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IMPLICATIONS OF PARTICLE SIZE TO TRANSIENT STAGE OF DEEP BED FILTRATION

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Abstract – This study was aimed at investigating the effect of particle size, mostly in the submicron range, on breakthrough stage of filtration. Latex beads, with diameters ranging from 0.46- to 2.967-μm were filtered through filter grains of diameters 0.1-, 0.175- and 0.45-mm. Experimental conditions were chosen so as to obtain breakthrough curves. The experimental results showed that the initial efficiency follows the pattern reported by previous experimental and theoretical studies, i.e., lower efficiency for 0.825-μm particles which fall in the range of critical size. However, the particle removal during the transient stage increased with an increase in particle size for the range of sizes studied. This pattern is qualitatively confirmed by the theoretical predictions of Vigneswaran and Chang (1986) model. This study also provides experimental verification of the effect of the ratio of particle size and grain size at different stages of filtration.

Key words : Particle Size, Submicron, Critical Size, Clean Bed Filter Efficiency, Breakthrough Stage, Transient Stage Filter Efficiency

INTRODUCTION

Deep bed filtration is affected by the design and operating parameters and the characteristics of the influent suspension. Apart from the density and chemical composition, the size of the particles also play an important role in determining the filter behaviour. Natural water contains particles of different sizes and it is understood that the particle size determines the filter efficiency in most cases. Particle size distribution is also important as the extent of removal of particles of one size can depend on the removal of particles of other sizes. However, at a fundamental level, in order to understand the behaviour of the filter under different chemical and physical conditions, it is necessary first to understand the removal of monodispersed particles.

The importance of the size of particles in suspension on clean bed filter efficiency is well established [Spielman and Goren, 1970; Yao et al., 1971]. The experimental results reported by Yao and et al. [1971] showed that apart from the design and operating parameters, particle size plays a major role on the removal of particles by a clean bed filter. They found that there exists a particle size where the clean bed removal filter efficiency is at its minimum. Later, during experiments conducted by many researchers [Habibian et al., 1975; Ghosh et al., 1975; Veerapaneni and Weisner, 1993] it was observed that this type of minimum also exists during the ripening stage of filtration. The ripening stage is the period where the removal efficiency increases with time (i.e., early stages of filtration). According to their results, it was found that the particles of around 1 μm size do exhibit the minimum removal during ripening as in the case of clean bed filtration.

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Experiments conducted using particles much larger than 1 μm [Vigneswaran and Ben Aim, 1985; Vigneswaran et al., 1990] showed that particle size also affects the filter efficiency during the breakthrough stage (where the particle removal efficiency deteriorates with time). They found that during the experiments with larger particles, breakthrough is achieved more quickly than with particles of smaller sizes. Natural water contains a large number of submicron particles and it is also important to study the effect of particles with submicron size range during transient stage (especially during breakthrough stage) of filtration. There is no literature available which documents the experimental results towards this end. This information is important because if the size of particles in the submicron range does have an effect on the transient stage of filtration, the design of the filtration system could be modified in order to accommodate the beneficial or the disadvantageous effect of particles of all sizes.

In the present research, polystyrene latex beads of sizes below and a little above a micron were chosen. Experiments were conducted with different sizes of filter grains in order to study the variation of filter performance under varying sizes of particles and filter grains. The chemical conditions in the system are chosen properly to obtain breakthrough curves. The experimental results represented by concentration profiles are discussed in this paper, in order to qualitatively and semi-quantitatively explain the effect of submicron size particles on the transient stage filter efficiency.

EXPERIMENTAL

In order to study the effect of particle size on filtration, under unfavourable conditions, three different sizes of unmodified polystyrene latex particles were chosen, i.e., 0.46 μm, 0.825

μm and 2.967 μm. The sizes were chosen so as to include particle transport by Brownian diffusion (submicron particles), interception and sedimentation (above micron size particles) and to investigate their effect on particle removal during the entire cycle of filtration. Filtration experiments were conducted for three different sizes of filter grains, i.e., 0.1 mm, 0.175 mm and 0.45 mm. These experiments were carried out in order to observe the variations in filter performance at different filter grain sizes.

A perspex column of 25 cm length was employed for the experiments. Glass beads were packed in the column to a height of 9 cm. Monodispersed latex suspension was chemically conditioned with 10^{-3} M KCl solution. The suspension of 10 mg/L was fed continuously to the filter column. Under this condition, both the latex particles and filter grains possess negative charges and aggregation of latex particles was not observed. The zeta potential of the particles varied from −6 mV to −10 mV while that of filter grains varied from −24 mV to −26 mV. Filtration was carried out from 120 to 160 minutes depending on the breakthrough curves. Effluent samples were collected at regular intervals and the turbidity was measured. The turbidity gives a direct measure of the particle concentration of the latex suspension used in this study. Headloss development was monitored using piezometric tubes. Table 1 summarizes the experimental conditions.

Table 1. Experimental parameters

Length of the bed, cm	9
Filter medium	Glass beads
Mean diameters of filter grains, d_c, mm	0.1, 0.175 and 0.45
Porosity of the filter bed	0.38, 0.39 and 0.4
Filter velocity, v, m/h	5
Filter run time, min	160
Particles used	Unmodified polystyrene latex beads
Particle sizes used, d_p, μm	0.46, 0.825 and 2.967
Influent particle concentration, mg/L	10
Electrolyte; concentration, mM	KCl; 10^{-3}

THEORY

O'Melia and Ali [1978] describe ripening stage of filtration and emphasize that the increased removal of particles in the ripening stage is mainly due to particle-particle attachment. Vigneswaran and Chang [1986] model, which describes the entire cycle of filtration is an extension of O'Melia and Ali [1978] model. This model takes account of the breakthrough stage.

