Water and Waste Water Filtration: Concepts and Applications

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■ A conceptual model for water and waste water filtration processes is presented and compared with the results of laboratory experiments. Efficient filtration involves both particle destabilization and particle transport. Destabilization in filtration is similar to destabilization in coagulation; effective coagulants are observed to be effective "filter aids." Particle transport in filtration is analogous to transport in flocculation processes. A particle size with a minimum contact opportunity exists; smaller particles are transported by diffusion while larger particles are transported by interception and settling. Applications of these concepts to water and waste water filtration are presented.

This paper is written with three objectives. First, mechanisms for coagulation and filtration processes are presented as analogous; similarities between these processes are particularly helpful in understanding filtration processes and in assessing their capabilities. Second, a theoretical or conceptual model of water and waste water filtration processes is set forth; the results of experiments designed to test this model are presented and discussed. Third, conclusions are reached concerning the capabilities of filters for removing pollutants in water and waste water treatment; suggestions are made for the design and operation of filters which accomplish this removal.

Coagulation and Filtration Processes. The overall rate of aggregation in a coagulation process is frequently evaluated by determining the rate at which collisions occur between particles by fluid motion (orthokinetic flocculation) and by Brownian diffusion (perikinetic flocculation), multiplied by a "collision efficiency factor" which reflects the ability of chemical coagulants to destabilize colloidal particles and thereby permits attachment when contacts occur (e.g., Swift and Friedlander, 1964; Birkner and Morgan, 1968; Hahn and Stumm, 1968). A similar approach is used herein to describe filtration processes. The removal of suspended particles within a filter is considered to involve at least two separate and distinct steps: First, the transport of suspended particles to the immediate vicinity of the solid–liquid interface presented by the filter (i.e., to a grain of the media or to another particle previously retained in the bed); and second, the attachment of particles to this surface (O'Melia, 1965; Ives and Gregory, 1967).

Viewed in this perspective, filtration and coagulation processes are quite similar. In both processes, the particles to be removed must be made "sticky" or, more formally, destabilized. The considerable research on colloid destabilization mechanisms during the last few decades can be used to understand these chemical aspects of filtration. In both processes, suspended particles must be transported so that contacts may be achieved. In coagulation, the transport models of Smoluckowski (1917) are used. These models predict that in water the transport of particles larger than about 1μ is accomplished by velocity gradients or fluid motion; for smaller particles, Brownian diffusion is effective. In water filtration, transport models are being derived which are based on models developed by investigators in air filtration (e.g., Friedlander, 1958). One such model is presented in this paper; others have been presented by Spielman and Goren (1970) and Cookson (1970). These models predict that suspended particles larger than about 1 μ are transported to the filter media by settling and interception; smaller particles are again effectively transported by Brownian diffusion.

Transport Model. Let us begin by considering a single spherical particle of the filter media. Assume that it is unaffected by its neighbors and is fixed in space in the flowing suspension (Figure 1). This single particle of filter media is a *collector*, emphasizing that the ultimate purpose of transporting suspended particles from the bulk flow to the external surfaces of media grains in packed beds is the collection of these particles, thereby accomplishing their removal from the water. The main flow direction is that of the gravitational force. A suspended particle following a streamline of the flow may come in contact with the collector by virtue of its own size (case A in Figure 1); this transport process is *interception*. If the density of the suspended particle is greater than that of water, the particle will follow a different trajectory due to the influence of the gravitational force field (case B). The path of the particle is influenced by the combined effects of the buoyant weight of the particle and the fluid drag on the particle. This transport process is *sedimentation*. Finally, a particle in suspension is subject to random bombardment by molecules of the suspending medium, resulting in the well-known Brownian movement of the particle. The term

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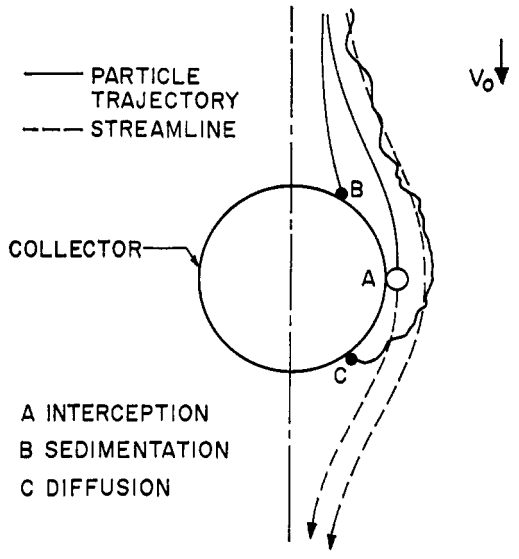

Figure 1. Basic transport mechanisms in water filtration

diffusion is used to describe mass transport by this process (case C).

