Fachtagung "Lasermethoden in der Strömungsmesstechnik"
4. – 6. September 2012, Rostock

EINFLUSS DER PARTIKELLAGERUNG AUF DEN STRÖMUNGSINDUZIERTER EINSATZ DER PARTIKELBEWEGUNG BEI NIEDRIGEN PARTIKELREYNOLDSZAHLEN

INFLUENCE OF THE SUBSTRATE GEOMETRY ON THE ONSET OF PARTICLE MOTION AT LOW PARTICLE REYNOLDS NUMBERS

J. Rodríguez, A. Wierschem
Lehrstuhl für Strömungsmechanik, Universität Erlangen-Nürnberg, D-91058 Erlangen

Granulare Medien, Partikel- und Sedimenttransport, Strömungsfeld
Granular systems, particle and sediment transport, flow field

Abstract

Using a standard rheometer and a camera equipped with a macro objective, we study the critical conditions for incipient motion of a single spherical particle deposited on a regular substrate under laminar flow conditions. The substrates are triangular and quadratic arrangements of identical glass spheres of same size. For the latter, the distance between the substrate spheres is varied, resulting in a partial shielding of the deposited particle to the shear flow. We find that for particle Reynolds numbers in the range between $3x10^{-4}$ and 3, 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 it is affected by the geometrical arrangement, the distance between the substrate spheres, and by the angle of orientation of the substrate with respect to the main flow direction.

Introduction

The onset of motion of solid particles on structured substrates is encountered in a wide variety of industrial operations, including oil extraction, cleaning of surfaces, (e.g. filtration and production facilities in food and pharmaceutical industries), and microfluidics. It also represents the initial phase of natural processes like sediment transport in waterbodies, erosion and dune formation (Groh et al 2008). Due to its importance in numerous applications, incipient particle motion has been studied intensively. Leighton and collaborators, for instance, studied the onset of motion of single particles in direct contact with a wall (Leighton and Acrivos 1985, King and Leighton 1995). Others studied the onset of motion of granular beds in turbulent flow like Shields 1936, Loiseleux *et al*. 2005, Dey and Papanicolau 2008, or Wierschem *et al.* 2008, 2009. It was not until the experimental approaches of Charru et al (2004), that the incipient motion was studied under laminar conditions. Accordingly, Ouriemi *et al.* (2007), Lobkovsky et al (2008) and J.J Derksen (2010) focused on the onset of particle motion by laminar shear flows using an irregularly arranged granular bed. Charru *et al.* (2004) observed the effect of bed armouring (i.e. an increase of the compactness of the granular bed due to the local arrangement of the particles) for particles with the same size. On the other hand, Ouriemi et al (2007) 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. In a later study of the onset of a single particle over a fixed irregular bed of identical beads, Charru *et. al.* observed a strong influence of the local substrate geometry on the incipient conditions (Charru *et. al.* 2007). Accordingly, they provided a critical Shields number range around 0.02 - 0.04 for onset of single particle. Others like Armanini *et. a*l 2005 and Marino *et. al.* 2009 have also recognized the strong dependence of the incipient motion on the geometrical substrate properties. Martino *et al*, for instance, studied experimentally the influence of the burial degree on the onset of motion of an isolated cylinder partially exposed to a laminar shear flow and provided a model for the resistance to particle motion due to burial. Here we study the geometrical impact of the substrate configuration on the incipient motion in laminar shear flow. Therefore, we analyze the motion of single particles on regular substrates of identical spherical beads. For particle Reynolds numbers ranging from creeping flow conditions to up about 3, we determine the critical Shields number in function of the substrate configuration, the gap distance between the substrate spheres and the angle of flow orientation with respect to the particle bed.

Experimental set-up

A laminar shear flow is produced using an MCR 301 rotational rheometer from Anton Paar in the parallel-disk configuration. As the upper disk we use a rotating glass plate of 65 mm diameter. The substrates are built from monodisperse spherical glass beads of (405.9 ± 8.7) µm diameter. The spheres are glued on stainless steel wire sieves of different mesh sizes and wire diameters to build different substrates of identical quadratically arranged particles. The sieves are from Bückmann GmbH & Co., which are produced for industrial screening. The configurations are given in Table 1. The triangular substrate was built by fixing the beads on an epoxy layer after the arranging them using small vibrations. The substrates are fixed on a support of 15 x 15 mm². Figure 1 shows different bed geometries.