1. Clean Bed Filter Efficiency

The relationship between the performance of a clean bed filter and the efficiency of a filter grain (collector) is given by:

$$\frac{dn}{dL}=-\frac{3}{2}\frac{(1-f_o)}{d_c}\alpha\eta n. \quad (1)$$

Integration of the above equation yields the following:

$$\ln\frac{n}{n_o}=-\frac{3}{2}(1-f_o)\alpha\eta\left(\frac{L}{d_c}\right). \quad (2)$$

2. Transient Stage Filter Efficiency

The filter efficiency during the transient stage is modified due to the capture of particles by the already retained particles which act as particle collectors. In Vigneswaran and Chang [1986] model, the decrease in filter efficiency during the post ripening period (or breakthrough period) is assumed to be caused by the hydraulic gradient and number of particles already retained on filter grain [Adin and Rehbun, 1977]. Therefore, the particle removal efficiency of a collector (is the sum of the efficiency of a filter grain and also the efficiency of the particles associated to the filter grain which act as additional particle collectors), η_r, can be written as:

$$\eta_{ri}v\frac{\pi}{4}d_c^2n=\eta\alpha vn\frac{\pi}{4}d_c^2+N\eta_p\alpha_p vn\frac{\pi}{4}d_p^2-\beta_2 J_{i-1}v\frac{\pi}{4}d_c^2\sum_{i=1}^{i}(\eta_r n)_{i-1} \quad (3)$$

Simplifying the above equation, one obtains:

$$\eta_{ri}=\eta\alpha+N\eta_p\alpha_p\left(\frac{d_p}{d_c}\right)^2-\beta_2\frac{J_{i-1}}{n_o}\sum_{i=1}^{i}(\eta_r n)_{i-1}. \quad (4)$$

The rate of change of the number of particle collectors, N, is calculated by assuming that a fraction (β) of the particles retained on the filter grain acts as particle collectors. This can be represented mathematically by the following equation:

$$\frac{\partial N}{\partial t}=\beta\eta\alpha nvd_c^2\frac{\pi}{4} \quad (5)$$

Here n is the influent concentration at depth L and time t and $\partial N/\partial t$ is the rate of change of the number of particle collectors.

The mass balance for a small element of the filter bed yields the following equation [O'Melia and Ali, 1978]:

$$\frac{\partial n}{\partial t}+v\frac{\partial n}{\partial L}+\frac{3}{2}\left(\frac{1-f_o}{d_c}\right)vn\eta_r=0 \quad (6)$$

Combining Eq. (4), (5) and (6) and considering n and n_r as step functions, one can obtain the following equation for the efficiency at the ith time step:

$$\eta_{ri}=\eta\alpha\left[1+\beta\eta_p\alpha_p v\frac{\pi}{4}d_p^2\left(\sum n_o\,\Delta t\exp\left\{-\frac{3}{2}(1-f_o)\eta_{ri-1}\frac{\Delta L}{d_c}\right\}\right)\right]-\beta_2\frac{J_{i-1}}{n_o}\sum_{i=1}^{i-1}(\eta_r n)_i \quad (7)$$

The headloss formulation was developed from Kozeny's equation for a clean filter. O'Melia and Ali [1978] in their formulation of the headloss profile equation, considered the increase in specific surface of the collector with time by the retention of particles. In this model, the decrease in porosity with filtration time and the porosity of deposit, (ε_d), were also taken into account [Eq. (8) and (9)].

$$f=1-\left[\frac{\pi\left(N_c d_c^3+\frac{N_p d_p^3}{1-\varepsilon_d}\right)}{6A\Delta L}\right]. \quad (8)$$

Shape factors of deposited particles (S_1) and filter sand (S_2) were introduced into the headloss equation. The final equation for headloss can, therefore, be written as:

$$\frac{hf}{L}=36K\frac{\mu}{\rho}\frac{v}{g}\frac{(1-f)^2}{f^3}\frac{1}{d_c^2}\left(\frac{S_2}{6}\right)^2\left[\frac{1+\beta'\left(\frac{N_p}{N_c}\right)\left(\frac{d_p}{d_c}\right)^2\left(\frac{S_2}{S_1}\right)^2}{1+\left(\frac{N_p}{N_c}\right)\left(\frac{d_p}{d_c}\right)^3\left(\frac{S_2}{S_1}\right)^3}\right]^2 \tag{9}$$

Details of the model are given elsewhere [Vigneswaran and Chang, 1986].

3. Significance of Model Parameters

The important model parameters are $\eta\alpha$, $\alpha_p\beta$, β_2 and β'.

The parameter $\eta\alpha$ denotes the clean bed filter efficiency. Higher the value of $\eta\alpha$, better is the removal efficiency at time=0. The parameter $\alpha_p\beta$ represents the attachment coefficient during the ripening period. Higher the value of $\alpha_p\beta$, greater is the improvement in the removal efficiency during the initial stages of filtration. The parameter β_2 represents the detachment coefficient during the breakthrough stage and β' is the headloss coefficient.