The general equation describing the temporal and spatial variation of particle concentration in such a system may be written as follows:

$$\frac{\partial C}{\partial t} + v \cdot \nabla C = D_{bm}\nabla^2 C + \left(1 - \frac{\rho}{\rho_p}\right)\frac{mg}{3\pi\mu d_p}\frac{\partial C}{\partial z} \qquad (1)$$

where C is the local concentration of suspended particles, v is the local velocity of the water, t is the time, D_{bm} is the diffusion coefficient of the suspended particles, ρ and ρ_p are the densities of the water and the suspended particles, respectively, μ is the water viscosity, m and d_p are the mass and diameter of the suspended particles, respectively, g is the gravitational acceleration, and z is the coordinate in the direction of the gravitational force. Equation 1 is derived from a mass balance of C about an elemental volume of suspension. The first term on the left-hand side of the equation ($\partial C/\partial t$) represents the temporal variation of C at any point with coordinates x, y, and z; the second term ($v \cdot \nabla C$) describes the effects of advection on the concentration at that point. On the right-hand side of Equation 1, the first term ($D_{bm}\nabla^2 C$) describes the effects of diffusion, and the second term characterizes the effects of gravitational settling on the system. The influence of interception is included in the boundary conditions used in integrating the equation. The form of Equation 1 has been widely used by engineers to describe the fate of pollutants in the atmosphere and in streams and estuaries, and has been applied to air and water filtration processes. Equation 1 cannot be solved analytically; numerical procedures and (or) simplifying assumptions may be used.

THE SINGLE-COLLECTOR EFFICIENCY. The contact efficiency of a single media particle or collector (η) is a ratio—i.e., the rate at which particles strike the collector divided by the rate at which particles flow toward the collector, as follows:

$$\eta = \frac{\text{rate at which particles strike the collector}}{v_o C_o \left(\frac{\pi d^2}{4}\right)} \qquad (2)$$

Here v_o and C_o are the water velocity and suspended particle concentration upstream from the collector where the flow pattern is undisturbed by the presence of the grain, respectively; d is grain diameter. Performance of a packed bed is related to the efficiency of a single spherical collector:

$$\frac{dC}{dL} = -\frac{3}{2}\frac{(1-f)}{d}\alpha\eta C \qquad (3)$$

where f is the bed porosity, L is bed depth, and α is a collision efficiency factor which reflects the chemistry of the system. Following practice in coagulation (e.g., Swift and Friedlander, 1964), α is defined as a ratio—i.e., the number of the contacts which succeed in producing adhesion divided by the number of collisions which occur between suspended particles and the filter media. Ideally, α is equal to 1 in a completely destabilized system. Equation 3 is similar in form to the first-order equation used by Iwasaki (1937), Ives (1960), and others to describe the effects of filter depth on filter performance.

Integration of Equation 3 yields the following:

$$\ln\frac{C}{C_o} = -\frac{3}{2}(1-f)\alpha\eta\left(\frac{L}{d}\right) \qquad (4)$$

where C_o and C are the influent and effluent concentrations for a packed bed.

An impression of the magnitude of η in real systems can be obtained by using a numerical example. Consider a conventional rapid sand filter with a bed depth of 24 in., a bed porosity of 40%, and containing media with a size of 0.6 mm. Assume that the suspended particles to be removed are completely destabilized ($\alpha = 1$). If such a filter removes 90% of the particles applied to it ($C/C_o = 0.1$), η is 2.5×10^{-3} (Equation 4). One is then led to ask what parameters affect η. Subsequently it will be shown that η depends not only on such parameters as the filtration velocity, media size, and water temperature, but also in a significant manner on the size and density of the particles to be filtered.

In this paper the results of a theoretical model for the determination of η are presented. The results of laboratory experiments in which the filtration performance of packed beds is characterized by influent and effluent concentrations (C_o and C) are included. Comparisons of theoretical predictions of η with experimental results are made using Equation 4.

NUMERICAL DETERMINATION OF η. The numerical solution to the problem of predicting η and filter efficiency involves four steps (Yao, 1968; Yao and O'Melia, 1968): (1) determining the distribution of particles in the region close to the surface of a single collector; (2) calculating the rate at which particles strike the collector surface; (3) computing the single-collector efficiency; and (4) calculating the overall removal efficiency of a given packed-bed filter.

In step 1, the diffusion equation (Equation 1) is integrated numerically to yield the distribution of particles in the region of interest. Several assumptions are made. First, a steady state is assumed; i.e., $\partial C/\partial t = 0$. Second, Stokes equations for the fluid velocities in laminar flow around a sphere are used in the advective term ($v \cdot \nabla C$). Subsequent experimental results and the work of other investigators (e.g., Spielman and Goren, 1970) suggest this assumption is not justified for an accurate description of packed-bed systems. Third, Einstein's equation is used to estimate the diffusion coefficient of the suspended particles:

$$D_{bm} = \frac{kT}{3\pi\mu d_p} \qquad (5)$$

where k is Boltzmann's constant, and T is the absolute temperature. Fourth, interception is included in the boundary conditions, which assume that $C = C_o$ at an infinite distance from the collector, and that $C = 0$ at a distance equal to $(d + d_p)/2$ from the center of the collector. Finally, the model applies most directly to clean filters, where deposition within the pores has not significantly altered the flow pattern or media characteristics.

