Existence of a Critical Particle Concentration in Plugging of a Packed Bed

Vishal B. Pandya, S. Bhuniya, and Kartic C. Khilar
Dept. of Chemical Engineering, Indian Institute of Technology, Powai, Mumbai-400 076, India

The transport of particles as particulate suspensions in porous media is an important process with a variety of industrial applications. Literature is largely associated with efforts to study the process of deep bed filtration and fines migration in porous media. Experimental and modeling studies by various authors focus on permeability reduction and the change in filter coefficients for the bed as a function of time during suspension flow (Fan et al., 1985; Herzig et al., 1970; Imdakm and Sahami, 1991; Khilar and Fogler, 1987; Mackie et al., 1987; Rege and Fogler, 1988; Sharma and Yortsos, 1987a, b, c; Vidyanathan and Tien, 1987). The effects of various parameters like particle size, grain size, ionic strength of the suspension and superficial velocity on the filter coefficient and/or permeability have been studied. The literature available on plugging and pore closure during the flow of a suspension through packed beds is, however, limited. Maroudas and Eisenklam (1965a,b) and Gruesbeck and Collins (1982) have conducted experimental studies on the effect of the particle diameter to bead diameter ratio on plugging. It is shown that the ratio of particle diameter to bead diameter has a strong effect on plugging. The concentration of the suspension is another important parameter and to the best of our knowledge, no previous work addressing this aspect has been reported.

While the particle size to bead size ratio is an important parameter, it is believed that the concentration of the suspension could play an important role in plugging particularly when the ratio of the particle size to bead size is low (say < 0.10). At a higher ratio of particle to bead size, straining occurs, while at much lower ratio, particles may not get entrapped. At intermediate values of the ratio, there may even exist a critical particle concentration (CPC) beyond which plugging may occur (Khilar et al., 1983).

In the present study, it is experimentally shown that there exists a CPC beyond which the plugging takes place during the flow of a suspension through a packed bed. CPC has been measured at different bead to particle-size ratios and flow rates. In addition, an analysis based on geometric considerations and multiparticle blocking is developed that gives a simple theoretical rationale for the concept of CPC.

Correspondence concerning this article should be addressed to K. C. Khilar.

Experimental Setup and Methods

Experimental setup

As shown in Figure 1, the experimental setup primarily consists of (1) a packed bed provided with flanges and a distributor collector arrangement to avoid channeling. A wire mesh provided just between the distributor plate and the bed supports the glass beads which form the bed packing; (2) a reciprocating type metering (dosing) pump which has a flow rate range from $0-10^{-2}/m^3 \cdot h^{-1}$ ($0-10$ L/h); (3) a U-tube manometer to measure the pressure drop across the bed; (4) a reservoir for the liquid suspension with a stirrer to prevent settling. The stirrer speed is controlled by a regulator.

The parameters, which characterize the system, are enumerated in Table 1 along with their respective range used in this study.

Experimental measurements

Critical Particle Concentration is determined in the following manner:

- Water is sent through the dry bed at the chosen flow rate and the pressure drop is noted after the flow is stabilized (steady-state pressure drop).
- Suspensions of increasingly higher concentrations are sent through the bed and the pressure drops are noted. The concentration at which the pressure drop is found to increase very rapidly is noted. In each case the effluent concentration is also measured.
- Experiments are conducted at different concentrations between the one at which plugging was found and the just lower one used to obtain a relatively more accurate estimate of the CPC.

The concentration of the suspension is measured using the Galai-Laser particle analyzer. The scanning electron microscope is used to determine the size and shape of the suspension particles as well as the glass beads. The porosity of the bed is determined by calculating the void volume for a fixed-bed volume of randomly packed glass beads. The ZetaPlus, Zeta Potential Analyzer is used to measure the zeta potential. Zeta potential of polystyrene particles in distilled water (neutral pH) is found to be low (below -10 mV).