4. Model Parameter Estimation

The value for $\eta\alpha$ was calculated using the experimental C_e/C_o values of the clean bed filter using Eq. (2). Here, C_e is the effluent concentration at t=0 and C_o is the influent concentration, both expressed in terms of mg/L. The suitable range of the remaining parameters, $\alpha_p\beta$, β_2 and β', were initially estimated through least square fitting of the experimental n/n_o and the headloss profiles. As there was no significant difference in the values of $\alpha_p\beta$ and β', for reasons described in the following section, their values were fixed and the values of β_2 were re-estimated once again using least square fitting. The details of this procedure are given elsewhere [Dharmappa, 1991; Vigneswaran and Chang, 1989].

RESULTS AND DISCUSSION

The results obtained showed that the performance varied during both the initial and transient stages of filtration depending on the particle size (d_p) and filter grain size (d_c). In the following section, the results are discussed in terms of clean bed filter efficiency and transient stage filter efficiency, respectively.

1. Clean Bed Filter Efficiency

Clean bed filter efficiency was calculated using Eq. (2). In all the experiments, the concentration of particles was measured in terms of mass per volume (mg/L) and thus the fraction of particles escaping the filter is depicted in terms of C_e/C_o. The performance of the clean bed filter performance in terms of initial C_e/C_o and $\eta\alpha$ for various particle sizes are presented in Table 2.

In order to compare the theoretical and experimental removal efficiencies by a clean bed, the theoretical collector efficiency, η was first estimated using Rajagoplan and Tien [1976] model

Table 2. Variation of initial filter efficiency during filtration of different sizes of latex particles

Filter grain size, d_c, mm	Particle size, d_p, μm	d_p/d_c	Initial C_e/C_o*	$\alpha\eta$
0.100	0.460	0.00460	0.026	0.00436
	0.825	0.00830	0.040	0.00390
	2.967	0.02970	0.011	0.00470
0.175	0.460	0.02600	0.067	0.00574
	0.825	0.00470	0.074	0.00553
	2.967	0.01700	0.053	0.00712
0.450	0.460	0.00100	0.399	0.00510
	0.825	0.00180	0.518	0.00365
	2.967	0.00660	0.487	0.00400

Note: *C_o and C_e are the influent and effluent concentrations of particles.

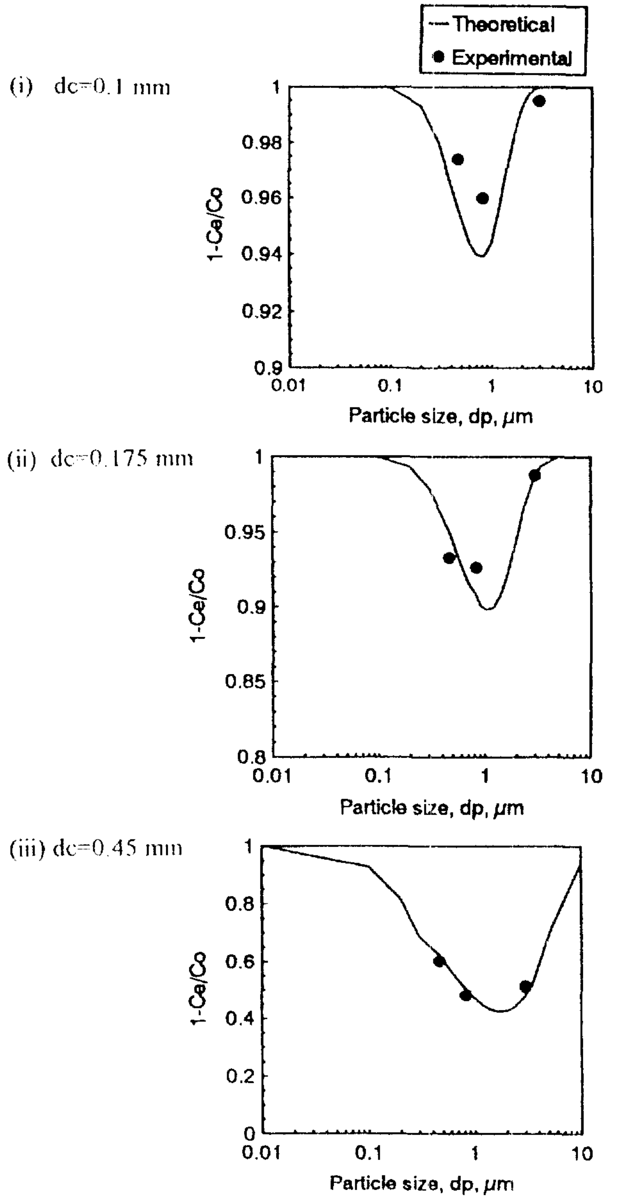

Fig. 1. Variation of the fraction of particles retained at time=0 with particle size for experiments with monodispersed latex suspensions.

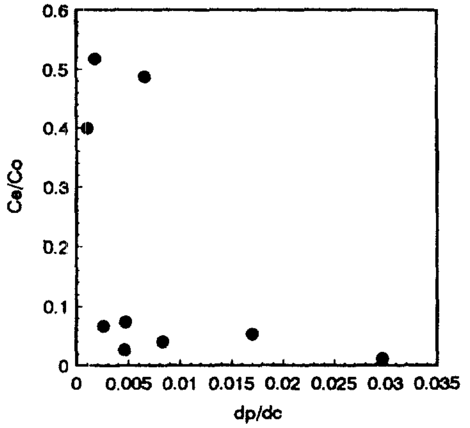

Fig. 2. Variation of initial C_e/C_o with d_p/d_c for filtration of latex particles.

