Effect of velocity on the clogging of particles in water-saturated porous media using the CFD–DEM

Dan Sun
National Institute of Clean-and-Low-Carbon Energy, Beijing, 102209, China

Correspondence
Dan Sun, National Institute of Clean-and-Low-Carbon Energy, Beijing, 102209, China, Email: dansuncfd@outlook.com

Abstract
The clogging of particles in a slurry passing through a water-saturated porous medium is mainly affected by the ratio of the particle diameter to the pore throat size of the medium. A previous study showed that the hydrodynamics conversion and particle concentration affect particle clogging and retention in porous media. Therefore, in this study, the effects of fluid velocity on particle clogging were investigated by analyzing the particle transport and retention in a homogeneous porous medium, when the particle motion was driven by liquid carrying without gravity. The fluid-particle two-phase flow in a porous medium was simulated using the computational fluid dynamics–discrete element method. The results showed that increasing the fluid velocity of particles such that the Stokes number was almost equal to 1 increased the separation efficiency of particles. Further increasing the fluid velocity reduced the residence time, which reduced the separation efficiency of the particles.

Keywords: porous media, particle clogging, particle retention, Stokes number, CFD-DEM

1 INTRODUCTION
Particle clogging in porous media is a key phenomenon in particle filtration in various industrial applications \[1,2,3,4,5,6,7\]. Particulate filtration through a granular bed is important because of the high separation efficiency. As the particle suspension passes through a porous medium, the particles are retained and become accumulated in the medium. Therefore, the diameter of the particles and the size of the pore throat are crucial factors that affect filtration \[8\]. Particles smaller than one-third but larger
than one-seventh of the pore diameter invade the formation and are trapped, forming an internal filter cake,\textsuperscript{[9]} which is the bridging that causes the particle clogging in porous media.\textsuperscript{[10]}

Particle clogging is significantly affected by both the particle diameter and the particle concentration\textsuperscript{[8, 11, 12]}. Recently, the mechanism of particle clogging in porous media was investigated by the numerical studies using the computational fluid dynamics–discrete element method (CFD–DEM). Lin et al.\textsuperscript{[11]} simulated the depth of particles invading a porous medium using the CFD–DEM and studied the effects of the particle diameter. Li et al.\textsuperscript{[13]} simulated the effects of the grain/particle size ratio on the clogging probability when particle bridging occurred using computational fluid dynamics discrete element method (CFD-DEM). Feng et al.\textsuperscript{[14]} studied the effect of particle size and concentration on the permeability of porous media in a simulation using CFD-DEM. Zhou et al.\textsuperscript{[15]} studied particle retention and permeability impairment in porous media due to exclusion when the particle sizes were larger than the pore-throat sizes. This microscopic study of particle clogging in a porous medium reveals the mechanism of particle clogging and the variation in the permeability of the porous medium due to clogging.

Extensive studies have been conducted on the effect of particle diameter on particle clogging. The larger the ratio of the particle diameter to the pore-throat size, the greater the prospect of particle clogging. In a previous study, the collection efficiency, pressure drop, and permeability of porous media owing to particle clogging were studied. Previous research\textsuperscript{[12]} has also discovered that particle clogging is affected by the Stokes number. When the Stokes number is lower than 1, diffusion is the dominant mechanism for particle motion in porous media, and the particles are seldom trapped in porous media by bridging. Whereas when the Stokes number is greater than 1, the particles can leave the flow path of the fluid carrier owing to inertia. The Stokes number is proportional to the fluid phase velocity and the square of the particle diameter. The Stokes number is the ratio of the characteristic time of particle to a characteristic time of flow, $St = \frac{\rho_p d_p^2}{18 \mu_f D} V_{rel}$. Therefore, Stokes number is affected by the particle density ($\rho_p$), particle diameter ($d_p$), fluid viscosity ($\mu_f$), size of the flow path ($D$) and relative velocity magnitude between the fluid and particle ($V_{rel}$). Extensive studies have been conducted on the effects
of particle diameter and the ratio of particle diameter to pore-throat size. However, studies on the effects of fluid velocity on particle clogging are limited.

Fo et al. \cite{16} studied the effect of fine particle flow in porous media by considering the velocity at the inlet using the LBM-DEM-IBM. Reportedly, an increase in the fluid inlet velocity increased the possibility of interaction between the particles and porous media. Bannacer et al. \cite{17} studied the effect of particle size and flow velocity on the transport and deposition of suspended particles in saturated porous media and found that the deposition coefficient is proportional to the velocity of the fluid phase. Liu et al. \cite{18} experimentally studied the filtration of particles through the porous media of a granular bed. The results revealed that the inlet velocity of the fluid influenced the collection efficiency and particle concentration. When the inlet velocity was increased, the collection efficiency decreased. Note that the inlet velocity should be sufficiently high to guarantee that particles can be separated from the flow path of the fluid when the Stokes number is greater than one; however, increasing the velocity reduces the separation efficiency. The Reynolds number also affects the permeability of the porous media. However, increasing the fluid velocity is not yet known to increase the separation efficiency. Therefore, the effects of fluid inlet velocity on the sustainable operation of separation systems must be studied.