The substrate is placed on a small non-concentric circular bottom plate into a circular container with transparent sidewalls. The container is shown in Figure 2. 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 can be displaced in radial direction to analyze the onset of motion in the range of radius, r, between 16 and 27 mm.

The container is filled with a liquid. Two silicone oils have been used with viscosities of (9.95 ± 0.30) mPas and (103.0 ± 3.3) mPas and densities of (0.935 ± 0.005) g/cm^3 and (0.965 ± 0.005) g/cm^3 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. Viscosities and densities are measured with a capillary viscometer and a Mohr balance, respectively. For the moving beads we use four different materials. Their properties are given in Table 2. The particles are illuminated and detected through the rotating disk. Therefore,

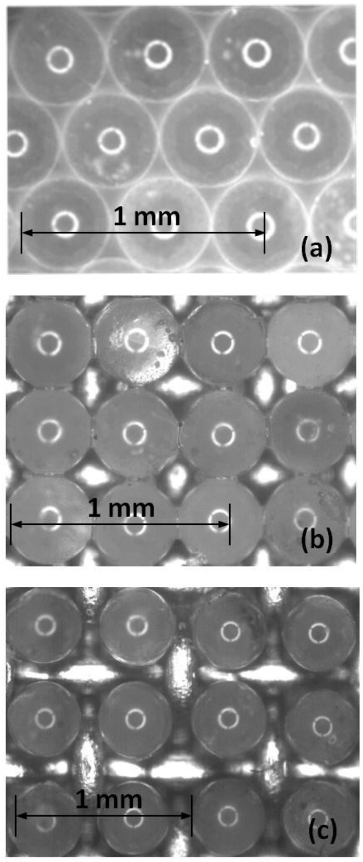

Fig.1: Top view of regular substrates of identical spheres of (405.9 ± 8.7) µm diameter. Triangular configuration (a) and quadratic configuration on a mesh, gap between particles: 14 µm (b) and 109 µm (c).

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.

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

TABLE 2. Particle properties of single beads according to providers

Material	Density ρ_p [g cm^{-3}]	Diameter D_p [µm]	Provider
PMMA	1.190 ± 0.002	406.0 ± 9.5	Micro particles GmbH
Soda lime glass	2.530 ± 0.025	405.9 ± 8.7	Technical Glass Company
Steel	7.73 ± 0.02	400 ± 1	Nanoball GmbH
Tungsten-carbide/ Cobalt (94:6)	14.95 ± 0.03	400 ± 20	Goodfellow

Experimental results and discussion

We consider the displacement of the particle to a neighboring equilibrium position on the substrate as the thresholds conditions, characterizing this incipient motion 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:

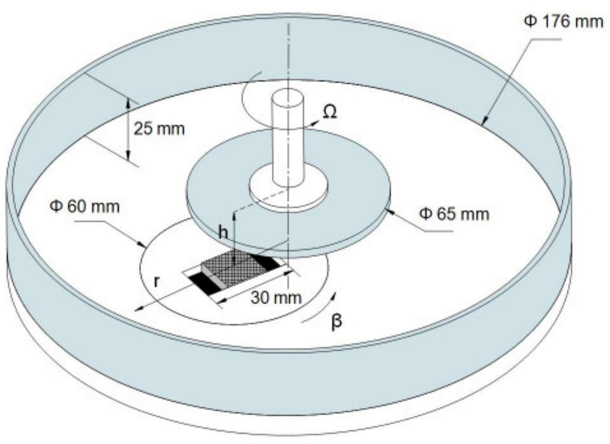

Fig.2: Container and the rotating rheometer disk. The geometry allows the rotation of the substrate with respect to the flow direction. The shaded regions are inlets of same height as the bottom that can be removed to vary the radial location of the substrate.

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

where $\nu = \mu/\rho$ is the kinematic viscosity, ρ_S and ρ are particle and liquid densities, respectively, g is the acceleration of gravity and D_p is the particle diameter. Accordingly, the Reynolds number for the shear flow and the particle Reynolds numbers are given by:

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

After identifying a parameter range, independent from any boundary effects, (i.e. independent from the distance from the rotation axis, finite-size effects and the gap height), we study the influence of the particle density and the substrate geometry on the critical Shields number. Experimental results represented in Figure 4, show that the setup yields critical Shields numbers that are independent from these boundary effects. These experimental values are in good agreement with the results obtained in previous studies of the incipient single particle with different container geometry (Rodríguez *et. al.* 2011).