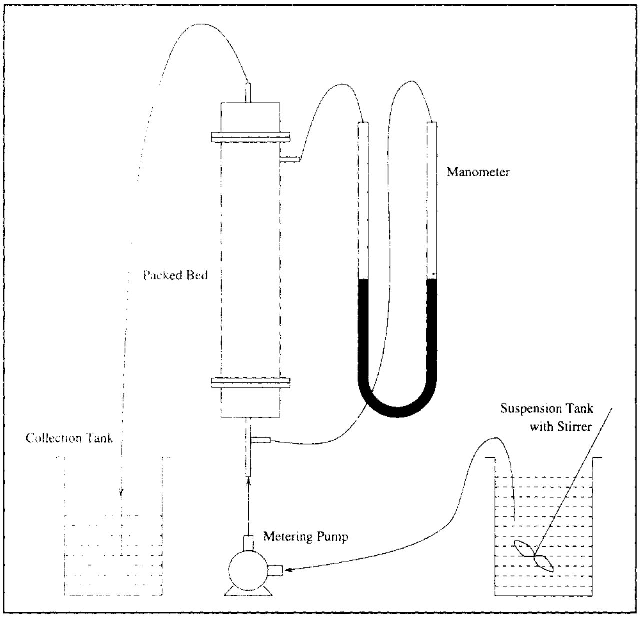

Figure 1. Experimental setup.

The reproducibility of the measurements has been checked for most of the experiments reported here. It has been found that the experiments are reproducible within an acceptable accuracy range. The pressure drops are measured with ±10% in repeat experiments.

Results and Discussion

Water flow through the bed

Water flow through the packed bed is necessary to wet and saturate the bed and also to ensure that the bed is permeable as expected. This is verified by measuring the clean bed pressure drop. It was found that within range of flow rate studied, the pressure drop virtually increased linearly with the increase in flow rate. The predictions of the Ergun equation compare well with the measurements, with the Ergun equation underpredicting by as much as 20%.

Suspension flow through the bed

Effect of Concentration. The effect of concentration on the plugging of a packed bed is typically shown in Figure 2. The plot shows the pressure drop vs. pore volumes plot for a ratio of bead diameter to particle diameter of 17.5. We observe from these plots that the pressure drop remains virtually unaltered when suspensions of concentration 0.5% v/v and 0.75% v/v are sent through the bed. At a concentration of 1% v/v, the pressure drop, however, increases steeply indicating that the bed is getting plugged during the flow. Further experiments at concentrations between 0.75% v/v and 1.0% v/v yielded a value of 0.875% v/v for CPC. In a similar manner, the CPC was determined for different values of the bead diameter to particle diameter ratio. The results are summarized in Table 2. We observe from this table that there exists a CPC for plugging during the flow of a suspension through a packed bed. Further, we observe that CPC increases with increase in the bead-size to particle-size ratio.

Table 1. Systems Parameters

Packed Bed	
Dimensions	$l = 500$ mm, $d = 50$ mm
Packing	Glass beads
Shape	Spherical
Size (mean)	0.5 mm, 1.1 mm, 1.6 mm, 3.0 mm
Distributor	53 holes, $d = 3$ mm each
Collector	$l = 30$ mm
Bed porosity (ϵ)	0.37
Suspension	
Liquid phase	Tap water
Solid phase	Polystyrene
Shape	Spherical
Size (mean)	40 μm, 63 μm
Flow rate	$0-10^{-2}$ m^3/h
Concentration	0–10% v/v

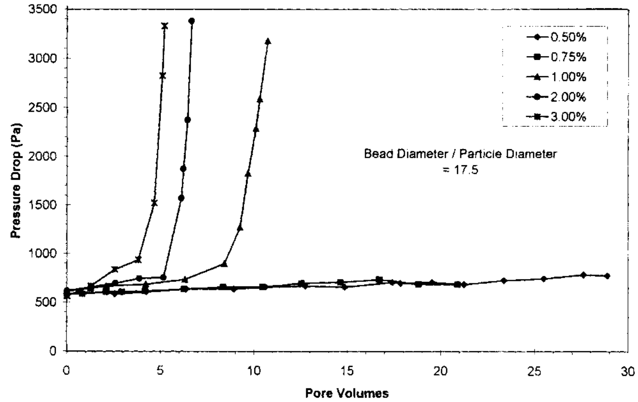

Figure 2. Effect of concentration on plugging.

$d_p = 63$ μm; $d_b = 1.1$ mm; flow rate = 9.20 lph.