In step 2, two additional numerical operations are used to compute the total rate at which suspended particles strike the collector. First, the particle fluxes at various points on the collector surface are calculated from the concentration gradients at the collector surface. These concentration gradients are determined from the concentration distribution computed in step 1. Second, these particle fluxes are integrated numerically over the whole collector surface, yielding the rate at which particles strike the collector.

In step 3, the single collector efficiency is calculated directly from the results of step 2 using Equation 3. Finally, in step 4, the efficiency of a packed-bed filter is calculated directly from η using Equation 4. Here the sticking factor is generally assumed to be 1.

The results of numerical calculations of η and filter efficiency as a function of the size of the suspended particles are presented in Figure 2. These results lead to the following conclusions: • There exists a size of the suspended particles for which the removal efficiency is a minimum. For the assumed conditions typical of conventional practice in water filtration, this critical suspended particle size is about 1 μ. • For suspended particles larger than 1 μ, removal efficiency increases rapidly with particle size. Removal is accomplished by sedimentation and (or) interception. • For suspended particles smaller than 1 μ, removal efficiency increases with decreasing particle size. Removal is accomplished by diffusion. (It is useful to note here that many suspended particles of interest in water and waste water treatment are about 1 μ in size or smaller. Included here are viruses, many bacteria, a large portion of the clays, and a significant fraction of the organic colloids in both raw and biologically treated waste water.)

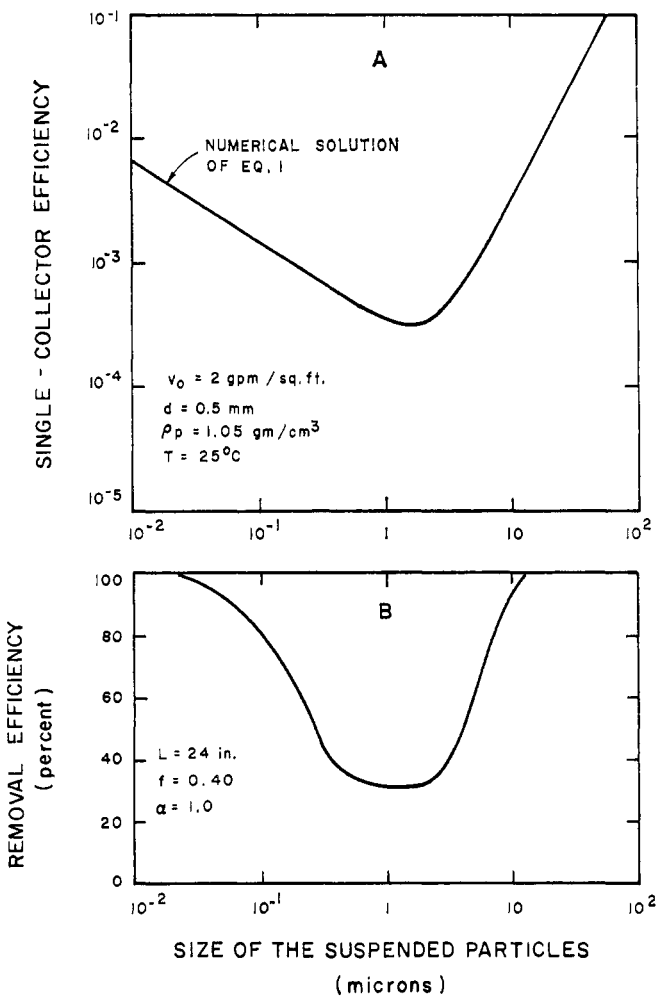

Figure 2. Theoretical model for filtration efficiency with single-collector and removal efficiencies as functions of the size of the suspended particles

ANALYTICAL DETERMINATION OF η. Equation 1 can be solved analytically to determine the single-collector efficiency if only one transport mechanism is operative. Assumptions concerning flow velocity (Stokes), steady state, and, where appropriate, the diffusion coefficient and the boundary conditions are made which are identical to those used in the numerical procedure. The case of diffusion alone has been developed by Levich (1962); methodology for considering sedimentation and interception alone is presented elsewhere (Yao, 1968). The following results are obtained:

$$\eta_D = 4.04\ \mathrm{Pe}^{-2/3} = 0.9\left(\frac{kT}{\mu d_p d v_o}\right)^{2/3} \tag{6}$$

$$\eta_I = \frac{3}{2}\left(\frac{d_p}{d}\right)^2 \tag{7}$$

$$\eta_G = \frac{(\rho_p - \rho) g d_p^2}{18\ \mu v_o} \tag{8}$$

Here η_D, η_I, and η_G represent theoretical values for the single-collector efficiency when the sole transport mechanisms are diffusion, interception, or sedimentation, respectively, and Pe is the Peclet number.

