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Transport of particles in fluids

Hans J. Herrmann*[,1,2], José S. Andrade Jr., Ascânio D. Araújo, Murilo P. Almeida

Departamento de Física, Universidade Federal do Ceará, 60451-970 Fortaleza, Ceará, Brazil

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Abstract

The interaction of moving fluids with particles is still only understood phenomenologically when the Reynolds number is not vanishing. I will present three different numerical studies all using the solver "fluent" which elucidate this issue from different points of view. On one hand, I will consider the case of fixed particles, i.e., a porous medium and present the distribution of channel openings, fluid velocities and fluxes. These distributions show a scaling law in the density of particles and for the fluxes follow an unexpected stretched exponential behavior. The next issue will be filtering, i.e., the release of massive tracer particles within this fluid. Interestingly, a critical Stokes number exists below which no particles are captured and which is characterized by a critical exponent of $\frac{1}{2}$. Finally, I will also show data on saltation, i.e., the motion of particles on a surface which when dragged by the fluid performs jumps. This is the classical eolian transport mechanism responsible for dune formation. The empirical relations between flux and wind velocity are reproduced and a scaling law of the deformed wind profile is presented.

Keywords: Granular matter; Drag; Saltation; Filters; Porous media

1. Introduction

Many applications in chemical engineering, fluid mechanics, geology and biology involve systems of particles immersed in a flowing liquid or gas [1–3]. Also fluid flow through a porous medium is of importance in many practical situations ranging from oil recovery to chemical reactors and has been studied experimentally and theoretically for a long time [4–6]. Due to disorder, porous media display many interesting properties that are, however, difficult to handle even numerically. One important feature is the presence of heterogeneities in the flux intensities due to varying channel widths. They are crucial to understand stagnation, filtering, dispersion and tracer diffusion.

The fluid mechanics in the porous space is based on the assumption that a Newtonian and incompressible fluid flows under steady-state conditions. The Navier–Stokes and continuity equations for this case reduce to

$$\rho\vec{u}\cdot\nabla\vec{u} = -\nabla p + \mu\nabla^2\vec{u}, \tag{1}$$

*Corresponding author.
E-mail address: hjherrmann@ethz.ch (H.J. Herrmann).
[1]Formerly at Institute for Computer Physics, University of Stuttgart.
[2]Also at: IfB, HIL E12, ETH Hönggerberg, 8093 Zürich, Switzerland.

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$$\nabla \cdot \vec{u} = 0, \tag{2}$$

where $\vec{u}$ and p are the local velocity and pressure fields, respectively, and ρ is the density of the fluid. No-slip boundary conditions are applied along the entire solid–fluid interface, whereas a uniform velocity profile, $u_x(0, y) = V$ and $u_y(0, y) = 0$, is imposed at the in-let of the channel. For simplicity, we restrict our study to the case where the Reynolds number, defined here as $Re \equiv \rho V L y/\mu$, is sufficiently low ($Re < 1$) to ensure a laminar viscous regime for fluid flow. We use FLUENT [7], a computational fluid dynamic solver, to obtain the numerical solution of Eqs. (1) and (2) on a triangulated grid of up to hundred thousand points adapted to the geometry of the porous medium.

The traditional approach for the investigation of single-phase fluid flow at low Reynolds number in disordered porous media is to characterize the system in terms of Darcy's law [4,6], which assumes that a *macroscopic* index, the permeability K, relates the average fluid velocity V through the pores with the pressure drop ΔP measured across the system,

$$V = -\frac{K}{\mu}\frac{\Delta P}{L}, \tag{3}$$

where L is the length of the sample in the flow direction and μ the viscosity of the fluid. In previous studies [9–15], computational simulations based on detailed models of pore geometry and fluid flow have been used to predict permeability coefficients.

In this paper, we present numerical calculations for a fluid flowing through a two-dimensional channel of width L_y and length L_x filled with randomly positioned circular obstacles [16]. For instance, this type of model has been frequently used to study flow through fibrous filters [30]. Here, the fluid flows in the x-direction at low but non-zero Reynolds number, and in the y-direction we impose periodic boundary conditions. We consider a particular type of random sequential adsorption (RSA) model [18] in two dimensions to describe the geometry of the porous medium. As shown in Fig. 1, disks of diameter D are placed randomly by first choosing from a homogeneous distribution between $D/2$ and $L_x - D/2(L_y - D/2)$ the random x–(y–) coordinates of their center. If the disk allocated at this position is separated by a distance smaller than $D/10$ or overlaps with an already existing disk, this attempt of placing a disk is rejected and a new attempt is made. Each successful placing constitutes a decrease in the porosity (void fraction) ε by $\pi D/4 L_x L_y$. One can associate this filling procedure to a temporal evolution and identify a successful placing of a disk as one time step. By stopping this procedure when a certain value of ε is achieved, we can produce in this way systems of well-controlled porosity. We study in particular configurations with $\varepsilon = 0.6$, 0.7, 0.8 and 0.9.

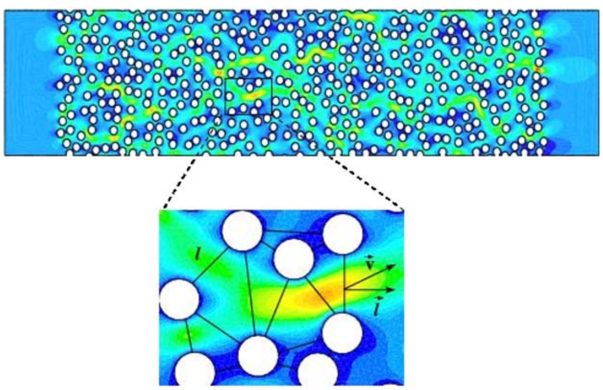

Fig. 1. Contour plot of the velocity magnitude for a typical realization of a pore space with porosity $\varepsilon = 0.7$ subjected to a low Reynolds number and periodic boundary conditions applied in the y-direction. The fluid is pushed from left to right. The colors ranging from blue (dark) to red (light) correspond to low and high velocity magnitudes, respectively. The close-up shows a typical pore opening of length l across which the fluid flows with a line average velocity v. The local flux at the pore opening is given by $q = vl\cos\theta$, where θ is the angle between v and the vector normal to the line connecting the two disks.