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Study on the Simulation for the Removal of Different Sized Particles in Suspension by Deep-Bed Filtration

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Abstract: A model was proposed for investigating the particle removal from suspension with particles of different sizes by deep-bed filtration, and the collection efficiency was predicted by computer simulation. Deposited particles on the pore surface may act as additional collector and reduce the pore size, which contribute to the improved collection efficiency with increase of deposition. Computer experiments for suspension of particles of three sizes and its equivalent size of mono particles were carried out and compared. The collection efficiency of suspension with poly-dispersed particles shows higher efficiency than that of suspension with mono-dispersed particles. Also the collection efficiency of small particle of mixture is higher that that of same uniform size particles.

Key words: filtration, water treatment, collection efficiency

1. Introduction

Deep bed filtration, which was used in the treatment of drinking water in Egypt 2000 years ago, is widely applied in treatment of drinking and waste water. Also in order to maintain stable and safe operation of water treatment process and to protect the expensive membrane for recycling of waste water, deep bed filtration is utilized as the pre-treatment process to remove suspended particles in water, because of its simple operation and low investment cost. Therefore, a large number of experimental data and operation know-how are accumulated. However theoretical studies are somewhat limited because of difficulties in predicting the flow field change and particle capturing capability with increase of particle deposition.

As a non-steady state process, the dynamic behavior of deep-bed filtration is characterized by the effluent concentration history and the history of the overall pressure drop requirement for the maintenance of constant throughput. The effluent concentration history directly reflects the changes in collection efficiency of a deep-bed filter resulting from the accumulation of deposited particles within the filter. The pressure drop history, on the other hand, represents the effect of deposition on the permeability of the filter medium. Ideally speaking, a properly formulated model should be capable of predicting both the changes in collection efficiency and permeability. However, because of the extremely complex nature of the particle deposition phenomena, as a practical matter, it is convenient to formulate separate models for predicting either the changes in collection efficiencies or permeability reduction. As the reduction in permeability is a direct consequence of deposition, an equivalent relationship between these two models must be established before one can predict the complete dynamic behavior [1-5].

Most of theoretical studies for particle removal efficiencies of granular filter bed are based on the consumption that particles within suspension are uniform size. However, actual suspension has certain size distribution of particles and this should be considered in analyzing the dynamic behavior of deep bed filtration [6, 7]. Therefore, when particles have a certain distribution, a new model and simulation technique are suggested for predicting the collection efficiency in this research. Also the collection efficiency caused by interactions between particles are considered and compared with that of uniform sized particles.

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2. Model Formulation

2.1 Unit bed element

In order to provide a realistic model and to understand filtration phenomena in granular filter beds, a filter bed may be considered as a series of unit bed elements (UBE), as suggested by Payatakes [8]. A schematic representation of deep bed filtration with the unit-bed-element concept is represented in Fig. 1. As shown, the unit bed elements of a given filter are uniform in thickness and have same properties, such as the initial void fraction, the initial permeability, etc. The thickness of unit bed element, l, is called the length of periodicity, and its magnitude is about the same size of a filter grain. Each unit collectors with their geometries specified by the porous media model selected to characterize the granular filter bed. Among the models which have been used in granular bed filtration studies are the isolated-sphere model, the sphere-in-cell model, and the constricted-tube model as shown in Fig. 1.

If one should assume the type of unit cell and flow field around unit cell in order to check the efficiency of particle removal, several kinds of models were suggested and analyzed. Also with the increase of particle deposition, it should be considered the effect of deposited particle on the flow field and the filtration efficiency. In this study, the UBE of filter bed is composed of capillaries of different diameter as shown in Fig. 1.

2.2. Prediction of collection efficiency

If one knows the flow field around the filter grain and the forces between collector and particle, the collection efficiency of filter can be obtained by trajectory analysis. However, the trajectory analysis in cylindrical pore gives much smaller prediction than that of experiment. One way to avoid low prediction is the use of sphere-in-cell model.

As shown in Fig. 2, the volume of a cylindrical pore

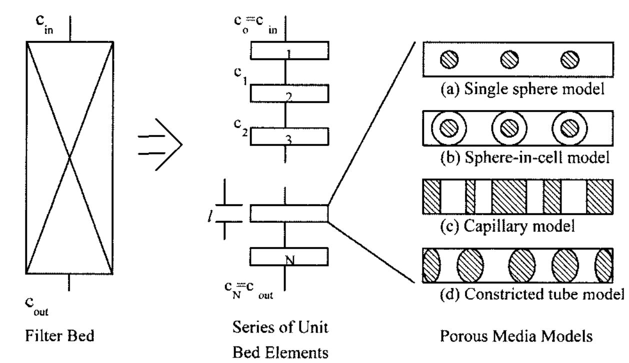

Fig. 1. Concept of unit bed element of fibrous bed.