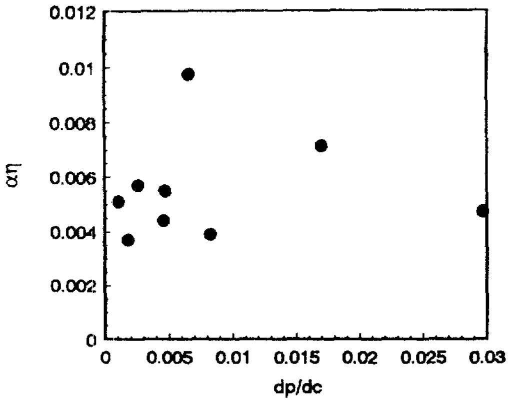

Fig. 3. Effect of d_p/d_c ratio on initial filter efficiency.

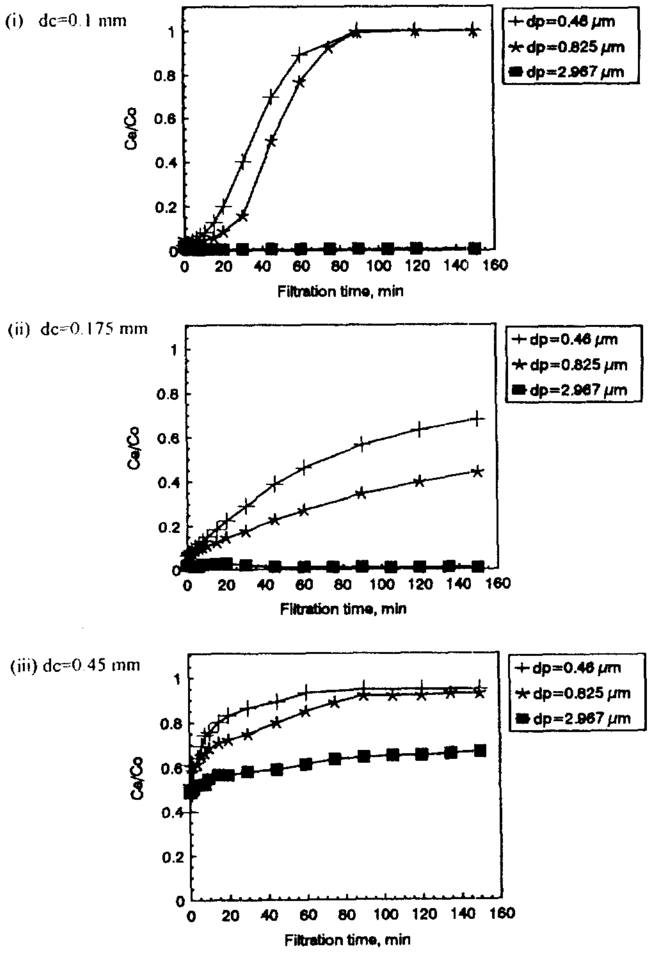

Fig. 4. Influence of particle size on filtration of latex particles: Experimental concentration profiles (C_o=10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH=3).

and α was estimated by fitting theoretical and experimental efficiencies (η and ηα, respectively). From these η and α values, the theoretical C_e/C_o values were calculated using Eq. (2). The theoretical and experimental values of the fraction of particles retained by the bed $(1-C_e/C_o)$ are presented in Fig. 1. The results presented in Table 2 and Fig. 1 show that the particles of 0.825-μm size are removed to a much lesser extent than either 0.46 μm or 2.967 μm particles. The enhanced removal for 2.967 μm particles is due to the dominant transport mechanisms, i.e., gravity and interception. On the other hand diffusion is the dominant mechanism for 0.46-μm particles. For particles of 0.825 μm (nearer to 1 μm in diameter), contacts between particles and the filter medium by interception, gravity and diffusion are minimal. The same trend was observed for all three filter media used. These results support the findings of the previous studies on clean bed particle removal, i.e., there exists a minimum removal for particles of around 1 μm size [Yao et al., 1971; Habibian and O'Melia, 1975; Veerapaneni and Wiesner, 1993; Tobiason et al., 1993].

The results obtained in this study also allowed to investigate the effect of d_p/d_c ratio on filtration. For the experiments conducted for various sizes of particles and filter grains, the d_p/d_c ratio varied from 0.001 to 0.0297 as shown in Table 2. Figs. 2 and 3 present the variation of initial C_e/C_o and ηα as a function of d_p/d_c ratio. From Fig. 2 it is evident that as d_p/d_c ratio increases the initial C_e/C_o decreases, which indicates that higher clean bed efficiency can be obtained at higher d_p/d_c ratio. However, Fig. 3 shows that there is no definite relationship between the initial efficiency, ηα and d_p/d_c.

