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EINSATZ DER PARTIKELBEWEGUNG BEI LAMINARE SHEARSTRÖMUNGEN

INCIPIENT PARTICLE MOTION IN LAMINAR SHEAR FLOWS

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Abstract

We study experimentally the critical conditions for incipient motion of spherical particles deposited on a regular substrate under laminar flow conditions. The substrates consist of a monolayer of wall-fixed spheres uniformly sized and regularly arranged in triangular and quadratic configurations. The particle motion is detected using a digital camera equipped with a macro-objective that incorporates a tilted mirror. The particle location is tracked optically and evaluated with image processing software. The onset of motion is characterized by the critical Shields number. We found that for particle Reynolds numbers of order one and smaller, the critical Shields parameter is independent from the particle density and from the particle Reynolds numbers but it depends significantly on the geometry of the substrate. We show how different geometrical parameters like the particle arrangement and exposure affect the critical Shields parameter. We particularly focus on the effect of neighboring particles on the onset of particle motion. Unlike single rolling particles, we observe switching between rolling and sliding motion as a consequence of friction between the moving neighbors. In our experiments, this two-particle interaction is the basic difference between the incipient motion of a single and multiple particles, being the limiting factor which governs the onset of motion and resulting in a significant increment of the critical Shields number.

Introduction

Prediction of the particle incipient motion has been studied intensively in fields such as hydrology, geology or civil engineering over the last century. It is encountered in several natural situations like sediment transport in rivers, bed erosion or dune formation (Groh et al 2008). Flow induced removal of particles finds also it application in a variety of different industrial operations, like pneumatic conveying, filtration or cleaning of surfaces in food and pharmacy industries. Typical bed-load transports as well as most of industrial applications are characterized by turbulent conditions and heterogeneous particle size distribution. Therefore, most of the studies found in literature have been performed under these conditions (Shields 1936, Dey and Papanicolau 2008, Wierschem *et al.* 2008, 2009). However, last advances in microfluidics, for instance, reveals that predicting the incipient motion of particles can be of great interest at very low Particle Reynolds numbers and under regular structured substrates (Sawetzki et al. 2008, Thompson et al. 2010). Some authors recently focused on the onset of particle motion under laminar conditions but using irregular structured bed particles (Charru et al. 2004, 2007, Loiseleux et al. 2005, Lobkovsky et al., Ouriemi 2007, and J.J. Derksen 2010). Ouriemi et al. provided a constant critical Shields number for incipient motion of about 0.12 in laminar flow independent from the particle

Reynolds number, being in agree with the values observed by Charru et al. (2004) for a saturated compact bed. The latter author observed an important role of the local grain arrangement on the incipient motion under laminar conditions. This was also pointed by Martino et al. (2009), which showed a strong dependence of the incipient motion on the geometrical properties of the bed. We recently corroborated the strong impact of the substrate geometry on the incipient motion of a single bead (J.R. Agudo and Wierschem 2012) but how multiple particles are affected by the substrate configuration still remains as an open question. Similarly, while the role of different mechanism on the incipient motion was intensively studied under turbulent conditions (Drake et al. 1988, Wu and Chou 2003, Valyrakis 2010), lack of information about neighboring beads affecting the mechanism of motion at low particle Reynolds numbers is found in literature. Here we study the geometrical impact of the substrate configuration on the incipient motion of multiple uniformly particles in laminar shear flow. We analyze how neighboring particles affect the onset of motion on regular substrates of identical spherical beads. For particle Reynolds numbers ranging from creeping flow conditions to up about 1, we determine the critical Shields number as a function of the substrate configuration, the different neighbors placement on the substrate, and the angle of flow orientation with respect to the particle bed.

Experimental set-up

The experiments are carried out using a MCR 301 rotational rheometer from Anton Paar with a parallel-disk configuration. We use two different rotating plates as the upper disk in order to generate the laminar shear flow. The first is a glass plate of 65 mm diameter, and the second is a rotating Plexiglas plate of 120 mm diameter. The substrates are built from monodisperse spherical soda-lime glass beads of (405.9 ± 8.7) µm diameter from The Technical Glass Company. To build different beds of quadratically arranged identical particles, the glass spheres are deposited and glued on stainless steel wire sieves of different mesh sizes and wire diameters from Bückmann GmbH & Co., which are produced for industrial screening. The configurations together with the sieves used are given in Table 1. The triangular substrate was built by fixing the spherical beads on an epoxy layer after the natural arrangement of the particles in a quadratic box had been submitted to small vibrations. Finally, the substrates are fixed on brass square islands of 15 x 15 mm² and 15 x 70 mm², respectively. Figure 1 shows microscopic pictures of different bed geometries.