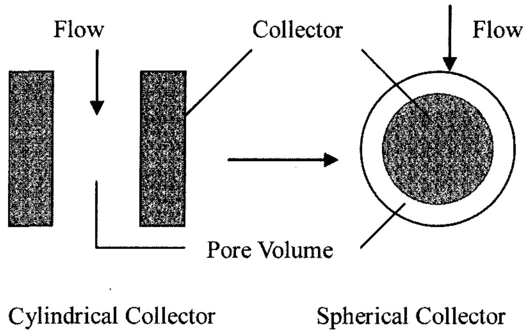

Fig. 2. Unit cell of i-th type of cylindrical pore and its corresponding spherical collector.

is considered to be the volume of liquid envelope surrounding spherical collector. Since the correlation equations for the particle capturing capability of spherical collector are found in literature, equation (1), which was proposed by Payatakes [8], is used as following:

$$\eta_{H_0}=1.5A_s(1-\varepsilon)^{2/3}N_R^2\left[\frac{2}{3}N_{Lo}^{1/8}+2.5\times10^{-3}N_G^{1.2}N_R^{-2.4}\right] +4(1-\varepsilon)^{2/3}A_s^{1/3}N_{Pe}^{-2/3} \quad (1)$$

where η_{Ho} is collection efficiency of the Happel's cell and N_{Lo}, N_G, N_R, N_{Pe} and A_s are respectively, London force parameter, Gravitational parameter, Interception parameter, Peclet number and Happel's parameter. When the pore size is small, $(1-\varepsilon)$ term in the equation (1) becomes large, and as a result, it gives high collection efficiency. With the increase of particle deposition, the pore space becomes filled with deposited particles and pore diameter is reduced. Therefore particle removal efficiency is improved.

2.3. Flow distribution within the cylindrical pore

The flow distribution through the cylindrical pore suggested in Fig. 1 can be obtained assuming that the Hagen-Poiseuille equation can be applied, and conductivity of each pore can be expressed as

$$\alpha_{ij}=\frac{\pi d_{ij}^4}{128\mu l} \quad (2)$$

where the first member of the double subscript denotes the i-th pore and the second subscript denotes the j-th UBE. α_{ij} and d_{ij} are the conductivity and diameter of the i-th pore in the j-th UBE. μ is the fluid viscosity. The volumetric flow rate is

$$q_{ij}=\alpha_{ij}(P_{j-1}-P_j) \quad (3)$$

where q and p are the flow rate and pressure of UBE.

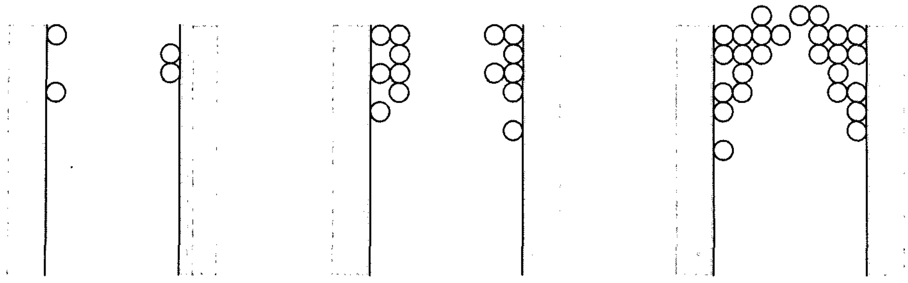

Fig. 3. Three stages of deposition process.

By the definition, the superficial velocity of a filter bed, u_s, is

$$u_s = \sum_{i=1}^{N} q_{ij} = (Q_T)_j \quad (4)$$

where $(Q_T)_j$ is the total flow rate through the j-th UBE and N represents the number of pores in one UBE.

Capturing mechanism within a cylindrical pore may be assumed to proceed in three different stages: During the first stage, particles are deposited individually on the pore surface, as shown in Fig. 3. As the number of deposited particles becomes sufficiently numerous, the deposited particles may be considered to form a deposit layer. The first stage of deposition continues until the thickness of deposit layer reaches a value equal to that of one particle diameter. During the second stages, particle deposition results in the formation and growth of multi-layer particle deposit with its geometry. The second stage ceases when the inlet diameter is reduced sufficiently such that sieving becomes the dominant mechanism of deposition. The last stage of deposition means blocking the pore and most of the fluid cannot pass through that pore.

3. Simulation Procedure

The computer experiments were carried out following steps:

1) Particles are introduced into the filter, one by one at a time changing particle size.

2) If a particle arrives at a particular UBE, it may enter any one of the pores of the UBE. By physical argument, the probability of the particle's entering a given pore in proportional to the fluid flow through the pore. For the pore selection, a random number (RAN A) is generated. If the generated random number is

$\frac{1}{(Q_T)_j}\sum_{k=1}^{i-1} q_{kj} \le RAN(A) \le \frac{1}{(Q_T)_j}\sum_{k=1}^{i} q_{kj}$, then the i-th pore is the pore into which the particle enters.