Equations 6–8 are presented in Figure 3, where the appropriate single-collector efficiency is plotted as a function of the size of the suspended particles. Included as points in Figure 3 are the results of the numerical analysis presented earlier (Figure 2A). It is apparent that for the conditions used in these calculations, the single-collector efficiency calculated

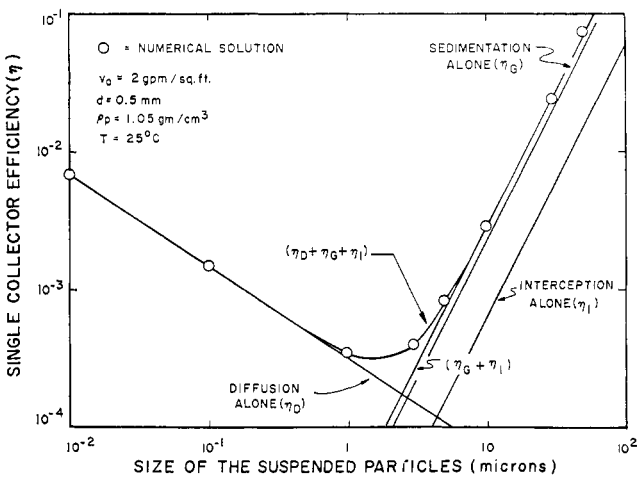

Figure 3. Comparison of numerical and analytical solutions of Equation 1

numerically can be approximated by the sum of the analytical expressions. In other words,

$$\eta = \eta_D + \eta_I + \eta_G \quad (9)$$

The analytical expressions (Equations 6–8) combined with Equation 4 provide a convenient picture of the effects of conventional filtration variables on filter efficiency as predicted by the model. The right-hand side of Equation 4 is seen to vary with v^0 to v^{-1}, μ^0 to μ^{-1}, d^{-1} to d^{-3}, and $d_p^{-2/3}$ to d_p^2 depending on the transport mechanism which is operative. These results correspond to the range of results observed by other investigators in laboratory experiments and in practice (Ives and Sholji, 1965). The effects of filtration velocity, water viscosity, media size, and the density of the suspended particles on the single-collector efficiency are presented graphically in Figure 4. For particles larger than 1 μ, this model predicts that the density of the suspended particles exerts significant effects on filtration due to settling (Figure 4D). Other conventional filtration parameters exert considerably less effect on the process (Figures 4A–C).

Experimental

Latex beads supplied by the Dow Chemical Co. have been used to prepare suspensions for filtering. Polystyrene latex particles with 0.091-, 0.357-, and 1.099-μ diameters and styrene divinylbenzene copolymer latex particles with 7.6- and 25.7-μ diameters were selected for use. Experiments were thus conducted within and on both sizes of the critical size where it was expected that filter efficiency would be poorest. These particles have a density of 1.05 gm/cc.

Suspensions for testing were made by diluting the stock supplied by the manufacturer to a suitable latex concentration (10 to 200 mg/liter) with $10^{-3}M$ NaCl and $10^{-3}M$ $NaHCO_3$. The final suspensions had a pH of 8.3. Absorbance measurements were made at appropriate wavelengths with a Beckman Model DB spectrophotometer to determine particle concentrations in samples from the filter influent and effluent.

Glass beads supplied by the Minnesota Mining and Manufacturing Co. were used as filter media. These beads were sieved for uniformity; the mean size of the sieved beads was 0.397 mm with a standard deviation of 0.0145 mm. Filter beds were generally 14 cm in depth, 2.6 cm in diameter, and had a porosity of 36%.

Both the suspended latex particles and the glass beads are negatively charged in water. To provide for efficient attachment (α approximating 1), a destabilizing chemical must be used. In the experiments described in this paper, a cationic polymer, diallyldimethylammonium chloride (Cat-Floc) supplied by the Calgon Chemical Corp. has been used. This polymer is reported by the manufacturer to have a molecular weight in the order of 5×10^5; its positive charge is constant below pH 11.

Two methods of applying this cationic polymer have been used. In one series of experiments the filter beds were precoated with a concentrated polymer solution (10,000 mg/liter) prior to use; no additional polymer was applied during the filtration runs. The purpose of these studies was to determine experimentally the single-collector efficiency at the start of a filter run when the theoretical model could be expected to characterize the system. In a second series of experiments the filter beds were precoated and, in addition, polymer was fed throughout the duration of the filter runs. The dosage of polymer was selected on the basis of jar tests similar to those used in coagulation processes. In these experiments the head loss developed during the filtration process was measured using piezometer tubes connected to the inlet and outlet of each filter.

