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CORIOLIS EFFECTS DURING FLUID FLOW THROUGH ROTATING GRANULAR POROUS MEDIA

EUGENIUSZ SAWICKI, CHRISTIAN GEINDREAU, JEAN-LOUIS AURIAULT

Laboratoire Sols, Solides, Structures Domaine Universitaire, BP53, 38041 Grenoble Cedex 9, Prance.
E-mails: Jean-Louis.Aurialut@hmg.inpg.fr. Tel. +33 4 76 82 51 68. Fax: +33 4 76 82 70 43
Christian.Geindreau@hgm.inpg. fr. Tel. +33 4 7682 51 76. Fax: +33 4 76 82 70 43

Abstract: Recently, the filtration law of an incompressible viscous Newtonian fluid flowing through a rigid non-inertial porous medium (e.g. a soil sample placed in a centrifuge basket) which takes into account the Criolis effects was developed by using an upscaling technique [2], [3], [7]. The structure of the law obtained is similar to that of the Darcy's law but the permeability tensor depends on the angular velocity ω of the porous matrix, i.e. on the Ekman number *Ek*. It satisfies the Hall–Onsager's relation and is a non-symmetric tensor. The present study aims at quantifying more precisely the Coriolis effects in a porous medium. For this purpose we performed some 3D numerical simulations for the flow through rotating periodic array of spheres. Our numerical results clearly show the influence of the Coriolis effects on the permeability at large Ekman number $\varepsilon << Ek^{-1} << 1$ and Ekman number $O(l)$. These results are analyzed according to the geometrical properties of the packings of spheres: soild volume fraction, arrangement and size. Under particular conditions, we finally show that in the first approximation the flow through rotating granular media can be described by a modified Darcy's law including a "macroscopic Coriolis force" which brakes and deviates the flow.

1. INTRODUCTION

In the absence of external forces, the steady-state slow flow of an incompressible liquid through a rigid inertial porous matrix is described by the well-known Darcy's law, in which the tensor of intrinsic permeability **K** [m^2] is positive and symmetrical. In many practical applications in engineering and geophysics [8], [9], [11], [12], [13], the rigid porous matrix rotates with an angular velocity ω with respect to a Galilean frame. The main issue is to determine the consequences of the angular velocity in Darcy's law. Recently, [2], [3], [7], the filtration law in a rotating porous medium was rigorously derived by upscaling the physics at the pore scale. A deterministic upscaling technique was used, namely the homogenisation method of multiple scale expansion for periodic structures [1], [4], [10]. Due to this the steady-state slow flow of an incompressible liquid through a rigid porous matrix within a non-Galilean framework is described by Darcy's law, but the permeability tensor $\mathbf{K}^{\text{rot}}$ presents the following remarkable properties: it depends upon the angular velocity of the porous medium through the Ekman number $Ek = \mu(2\rho\omega l^2)$ which measures the ratio of the viscous term to the Coriolis term in the Navier–Stokes equations, where l is a characteristic length of the porous medium and ρ is the fluid density; it verifies the Hall–Onsager's relationship $K_{ij}^{\text{rot}}(\omega) = K_{ji}^{\text{rot}}(-\omega)$ and is a non-symmetric tensor.

Fluid flow through granular porous media is considered to be important in many engineering applications and natural processes. Thus, in the literature, there exist extensive theoretical and numerical studies concerning the Stokes flow in periodic arrays of spheres. These studies on particular geometry also represent an effective step in understanding the flow through more complex porous media. From these works, it is now well known that the permeability $\mathbf{K}$ of a porous medium of spheres depends on the size, concentration and arrangement of spheres. In the case of size, the logical dimension is the radius a of the spheres. In order to characterize the concentration, we can choose the solid volume fraction c or the porosity $\phi = 1 - c$. Thus, the permeability $\mathbf{K}$ of a granular porous medium is the function of a, c or ϕ, and the arrangement of spheres. The aim of this paper is to estimate the permeability of rotating periodic arrays of spheres which now depends on the Ekman number: $\mathbf{K}^{\text{rot}}$ (a, c, arrangement, Ek). A brief review of the derivation of Darcy's law in a rotating porous matrix by upscaling the pore-scale description is given in Section 2. Then we present the results of numerical simulations carried out for the flow through a rotating porous medium. The porous medium under consideration is composed of simple cubic (SC) and body-centered cubic (BCC) packings of spheres. The influence of the Coriolis effect on the permeability at large Ekman number $\varepsilon << Ek^{-1} << 1$ and Ekman number $O(l)$ is successively presented and analyzed according to the geometrical properties of the porous medium. Comparison is made with $Ek^{-1} = 0$.

