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Tangential viscous force models for pendular liquid bridge of Newtonian fluid between moving particles

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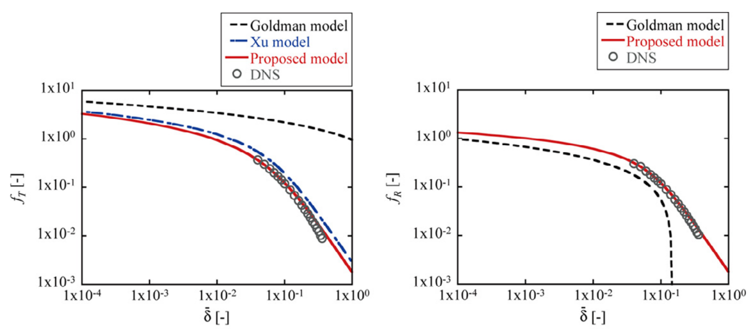
HIGHLIGHTS

- Tangential viscous force models for pendular liquid bridge are proposed.
- The proposed models show improvements compared to other models in literature.
- Explicit relationship between the bridge volume and bridge radius is derived.

GRAPHICAL ABSTRACT



Force due to translational motion

Force due to rotational motion

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ABSTRACT

In wet powder handling processes, it is of paramount importance to accurately estimate the viscous force acting on particles. In the present work, the tangential viscous force models for a pendular liquid bridge used in Discrete Element Method (DEM) in literature are reviewed first, and then new models are proposed by modifying the Xu model (Xu et al., 2005) based on the numerical solution of the pressure equation derived from the lubrication theory. The results obtained from the proposed models are compared with those from Direct Numerical Simulation (DNS) to find that they show good agreement with each other when the separation distance is sufficiently small, i.e. when the lubrication approximation is valid. The validity and accuracy of the models in literature are also discussed.

1. Introduction

Wet granular flow can be found in many processes including pharmaceutical, food and chemical industries. There are many applications that mixes liquid with powder to improve the particle characteristics and ease the powder handling such as wet agglomeration and tablet coating. On the contrary, powder sometimes captures liquid spontaneously from the surroundings such as environmental moisture absorption in silo, which is undesirable in most cases.

When liquid exists in inter-particle pores, bridges may be formed and the liquid bridge forces are exerted on the particles, i.e. capillary and viscous forces. The capillary force is caused by the surface tension and the Laplace pressure whilst the viscous force comes from the liquid viscosity and the relative velocity of particles. In some applications including detergent manufacturing process, liquid with extremely high viscosity is mixed with powder. In such applications, the viscous force is dominant and has a significant impact on the flow pattern. Typical examples of highly viscous liquids are honey, sugar solution and polyethylene glycol (PEG) with high molecular weight whose viscosity is more than 1000 times higher than that of water.

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Discrete Element Method (DEM), which was originally proposed by Cundall and Strack (1979), was widely used in the past two decades to simulate wet granular flow by taking into account the liquid bridge forces acting on particles (Muguruma et al., 2000; Willett et al., 2000; Mikami et al., 1998; Soulié et al., 2006; Lian et al., 1998; Liu et al., 2013; Tang et al., 2016). Although the advancement of the simulation model and computation power makes it possible to perform resolved DEM-CFD simulations with liquid bridges (Washino et al., 2013; Kan et al., 2015), it is still impractical to carry out resolved DEM-CFD simulation with large number of particles. Hence, it is required to employ force models to consider the effect of the liquid. Liquid between particles may exist in different states depending on the liquid-particle volume ratio, that is, pendular, fanicular and capillary states (Iveson, 2001) as shown in Fig. 1. A number of capillary force models are proposed in literature (Muguruma et al., 2000; Willett et al., 2000; Mikami et al., 1998; Soulié et al., 2006; Rabinovich et al., 2005; Lambert et al., 2008) based on a static and symmetric pendular bridge, i.e. one bridge formed between a pair of particles and they can provide largely comparable results (Liu et al., 2011).