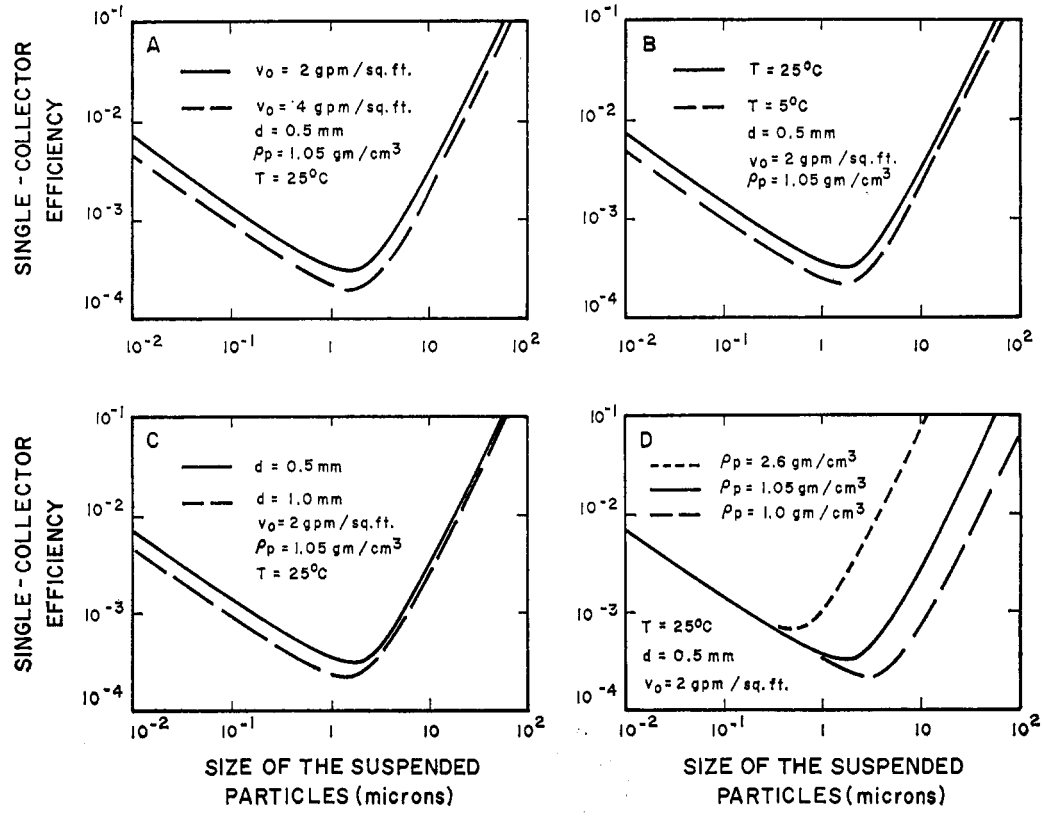

Figure 4. Theoretical model for the single-collector efficiency: effects of filtration velocity (v_o), temperature (T), media size (d), and the density of the suspended particles (ρ_p)

Results

Typical results of those experiments in which only a precoating of polymer was used are presented in Figure 5. Removal efficiency is plotted as a function of filtration time. Data for both coated and uncoated media are presented for comparison. In these experiments clean water is passed through the filters for several minutes while the flow rate is established; the latex suspension is then introduced into the apparatus at zero time (Figure 5). Clean water in the filter apparatus requires about 2 to 3 min for displacement; after this time an additional 1 or 2 min is required to elute latex suspension which has mixed with the original clear water. After about 5 min, the effluent from the filter represents undiluted latex suspension.

Very little removal is accomplished by the uncoated filter; after 5 min the effluent concentration equals or exceeds 95% of the influent concentration. Using a polymer-coated filter, 44% of the latex particles is removed; this corresponds to a single-collector efficiency (Equation 4) of 1.6×10^{-3}. In this system, negatively charged latex particles are able to adhere to the positively charged filter media.

Results of experiments using five different sizes of latex particles are summarized in Figure 6. The removal efficiency of the packed beds and the single-collector efficiency are plotted as a function of the diameter of the suspended latex particles which are filtered. The predictions of the theoretical model are also presented in Figure 6 for comparison. This comparison reveals:

- A suspended-particle size with a minimum opportunity for removal is observed to exist; this is in agreement with the model. Furthermore, the magnitude of this critical particle size (about 1 μ) is in good agreement with the predictions of the model.
- The general trend in the observed relationship between the single-collector efficiency and the size of the suspended particles is in reasonable agreement with the model. The comparison suggests that the transport mechanisms used in developing the model are in fact operative in filtration. In other words, diffusion is operative in transporting small particles, while settling and interception are able to transport particles larger than about 1 μ in size.
- Experimental filter efficiencies are higher (better) than theoretical predictions. Possible reasons for these discrepancies are discussed subsequently.

The results of experiments using several filtration rates are presented in Figure 7. The single-collector efficiency is plotted as a function of the filtration velocity. The latex particles used in these experiments had a diameter of 0.091 μ so that transport by diffusion was operative. The predictions of the Levich model (Equation 6) for diffusion alone are plotted in Figure 7 for comparison. According to this model, η varies with $v^{-2/3}$; the experimental data are in reasonable agreement with this prediction. Again, experimental filters are observed to exceed the performance predicted by the conceptual model outlined previously in this paper.