3) To determine whether or not the particle is captured by the i-th pore, another random number (RAN B) is generated. When the generated random number is less than the collection efficiency of the i-th pore, the particle is assumed to be deposited on that pore.

4) If the particle escapes collection, it goes to the next UBE. Repeat step 2 and 3 until the particle either becomes deposited or escapes. If the particle is not captured by the filter bed, go to step 1.

5) If the particle is captured by the i-th pore of the j-th UBE, the deposit distribution and flow field are adjusted. Also the collection efficiency of the pore is updated. The detailed calculation procedure can be found in Choo and Tien [9].

Following the above steps, the simulation algorithm

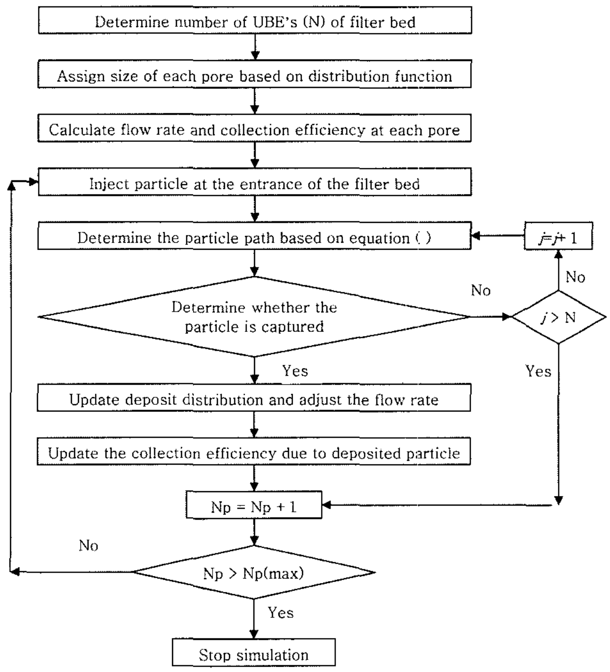

Fig. 4. Simulation algorithm for the prediction of particle removal efficiency.

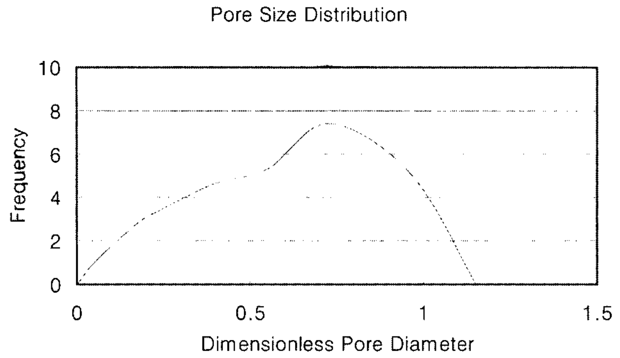

Fig. 5. Pore size distribution used in this study.

for the prediction of particle removal efficiency is shown in Fig. 4.

4. Results

4.1. Pore size distribution

In this study, the size distribution of capillary tubes in unit bed elements is based on the Rayleigh distribution function and its results are shown in Fig. 5, where the diameter of tube is normalized by that of collector grain.

4.2. Effect of random number on the collection efficiency prediction

The capillary pore for the particle path through the unit bed element is selected by random number in computer simulation. Also whether the particle is captured or not is determined by another random number. If the generated random number is smaller than that of collection efficiency of that pore, then the particle is captured on the pore wall. Therefore, the random number selection may be important in predicting collection efficiency and the effect of random number is shown in Fig. 6. The predicted collection efficiency is almost independent of initial random number selected. Collection efficiency is obtained by averaging results of four set of

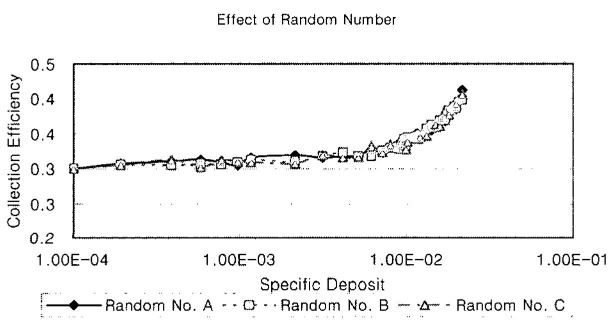

Fig. 6. Effect of random numbers on collection efficiency.

