^*: (a), V^*=0.00; (b), V^*=0.001; (c) V^*=0.01.



(a) (b)

Figure 3: Typical results when gas velocity is 40 m/s and V^*=0.00, demonstrating the distributions of: (a) gas velocity and fluid drag force; (b) particle velocity and the sum of inter-particle and cohesive forces; all forces are expressed as ratios of their magnitude to the gravity of a particle on a logarithm scale.



(a) (b)

Figure 4: Typical results when gas velocity is 40 m/s and V^*=0.01, demonstrating the distributions of: (a) gas velocity and fluid drag force; (b) particle velocity and the sum of inter-particle and cohesive forces; all forces are expressed as ratios of their magnitude to the gravity of a particle on a logarithm scale.

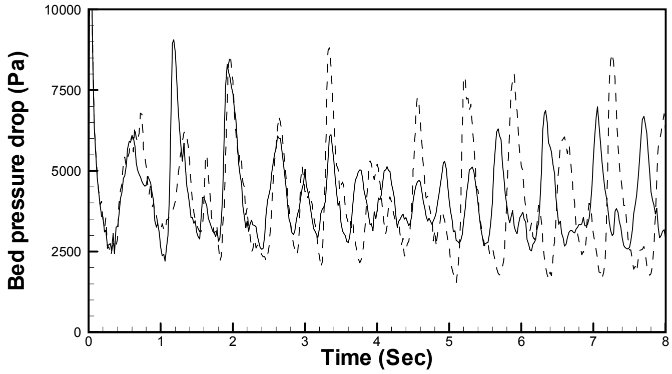


Figure 5: Pressure drop fluctuations for different V^*: (——) V^*=0.00; (-----) V^*=0.01.

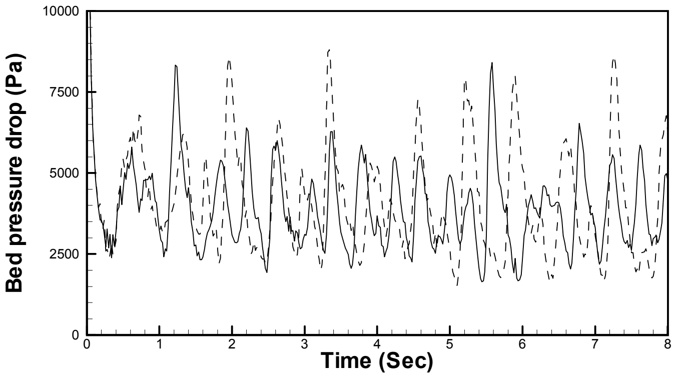


Figure 6: Pressure drop fluctuations when V^*=0.01, with (-----) and (——) without viscous force.

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