Einsatz der Partikelbewegung bei laminarer Scherströmung in Abhängigkeit des Partikeldurchmessers

SHEAR INDUCED ONSET OF PARTICLE MOTION AS A FUNCTION OF PARTICLE DIAMETER

Christian Illigmann[1], Annette Goldenstein[1], Samet Retzepoglu[1], José R. Agudo[2], Andreas Wierschem[1]

[1]*Institute of Fluid Mechanics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), D-91058 Erlangen, Germany*

[2]*Institute of Fluid Mechanics, FAU Busan Campus, University of Erlangen-Nuremberg, 618-230 Busan, Republic of Korea*

Granulare Medien, Partikel- und Sedimenttransport
granular systems, particle and sediment transport

Abstract

We experimentally study the onset of motion of single spherical particles on regularly arranged substrates as a function of the particle diameter. The experiments are carried out in laminar shear flow at particle Reynolds numbers below 1. Experimental studies have shown a strong dependence on the arrangement of the substrate bed geometry. We now characterize the influence of the particle diameter of single spheres on the incipient particle motion on three different substrate beds. The particle diameter of the spherical particles forming the substrate bed is held fix. We then vary the particle diameter of the single sphere placed in a valley of the substrate bed. We found that the critical shields number is decreasing for increasing particle diameter. Numerical studies are in good agreement with the experimental data. The experimental setup consists of a rotational rheometer to induce the shear flow and a digital camera equipped with a macro-objective to track the particles.

Introduction

Shear induced onset of motion encounters in a wide variety of industrial and scientific applications like pneumatic conveying, filtration and cleaning. The incipient motion can also be noticed in situations like river bed erosion, sediment transport and dune formation. (Groh *et al.* 2008) Therefore, the prediction of particle motion has been intensively investigated during the last decades. While most of the studies are performed under turbulent conditions and heterogeneous substrate beds (Dey 2008, Wierschem *et al.* 2008) new studies reveal the importance of the onset of motion at laminar conditions and particularly for regular substrates (Derksen 2011, Ouriemi 2007, Charru *et al.* 2004, Martino et al 2009, J.R. Agudo and Wierschem 2012). The influence of neighboring particles on the incipient particle motion has recently been studied (J. R. Agudo and Wierschem 2014) while the interaction between surface occupancy and burial degree is still not studied and absent in literature. We now study the geometrical impact of different bead diameters on the onset of motion at particle Reynolds numbers below 1 in laminar shear flow. The bed grain size D_p is held fix while the particle diameter d for particles resting on the bed is changed. Furthermore, we change the particle spacing a/D_p of about 0.035, 0.232 and 0.268. We determine the critical Shields number as a function of particle diameter.

Experimental set-up

All experiments are performed with a rotational rheometer MCR 301 from Anton Paar using a parallel disk configuration. As a plate we use a PMMA plate of 150 mm diameter. The substrates are formed by a monolayer of soda-lime glass beads of 405.9 ± 8.7 μm diameter D_p from The Technical Glass Company. The substrate spheres are glued on to different stainless steel wire sieves from Bückmann GmbH & Co.. The sieves with dimensions of 15 x 70 mm^2 are fixed on microscope slides. These slides are concentrically placed into a circular container. As shows figure 1 (a) the center of the substrate bed is located at a distance r of 50 mm from the rotational axis while the gap height h is $5{\cdot}d$. The container consists of a brass bottom plate with transparent sidewalls of PMMA. As mobile bead we also used soda-lime glass beads with diameters d between 200 and 1000 μm. The mobile bead is placed right in the middle of the substrate bed, figure 1 (b). These parameters ensure that the results are independent from any boundary effects (Agudo & Wierschem 2012). The container is filled with silicone oil with viscosity of 103 ± 3.3 mPas and density of 965 ± 5 kg/m^3 at working temperature of 295.16 ± 0.5 K. The particle Reynolds number is of Order 10^{-4} and 10^{-3}. The oil temperature is controlled by using the rheometer's Peltier element. The mobile bead is detected through the rheometer plate using a digital camera with 1280 x 1024 pixels and a macro objective. The speed of the rheometer plate spinning with angular frequency, Ω, is increased in small steps of less than 0.5 % until the particle starts to move from its equilibrium position.