2. Transient Stage Filter Efficiency

The temporal variation of C_e/C_o for different particle sizes are presented in Fig. 4. This figure presents the results of the experiments conducted for three different sizes of filter grains: 0.1 mm, 0.175 mm and 0.45 mm. It is evident from Table 2 that for smaller particles (0.46-μm), though the initial removal is higher, the transient stage filter efficiency, as illustrated in Fig. 4, deteriorates at a rapid rate than that for 0.825 μm size particles. For larger particles (both 0.825 μm and 2.967 μm), the deterioration rate of filter efficiency was slower (Fig. 5). This behaviour can easily be visualised by comparing the time taken for breakthrough and the C_e/C_o values at that time (Table 3). These values were directly obtained from Fig. 4. Here, the beginning of breakthrough period is defined as the point where the quality of the effluent declines steeply over a short period of time. As can be observed from Table 3, for experiments with 0.1 mm and 0.175 mm filter grains, breakthrough began as early as 15 min for particles of size 0.46 μm and 30 min for particles of size 0.825 μm (i.e., the time taken for breakthrough

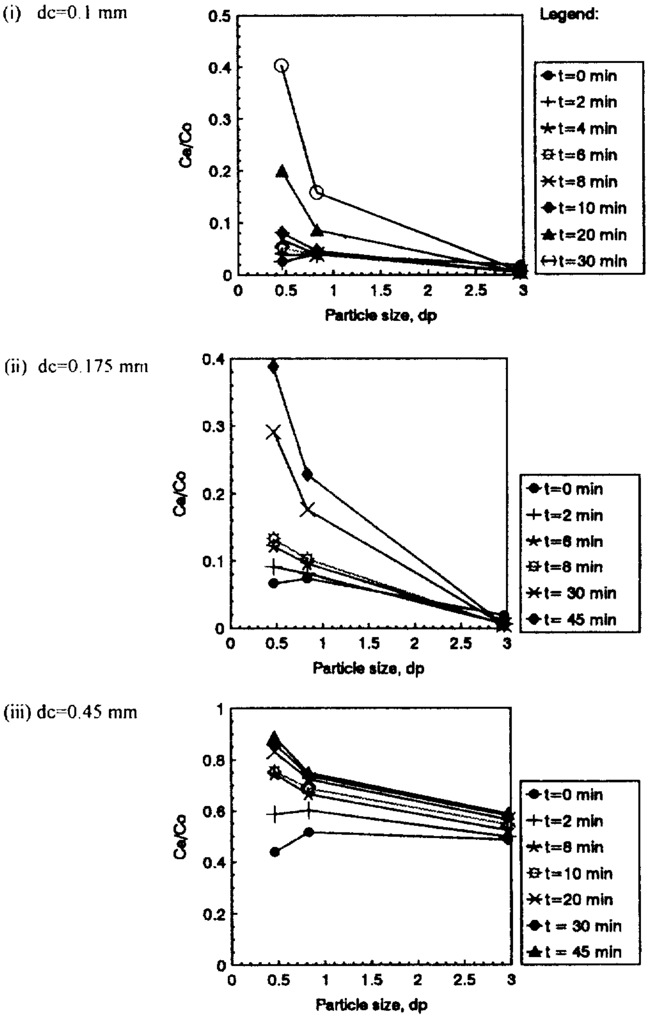

Fig. 5. Variation of C_e/C_o with particle size at different filtration times (C_o=10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH =3).

Table 3. Variation of C_e/C_o depicting breakthrough with time

Filter grain size, d_c, mm	Particle size, d_p, μm	Breakthrough point* Time, min	C_e/C_o
0.100	0.460	15	0.159
	0.825	30	0.098
	2.967	150	Ripening still continued
0.175	0.460	15	0.185
	0.825	30	0.176
	2.967	150	Ripening still continued
0.450	0.460	6	0.696
	0.825	8	0.688
	2.967	2	0.316

*Breakthrough point is when the effluent quality declines steeply

was as follows: 0.46 μm>0.825 μm). For particles of size 2.967 μm, the working stage, i.e., where the removal efficiency remains almost constant, still continued even at the end of the experiments with 0.1- and 0.175-mm filter grains. When 2.967 μm particles were filtered through filter grains of size 0.45 mm, although an early breakthrough was observed (Table 3), the transient stage removal efficiency was much superior compared to

Table 4. The $(C_e/C_o)_{time\text{-}av}$ values at the end of 150 min of filtration, depicting the transient stage removal efficiency

Filter grain size, d_c, mm	Particle size, d_p, μm	$(C_e/C_o)_{time\text{-}av}$ (at the end of 150 min)
0.100	0.460	0.7890
	0.825	0.7070
	2.967	0.0067
0.175	0.460	0.4660
	0.825	0.2904
	2.967	0.0185
0.450	0.460	0.9007
	0.825	0.8940
	2.967	0.6091

Table 5. Comparison of mass and number concentrations for different particles

Particle size, d_p, m	Influent particle concentration, C_o Mass, mg/L	No. of particles /cm^3	Surface area, cm^2/cm^3
0.460	10	1.9×10^{8}	6.65×10^{-9}
0.825	10	3.2×10^{7}	2.14×10^{-8}
2.967	10	6.9×10^{5}	2.77×10^{-7}

that of other two sizes of particles (Fig. 4).

The transient stage removal efficiency was also compared with the time averaged C_e/C_o [$(C_e/C_o)_{time\text{-}av}$] values obtained at the end of 150 min of filtration for each experiment. The $(C_e/C_o)_{time\text{-}av}$ values were calculated as follows:

$$\left(\frac{C_e}{C_o}\right)_{time-av} = \frac{(C_e)_{av}}{C_o} \tag{10}$$

$$(C_e)_{av} = \frac{\left[\sum_{i=1}^{n}\left(\frac{C_i + C_{i+1}}{2}\right)(t_{i+1} - t_i)\right]}{t_x - t_1} \tag{11}$$

Table 4 presents the time averaged values of C_e/C_o for all sizes of particles and filter grains. From this table it is evident that the $(C_e/C_o)_{time\text{-}av}$ values, at the end of the experiment are smaller for larger particles. This analysis shows that the particle retention during the filter run increases with an increase in particle size, irrespective of the particle size range.