In this study, the particle retention by bridging in a homogeneous porous media was studied on the effect of the stokes number using CFD-DEM. The Stokes number is proportional to both the fluid velocity and square of the particle diameter, and inversely proportional to the pore-throat size of the porous media. In this study, the pore throat size was fixed and consistent in a homogeneous porous media. The particle motion was driven by the fluid carrying without gravity. The particle diameter and the fluid velocity were varied to investigate their effects on particle clogging in porous media.

2 CFD-DEM
Particle filtration in a porous medium was simulated using the Eulerian–Lagrangian simulation method, CFD-DEM. This study focused on the filtration of particles by means of the particle bridging with the effects of the slurry velocity and Stokes number. The research methodology was designed to be able to neglect the filtration of particles owing to the exclusion, straining, segregation, and electrostatic
attraction \cite{19}. Therefore, the particles are assumed to be non-cohesive, smooth spheres of uniform
diameters, with neglectable electrostatic effects. The effects of particle properties such as the particle
shapes \cite{20} and particle-wall interactions \cite{21} will be studied in the future.

In CFD-DEM, the fluid dynamics of the liquid were simulated by solving the Reynolds-averaged
Navier–Stokes equation \cite{22}:

\[
\frac{\partial \alpha_l \rho_l}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l) = 0 \tag{1}
\]

\[
\frac{\partial \alpha_l \rho_l \mathbf{u}_l}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l \mathbf{u}_l) = -\nabla p + \nabla \cdot (\tau_l) - \frac{\rho_l (R_{D,0})}{\nu_{cell}} \cdot \frac{\mathbf{u}_l - \mathbf{v}_s}{|\mathbf{u}_l - \mathbf{v}_s|} \tag{2}
\]

where \( \alpha_l \) is the volume fraction of the liquid (The subscript \( l \) and \( s \) represent the liquid and solid phase, respectively), \( \rho \) is the density, \( \mathbf{u}_l \) is the vector of the mean velocity, \( p \) is the pressure of liquid, \( V \) is the
volume, and \( \tau \) is the stress tensor (\( \mu_l \) is the kinematic viscosity of liquid),

\[
\tau_l = (\lambda_l - (2/3)\mu_l)(\nabla \cdot \mathbf{u}_l)\mathbf{I} + \mu_l ((\nabla \mathbf{u}_l) + (\nabla \mathbf{u}_l)^T) \tag{3}
\]

DEM was used to trace the particles under the Lagrangian reference frame. Discrete particle trajectories
were predicted by integrating the force balance of the particles. The governing equations of the
translational and rotational motions of the particles are as follows:

\[
m \frac{d \mathbf{u}_p}{dt} = \mathbf{F}_D + \mathbf{F}_p + \mathbf{F}_r + \mathbf{F}_c \tag{4}
\]

\[
l \frac{d \mathbf{\omega}_p}{dt} = \mathbf{F}_c + \mathbf{F}_r \tag{5}
\]

Where \( m \) is the mass of the particle, \( \mathbf{F}_c \) is the contact force due to particle–particle collisions and \( \mathbf{F}_D \) is
the drag force. The pressure gradient force \cite{23},

\[
\mathbf{F}_p = -\nabla p \cdot \mathbf{V}_p \tag{6}
\]

and the viscous force \cite{24},

\[
\mathbf{F}_r = -\nabla \cdot \tau \mathbf{V}_p \tag{7}
\]

2.1 Drag force

The drag force on a single particle was calculated by Koch and Hill model \cite{25,26} based on the lattice-
Boltzmann simulations:
where, \( dp \) is the particle diameter. The volume fraction of particles, \( \alpha_p + \alpha_t = 1 \) and \( Re_p \) is the Reynolds number of the particle, calculated by

\[
Re_p = \frac{\alpha_p dp}{\mu_t} \left| \bar{u}_i - \bar{u}_p \right|
\]

2.2 Contact force

In DEM, contact forces are simulated using a spring–dashpot model [27]. The spring generates repulsive forces pushing particles apart, and the dashpot represents viscous damping and allows the simulation of collision types other than perfectly elastic. A parallel linear spring–dashpot model represents the normal force, and a parallel linear spring–dashpot model in series with a slider represents the tangential force with respect to the normal vector of the contact plane. In both cases, the spring accounts for the elastic part of the response, and the dashpot accounts for the energy dissipation during the collision. A linear spring contact model was used here to define the contact force [28,23]. The normal component of the contact force between particle i and particle j was expressed as

\[
F_n = -k_n d_n - c_n \left( u_{n,i} - u_{n,j} \right)
\]