2. FILTRATION LAW IN ROTATING POROUS MEDIA

The objective of the present section is to give a brief review of the derivation by homogenisation of the filtration law in a rotationg porous medium. For details the reader is referred to [2], [3], [7].

2.1. UPSCALING PROCESS

Physical phenomena in heterogeneous systems such as porous media are homogenisable, i.e. they may be modelled by means of an equivalent continuous macroscopic description, provided that the condition of separation of scales is satisfied [1], [4], [10]. This fundamental condition may be expressed as $\varepsilon = l/L << 1$, in which l and L are the characteristic lengths of the heterogeneities (here, the pore characteristic size) and of the macroscopic sample or excitation, respectively. The macroscopic equivalent model is obtained based on the description made at the heterogeneity scale according to the method presented in [1]: i) assuming that the medium is periodic, without loss of generality; ii) writting the local description in a dimensionless form; iii) estimating the order of magnitude of the dimensionless numbers with respect to the scale ratio ε; iv) looking for the unknown fields in the form of asymptotic expansions in powers of ε; v) solving the boundary-value problems that arise at the successive orders of ε after introducing the asymptotic expansion in the local dimensionless description. The macroscopic equivalent model is obtained from the compatibility conditions, which are the necessary and sufficient conditions for the existence of the solutions of the boundary-value problems.

2.2. DIMENSIONLESS PHYSICS AT THE PORE SCALE

Consider the flow through a porous medium of the period Ω bounded by $\partial\Omega$ that is placed in a centrifuge of the radius r. Within the periodic cell, the fluid occupies the domain Ω_p, and the fluid–solid interface is denoted by Γ (figure 1). We also assume the porous matrix to be rigid. In the case of the moving porous matrix frame $R1$, the dimensinless description of the quasi-static flow of an incompressible viscous Newtonian liquid is written as

$$\mu\Delta\mathbf{w} - Q\nabla p = \rho(R\gamma(O) + Ek^{-1}\boldsymbol{\omega}\times\mathbf{w} + RA\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{OM})) \quad \text{in } \Omega_p, \tag{1}$$

$$\nabla\,\mathbf{w} = 0 \quad \text{in } \Omega_p, \quad \mathbf{w} = \mathbf{0} \quad \text{on } \Gamma, \tag{2}$$

where the vector $\mathbf{w}$ is the fluid velocity relative to that of the solid matrix of the porous medium, p denotes the pressure and μ represents the fluid viscosity. Acceleration due to gravity is included in the pressure term. In the above equations, $\boldsymbol{\omega}$ denotes the angular velocity of the porous matrix (i.e. of the centrifuge), O is a fixed point of the porous matrix within the period and M represents a current point in Ω_p. We use the local pore length-scale l a the characteristic length scale for normalising the variations of the differential operators: in other words, we apply the so-called microscopic point of view [1]. Let consider a centrifuge of the radius r whose angular velocity is $\boldsymbol{\omega} = \omega\,\mathbf{e}_\omega$, ω being constant. Based on the pore-scale description it is possible to derive four dimensionless numbers Q, which repersent the ratio of the pressure term to the viscous forces $\mu\Delta\mathbf{w}$. According to the physical reasoning presented in [1] we have $Q = O(\varepsilon^{-1})$, the ratio R of the macroscopic convective inertia $\rho\gamma(O)$ to the viscous force $\mu\Delta\mathbf{w}$; the ratio A of the local convective inertia $\rho\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{OM})$ to the macroscopic convective inertia $\rho\gamma(O)$ and the Ekman number Ek; the ratio of the viscous force $\mu\Delta\mathbf{w}$ to the Coriolis inertia $2\rho\boldsymbol{\omega}\times\mathbf{w}$. We have $A = O(l/r) = O(\varepsilon^2)$ and we assume $R = O(l)$. It should be noticed that the requirement $R \le O(l)$ is linked with the hypothesis of separation of scales regarding to excitation. Greater orders of magnitude of R would yield non-homogenisable problems, i.e., problems for which any equivalent macroscopic description does not exist. As it was mentioned in the introduction, to account for the Coriolis effects, we assume that $Ek = O(l)$.