To explain the observed concentration effects, we consider the following mechanism. The deposition that takes place will be the net result of two opposing tendencies-deposition due to particle capture and entrainment/detachment into the flowing suspension stream. In the case where plugging does not take place, after initial deposition, the interstitial velocity increases and there is a tendency to move towards an equilibrium where the rate of deposition is equal to the rate of entrainment. This is reflected in the outlet concentration which is found to be comparable to the inlet concentration. The small rise in pressure drop is caused by the retained particles which indicates that the particles most likely occupy cavern and other sites and do not plug the pore constriction.

As the concentration is increased, the simultaneous approach of a number of particles to a pore throat/constriction causes plugging of the constriction space. Flow is then diverted to unplugged pores with higher interstitial velocities. This multiparticle straining/convective jamming phenomenon can occur almost simultaneously at a large number of pore

Table 2. Summary of Results

d_b/d_p	Flow Rate 10^{-3} m^3/h^{-1}	CPC % v/v
12.5	7.2	**0.350**
17.5	9.2	**0.875**
27.5	7.2	**1.750**
40.0	7.2	**9.000**
75.0	7.2	> **10.000**

constriction sites and, hence, it is manifested by a rapid and drastic rise in the pressure drop. At higher bead size to particle size ratios, higher numbers of particles are required for multiparticle blocking to occur at the pore constrictions. As a result, at the concentration at which plugging occurs, CPC increases at higher bead to particle size ratios.

Effect of Flow Rate. Figure 3 shows the pressure drop vs. pore volume data at a concentration of 1% v/v for different flow rates. We observe from this figure that while there is a rapid rise in pressure drop at a flow rate of $4\times10^{-3} m^3\cdot h^{-1}$, there is, however, slow rise at the lower flow rate of $3.36\times10^{-3} m^3\cdot h^{-1}$. That is, at the lower flow rate, plugging did not occur during the flow. This observation indicates that flow rate has an effect on the multiparticle bridging/straining phenomenon at the pore constrictions. At this stage, this aspect is, however, not clearly understood and certainly needs further investigations. Nevertheless, it can be noted that the interstitial velocity is likely to affect the process of particle approach to each other as the cross-sectional area of flow reduces at the constriction and thereby affects the multiparticle bridging phenomenon.

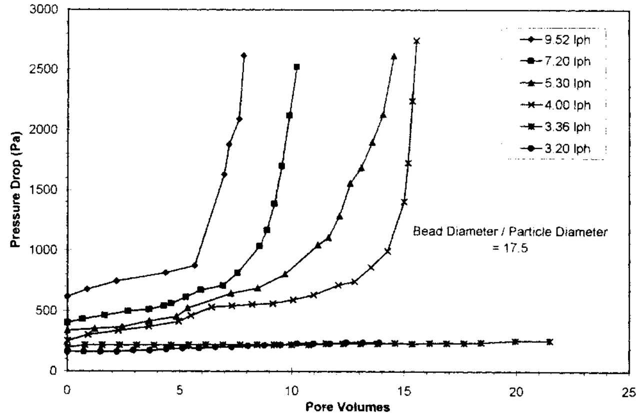

Figure 3. Effect of flow rate on plugging.
$d_p = 63\ \mu m$; $d_b = 1.1$ mm; $C = 1.0\%$ v/v.

Simple geometric model

A simple model is developed to estimate the CPC of the bed. The model is based on a two-dimensional approximation of the unit cell element of the bed, as shown in Figure 4. From geometrical considerations, the number of particles required for plugging N_p is given by

$$N_p = \frac{d_c^2(1-\epsilon)}{d_p^2} \tag{1}$$

where $d_c = d_b/6.49$ from geometry (see Figure 4). The volume fraction is assumed to be equal to the area fraction and, hence, the number of particles at any cross-section of the pore chamber is given as

$$N_{cs} = C_s\left(\frac{d_{ch}}{d_p}\right)^2 \tag{2}$$

The following assumptions are made concerning the particle motion and dispersion.