Figure 5 shows the critical Shields number as a function of the relative particle density for five different geometrical configurations. The Reynolds numbers cover the range from creeping flow conditions to about 1, corresponding to particle Reynolds numbers up to about 0.05. Within the measured range, the critical Shields number appears to be independent from relative density and viscosity. Other effects like adhesion or differences in surface roughness of the different materials neither seem to have any major impact. It is also shown, that the larger the gap between substrate beads and hence the less the loose particle is exposed to the flow, the higher is the critical Shields number. Accordingly, with increased spacing of the quadratic substrates, the critical Shields number increases by

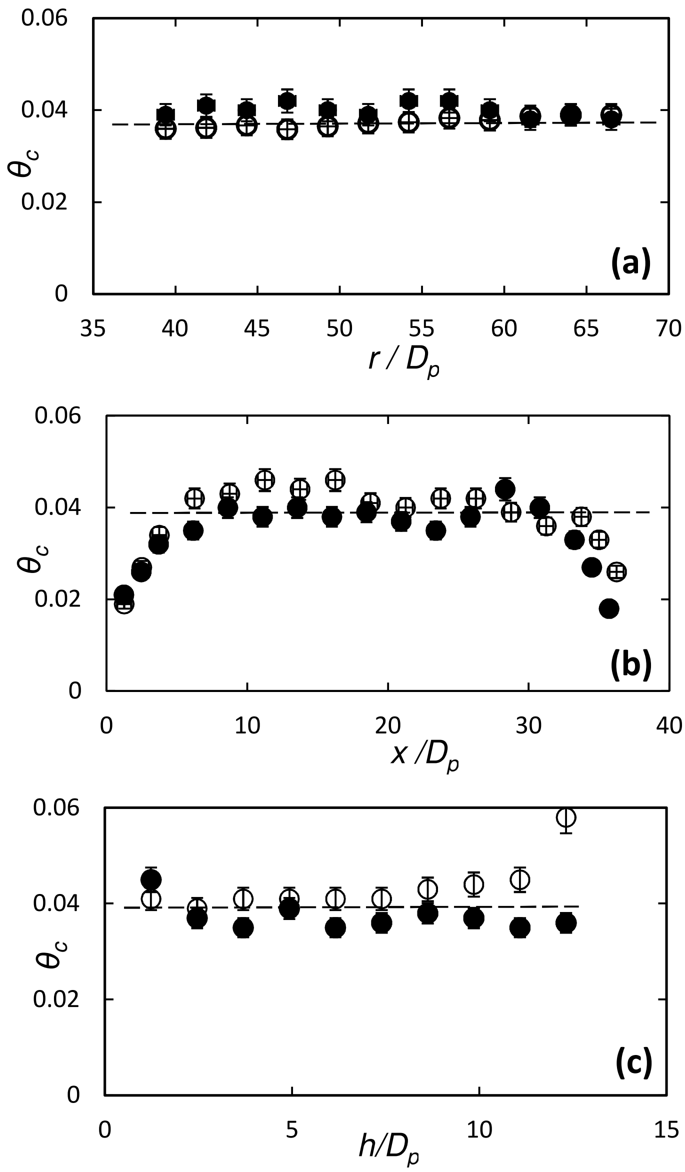

Fig. 4: Critical Shields number dependence on radial particle distance from the disk's turning axis (a), the particle distance from the substrate's upstream border (b), the gap width (c). Configuration: glass beads, quadratic substrate, gap between beads: 14 µm. Open and solid symbols: less and higher viscous oils, respectively. Gap height in (a) and (b): 2 mm, distance from upstream step of the substrate island in (a) and (c): 7.5 mm, distance from turning axis in (b) and (c): 21 mm.

50%. For the triangular substrate geometry, the critical Shields numbers are lower that for quadratic ones. Depending on the flow direction, the critical Shields number changes by a factor of 2.

