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Viscous force — An important parameter for the modeling of deep bed filtration in liquid media

Fabian Heuzeroth [a,*], Jörg Fritzsche [a], Eric Werzner [b], Miguel A.A. Mendes [b], Subhashis Ray [b], Dimosthenis Trimis [c], Urs Alexander Peuker [a]

[a] Institute of Mechanical Process Engineering and Mineral Processing, TU Bergakademie Freiberg, Agricolastraße 1, 09599 Freiberg, Germany
[b] Institute of Thermal Engineering, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 7, 09596 Freiberg, Germany
[c] Engler-Bunte-Institute, Karlsruhe Institute of Technology, Engler-Bunte-Ring 1, 76131 Karlsruhe, Germany

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ABSTRACT

Deep bed filtration of liquid media is a unit process step with a wide range of applications. For the description of both the impact and the adhesion probability of particles many publications and theories are available. This paper investigates in detail the influence of the viscous force theory in combination with the roughness of participating solids on the filtration process. The proposed model illustrates the necessity of including the energy dissipation by the disjoining liquid film in the modeling of deep bed filtration processes. Furthermore, the model can be used in order to estimate the influence of roughness, particle size and viscosity on the probability of particle impact and adhesion.

1. Introduction

The efficiency of the deep bed filtration process strongly depends on the probability of particle impact and adhesion on the surface of the filter structure. For the latter case, the authors [1] proposed a model in order to estimate the adhesion probability by balancing the kinetic energy of the converging particle and the adhesion energy between the particle and the surface, which is obtained from the measured adhesion energy distribution [2]. The proposed model clearly shows the significant influence of the particle impact velocity on the adhesion probability for a given material system. The particle impact velocity is primarily affected by the fluid flow, the gravitational force field (buoyancy) and the particle inertia. Numerical simulations, which calculate the particle trajectories based on the fluid flow and the external force field, are widely used for the past several decades in order to acquire information about the impact probabilities [3–6]. Fig. 1a schematically illustrates the possible deposition of particles in a representative section of a deep bed filter. Depending upon the governing impact mechanism and the particle size, particles adhere on the surface of the collectors within the deep bed filter (e.g., struts of ceramic foam filter). For the fundamental analysis of the relevant filtration mechanisms, it is quite common to use the single collector model, as displayed in Fig. 1b [7–10].

For aerosol filtration, many experimental as well as theoretical studies on the probability of adhesion can be found in the literature [7,8, 11–15]. For the filtration of liquids, however, this has not yet been systematically performed. Therefore, the present investigation focuses on the particle adhesion in liquid media. The major differences between the aerosol filtration and the filtration of liquid media are the density ratio between the particle and the fluid as well as the fluid viscosity. The latter aspect is of primary interest for the present investigation since it is expected that the fluid film in the converging gap between the particle and the surface of the filter structure would strongly affect the particle motion onto the filter.

It is well known that a relative movement between two solid objects, immersed in a liquid medium, causes disjoining of the liquid phase which results in a viscous force opposing this relative movement of the two solids. Stefan [16] and Reynolds [17] worked independently on an equation for describing the energy that is necessary in order to change the gap between two solid surfaces filled with a liquid. Their solution, named "lubrication approximation", defines the viscous force that is required in order to squeeze out the fluid from the gap between both surfaces.

The primary aim of the present investigation is to evaluate the relevance of the viscous force that exists between a converging particle and the surface of a filter structure during the deep bed filtration process in liquid media. Therefore, a numerical simulation is performed in order to

Abbreviations: AFM, atomic force microscope; Hi, Hiller; Rms, root mean square, µm.

* Corresponding author.
E-mail address: Fabian.Heuzeroth@mvtat.tu-freiberg.de (F. Heuzeroth).

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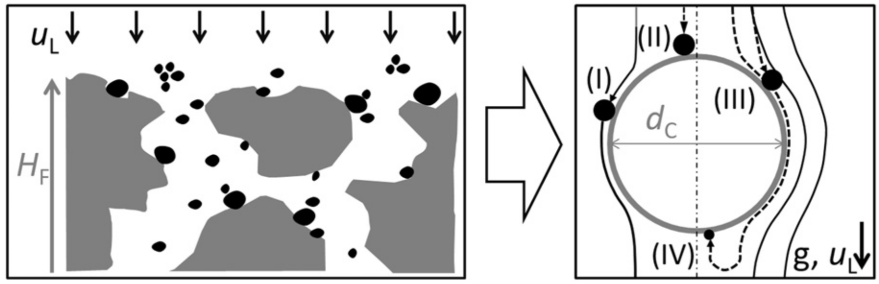

Fig. 1. a: Schematic representation of the deep bed filtration process in order to illustrate the particle deposition over the filter height (H_F); b: Conceptual visualization of the four major filtration mechanisms for separation of particles coarser than 1 μm in liquid media by a single collector: (I) interception, (II) sedimentation, (III) inertia and (IV) hydrodynamic forces.

estimate the impact velocity of particles on a single collector, assuming a one-way coupling between the fluid flow and the particles. These simulations are carried out for different particle sizes and bulk velocities. In order to consider the effect of viscous force on the particles, the model predictions are subsequently corrected employing the lubrication approximation. The numerical simulation is carried out for a single collector. Hence, the present investigation refers to the concept of the single collector.