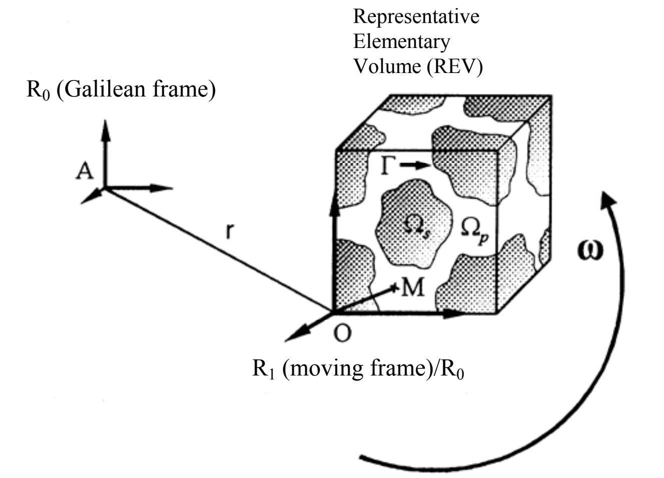

Fig. 1. Scheme of the periodic cell Ω in a non-Galilean frame R_1

2.3. MACROSCOPIC DESCRIPTION

2.3.1. EKMAN NUMBER $Ek = O(l)$ ($\varepsilon << Ek^{-1} << \varepsilon^{-1}$)

By applying the technique of multiple-scale expansions, it can be shown [2], [3], [7] that the macroscopic filtration law of rotating porous media takes the form

$$\nabla \mathbf{v} = 0, \quad \mathbf{v} = -\frac{\mathbf{K}^{\mathrm{rot}}(Ek^{-1})}{\mu}(\nabla p + \rho\gamma(O)) \tag{3}$$

which represents the macroscopic equivalent behaviour at the order of $O(\varepsilon)$ of approximation. It can be shown that

$$\mathbf{v} = \langle \mathbf{w} \rangle = \frac{1}{\Omega}\int_{\Omega_p} \mathbf{w}^{(0)} dy = -\frac{1}{\Omega}\frac{1}{\mu}\int_{\Omega_p} \mathbf{K}^{\mathrm{rot}}(\omega) dy (\nabla p + \rho\gamma(O)) = -\frac{\mathbf{K}^{\mathrm{rot}}(\omega)}{\mu}(\nabla p + \rho\gamma(O)), \tag{4}$$

where the velocity field $\mathbf{w}^{(0)}$ is obtained by solving the following dimensional boundary value problem over the periodic cell Ω:

$$\mu\Delta\mathbf{w}^{(0)} - (\nabla p + \rho\gamma(O)) - \nabla p^{(1)} = 2\rho\, \boldsymbol{\omega} \times \mathbf{w}^{(0)} \quad \text{in } \Omega_p, \tag{5}$$

$$\nabla\, \mathbf{w}^{(0)} = 0 \quad \text{in } \Omega_p, \quad \mathbf{w}^{(0)} = \mathbf{0} \quad \text{on } \Gamma. \tag{6}$$

The unknows $\mathbf{w}^{(0)}$ and $p^{(1)}$ are also Ω-periodic. The macroscopic force term (∇p +

$\rho\gamma(O)$) and the angular velocity ω are supposed to be given. From equation (4) we see that the filtration tensor $\mathbf{K}^{\text{rot}}$ depends on the angular velocity ω, the kinematics viscosity μ/ρ and the characteristic length l through the Ekman number. Although this formula is similar to Darcy's law, they differ considerably. In effect, it can be seen [2], [3] that the effective permeability $\mathbf{K}^{\text{rot}}$ is a positive but non-symemtric tensor and that it verifies Hall–Onsager's relationship $K_{ij}^{\text{rot}}(\omega) = K_{ji}^{\text{rot}}(-\omega)$ which expresses the analogue of Hall's effect for filtration [5].