- Particles are assumed to be neutrally buoyant, uniformly dispersed and carry no electric charge.
- Particles follow streamlines and move with the local velocity of the flow.
- Particles with the same velocity reach the pore throat at the same time and, hence, the particles reaching the pore throat at the same time are assumed to be on concentric circles, as shown in Figure 4b.
- The maximum number of such particles is obtained by finding the number of particles located on the largest circle, that is, the circle closest to the pore chamber wall.

It can be noted that the implicit assumption is that the cross-section of the conduit is circular and, hence, streamlines are concentric circles at a cross-section. Using geometry, the total number of particles at a cross-section is given as

$$N_{cs} = \sum_{n=1}^{N} 2n\pi \tag{3}$$

where N is equal to $d_{ch}/2l$ and N_{cs} can be rounded to the nearest integer. The minimum distance of separation l (m)

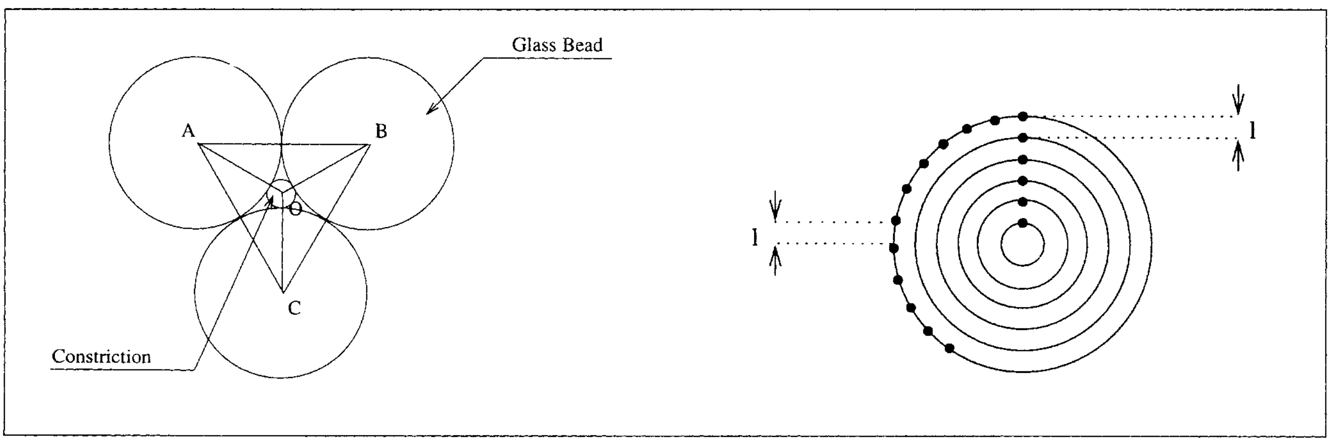

Figure 4. (a) Two-dimensional representation of a unit cell in the packed bed; (b) geometric location of particles in a circular shell.

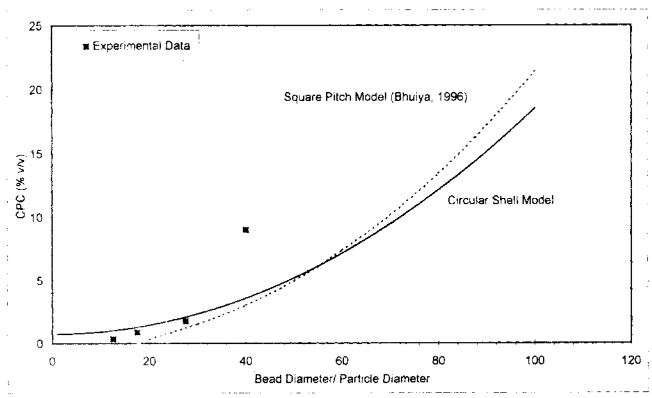

Figure 5. CPC by the simple geometric model.

required for plugging can be determined by equating the number of particles on the circle closest to the wall to the number of particles required for plugging. It is given as

$$l = \frac{\pi d_{ch}}{(1-\epsilon)} \left(\frac{d_p}{d_c} \right)^2 \tag{4}$$

The CPC is determined by substituting for l in N_{cs} and equating with Eq. 2. Calculations are conducted assuming d_{ch} equal to the bead diameter d_b(m) which is quite reasonable and fits into the simplicity of the model.