The 15 x 15 mm² substrate is placed on a small non-concentric circular bottom plate into a circular container with transparent sidewalls. It is fixed concentrically to the rheometer. The small plate permits to rotate the substrate and study the impact of the flow direction on the incipient motion. Furthermore, the substrate placed in the bottom plate can be displaced in radial direction, r, between 16 and 27 mm. The gap width, h, defined as the distance from the top of the substrate spheres to the rotating plate, and the angular frequency, Ω, are controlled with the

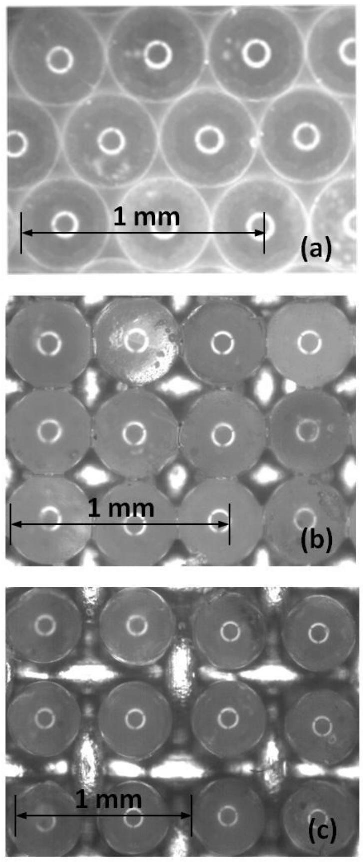

Fig.1: Top view of regular substrates of identical spheres of (405.9 ± 8.7) µm diameter. Triangular configuration (a) and quadratic configuration on a mesh, gap between particles: 14 µm (b) and 109 µm (c).

rheometer. The free target particles are located in this substrate within a distance from the turning axis, r = 21 mm, and within a distance from the upstream border, x = 7.5 mm (i.e. exactly in the middle of the substrate). Finally, the gap width selected is h = 2 mm. This parameter range resulted to be independent from any boundary effects within the particle Reynolds number range between $3x10^{-4}$ and 3 (J.R. Agudo and Wierschem 2012).
The 15 x 70 mm^2 substrate is placed directly on the circular container bottom. The free target beads here are located within a radial distance, r = 50 mm and a distance from the right border of x = 25 mm. The gap width remains at h = 2 mm. Preliminary investigations showed that the incipient particle motion are barely affected by the angle of orientation of the substrate with respect to the flow direction in a range of about ±10 (J.R. Agudo and Wierschem 2012). Hence, this permits to study the motion of several free spheres deposited on the substrate, ensuring that all the beads are equally affected by the rotating disk within the uncertainty range. The container, its components and dimensions are shown in Figure 2.
This container is filled with two different silicone oils with viscosities of (9.95 ± 0.30) mPas and (103.0 ± 3.3) mPas and densities of (0.935 ± 0.005) g/cm3 and (0.965 ± 0.005) g/cm3 at the working temperature of (295.16 ± 0.5) K, respectively. The temperature is controlled with the rheometer's Peltier element and measured independently with an external thermometer. We use four different beads: PMMA spheres from Micro particles GmbH with a density of (1.190 ± 0.002) g cm^{-3} and a diameter of (406.0 ± 9.5) µm, soda lime glass spheres from the Technical Glass Company with a density of (2.530 ± 0.025) g cm^{-3} and a diameter of (405.9 ± 8.7) µm, steel spheres from Nanoball GmbH with a density of (7.73 ± 0.02) g cm^{-3} and a diameter of (400 ± 1) µm and tungsten-carbide/cobalt (94:6) spheres with a density of (14.95 ± 0.03) g cm^{-3} and a diameter of (400 ± 20) µm.
The particles are illuminated and detected through the rotating disk. Therefore, we use a digital camera with a chip of 1280x1024 pixels and equipped with a macro objective that incorporates a tilted mirror. The onset of particle motion is determined by increasing the speed on the rotating plate in small steps of less than 0.5% until the particle starts to move crossing the line that separates the equilibrium location from the neighboring position.

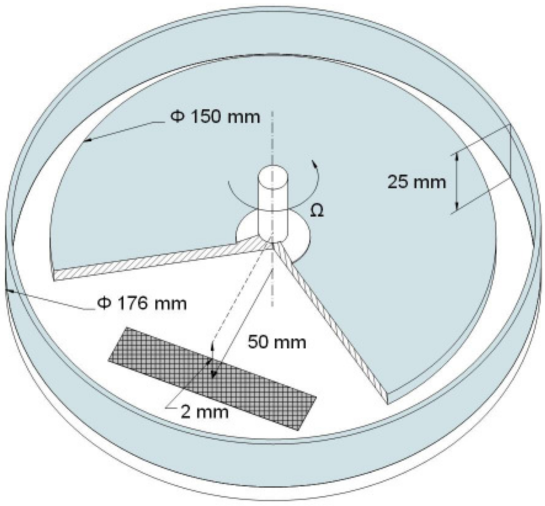

Fig.2: Sketch of the container and the rotating rheometer disk.