2.3.2. LARGE EKMAN NUMBER ($\varepsilon << Ek^{-1} << 1$)

In this particular case, and these which correspond to many engineering applications where ω is small, it can be shown that the filtration law in dimensional form and at the second order of approximation can be given in the following form:

$$\mathbf{v} = -\frac{(\mu\mathbf{K}\cdot - 2\rho\mathbf{H}\cdot\boldsymbol{\omega}\times)}{\mu^2}(\nabla p + \rho\gamma(O)), \tag{7}$$

where $(\mathbf{K}\cdot - (2\rho/\mu)\,\mathbf{H}\cdot\boldsymbol{\omega}\times)$ stands for an approximation of $\mathbf{K}^{\text{rot}}$ at large Ekman number. Tensor $\mathbf{K}$ [m^2] is a classical Galilean permeability tensor and $\mathbf{H}$ [m^4] is the second-order tensor. They are defined as

$$K_{ij} = \frac{1}{\Omega}\int_{\Omega_p} k_{ij}\,dy, \quad H_{1j} = -\varepsilon_{plq}\varepsilon_{ijk}\frac{1}{2\Omega}\int_{\Omega_p} k_{kq}k_{ip}\,dy, \tag{8}$$

where ε_{ijk} denotes the permutation symbol and $k_{ij} = k_{ij}^{\text{rot}}$ ($Ek^{-1} = 0$) is the solution of the boundary value problem (5)–(6) in the particular case, where $\omega = 0$.

3. PERMEABILITY OF ROTATING PERIODIC ARRAYS OF SPHERES

A porous medium under consideration is composed of simple cubic (SC) and body-centered cubic (BCC) packings of spheres (figure 2). The radius of spheres is denoted by a, while e is the size of the periodic cell. The porosity of the porous medium varies from 0.476 to 1 for the SC packing and from 0.32 to 1 for the BCC packing. After a brief description of the numerical method used, numerical results of the permeability of the rotating periodic arrays of spheres for a large Ekman number $\varepsilon << Ek^{-1} << 1$ and the Ekman number $O(l)$ are successively presented and compared with the case where $Ek^{-1} = 0$.

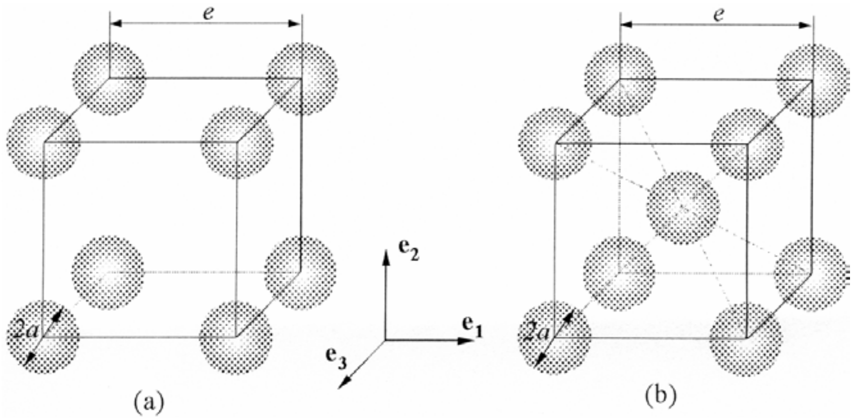

Fig. 2. Simple cubic (SC) (a) and body-centered cubic (BCC) (b) packings of spheres

3.1. COMPUTATIONAL PROCEDURE

The numerical results presented below have been obtained by solving the dimensional boundary-value problem (5)–(6) over the periodic cell Ω. This boundary value problem is solved with a mixed pressure–velocity formulation implemented in the finite-element software FEMLAB [6]. $P2$–$P1$ finite elements are used: a quadratic $P2$ and a linear $P1$ polynomial approximations are adjusted to the velocity field $\mathbf{w}^{(0)}$ and the pressure field $p^{(1)}$, respectively. Then, the components of permeability tensor $\mathbf{K}^{\mathrm{rot}}$ (or $\mathbf{K}$) of the porous medium are determined by calculating the magnitude of the cell-averaged velocity of the fluid $\langle\mathbf{w}^{(0)}\rangle$ (4).