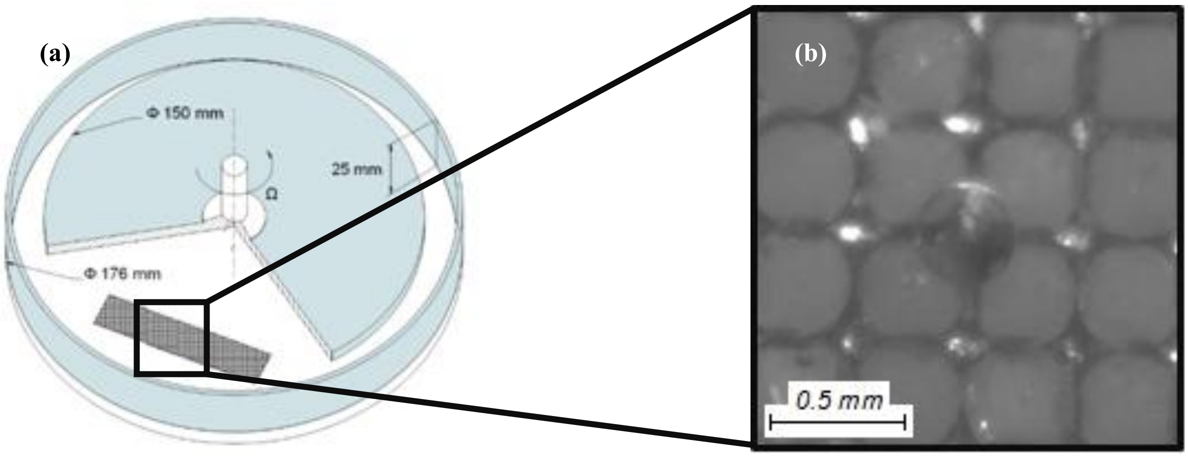

Fig. 1 – PMMA Container carrying substrate bed and rheometer disk of 150 mm diameter (a). Distance between substrate bed top and rheometer plate is $5{\cdot}d$. Mobile sphere with diameter d of 406 μm on top of substrate bed (b). The substrate bed with particle spacing a/D_p of 0.035 is formed by spheres of diameter D_p of 406 μm.

Experimental results and discussion

We characterize the incipient particle motion by the critical Shields number which compares shear stress acting on the particles surface with resistant specific particle weight. The fluid motion is created by the rotational plate spinning with angular velocity Ω at a gap height h. This produces a shear rate $\dot{\gamma} = \Omega \cdot r/h$ at the radial distance r of the turning axis. The shear stress reads $\tau = \mu \cdot \Omega \cdot r/h$ where μ is the dynamic viscosity. The Shields number is given by:

$$\theta = \frac{\nu \cdot \Omega \cdot r}{(\rho_S / \rho - 1) \cdot h \cdot g \cdot d} \tag{1}$$

The Reynolds number for the shear flow and the particle Reynolds number are given by:

$$\mathrm{Re} = \frac{\dot{\gamma}}{\nu} \quad , \quad \mathrm{Re}_P = \frac{\dot{\gamma} \cdot d^2}{\nu} \tag{2}$$

We study the incipient particle motion for three different particle spacing's. The threshold for the incipient motion is considered to be the displacement of the sphere from its equilibrium position to its neighboring equilibrium position. Figure 2 depicts the dependence of the critical Shields number from the particle spacing a/D_p. Rhomboids, rectangles and Circles indicate critical Shields number for particle spacing of about 0.035, 0.232 and 0.268, respectively. With growing particle spacing the critical Shields number increases while for bigger particle diameters the critical Shields number decreases. This is due to the fact that increasing the particle spacing results in an increased burial degree and in a decreased particle surface exposed to the main flow, respectively. While increasing the particle diameter d/D_p increases the surface occupancy to the main flow and decreases the burial degree. This concludes to an increasing critical Shields number for higher particle spacing's and a decreasing critical Shields number for higher particle diameter, respectively. The critical Shields number nearly halves between particle diameter of about 0.94 and 2.4 and fixed particle spacing's and almost doubles between particle spacing's a/D_p of about 0.035 and 0.268. This is due to the before mentioned fact of decreased surface exposure to the flow for higher particle spacing's as well as to the fact that substrate beads only behave like sand roughness for higher particle diameter.