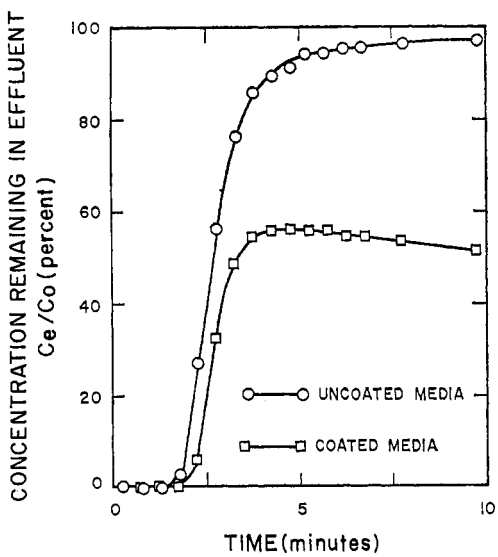

Figure 5. Typical experimental results for coated and uncoated filter media

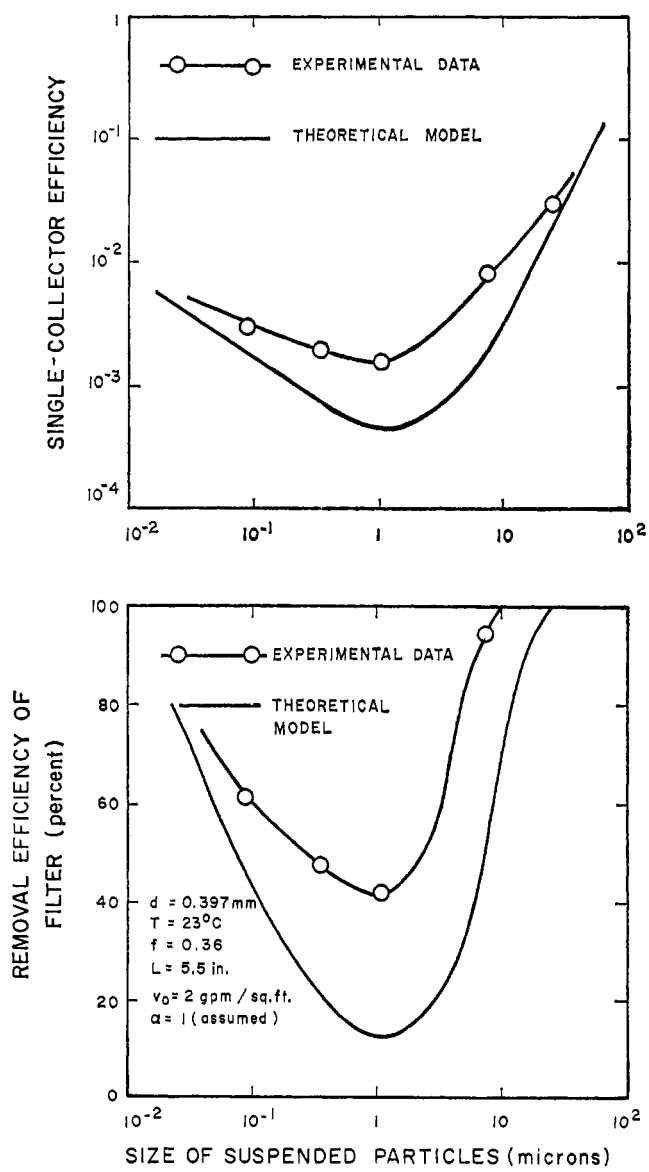

Figure 6. Comparison of theoretical model and experimental data

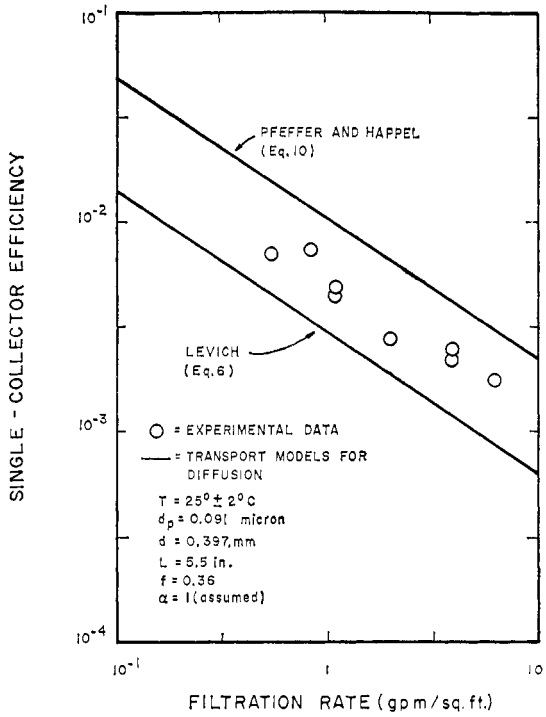

Figure 7. Comparison of theoretical models and experimental data

In these experiments where precoated filter media were used without any additional use of destabilizing chemical, it was expected and observed that the ability of the filter beds to remove particles would be exhausted in a short time. In this system the filter media can retain only a monolayer of particles; after this time the latex particles in suspension collide with negatively charged latex particles previously removed in the bed. In any real filtration process, the particles to be removed must be able to adhere to each other on contact; this can be achieved by continuous addition of polymer. An important question then arises—how much polymer is needed? To answer this question, it is proposed that the chemical aspects of filtration are similar to the chemical aspects of coagulation. If this is so, then jar tests used to determine chemical dosages for coagulation could serve the same purpose for filtration.

