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Numerical simulation of deep-bed water filtration

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ABSTRACT

A two-dimensional simulator based on network model has been employed to design structure of filter composed of a few layers. The complex structure of the filter was represented by system of cylindrical channels connected via nodes, which represent basic quantities of the filter structure, like porosity or permeability. Performance of monolayer, multilayer and gradient filters was compared. Results show that depending on the number of layers, their porosities, the sequence of each layer aligned in the structure and channel diameter distribution significantly influence the amount of particles collected by the particular structure. Evolution of pressure drop, collection efficiency of particles and quality factors are the aspects, which should be tackled, to design an optimal filter structure.

1. Introduction

Deep bed filtration is a common technique to separate solid particles from the liquid in dilute suspensions [19]. The essence of this technique is deposition of particles during the flow of a suspension through a porous medium. As the suspension flows through the porous structure, suspended particles under the influence of various forces move towards the surface of fibres or grains where they become deposited mainly by London-van der Waals forces [17]. Deposited mass reduces the porosity of the filtration structure. It yields an increasing pressure drop of the filter. When the pressure drop achieves the critical level, the filter is "blocked" and must be replaced. As a result, deep-bed filtration, by nature, is an unsteady – state process. In order to deal effectively with collection of particles and at the same time keep the cartridge permeable, which guarantees long usage, one should produce an optimised porous structure. Experiments on air filtration show that using a pre-filter composed of microfibres can capture most particles, prolong loading time of next layers composed of nano-fibres and that it makes the "life" of entire filter much longer [11,18]. "Gradient" or multilayer filters composed of many layers, with different porosity and thickness may be a solution to produce optimal filters. A number of theories and hypothesis have been advanced to explain the transient behaviour of deep-bed filters during particle deposition. Although some of these studies have achieved a degree of success [5,16], they did not focus on the optimisation of filter internal structure and in many cases are too computationally demanding and require a procedure of establishing relationships between filter coefficient and extent of deposition from experimental data.

The aim of this work is to investigate theoretically the influence of morphology of a deep bed fibrous filter internal structure on its filtration ability using a simple network model. It is necessary to identify the effects of spatial distribution of local porosity and channel diameters on particle deposition rates. We use the quality factor, which is the most reasonable quantity to judge the performance of each created filter structure. We also focus on another contributing factor, like the evolution of the inner structure of a filter, which is important when predicting filter's cartridge optimal working time. The flow profile and the pressure field inside a porous structure can be easily obtained by a system of linear equations. Particle movement in the system was performed under the DLVO forces. The dominant contribution in DLVO forces comes from the attractive London-van der Waals force, which is referred in the work as "barrier-less" or favourable deposition conditions. Hydrodynamic and gravity force were also included. In order to integrate the trajectory of particles inside the cylindrical channels, *Brownian dynamics* algorithm was used, which is suitable for particles with arbitrary sizes. The accuracy of the proposed approach was tested in a number of sample calculations performed for different kinds of porous structures, which porosities values are characteristic for fibrous filters.

2. Model description

2.1. Network model of porous media

In order to describe the effect of spatial distribution of porosity on the particle or droplet behaviour along the porous structure the

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Nomenclature

C_{in}	influent particle concentration (ppm)
$d_{i,j}$	diameter of channel between i and j nodes (m)
d_p	diameter of the particle (m)
d_{av}	average diameter of channel (m)
$d_{f,i}$	average value of diameter of the channel in i-th layer
D	height of layer (m)
e	elementary charge of an electron (C)
F_g	gravity force (N)
F_{DL}	electric double layer force (N)
F_{LO}	London-van der Waals force (N)
g	gravity acceleration (m/s^2)
$g_{i,j}$	hydraulic conductance of the channel between adjacent nodes i and j
G_{vi}	Gaussian random number
G_{Li}	Gaussian random number
H_{pwc}	Hamaker's constant (J)
H_p	Hamaker's constant for a solid particle (J)
H_w	Hamaker's constant for water (J)
H_c	Hamaker's constant for a collector (J)
H	defined as $2r/d_p$
L_p	length of the channel (m)
L	length of the layer (m)
k_B	Boltzmann constant (J/K)
K	factor
m_p	mass of the particle (kg)
m_j	mass of the ion (kg)
M	number of units placed horizontally
n_k	number of the particles which exit the structure
n_0	number of the particles which were injected into the filter's structure
N	number of the entrance nodes placed vertically
P_i	pressure in the i-th node (Pa)
p_0	pressure at inlet of the network (Pa)
$p.v.$	pore volume
r	separation distance (m)
$r_{i,j}$	radius of channel between adjacent nodes i and j (m)
$r_{ij,new}$	new channel radius (m)
r_p	diameter of the particle (m)
q_f	quality factor (Pa^{-1})
Q_{in}	inlet fluid flow value (m^3/s)
$Q_{i,j}$	fluid flow in the channel between i and j nodes (m^3/s)
s	random number from interval [0; 1]
T	temperature of water (K)
W	total number of the nodes in the filter's structure
v_{ix}	velocity of the particle in x-direction
v_{iy}	velocity of the particle in y-direction
V_{DL}	electric double layer potential energy (N)
V_{LO}	London-van der Waals potential energy (N)
u_{ij}	velocity of the fluid in the ij channel (m/s)
u_{in}	inlet velocity of the fluid (m/s)
z_j	integer charge number of j-th ionic spaces