3.2. NUMERICAL RESULTS

3.2.1. $Ek^{-1} = 0$

When $Ek^{-1} = 0$, i.e. $\omega = 0$, the permeability tensor of both microstructures is isotropic and can be put in the form

$$\mathbf{K}^{\mathrm{rot}} = \mathbf{K} = K\mathbf{I} = a^2K^*\mathbf{I}, \tag{9}$$

where $\mathbf{I}$ stands for the identify tensor, and K^* is the dimensionless permeability which depends on the solid volume fraction c and the arrangement of spheres: $K^* = K^*$ (c, arrangement). Figure 3 shows the evolution of the dimensionless permeability K^* with the solid volume fraction c for both arrays of spheres. The dimensionless permeability proposed by Kozeny–Carman is plotted in figure 3. This relation is in agreement with our numerical results for solid volume fraction larger than 0.4. The following function (see the fitted curve in figure 3)

$$K^* = \frac{1}{28.2} \frac{(1-c)^3}{c^{4/3}} \tag{10}$$

appears to be a good approximation of the dimensionless permeability for both arrangements of spheres in the whole investigated range of the volume solid fraction ($0 < c < 0.68$).

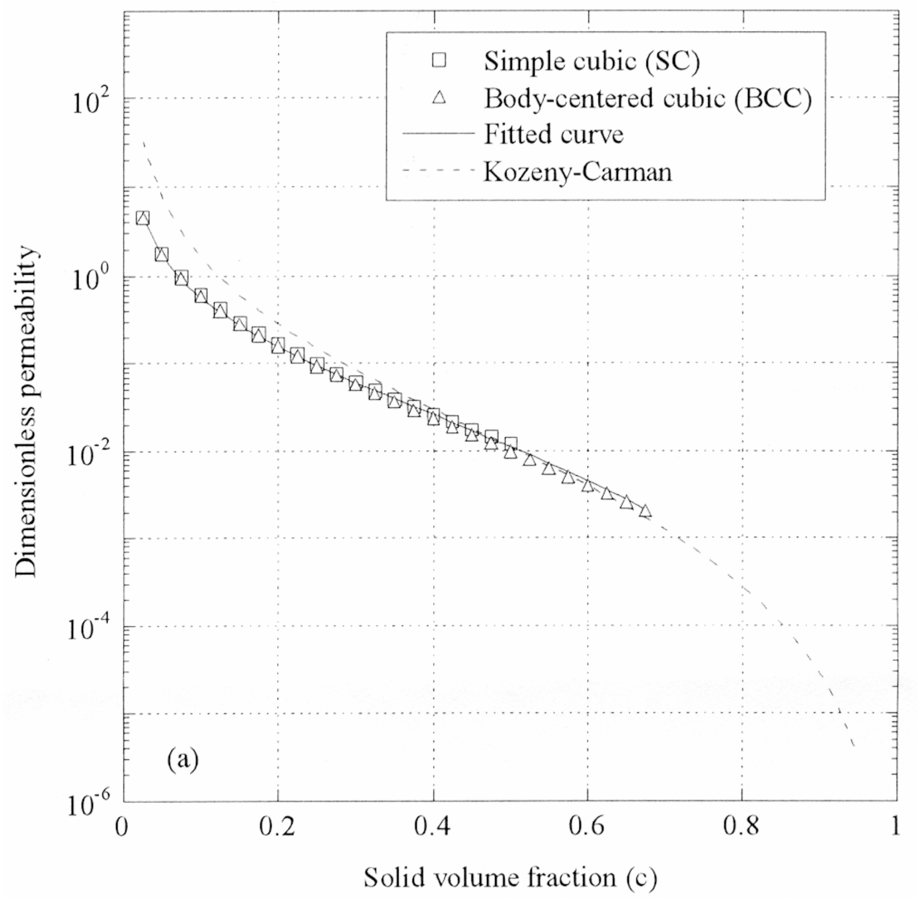

Fig. 3. Simple cubic (SC) and body-centered cubic (BCC) packings of spheres.
Evolution of the dimensionless permeability $K^* = K/a^2$ versus the solid volume fraction c

3.2.2. $\varepsilon << Ek^{-1} << 1$

We now consider $\varepsilon << Ek^{-1} << 1$, i.e. small ω. In this particular case, the permeability tensor of both arrangements of spheres is given by:

$$\mathbf{K}^{\text{rot}} = (\mu\mathbf{K} \cdot -2\rho / \mu\, \mathbf{H} \cdot \boldsymbol{\omega}\times), \tag{11}$$