Tangential shear forces occur upon collision and increase the torque. The Coulomb friction law was used to determine the tangential contact force:

\[
F_t = \min \left\{ k_t \int_{t_c,0}^{t} (u_{t,i} - u_{t,j}) dt + c_t (u_{t,i} - u_{t,j}) \right\}, \mu_c F_n
\]

where \( d_n \) and \( d_t \) are the overlaps in the normal and tangential directions, respectively, at the contact point; \( \mu_c \) is the Coulomb friction coefficient; \( k \) is the spring stiffness; and \( c \) is the damping coefficient.
\( \overline{T}_c \) and \( \overline{T}_r \) are the torques generated by the tangential force and rolling friction, respectively. The torque due to friction at the contact point was calculated by

\[
\overline{T}_c = \overline{r}_c \times \overline{F}_t
\]  

(14)

In addition, a directional contact torque model was applied as a rolling friction model \cite{29}:

\[
\overline{T}_r = R_n k_n \Delta d_n \overline{\omega}_{rel} r_p
\]  

(15)

Where \( r \) is radius and \( R_n \) is the rolling friction model parameter and the relative angular velocity at contact is defined as

\[
\overline{\omega}_{rel} = \frac{r (\overline{\omega}_i + r \overline{\omega}_j)}{r_i + r_j}
\]  

(16)

The simulation was carried out using the open-source software CFDEM using the pseudo-particle-resolved solver. The detailed physical model and numerical method can be found in the publication by Goniva et al. \cite{23, 30} The validation of the numerical method in this study is in Appendix A.

### 3 SIMULATION AND ANALYSIS

Homogeneous porous media were designed by a package of spherical particles at a diameter of 1 mm. The throat gap between the two neighbouring particles was 50 µm. The particle size was less than the gap size and 1/20 of the diameter of the packed particles of the porous media, therefore, the porous media was simplified as a two-dimensional region. This 2D porous media was also applied in the filtration with fabrics \cite{31, 32}. The liquid density was \( 1.0 \times 10^3 \) kg/m\(^3\), viscosity was \( 1.23 \times 10^{-3} \) kg/m·s, and particle density was \( 2.4 \times 10^3 \) kg/m\(^3\). The poisons ratio and young’s modulus of particles were 0.22 and 50 GPa, respectively. The coefficients of restitution and friction of the particles-particle and particle-wall interactions were both 0.99.

Figure 1(a, b) show the fluid dynamics of the pure liquid phase injected into the porous medium from the left as a pressure-driven flow. Without particles, the pressure gradually decreases from the inlet on the left to the outlet on the right. At the pore throat, the liquid velocity is the highest (1.2 m/s, \( u_{max, gap} \)).

Varying the pressure changes the velocity in the porous medium. Figure 1(c) shows the superficial
velocity of the liquid, \( u_{\text{sup}} \), in the porous medium. Figure 1(d) displays the calculated Stokes number of the particles with diameters varying from 5 to 45 \( \mu \text{m} \) at the gap throat. When the superficial velocity of the liquid is high, the Stokes number is also high. When the particle concentration in the median reconcentration region, \( \alpha_s \), is varied from 0.0005 to 0.05, the Stokes number of the particles exhibits an insignificant change. As depicted in Figure 1(d), the Stokes numbers of all particles having diameters smaller than the pore throat size are less than 1 when the liquid velocity is equal to \( u_{\text{sup},0} \). Under the conditions of \( u_{\text{sup},2} \) and \( u_{\text{sup},3} \), the Stokes numbers of the particles having diameters of 30, 15, and 10 \( \mu \text{m} \) are greater than 1; this is calculated using the maximum velocity of the liquid in the gap throat.

![Figure 1. Fluid Fluid dynamics of particle-free water in the porous medium](image)

Mono-sized particles were injected into the porous medium to cause large-sized particles to generate particle clogging. Figure 2 shows the particle distribution during the early stage of injection in the porous medium when \( \alpha_s = 0.005 \). The particle diameters are 30, 35, and 40 \( \mu \text{m} \). When \( u_{\text{sup},1} \) and \( u_{\text{sup},2} \) are used, particles having diameters larger than 35 \( \mu \text{m} \) are trapped. At a higher speed, \( u_{\text{sup},2} \), particle clogging occurs in the earlier sections, namely, sections B, D, and H. At a lower speed, \( u_{\text{sup},1} \), particle clogging occurs downstream of section F. Thus, the possibility of particle clogging is higher when the
velocity increases. However, at speed $u_{3}$, particles having diameters larger than 40 µm are trapped.