Greek letters

β_i	inverse of the free-particle relaxation time
σ	deviation in Gaussian distribution
σ_{vi}	standard deviations for velocity
σ_{Li}	standard deviations for displacement
ΔL_i	displacement of the particle (m)
$\langle \Delta L_i \rangle$	linear displacement of the particle (m)
Δv_i	change of particle velocity (m)
$\langle \Delta v_i \rangle$	velocity change of the particle (m)
Δp	pressure drop (Pa)
Δt	time step used to integrate the equation of trajectory (s)
ε	porosity of the layer
ε_r	dielectric constant of water
ε_0	dielectric constant of vacuum
φ_1	particle surface potential (mV)
φ_2	collector surface potential (mV)
ζ	coordination number of the node
κ	Debye's length (m)
μ	viscosity of water (Pa s)
μ_m	mean value in Gaussian distribution
η	efficiency of particle collection
ρ_i	coefficients of correlation
ρ_p	density of particle (kg/m^3)
ρ	density of water (kg/m^3)

network model has been applied extensively for many years [8,15,7,2,4,14]. The complex filter can be represented by 2-D network model [21,22,13]. Network may be composed of a system of micro-sized cylindrical channels with a defined diameter, connected through nodes. A picture depicting the structure is given in Fig. 1. This approach has similarities with real porous structures of filters and can provide much information when predicting collection efficiency of particles. From the real point of view, it is impossible to describe the complex geometry of fibrous filters; therefore a detailed description of real filters is avoided in network models. Performance of the layer capable to collect a certain amount of particles is analysed from the macroscopic point of view, as an object with a distribution of channel sizes, specified porosity and permeability of the structure. Calculations, using network models, are fast and simple, therefore suitable for engineering practise compared to other more complicated models in geometrical and mathematical aspects. Network models are suitable to investigate particle movement in a porous structure. There are many types of network models such as square, hexagonal, triangular and random ones, which differ in the pattern of connected channels. In this study we choose a regular square lattice rotated around 45° to the flow axis [4]. This rotation makes the channels not to be aligned with the direction of the gravity force, which would enhance deposition rates [3]. The network has a rectangular shape with $L \times D$ size, where L is the length of the layer and D is its height. A network composed of W number of nodes was used to imitate a single slice of the filter [20]. We designated a number of entrance nodes on the left side of the network by N number and M number of units aligned with the flow direction, Fig. 1. Therefore, the total number of the nodes can be obtained from the following relationship $W = M(N-1) + (M+1)N$.

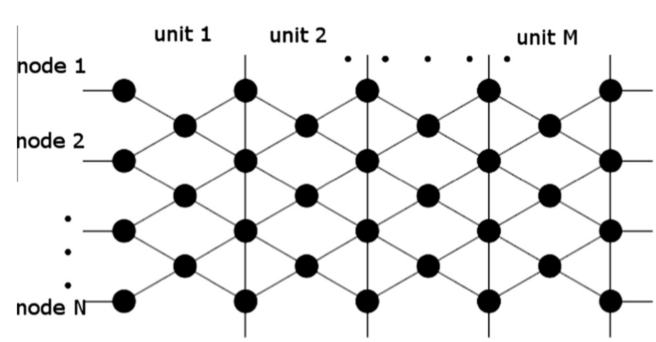

Fig. 1. Illustrative picture of network structure composed of system of connected channels via cycle nodes.