where **K** [m²] is the permeability tensor at $\omega = 0$, and **H** [m⁴] is the second-order tensor defined by relation (8). In the current case, tensors **K** and **H** are isotropic: $\mathbf{K} = K\mathbf{I} = a^2\ K^*\mathbf{I}$ and $\mathbf{H} = H\mathbf{I} = a^4H^*\mathbf{I}$, where H^* is a dimensionless coefficient which depends on the solid volume fraction c and the arrangement of spheres, i.e. on the microstructure: $H^* = H^*(c$, arrangement). Figure 4 shows the evolution of H^* with the solid volume fraction c for both arrays of spheres. Neglecting the effect of the arrangement of spheres on H^*, our numerical results have been adjusted by the following relation (see the fitted curve in figure 4):

$$H^*(c) = (1 + 1.5c + 5c^{14/3})\ (K^*)^2 = \beta(c)\ (K^*)^2. \qquad (12)$$

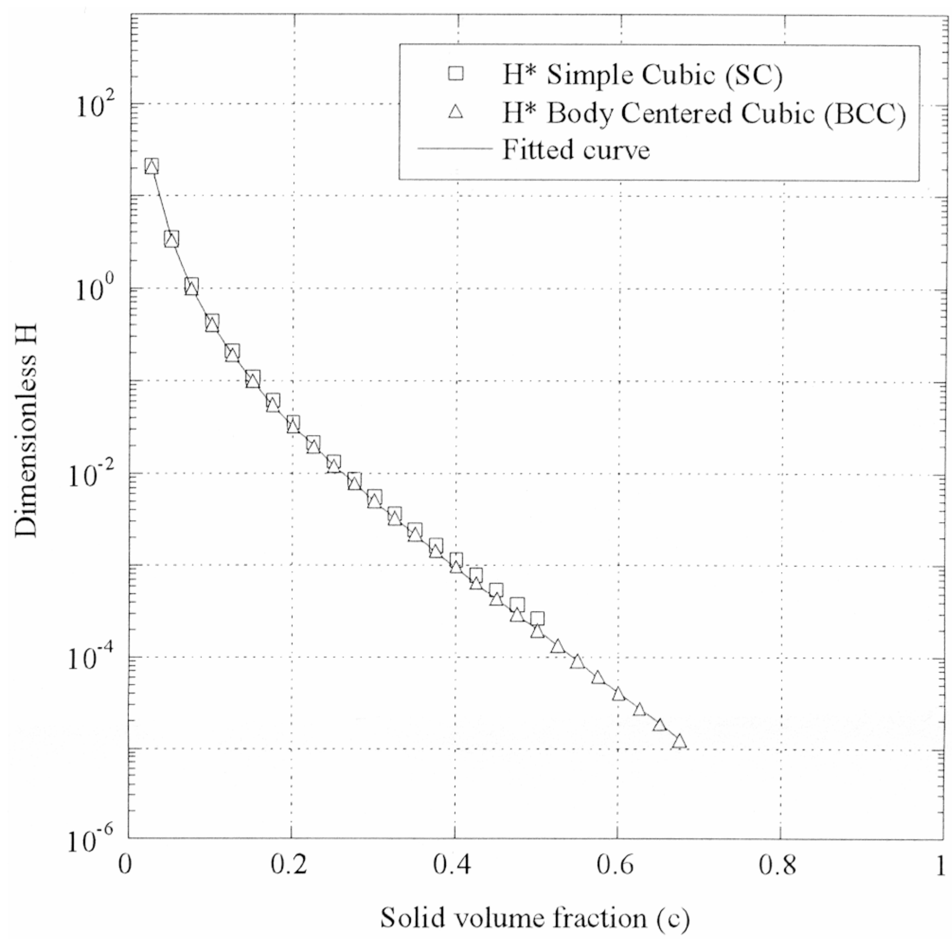

Fig. 4. Simple cubic (SC) and body-centered cubic (BCC) packings of spheres.
Evolution of the dimensionless coefficient $H^* = H/a^4$ versus the solid volume fraction c

Thus, the permeability tensor $\mathbf{K}^{\mathrm{rot}}$ for $\varepsilon << Ek^{-1} << 1$ can be given by:

$$\mathbf{K}^{\mathrm{rot}} = K^* a^2 \begin{pmatrix} 1 & -Ek^{-1}\omega_2 & Ek^{-1}\omega_2 \\ Ek^{-1}\omega_3 & 1 & -Ek^{-1}\omega_1 \\ -Ek^{-1}\omega_2 & Ek^{-1}\omega_1 & 1 \end{pmatrix}, \qquad (13)$$
$$Ek^{-1} = \frac{2\rho a^2}{\mu}\frac{H^*}{K^*} = \beta(c)\frac{2\rho a^2}{\mu}K^*,$$

where $\boldsymbol{\omega} = (\omega_1, \omega_2, \omega_3)$ and l used to calculate Ek^{-1} is equal to $\sqrt{\beta(c)a^2K^*}$.