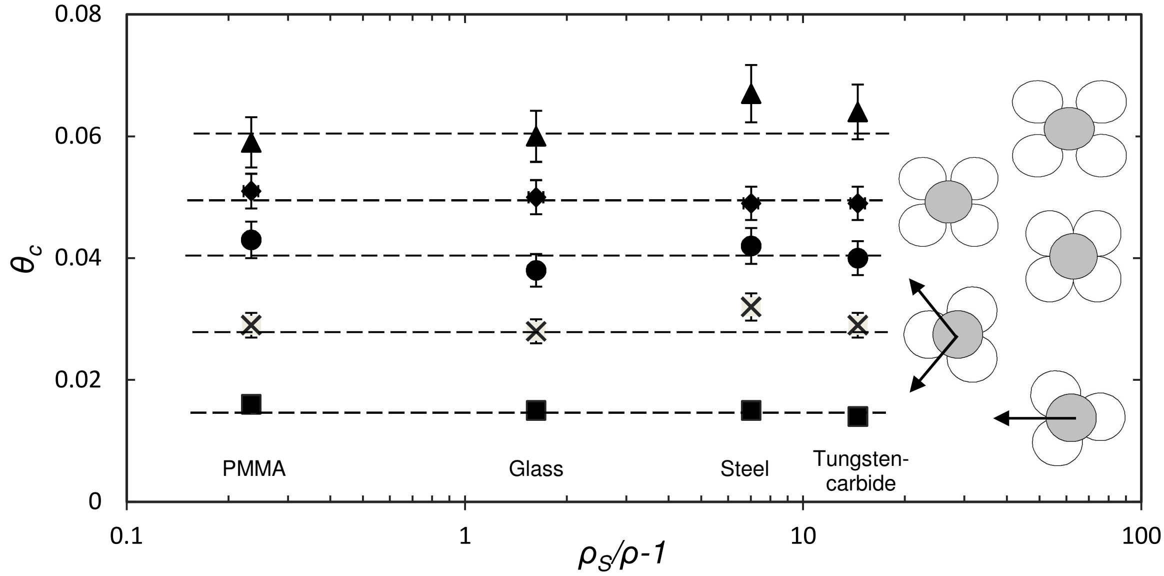

Fig. 5: Critical Shields number for different relative densities and substrates. Square and cross symbols show the results obtained using the two symmetrical triangular configurations. Circles, diamonds and triangles depict the results obtained with the quadratic substrates with gaps between substrate particles of 14, 94 and 109 µm, respectively. Experiments were performed with the less viscous oil. The dotted lines are drawn to guide the eye. Gap height: 2 mm, distance from upstream step of the substrate island: 7.5 mm, radius: 21 mm.

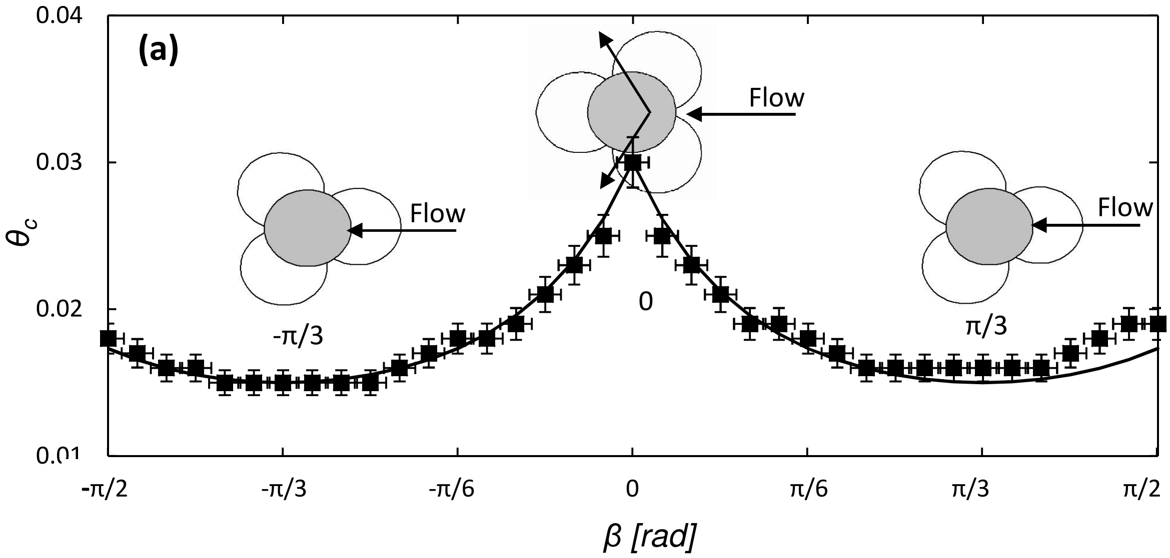

Fig. 6: Dependence of the critical Shields number on the angle of orientation for triangular substrate configurations. Experiments performed with the higher viscous oil. The solid line indicates the function $\theta_C(\beta) = \theta_{C\min} / \cos(\pi/3 - |\beta|)$. Radius: 21 mm, distance from upstream step of the substrate island: 7.5 mm, gap height: 2 mm.