The proposed model allows one to estimate the effects of roughness of the filter surface, particle size and fluid bulk velocity on the probability of particle impact and adhesion. The present study focuses on hydrophobic solids, which have a static wetting angle for water larger than 100°. In this case, hydrophobic effects increase the adhesion force between the particle and the filter surface [2].

2. Theory and methods

Stefan [16] and Reynolds [17] were the first scientists who investigated the stability of films for lubrication applications by simplifying the conventional Navier–Stokes equations in order to describe the forces acting on the liquid film between two solids. The obtained solution is referred to as the "lubrication approximation". Based on their theory, the formal "lubrication approximation" was extended in order to determine the generated forces when a particle moves through a liquid medium towards a solid surface [18–23]. The fluid film forces the moving particle to dissipate its kinetic energy and influences the probability of impact [20,21,24,25]. The resulting viscous force F_{vis} describes the drag between a spherical particle moving towards a plane surface (collector) through a stagnant liquid film and is expressed as [19,21]:

$$F_{vis} = \frac{3\pi \cdot \eta_L \cdot d_P^2}{2h} \frac{dh}{dt} \tag{1}$$

- η_L — dynamic viscosity, Pa s
- d_P — particle diameter, m
- h — distance between the particle and the collector surface, m
- t — time, s

Eq. (1) illustrates the dependence of the viscous force on the instantaneous distance h between the particle and the collector as well as the corresponding particle velocity $u_P = dh/dt$. However, in order to reduce the complexity of the calculation, it is convenient to approximate the interacting collector as a plane surface.

The viscous force, given by Eq. (1), is balanced by the inertial force of the moving particle, which reads as:

$$F_t = \frac{1}{6}\pi \cdot \rho_P \cdot d_P^3 \cdot \frac{du_P}{dt} \tag{2}$$

- ρ_P — particle density, kg m^{-3}
- u_P — particle velocity, m s^{-1}

It is evident that the forces in both Eqs. (1) and (2) take into account the particle velocity u_P, which depends on the particle to collector distance h. In order to combine these two forces and to derive information about their effect on the particle motion, they are transferred into their corresponding energy (Eqs. (3) and (4)). The balance of these two energies enables the calculation of local particle velocity that includes the effect of viscous force. Owing to the fact that no analytical solution is available to the best of the authors' knowledge, the energy balance is solved numerically by applying a suitable discretization scheme, as presented in Eq. (5). The increment in the distance of Δh is set as 0.5 nm. The examination of the overall energy balance, that is explicitly represented by Eq. (5), enables a direct estimation of the viscous force based on the particle velocity $u_{P,i}$ and the respective distance from the collector h_i. Hence, it is possible to describe the instantaneous (local) kinetic energy as a function of h_i. The employed energy balance, however, neglected the drag force exerted on the particles by the bulk fluid flow, owing to the assumption of a stationary boundary layer in the observed collector distances.

$$E_{vis} = \frac{3}{2}\pi \cdot d_P^2 \cdot \eta_L \frac{u_P}{h} \cdot dh \tag{3}$$

$$E_{kin} = \frac{1}{12}\pi \cdot d_P^3 \cdot \rho_P \cdot u_P \cdot du_P \tag{4}$$

$$E_{kin,i+1} = E_{Kin,i} - E_{Vis,i} = \left(\frac{1}{12}\rho_P - \frac{3\eta_L}{2d_P \cdot h_i \cdot u_{P,i}}\Delta h\right) \cdot \pi \cdot d_P^3 \cdot u_{P,i}^2 \tag{5}$$

- h_i — distance between the particle and the collector at step i, m
- $u_{P,i}$ — particle velocity at step i, m s^{-1}
- Δh — step length, m

The viscous force by the disjoining stagnant fluid film has to be considered between a distance h_1 up to the film rupture distance h_{min}, defined in Eq. (6). Luttrell and Yoon [18] defined h_1 as 5% of the particle diameter in their study on bubble/particle attachment. Furthermore, they reported the spread of h_{film} for hydrophobic objects in water to be approximately 100–150 nm. Therefore, for the following calculation which is subsequently referred to as the semi-analytical solution, 100 nm is used for h_{film}.

$$h_{min} = h_{film} + h_R. \tag{6}$$

The film rupture distance depends on the minimum film thickness h_{film} and on the effective roughness h_R, which is the sum of the rms values of the collector and the particle roughness, as illustrated by the dashed line in Fig. 2a [21,26]. The roughness affects the range of the