The smaller particles (0.46 μm), due to their inherent nature of being submicron particles and being transported by Brownian motion, yield higher clean bed filter efficiency (ηα) compared to 0.825 μm particles as was observed from Table 2 and Fig. 1. Due to this high initial removal, the filter grains become quickly saturated with the particles, leading to reduced removal for particles later approaching the filter grains. Thus for small particles, the transient stage removal efficiency deteriorates faster as the filtration proceeds. For particles of 0.825 μm, since the filter grains are not completely saturated initially, further contact between particles and filter grains is more possible compared to the smaller particles.

Also, while the mass concentration is constant, the particle number concentration for smaller particles is higher than that

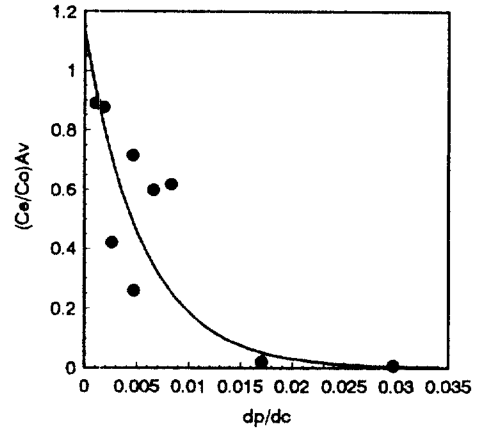

Fig. 6. Effect of d_p/d_c ratio on time averaged C_e/C_o after a filtration period of 120 min.

Table 6. Model parameters for studying the effect of particle size

d_c, mm	d_p, µm	$\alpha\eta$	$\alpha_p\beta$	β_2	β'
0.1	0.460	0.0044	0.0001	0.0059	0.00001
	0.825	0.0039	0.0001	0.004	0.00001
	2.967	0.0063	0.0001	0.0001	0.00001
0.175	0.460	0.0057	0.007	0.0075	0.2
	0.825	0.0055	0.007	0.00275	0.2
	2.967	0.0094	0.007	0.00003	0.2
0.45	0.460	0.0051	0.01	0.4609	0.06
	0.825	0.0037	0.01	0.123	0.06
	2.967	0.0040	0.01	0.016	0.06

for larger particles (Table 5). The reason for the delay in saturation of larger particles (0.825 µm and 2.967 µm) could also be that the number of particles entering the bed are fewer compared to the suspension with smaller particles. This leads to a gradual and slow rate of saturation for larger particles, thus allowing for delayed breakthrough.

For particles of size 2.967 µm, though the initial removal was very high, the number of particles or the surface area of the particles attached to the filter grains was much lower compared to that of submicron particles. In addition, the d_p/d_c ratio for these particles varied from 0.066 to 0.03 for the given conditions of filter grain sizes (Table 2). At such a higher d_p/d_c ratio, the mechanism of interception was predominant, thus a large number of particles were deposited.

Fig. 6 presents the $(C_e/C_o)_{time-av}$ values with d_p/d_c ratio after 150 min of filtration. This figure shows that the time averaged effluent concentration decreases with an increase in d_p/d_c ratio. This indicates that the transient stage filter efficiency is higher for higher d_p/d_c ratios.

3. Filter Behaviour According to Vigneswaran and Chang [1986] Model

The model, describing the entire cycle of filtration, was used in an attempt to quantify the filter behaviour. The model parameters calculated using the experimental concentration and headloss profiles are presented in Table 6.

Figs. 7, 8 and 9 depict the removal efficiencies and headloss developed for different sizes of particles with filter grains of 0.1 mm, 0.175 mm and 0.45 mm, respectively. As can be seen from the figures, the different stages of filtration are predicted fairly well by the model. For most of the experiments since no ripening was observed, a constant value of $\alpha_p\beta$ was used after a preliminary calibration. The model parameter, β_2 which varies with filter efficiency during breakthrough stage is more significant in this present study. It can be observed from Table 6 that for a given filter grain size, β_2 reduces as the particle size increases. The lower the β_2 value, the less steeper the breakthrough curve and better the filter removal efficiency.