The normal and tangential components of the viscous force are often modelled separately. This is valid if the Reynolds number of the system is sufficiently small and the momentum equation is reduced to the Stokes equation where the superposition principle of the solutions can be applied. The pioneering work to take into account the viscous force in DEM is reported by Lian et al. (1998). They used the Adams and Perchard model (Adams and Perchard, 1985) for the normal component of the viscous force and the Goldman model (Goldman et al., 1967) for the tangential component. However, both the Adams and Perchard and Goldman models are for the forces acting on a fully immersed particle in fluid, and not for the forces due to a pendular liquid bridge. Despite that, many researchers apply these models in DEM (Tang et al., 2016; Yang, 2006; Shi and McCarthy, 2008). A couple of normal viscous force models for a pendular liquid bridge are proposed in literature. Pitois et al. (2000) assumed a cylindrical pendular bridge to determine a correction coefficient to the Adams and Perchard model and Liu et al. (2013) used the Pitois model in their DEM simulation. More recently, Washino et al. (2017) modified the Pitois model based on the Direct Numerical Simulation (DNS) results and the applicability of the normal viscous force models is discussed.

For the tangential viscous force, Xu et al. (2005) proposed a model considering a cylindrical pendular liquid bridge of power-law fluid between two particles without rotation. However, the validity of this model is not fully discussed and most of the DEM simulation work in literature today still uses the Goldman model for the a pendular liquid bridge. In the present work, important points of the Goldman and Xu models are reviewed first. Then new tangential viscous force models for a pendular liquid bridge of Newtonian fluid are proposed by modifying the Xu model. The Goldman, Xu and the proposed models are compared with the DNS results to discuss the model validity and accuracy.

2. Tangential viscous force models in literature

2.1. The Goldman model

Many pieces of work can be found in literature which takes into account the tangential viscous force of a pendular liquid bridge in DEM as mentioned in Section 1. To the best of the authors' knowledge, almost all of them use the Goldman model (Goldman et al., 1967) following the pioneering work by Lian et al. (1998). The Goldman model was originally developed to calculate the force acting on a fully immersed particle in Newtonian fluid near a plane wall as shown in Fig. 2. The wall is stationary and the particle is either translating parallel to the wall with constant velocity U in the x-direction *without rotation* or rotating with angular velocity of ω *without translation*. The asymptotic form of the tangential viscous force (in the x-direction) acting on the particle without rotation is given as follows which is valid when the inter-particle separation distance δ is sufficiently small:

$$F_T^{Goldman} = -6\pi\mu RU f_T^{Goldman} \tag{1}$$

where μ is the liquid viscosity, R is the particle radius and the subscript $_T$ denotes the translational contribution. The dimensionless factor $f_T^{Goldman}$ is given as:

$$f_T^{Goldman} = \frac{8}{15}\ln\left(\frac{R}{\delta}\right) + 0.9588 \tag{2}$$

The second constant term is obtained from O'Neill's numerical solution (O'Neill, 1964). When the Goldman model is used in DEM for particle-particle interaction, the particle radius R is replaced with the reduced radius $R^* = R_1R_2/(R_1 + R_2)$ where R_1 and R_2 are the radii of the particles.

Similarly, the tangential viscous force acting on the particle without translation is given as follows:

$$F_R^{Goldman} = -6\pi\mu R^2\omega f_R^{Goldman} \tag{3}$$

where ω is the angular velocity, the subscript $_R$ denotes the rotational contribution and the dimensionless factor $f_R^{Goldman}$ is given as:

$$f_R^{Goldman} = \frac{2}{15}\ln\frac{R}{\delta} - 0.2526 \tag{4}$$

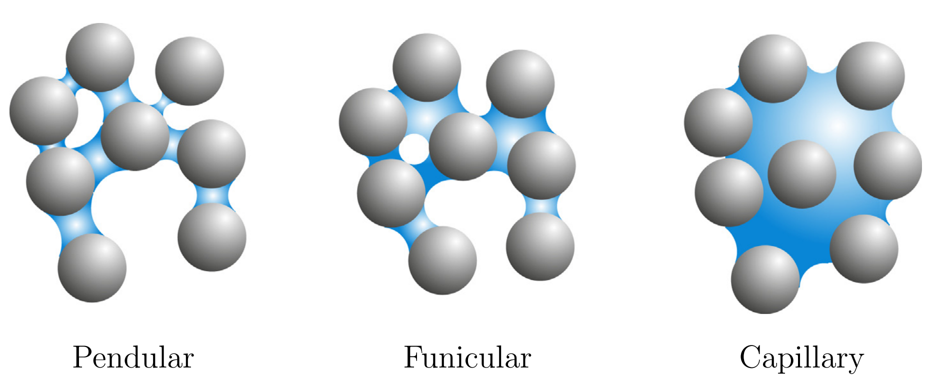

Fig. 1. Pendular, funicular and capillary liquid bridges.