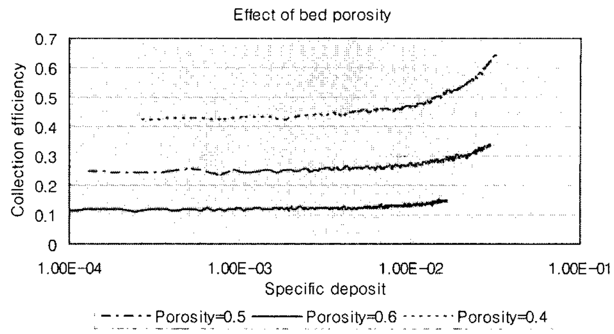

Fig. 7. Effect of bed porosity.

different random numbers, counting the captured particles on the pore at every 1000 particles injected.

4.3. Effect of bed porosity

The effect of filter bed porosity is presented in Fig. 7. When the filter bed is filled compactly with filter grain, the pore size becomes small and the particle capturing capability of filter bed is improved. As expected, the collection efficiency increases with reduction of bed porosity which is shown in Fig. 7.

4.4. Effect of the interaction between mixed particles

When the suspension includes particles of different sizes, the interactions between the particles are investigated by using mixed particles with 4 μm, 8 μm and 18 μm sizes.

Collection efficiency of poly-dispersed particles and its equivalent mono-dispersed particles, which is obtained by averaging volume of mixed particles, are compared and shown in Fig. 8. The mixture shows enhanced collection efficiency 30% more than that of uniform sized particles.

The overall collection efficiency of mixed particles is higher than that of uniform particles. However, the individual collection efficiency of particle of each size is somewhat different tendency in a given specific deposit,

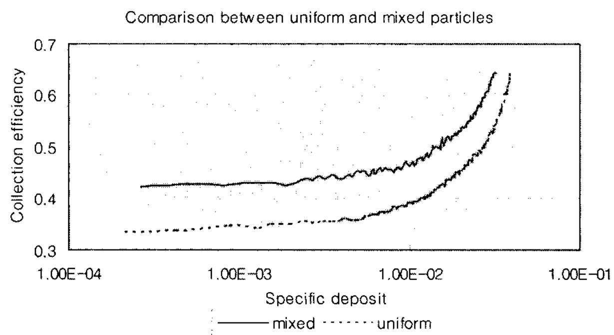

Fig. 8. Comparison between mono-dispersed and poly-dispersed particles.

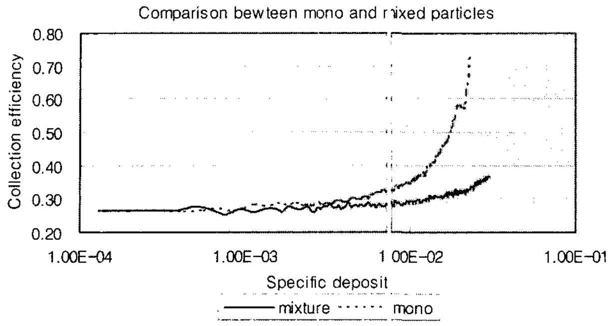

Fig. 9. Comparison between suspensions of mono size particles and mixtures (16 μm).

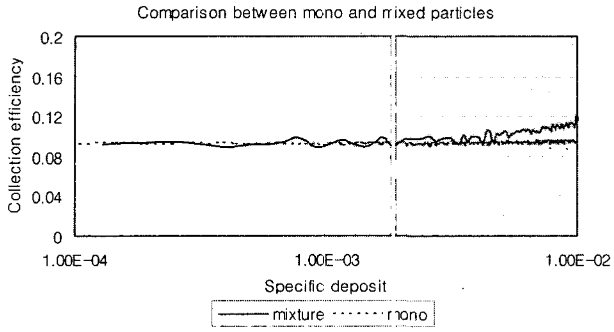

Fig. 10. Comparison between suspensions of mono size particles and mixtures (8 μm).

as shown in Fig. 9 and Fig. 10.

Collection efficiency of large particles within mixture is smaller than that of equal size of mono-dispersed particles as presented in Fig. 9. On the other hand, collection efficiency of small particles within mixture represents higher collection efficiency as shown in Fig. 10. These phenomena may be explained by assuming that the smaller particles are captured within the space formed by deposited large particles. Also large particles may block the pore earlier than small particles, which cause enhanced filtration performance.

5. Concluding Remarks

A new model is proposed in this study for predicting the collection efficiency of filter bed with poly-dispersed suspension. The predicted efficiencies show a little fluctuation as shown in figures because of the stochastic nature of computer simulation. However, the capturing capability of filter bed with the suspension with the poly-dispersed particles shows a different tendency from that of suspension with mono-dispersed particles. As shown in figures, the effect of particles of different size should be considered in predicting the performance of filter bed. Even though the experimental data are not available at present moment, this kind of modeling work can provide one way of analyzing real filtration processes. Future work is required for predicting collection efficiency as well as the pressure drop increase with the deposition.

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