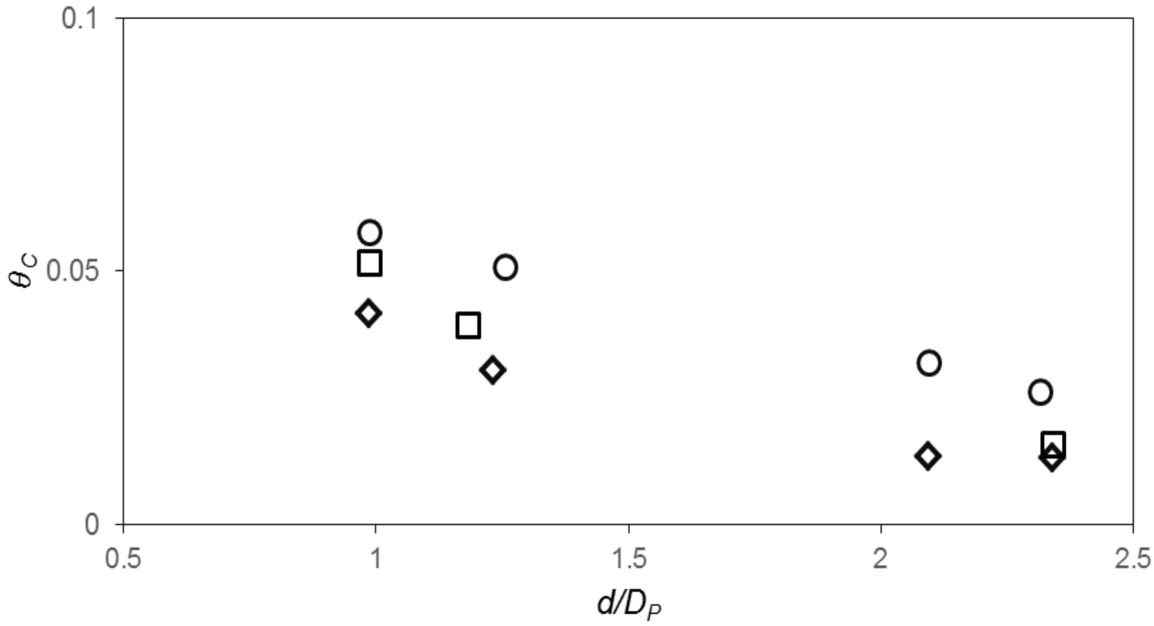

Fig. 2 – Critical Shields number for mobile glass beads with diameter d/D_p varying between about 0.94 and 2.4 as a function of particle spacing a/D_p on regular arranged quadratic substrates with particle diameter D_p. Rhomboids, rectangles and Circles indicate critical Shields number for particle spacing of about 0.035, 0.232 and 0.268, respectively.

Numerical results

We also performed numerical simulation in OpenFOAM®-2.3.1 for a particle spacing a/D_p of about 0.035. We solved the steady Navier-Stokes equations with the finite volume method and the SIMPLE-Algorithm. For the substrate we used a monolayer of spheres, as shows figure 3. The mobile bead (blue) is placed as in the experimental set-up in the middle of the substrate bed (grey). We compare experimental and numerical data in figure 4. One can see that numerical and experimental data are in good agreement for the critical Shields number.