3.2.3. $Ek^{-1} = O(l)$

Now, we consider the case where $Ek^{-1} = O(l)$. For the sake of simplicity we assume that $\boldsymbol{\omega} = \omega_3\mathbf{e}_3$. As a result of the geometry and angular velocity, the permeability tensor $\mathbf{K}^{\mathrm{rot}}(\omega_3)$ of arrays of spheres takes the form:

$$\mathbf{K}^{\mathrm{rot}} = \begin{pmatrix} K_{11}^{\mathrm{rot}}(\omega_3) & -K_{21}^{\mathrm{rot}}(\omega_3) & 0 \\ K_{21}^{\mathrm{rot}}(\omega_3) & K_{11}^{\mathrm{rot}}(\omega_3) & 0 \\ 0 & 0 & K_{33} \end{pmatrix}, \qquad (14)$$

where $K_{33} = K$ and $K_{11}^{\mathrm{rot}}(\omega_3 = 0) = K$. The plots of the dimensionless permeabilities for the simple cubic (SC) arrangement of spheres, $K_{11}^{\mathrm{rot}}(\omega_3)/K$ and $K_{21}^{\mathrm{rot}}(\omega_3)/K$ with respect to ω_3 for three different values of solid fraction c(0.1, 0.3, 0.5) and for two values of e(2 mm and 1.5 mm) are shown in figure 5a. At a given angular velocity we observe that the influence of the Coriolis effects on the permeability decreases with an increase in the solid volume fraction c and with a decrease in the length e. We stress that the above results are valid only if $\boldsymbol{\omega} = \omega_3\mathbf{e}_3$. Figure 5b shows the evolution of all these numerical results with respect to Ek^{-1} (13). We obtained different curves $K_{11}^{\mathrm{rot}}(\omega_3)/K_{11}^{\mathrm{rot}}(\omega_3 = 0)$ and $K_{21}^{\mathrm{rot}}(\omega_3)/K_{11}^{\mathrm{rot}}(\omega_3 = 0)$ which in this case depend on the Ekman number and also on the solid volume fraction c. The following relations

$$K_{11}^{\mathrm{rot}}(\omega_3) = K_{11}^{\mathrm{rot}}(\omega_3 = 0)\frac{1}{1 + (Ek^{-1})^2}, \qquad (15)$$

$$K_{11}^{\mathrm{rot}}(\omega_3) = K_{11}^{\mathrm{rot}}(\omega_3 = 0)\frac{Ek^{-1}}{1 + (Ek^{-1})^2} \qquad (16)$$

have been plotted in figure 5b (continuous line). These simple relations are in agreement with our numerical data if $Ek^{-1} < 0.5$. For higher values of Ek^{-1}, the difference between the above relations and our numerical data are less than 10%. From relations (15)–(16) and the definition of the dimensionless number Ek^{-1} (13), it can be shown that in the first approximation, the flow can be given in the followign form:

$$\mathbf{v} = -\frac{\mathbf{K}^{\mathrm{rot}}(Ek^{-1})}{\mu}(\nabla p + \rho\gamma(O)) = -\frac{\mathbf{K}}{\mu}(\nabla p + \rho\gamma(O) + \beta(c)2\rho\omega_3\mathbf{e}_3 \times \mathbf{v}), \qquad (17)$$

where the term $\beta(c)2\rho\omega_3\mathbf{e}_3\times\mathbf{v}$ appears as a "macroscopic Coriolis force" which brakes and deviates the flow. The above results remain valid for the porous medium composed of body-centered cubic (BCC) packing of spheres.