The model predictions for the CPC are shown in Figure 5. The results agree reasonably well in a qualitative manner with the experimental measurements. The results are also shown for the case where particles are kept in a square pitch of length l (Bhuniya, 1996). Both show that the CPC is strongly dependent on the bead-size to particle-size ratio. The measurements, however, show a relatively stronger dependency. It is clear that the model requires improvements for its predictions at higher bead size to particle size ratios. Attempts should be made to incorporate the effects of other parameters such as the suspension flow rate, electric charge on particles, and so on in the model.

Conclusions

Based on the experimental results obtained from this study, we conclude that there exists a CPC in the intermediate range of particle size to bead size ratio, beyond which plugging of the bed takes place. The CPC is strongly dependent on the bead size to particle size ratio. Flow rate affects the CPC, however, further work is necessary to understand its effect.

A simple geometric model based on multiparticle blocking at the pore constrictions is developed that provides a theoretical rationale for the existence of the CPC.

Notation

d_c = constriction diameter, m
d_p = particle diameter, m
d_{ch} = pore chamber diameter, m
C = volume fraction of particles in suspension
ϵ = bed porosity
ϵ_0 = initial bed porosity

Literature Cited

Bhuniya, S. B., "Flow of Suspension Through Packed Beds: Studies on the Influences of the Particle Concentration," M. Tech. Diss., ITT Bombay, Mumbai, India (1996).

Fan, L. T., R. Nassar, S. H. Hwang, and S. T. Chou, "Analysis of Deep Bed Filtration Data: Modelling as a Birth-Death Process," *AIChE J.*, **31**(11), 1781 (1985).

Gruesbeck, C., and R. E. Collins, "Entrainment and Deposition of Fine Particles in Porous Media," *SPE J.*, 847 (1982).

Herzig, J. P., D. M. Leclerc, and P. Legoff, "Flow of Suspensions through Porous Media-Application to Deep Filtration," *Ind. Eng. Chem.*, **62**(5), 8 (1970).

Imdakm, A. O., and M. Sahami, "Computer Simulation of Particle Transport in Flow Through Porous Media," *Chem. Eng. Sci.*, **46**, 1977 (1991).

Khilar, K. C., and H. S. Fogler, "Colloidally Induced Fines Migration in Porous Media," *Rev. in Chem. Eng.*, **4**(1,2), 41 (1987).

Khilar, K. C., H. S. Fogler, and J. S. Ahluwalia, "Sandstone Water Sensitivity: The Existence of a Critical Rate of Salinity Decrease," *Chem. Eng. Sci.*, **38**(5), 789 (1983).

Mackie, R. I., R. M. W. Horner, and R. J. Jarvis, "Dynamic Modelling of Deep Bed Filtration," *AIChE J.*, **33**, 1761 (1987).

Maroudas, A., and P. Eisenklam, "Clarification of Suspensions: A Study of Particle Deposition in Granular Media: I. Some Observations on Particle Deposition," *Chem. Eng. Sci.*, **20**, 867 (1965a).

Maroudas, A., and P. Eisenklam, "Clarification of Suspensions: A Study of Particle Deposition in Granular Media: II. A Theory of Clarification," *Chem. Eng. Sci.*, **20**, 875 (1965b).

Rege, S. D., and H. S. Fogler, "A Network Model for Deep Bed Filtration of Solid Particles and Emulsion Drops," *AIChE J.*, **34**(11), 1761 (1988).

Sharma, M. M., and Y. C. Yortsos, "Transport of Particulate Suspensions in Porous Media: Model Formulation," *AIChE J.*, **33**(10), 1636 (1987a).

Sharma, M. M., and Y. C. Yortsos, "A Network Model for Deep Bed Filtration Processes," *AIChE J.*, **33**(10), 1644 (1987b).

Sharma, M. M., and Y. C. Yortsos, "Fines Migration in Porous Media," *AIChE J.*, **33**(10), 1654 (1987c).

Vidyanathan, R., and C. Tien, "Hydrosol Deposition in Granular Beds," *Chem. Eng. Sci.*, **43**(2), 289 (1987).

Manuscript received June 23, 1997, and revision received Nov. 4, 1997.