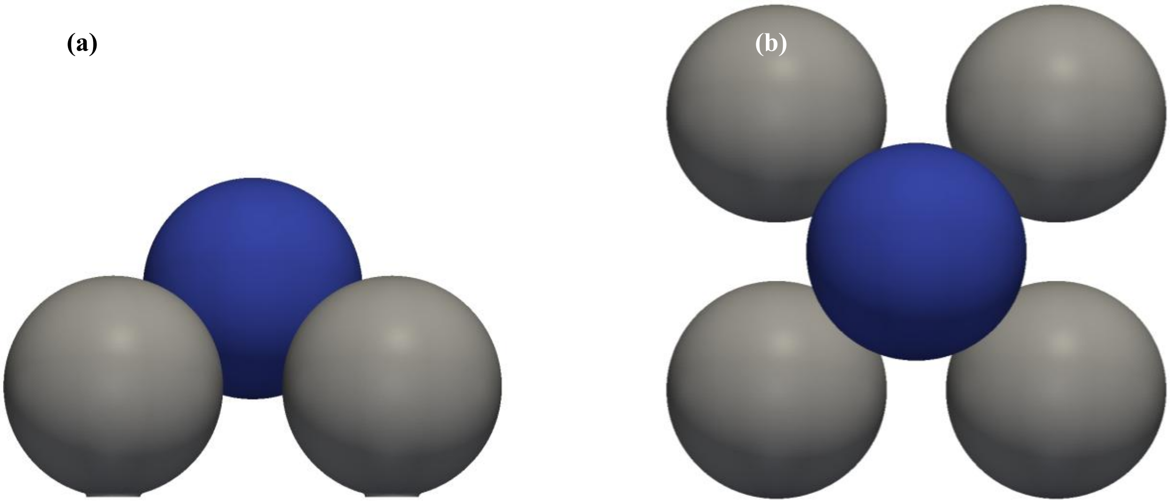

Fig. 3 – Mobile bead resting on substrate bed for a particle spacing a/D_p of about 0.268. Blue and grey sphere indicates mobile bead and substrate beads, respectively. (a) Side view normal to x-z plane and (b) view from top.

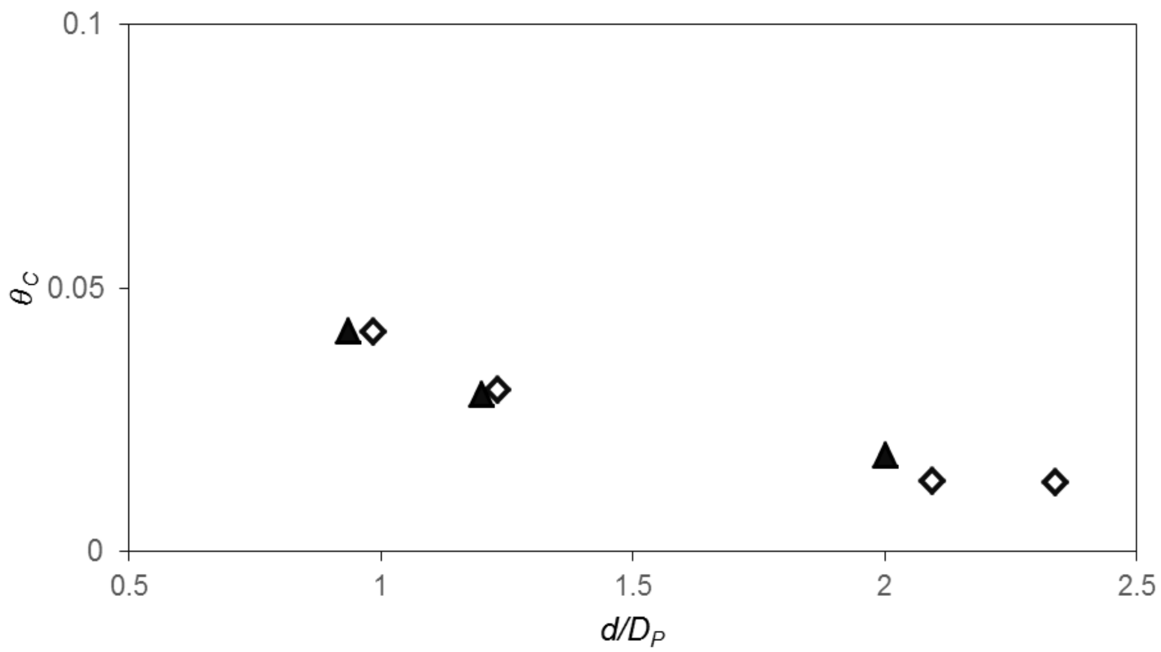

Fig. 4 – Critical Shields number for mobile glass beads with diameter d/D_p varying between about 0.94 and 2.4 and numerical data for a particle spacing a/D_p of about 0.035.

Summary

We studied the influence of particle spacing coupled with mobile bead diameter on the onset of particle motion in a rotational rheometer working in a parallel disk configuration. The incipient particle motion is characterized by the critical Shields number. It arises that the particle resistance to the onset of motion decreases with increasing particle diameter and decreasing particle spacing.

Acknowledgement

The support from Deutsche Forschungsgesellschaft through WI 2672/7-1 is gratefully acknowledged.

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