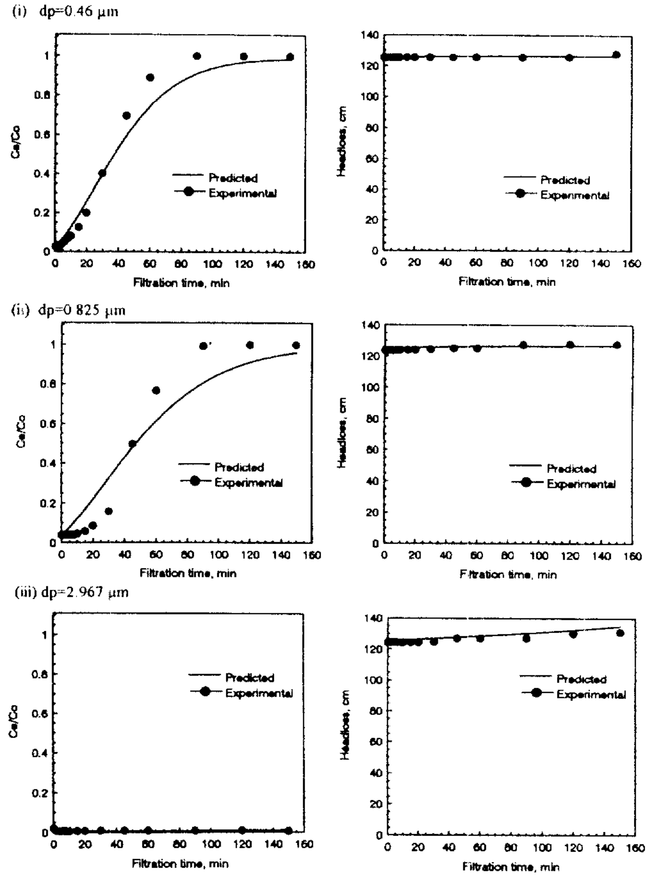

Fig. 7. Experimental and model profiles of concentration and headloss for different sizes of particles (d_c=0.1 mm, C_o=10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH=3).

All the above experimental observations and discussions reveal that the filter efficiency during the transient stage is dependent on the particle size and it increases with an increase in particle size for the size range investigated in this study (0.46- to 2.967-µm). This can be better understood by comparing the theoretical and experimental particle removals at different time intervals. As an example, filtration with 0.1-mm filter grains are considered. Using Vigneswaran and Chang [1986] model and the model parameters as listed in Table 6, theoretical simulations were carried out for particles of sizes ranging from 0.3- to 10-µm. The value of β_2 in these simulations was estimated using the following equation:

$$\beta_2 = 0.1399 \times 10^{-1}\, e^{-1.66\, dp} \tag{13}$$

This equation was derived by fitting an exponential equation

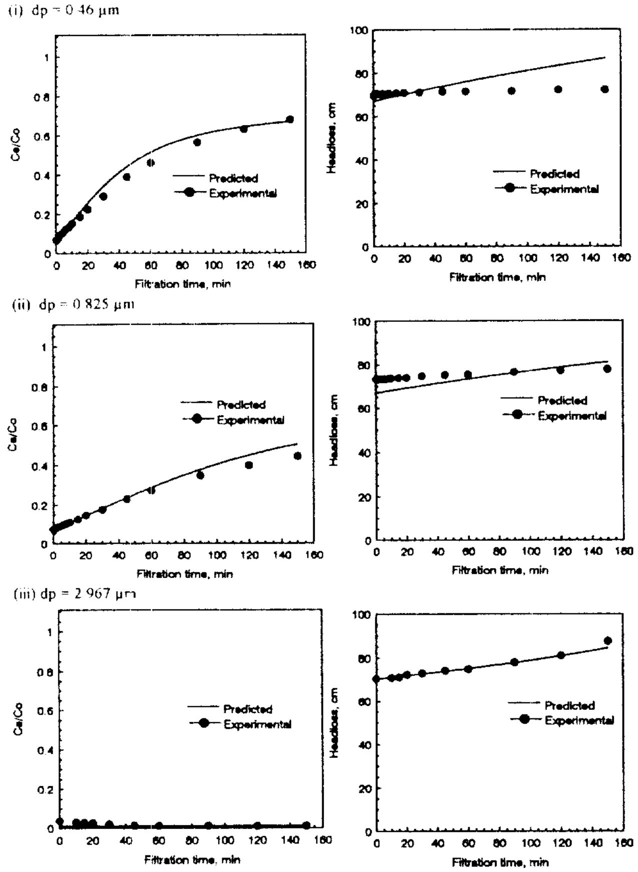

Fig. 8. Experimental and model profiles of concentration and headloss for different sizes of particles (d_c=0.175 mm, C_o= 10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH=3).

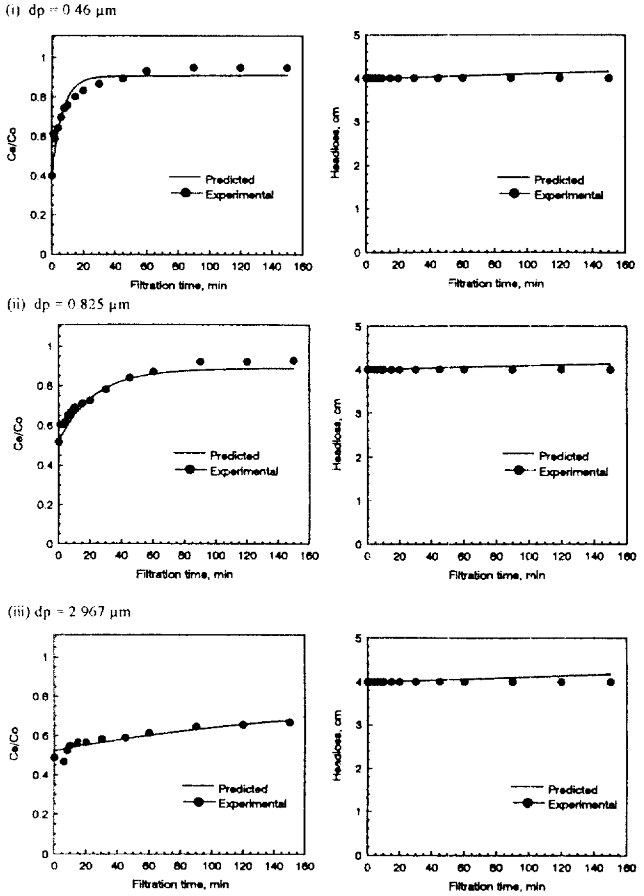

Fig. 9. Experimental and model profiles of concentration and headloss for different sizes of particles (d_c=0.175 mm, C_o= 10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH=3).

to the data presented in Table 6. For the simulation, all the influent characteristics were taken similar to those used in the experimental study.