The results of experiments designed to test this hypothesis are presented in Figure 8. The results of jar tests are depicted in 8A; residual turbidity after settling is plotted as a function of the applied dosage of cationic polymer. An optimum polymer dosage of 0.07 mg/liter is observed for this suspension. Vertical arrows correspond to dosages selected for study in filtration. The results of a filtration experiment are presented in 8B and C; effluent concentration and head loss are plotted as a function of filtration time. Clean water again requires a period for displacement. Based on these results the following statements can be made:

- Effective filtration is achieved using the optimum polymer dose observed in the coagulation (jar) tests.
- Underdosing and overdosing with polymer are observed. Again, these phenomena are observed in jar tests. Overdosing in this case is probably due to sufficient adsorption of the cationic polymer to produce charge reversal of the latex particles.
- When no polymer is added to a precoated filter bed (filter no. 1), the variation of effluent concentration with time is similar to that observed in earlier tests (e.g., Figure 5). The filtration capacity is exhausted after only a few minutes. At the optimum polymer dose (filter no. 4), the effluent concentration is significantly better than that observed in the earlier experiments. When polymer is added continuously, a removal efficiency of 93% of these 0.09-μ latex particles is observed after about 1 hr, compared with a bed efficiency of 61% when only a precoat of polymer is used (Figure 6B). This is probably not due to coagulation in the filter pores since particle growth of these small particles (0.09 μ) would lead to less efficient filtration (6B).
- During the first hour of filtration an initial relatively high concentration of particles appears in the effluent, after which the removal efficiency improves considerably. This initial breakthrough would be less noticeable if a deeper and more conventional filter bed were used.
- At the optimum polymer dose, filtration (transport and attachment) is so effective that the available head loss is utilized in about 3 hr. It is significant to note that this occurs even with particles with a size in the order of 0.1 μ.
- These results suggest that when conventional filters fail to produce efficient filtration, effective improvements can be made by altering the chemistry of the system. In other words, attention should be directed toward increasing α, rather than merely changing, such conventional filtration parameters as d, v, and L.
- Transport is so efficient in water and waste water filters that when polymers are used to improve α, the filtration process will be so effective that short filter runs will result with conventional beds due to rapid clogging of the filter pores. It is probable that effective filtration without excessive head loss can be achieved with polymers and dual medium filters, upflow filters, biflow filters, moving bed filters, etc.

Two additional statements can be made on the basis of other experiments. First, if polymers are used continuously but without a precoat of polymer applied to the filter media; the time for filter *ripening* can be several hours. Latex particles with polymer adsorbed at the optimum dose for coagulation may be only partially removed by negatively charged media. In practice such precoating could easily be achieved by adding polymer to the backwash water (Harris, 1970). Second, the optimum concentration of polymer required for filtration depends on the concentration of colloids to be filtered. Here again, filtration is analogous to coagulation. Stoichiometry in coagulation has been reported by many investigators (e.g., Black and Vilaret, 1969; Stumm and O'Melia, 1968).

Discussion

Let us consider here some plausible causes for the discrepancies between model and observation (Figures 6 and 7). First, the assumption that Stokes equation for the velocity pattern about an isolated sphere can describe the velocity distribution in a packed bed with a porosity of 36% is probably unrealistic. Pfeffer (Pfeffer, 1964; Pfeffer and Happel, 1964) has used the cell model developed by Happel (1958) to describe the velocity terms characterizing mass transfer by diffusion in packed beds having porosities of 40% and higher. Cookson (1970) has applied this model to the filtration of viruses. The results of the Pfeffer and Happel model are similar to the Levich equation (Equation 6), with the addition of a porosity term:

$$\eta = 4B\mathrm{Pe}^{-2/3} \tag{10}$$

where $B = 1.26\left(\frac{1-\gamma^5}{W}\right)^{1/3}$; $W = 2 - 3\gamma + 3\gamma^5 - 2\gamma^6$;