TABLE 1. Substrate properties, mesh size, wire diameter and corresponding gap between particles.

Configuration	Mesh size [µm]	Wire diameter [µm]	Gap between particles [µm]
Triangular	-	-	0 + 4
Quadratic	260 ± 15	160	14 ± 12
Quadratic	300 ± 17	200	94 ± 17
Quadratic	315 ± 18	200	109 ± 20

Experimental results and discussion

The incipient motion is characterized by the critical Shields number, which compares the shear stress acting on the particle to the resistant specific particle weight that retains it in place. The fluid motion is created by the moving top plate. For the parallel disks geometry with an angular velocity Ω and a gap width h, the shear rate $\dot{\gamma}$ at the radial distance of the particle from the turning axis r is given by $\dot{\gamma} = \Omega r / h$. Hence the shear stress results in $\tau = \mu \Omega r / h$ where μ is the dynamic viscosity. Thus, for our setup the Shields number is given by:

$$\theta = \frac{\nu \Omega r}{(\rho_s / \rho - 1) h g D_p} \tag{1}$$

Accordingly, the Reynolds number for the shear flow and the particle Reynolds numbers are given by:

$$\mathrm{Re} = \frac{\Omega r h}{\nu} \quad , \quad \mathrm{Re}_p = \mathrm{Re}\left(\frac{D_p}{h}\right)^2 \tag{2}$$

We first study the influence of the particle material and the substrate geometry on the incipient motion of two identical free particles. The threshold criteria for the incipient motion here considered is the displacement of both spheres to the adjacent equilibrium position. After reaching the critical value, the particles move continuously, yet the substrate geometry remains constant along the trajectory. Configuration a of Figure 3 depicts the results for different bead materials placed on different substrates. The critical Shields number depends on the substrate arrangement. Accordingly, we observe an increase by about a factor of two for the quadratic configuration as compared with the triangular one.
Besides two identical particles, we study how immobile particles with the same diameter affect the critical Shields number by perturbing the flow profile around the free bead. Here, tungsten-carbide particles, which start moving at much higher shear rate that PMMA, glass and steel beads, are used as stationary particles. Configurations b of Figure 3 show an increase of around 25% on the critical Shields number as compare to a single bead for both of the geometries considered. Placing laterally beads, as in configuration c of Figure 3, further enhance Shielding yielding in a higher augment of the critical Shields number. Direct contact between identical beads, however, results in a higher critical Shields number as compared to Shielding effect (compare configuration a to b and c in Figure 3).
At the studied particle Reynolds numbers, the critical Shields number seems to be independent from relative density and viscosity and therefore from inertia.

Figure 4 shows that the critical Shields number of two identical beads strongly depends on the substrate orientation with respect to the flow direction. The particles are deposited in a row on a quadratic substrate with a gap between beads of 14 µm. The threshold condition for the onset of motion is given by the displacement of either one or two of the particles studied to an adjacent equilibrium position. The angle dependence reflects the symmetry of the substrate.