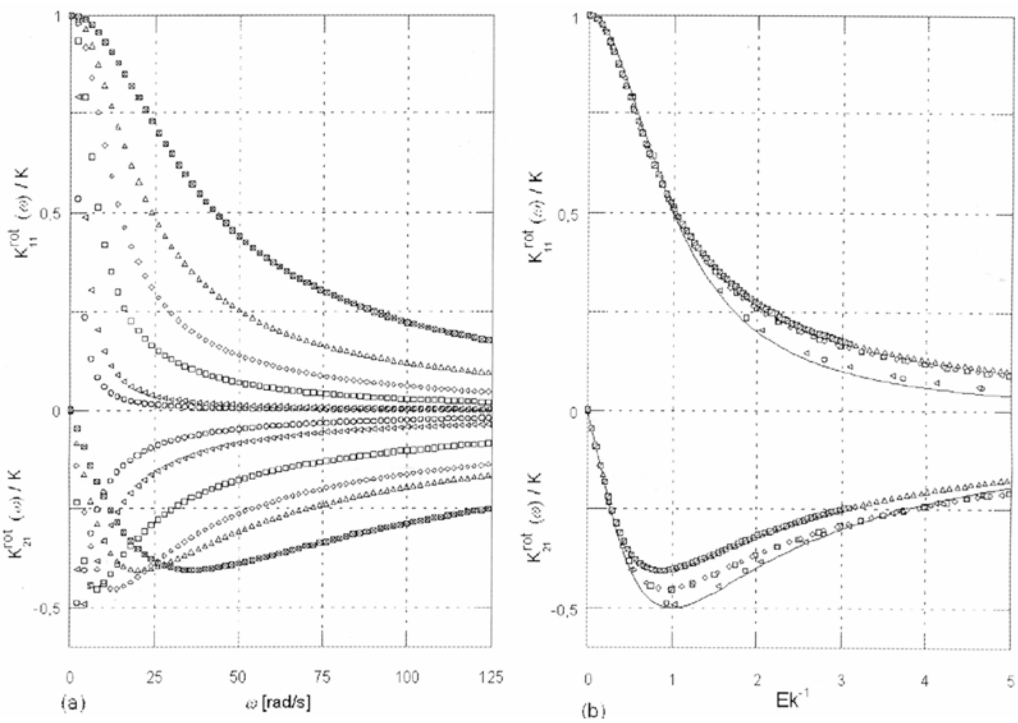

Fig. 5. Simple cubic (SC) packings of spheres.
Dimensionless permeabilities $K_{11}^{\mathrm{rot}}(\omega_3)/K$ and $K_{21}^{\mathrm{rot}}(\omega_3)/K$ versus angular velocity ω_3 (a) and versus Ek^{-1} (b) defined by equation (13) for three different values of the solid volume fraction c (0.1, 0.3, 0.5) and for two values of e (2 mm and 1.5 mm):
(○) $c = 0.1$, $e = 2$ mm, (□) $c = 0.3$, $e = 2$ mm, (Δ) $c = 0.5$, $e = 2$ mm, (◁) $c = 0.1$, $e = 1.5$ mm, (◊) $c = 0.3$, $e = 1.5$ mm, (⊠) $c = 0.5$, $e = 1.5$ mm. The continuous line represents equations (15)–(16)

4. CONCLUSION

The filtration law of an incompressible viscous Newtonian fluid flowing through a rigid non-inertial porous medium, which takes into account the Coriolis effects, was developed by using an upscaling technique. The structure of the law obtained is similar to that of Darcy's law but the permeability tensor depends on the angular velocity ω of the porous matrix, i.e. on the Ekman number Ek; it satisfies the Hall–Onsager's relation and is a non-symmetric tensor. Numerical simulations of the flow through a rotating porous medium were presented. The porous medium under consideration was composed of simple cubic (SC) and body-centered cubic (BCC) packings of spheres. Our numerical results showed the influence of the Coriolis effects on the permeability. When the Ekman number is large, i.e. $Ek^{-1} << 1$, which is the case in many practical applications, the influence of the Coriolis effect on the permeability can be described by a simpel relation which is valid for both microstructures (i.e. it does not depend on the arrangement of spheres) and for any orientation of the angular velocity vector. When $Ek^{-1} = O(l)$, the influence of the Coriolis effect on the permeability has been studied in a particular case where the angular velocity vector is perpendicular to one face of the simple cubic (SC) or body-center cubic (BCC) packings of spheres. Our results showed that the permeability strongly depends on ω and the geometrical properties of the porous medium: solid volume fraction, sphere arrangement and the size of the periodic cell. Finally, we showed that in the first approximation, the flow through rotating granular media can be described by modified Darcy's law including a "mascroscopic Coriolis force" which brakes and deviates the flow.

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