Figure 3(a) presents the mean particle concentration in the pore space of the porous medium at various velocities. The particle concentration at $u_{3}$ is lower than that at $u_{2}$, when the particle diameter is 30 and 35 µm. In particular, when the particle diameter is 30 µm, the particle concentration at $u_{3}$ is the lowest. The high velocity of the liquid increases the particle velocity and, consequently, reduces the residence time and concentration of particles in the porous medium.

Figure 2. Particle migration in the porous medium in median concentration, $\alpha_{tr} = 0.005$ (a. $u_{1}$, 30 µm, b. $u_{1}$, 35 µm, c. $u_{2}$, 30 µm, d. $u_{2}$, 35 µm, e. $u_{3}$, 35 µm, and f. $u_{3}$, 40 µm)
Figure 3. Mean particle concentration affected by the velocity of the liquid

Figure 4. Particle migration in the porous medium in median particle concentration, $\alpha_{tn} = 0.05$

(a. $u_{sup,1}$, 25 µm, b. $u_{sup,1}$, 30 µm, c. $u_{sup,2}$, 25 µm, d. $u_{sup,2}$, 30 µm, e. $u_{sup,3}$, 25 µm, and f. $u_{sup,3}$, 30 µm)
Figure 3 (b) shows that the initial particle concentration is 0.05. The particle concentration at $u_{sup,3}$ is close to that at $u_{sup,2}$. Figure 4 shows the particle distribution during the early stage of injection in the porous medium when $\alpha_s = 0.05$. In all the cases, particle clogging occurs when the particle diameter is 35 $\mu$m. The particle distribution in Figure 4 (f) shows that particle clogging at high velocity occurs upstream, the distribution in Figure 4 (b) displays that clogging at low velocity occurs downstream, and Figure 4 (d) depicts clogging in the middle. Therefore, a high velocity increases the possibility of particle clogging and causes clogging during the early stage of the flow.

As presented in Figure 5, the particle velocity is averaged over the entire porous medium. The particle velocity is lower when the particle concentration is higher ($\alpha_s = 0.05$). This is due to the higher concentration of particles, which increases the dissipation of the momentum of the liquid. The particle velocity in the porous medium is high when the inlet velocity of the liquid is high, as observed at $u_{sup,3}$. Moreover, the velocity of small particles is considerably higher than that of large particles at $u_{sup,3}$. However, the particle diameter affects the particle velocity only slightly when the inlet velocity of the particles is low (at $u_{sup,1}$ and $u_{sup,2}$).

![Figure 5 Particle velocity affected by the velocity of liquid](image)

Figure 3 reveals that in the median concentration, the higher velocity of the liquid increases the carrier capability of the particles and reduces particle concentration, which reduces the separation efficiency of the particles by clogging. Figure 1(d) shows the calculated Stokes number for each inlet velocity of
the liquid. The Stokes number at $u_{sup,2}$ is $0.1 \sim 10$, where increasing the fluid velocity can increase the possibility of particle clogging, thereby increasing the separation efficiency. However, the Stokes number at $u_{sup,3}$ is 1 to 100. Under this condition, increasing the velocity reduces the particle concentration and eventually reduces the separation efficiency.

### 4 CONCLUSIONS

The effect of fluid velocity on the transport and retention of particles in a slurry through a homogeneous porous medium was numerically studied using the CFD-DEM. The mechanism of particle clogging due to bridging was investigated where the motion of particles driven by the liquid. The velocity of the liquid was found to affect particle clogging by varying the Stokes number and particle concentration in the porous media.

Particle clogging due to bridging was also studied based on the effect of the Stokes number. The Stokes number is related to the particle diameter, pore-throat size, and fluid velocity. The homogeneous porous media used in this study had a fixed pore-throat size. Particle clogging affected by the fluid velocity at the entrance of the porous media was also studied. Increasing the fluid velocity, when the Stokes number was 1~10, increased the particle separation efficiency. Further increasing the fluid velocity reduced the particle separation efficiency because the residence time and concentration of the particles were reduced. When the Stokes number was less than 1, the particles passed through porous media with little interaction between the particles and porous media. Particle clogging by bridging occurred when the Stokes number was greater than 1.

### Appendix A [12]

The numerical method used in this study was validated using the experimental data of one particle sedimentation in oil by Cate et al. The fluid domain was 0.1 m x 0.1 m x 0.16 m in size, and the particle was released at the height of 0.12 m from the bottom. The density and viscosity of the oil were $960$ kg/m$^3$ and $0.058$ Pa·s, respectively, and the density and diameter of the particle were $1120$ kg/m$^3$ and $15$ mm. Figure A shows the comparison of the particle location between the simulation and
experimental results. The simulation result using the fine mesh in case 3 was predicted in better agreement with the experimental data. Therefore, in this study, the mesh size in case 3 was used.

![Figure A. Numerical method validation. [12]](image)

Reference