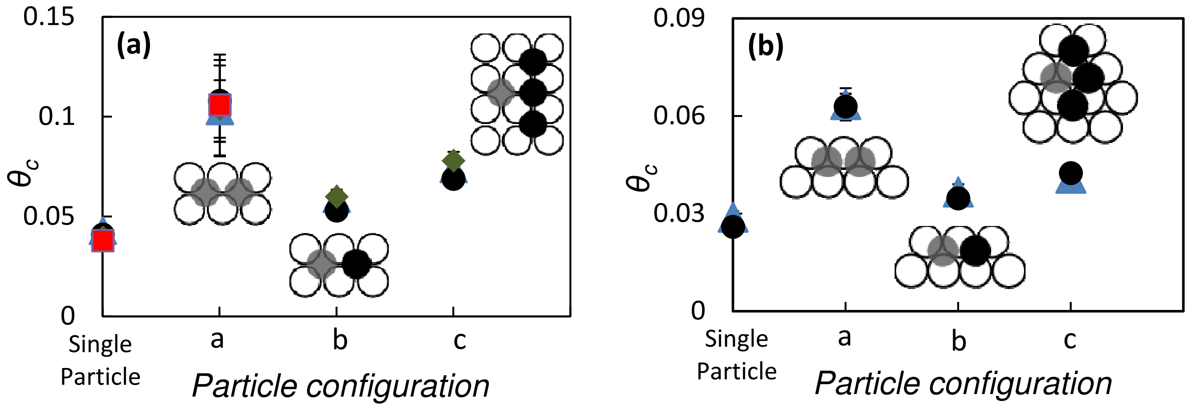

Fig. 3: Critical Shields number for different multi-particle configurations on the quadratic substrate with a particle spacing of 14 µm (a) and on the triangular one (b). Triangles, circles, rhomboids and squares: experiments performed with PMMA, glass, steel and tungsten-carbide beads respectively. The experiments are carried out with the higher viscous oil. Black particles in inlet figures represent immobile tungsten-carbide particles acting as shielding to the main flow direction.

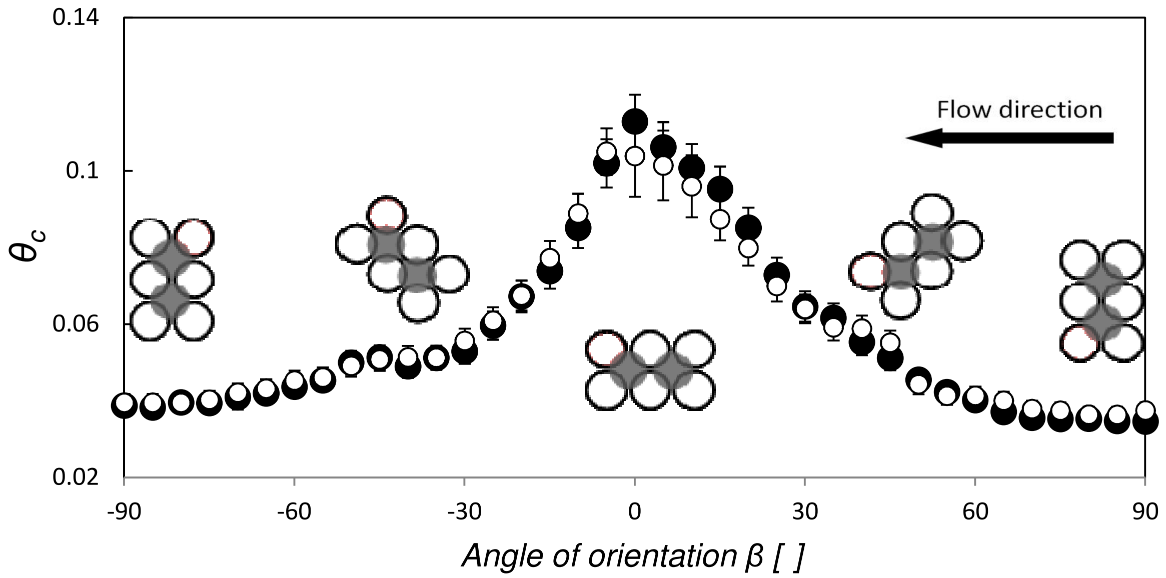

Fig. 4: Dependence of the critical Shields number on the angle of orientation for triangular substrate configurations. Experiments performed on the quadratic substrate with narrow spacing and using the higher viscous oil. Red particles in inlet illustrates counterclockwise turning of the substrate

The critical Shields number at an angle β of -90° is equal to about 0.04 and coincides to the obtained for a single bead (J.R. Agudo and Wierschem 2012). The critical Shields number remains roughly constant within an interval of 15° (up to -75). For these angles, both beads move almost simultaneously. Beyond this value, the critical Shields number slightly increases up to a value of about 0.05 up to reach an angle β of about -45°. Here, the upstream particle, which is most exposed to the flow, moves first without touching its neighbor. At orientation angles of 45°, however, the upstream bead also moves first but enters into contact with its adjacent bead. Approaching the angle 0 yields a continuous increase of the critical Shields number. At this angle, the two beads are placed together in the stream-wise direction (see Inlet in Figure 4), and the mechanism of motion coincides to the previously commented. The critical Shields number results in about 0.12, being therefore the same that the obtained for two identical beads in the previous case.

Summary

The influence of a regular substrate on the onset of multiple beads motion was studied using a rheometer working in the parallel-disk configuration. The particle's incipient motion was characterized by the Shields number. It resulted to be independent from the particle density and from inertia for particle Reynolds lower than one. We found a strong influence of the substrate arrangement on the onset of motion. Furthermore, neighboring particles strongly affects the critical Shields number by Shielding and by direct contact, having the latter a greater impact on the critical Shields number. Finally, the orientation angle of the substrate with respect to the flow direction resulted to have a significant influence on the critical Shields number of up to a factor of 3.

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