Finally, figure 6 depicts the variation of the critical Shields number with the flow direction for the triangular substrate. The angle dependence reflects the symmetry of the substrate. At angles around $\pm\pi/3$ the critical Shields number is minimum and hardly changes in an interval of about $\pm\pi/12$. Beyond this range, there is a slight increase of the critical Shields number with a small buckle. Approaching the angle 0 yields a continuous increase of the critical Shields number.

Summary

The influence of a regular substrate on the onset of particle 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 within the range of 0.007-70, and the corresponding particle Reynolds number range of 0.0003-3. We found a strong influence of the substrate's geometrical arrangement and the gap distance between substrate beads on the onset of motion showing the strong impact of exposure to the flow. Similarly, 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 2.

Acknowledgements

The authors are thankful to Mrs. J. Schwendner and Mr. M. Kobylko and M. Meidenbauer for collaborating in setting up the experiment. The support from Deutsche Forschungsgemeinschaft through WI 2672/4-1 is gratefully acknowledged.

References

Armanini, A., Gregoretti, C., 2005: “Incipient sediment motion at high slopes in uniform flow condition”, Water Resour. Res. 41, pp. W12431

Charru, F., Mouilleron, H., Eiff, O., 2004: “Erosion and deposition of particles on a bed sheared by a viscous flow, J. Fluid Mech., 519, pp. 55-80

Charru, F., Larrieu, E., Dupont, J.-B., Zenit, R., 2007: “Motion of a particle near a rough wall in a viscous shear flow”, J. Fluid Mech., 570, pp. 431-453

Dey, S., Papanicolaou, A., 2008: “Sediment Threshold under Stream Flow: A State-of-the-Art Review”, KSCE J. Civ. Engng., 12, pp. 45-60

Derksen, J. J., 2011: “Simulations of granular bed erosion due to laminar shear flow near the critical Shields number”, Phys. Fluids 23, pp. 113303

Groh, C., Wierschem, A., Aksel, N., Rehberg, I., Kruelle, C. A., 2008: “Barchan dunes in two dimensions: experimental tests of minimal models”, Phys. Rev. E 78, 021304

King, M. R., Leighton, D. T., 1997: “Measurement of the inertial lift on a moving sphere in contact with a plane wall in a shear flow”, Phys. Fluids, 9, pp. 1248-1255

Leighton, D., Acrivos, D., 1985 “The lift on a small sphere touching a plane in the presence of a simple shear flow”, ZAMP, 36, pp. 174-178

Lobkovsky, A. E., Orpe, A. V., Molloy, R., Kudrolli. Rothman, D. H., 2008: “Erosion of a granular bed driven by laminar fluid flow”, J. Fluid Mech. 605, pp. 47

Loiseleux, T., Gondret, P., Rabaud, M., Doppler, D., 2005: “Onset of erosion and avalanches for an inclined granular bed sheared by a continuous laminar flow”, Phys. Fluids 17, 103304

Martino, R., Paterson, A., Piva, M., 2009: “Onset of motion of a partly hidden cylinder in a laminar shear flow”, Exp. Fluids 39, pp. 036315

Ouriemi, M., Aussillous, P., Medale, M., Peysson, Y., Guazzelli, E., 2007: “Determination of the critical Shields number for particle erosion in laminar flow”, Phys. Fluids, 19, 061706

Robinson, S. K., 1991: “Coherent motions in the turbulent boundary layer”, Annu. Rev. Fluid Mech., 23, pp. 601-639

Rodríguez, J, A. Wierschem: "Influence of the substrate geometry on the onset of particle motion in a shear flow", Proceeding of 19. Fachtagung Lasermethoden in der Strömungsmesstechnik, 6. -8 Sep. 2011, eds: A. Thess, C. Resagk, B. Ruck, A. Leder, D. Dopheide, Ilmenau, pp. 6- 1 – 6 -7

Shields A., 1936: "Anwendungen der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung", Mitteilungen der Preußischen Versuchsanstalt für Wasserbau und Schiffbau ,26, pp. 1-26

Wierschem, A., Groh, C., Rehberg, I., Aksel, N., Kruelle C. A., 2008: "Ripple formation in weakly turbulent flow", European Physical Journal, E 25, pp. 213-221

Wierschem, A., Groh, C., Rehberg, I., Aksel, N., Kruelle C. A., 2009: "Materialtransport bei der Rippelbildung in granularen Medien", Proceeding of Lasermethoden in der Strömungsmesstechnik, 17. Fachtagung 2009, eds: A. Delgado, C. Rauh, H. Lienhart, B. Ruck, A. Leder, D. Dopheide, Erlangen, pp. 33.1 – 33.7