The theoretical and experimental data of the fraction of particles removed at different time intervals are plotted against the particle size in Fig. 9. From this figure it is evident that the transient stage filtration increases with an increase in particle size. As indicated in Fig. 9, the minimum efficiency for 0.825-μm particles at initial stage (t=0) is overridden as filtration proceeds. And when filtration continues up to 150 min, no minimum efficiency exists for the range of particle's size studied.

The overall removal efficiency in these experiments was not very high and as such, the headloss difference for particles of different sizes was not significant (Figs. 6, 7 and 8). The model parameter β', describing the headloss development, remained constant for the experiments for the same size of filter grains.

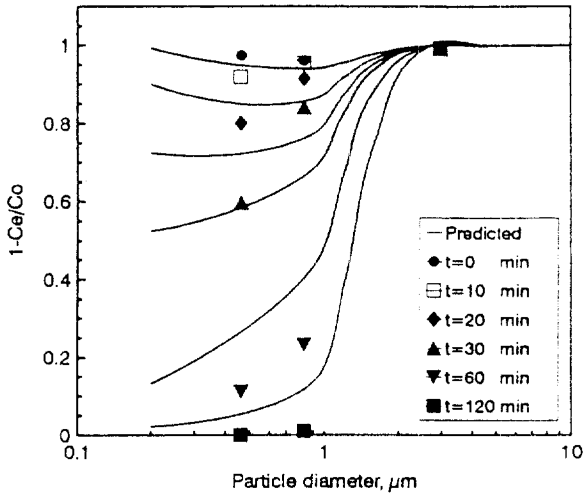

Fig. 10. Variation of particle removals at different times depicting the effect of particle size on transient stage of filtration (d_c=0.1 mm, C_o=10 mg/L, L=9 cm, v=5 m/h, KCl=0.001 M, pH=3).

CONCLUSION

From the results of the experiments conducted to study the effect of particle size on filtration, it is concluded that the particle size (varying from 0.46 μm to 2.967 μm) does have an effect both on the clean bed and transient stage filtration. This effect relates not only to the early stages of filtration but also to the stages during and after breakthrough. During early stages, the filter performance shows a minimum at the critical size, i.e., particles of size 0.825-μm (of around 1 μm) exhibited minimum efficiency. But the filter efficiency during and after breakthrough stages does not follow the same trend. The efficiency improves with an increase in particle size, irrespective of the range of particle size. It was observed that there exists no critical size and the filter removal efficiency increases with particle size (i.e., 0.46 μm<0.825 μm<2.967 μm), thus yielding longer filter runs for larger size particles.

Some evidence on the effect of d_p/d_c ratio on filtration was also obtained. It was found that though the initial efficiency ($\eta\alpha$) does not follow any particular trend for lower d_p/d_c values, it increases when d_p/d_c ratio was higher than 0.017 under present experimental conditions. The increase in transient stage filter efficiency with an increase in d_p/d_c ratio was more significant than that of initial efficiency as indicated by the time averaged C_e/C_o values after a filtration period of 150 min.

This study provides ample evidence of the effect of particles in the submicron size range, on the entire cycle of filtration and would help to formulate new concepts to improve existing models. Based on this study for monodispersed suspensions, further experimental investigations for polydispersed suspensions of submicron and above micron size particles have to be carried out to understand the performance of the filter during breakthrough stage.

NOMENCLATURE

- A : cross sectional area of the filter bed $[L^2]$
- C_e : effluent concentration $[M/L^{-3}]$
- $(C_e)_{av}$: time averaged effluent concentration $[M/L^{-3}]$
- C_i : effluent concentration at time t_i $[M/L^{-3}]$
- d_c : diameter of the filter grain [L]
- d_p : diameter of the suspended particle [L]
- f_o : porosity of the clean filter bed
- f : porosity of the filter bed at any given time t
- g : acceleration due to gravity $[LT^{-2}]$
- hf : headloss through a clogged bed [L]
- J : hydraulic gradient
- K : Kozeny's constant
- L : depth of the filter bed [L]
- ΔL : filter increment in filter depth [L]
- n : number concentration of particles in the effluent at a given time and depth $[L^{-3}]$
- N : number of retained particles on the filter grain that can act as collectors
- N_c : total number of filter grains retained in the depth ΔL of filter bed
- n_o : initial number concentration of particles $[L^{-3}]$
- N_p : total number of particles retained in depth ΔL of the filter bed
- S_1 : shape factor of particles
- S_2 : shape factor of filter grains
- t : filtration time [T]
- t_i : starting time at ith time step [T]
- Δt : increment in time interval [T]
- v : filtration velocity $[LT^{-1}]$
- x : the last time step considered
- α : particle-to-filter grain attachment coefficient
- α_p : particle-to-particle attachment coefficient
- η : single collector efficiency of a clean collector
- η_p : contact efficiency of a retained particle
- η_r : single collector removal efficiency of a filter
- η_{ri} : single collector removal efficiency at ith time step
- μ : viscosity of suspension $[ML^{-1}T^{-1}]$
- β : coefficient that represents the fraction of retained particles that contribute to the additional surface area
- β' : headloss coefficient
- β_2 : detachment coefficient
- ρ : density of fluid $[ML^{-3}]$
- ε_d : porosity of deposit

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