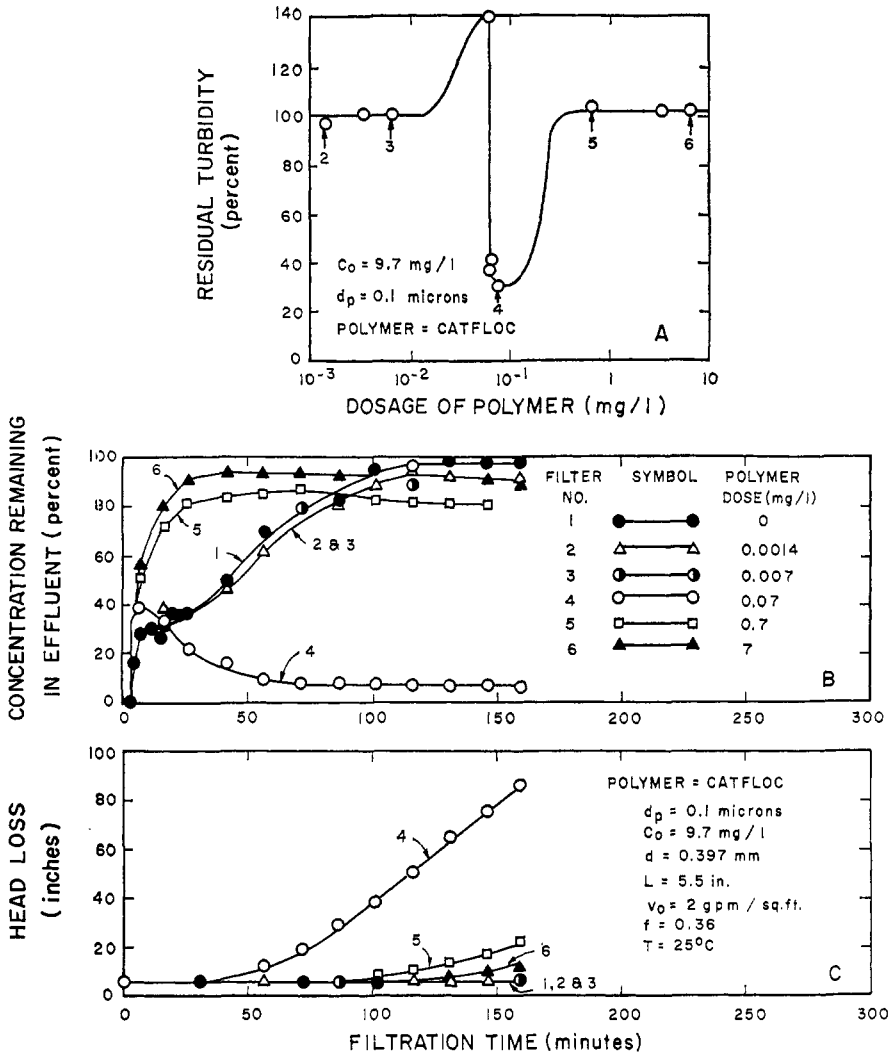

Figure 8. Comparison of jar test results (A) with filter performance (B and C)

and $f = 1 - \gamma^5$. For a packed bed with a porosity of 36%, $B = 3.81$, and $\eta = 15.24\ \mathrm{Pe}^{-2/3}$.

The results of the Pfeffer and Happel model are presented in Figure 7, together with the Levich model and the results of experiments describing the effects of filtration on η. As noted earlier, experimental points are computed from observed removal efficiencies of packed beds using Equation 4 and assuming $\alpha = 1$. The observed data are consistent with the Pfeffer and Happel model if α is 0.5. In other words, if half of the contacts between the negatively charged latex particles and the polymer-coated filter media are successful in achieving attachment, these data are quantitatively consistent with the Pfeffer and Happel model for mass transport by diffusion in packed beds.

All terms on the right-hand side of Equation 4 are commonly combined in a filter coefficient, λ (e.g., Ives, 1960); in the model described herein, $\lambda = 3(1 - f)\alpha\eta/2d$. When interception is the dominant transport mechanism this model predicts that the filter coefficient is independent of the flow rate and varies as the square of the suspended particle size and the inverse cube of the media size. Limited experimental results (Figure 6A) suggest that η and consequently λ vary with the first power of the suspended particle size when interception and settling are dominant. Spielman and Goren (1970) note that a suspended particle approaching a collector will deviate from an undisturbed streamline (i.e., a fluid streamline unaffected by the presence of the suspended particle) due to the difficulty in draining fluid from between the collector and the particle as the distance between them narrows. London–van der Waals forces are invoked to overcome this otherwise slow drainage. These authors developed a model which predicts that when interception alone is operative the filter coefficient can in fact vary with the first power of the suspended particle size, as well as inversely with the 2.5 power of the collector size and the 0.25 power of the filtration rate.

Next let us consider that experiments using a continuous dosage of polymer indicated that filtration efficiency after a ripening period was considerably better than that observed when a precoated filter media was used alone, and an initial ripening period always occurred. Possible explanations for these phenomena include one or more of the following:

- Latex particles coated with the optimum dosage of polymer may find it more difficult to adhere to polymer-coated glass beads than to previously retained latex treated with the optimum polymer dosage. In other words, α for a latex–glass bead interaction could be lower than for a latex–latex interaction, even when all surfaces receive the appropriate polymer treatment.
- For particles greater than 1 μ, coagulation within the pores could produce an increase in the effective size of these

particles and enhance their removal. This cannot explain the results in Figure 8 but could contribute to similar results observed in other experiments with larger suspended particles. Coagulation within filter pores will depend upon the concentration of particles in suspension; for dilute suspensions sufficient contact opportunities would not be available.

- It is possible that particles which are removed may act as collectors themselves. Recall that λ varies with d^{-1} to d^{-3}; if small particles which have been removed can act as collectors, λ and η can be large. Billings (1966) has photographed the accumulation of latex particles on glass rods in air filtration and showed the development of fibrous strands of individual latex spheres which extended considerable distances into the airstream. After an initial period most removal was achieved by attachment to other latex particles previously retained, rather than to the considerable amount of remaining available surface on the glass rods.

Conclusions

Based on the conceptual model and the experimental results presented in this paper, we conclude that conventional sand filters provide ample contact opportunities for the removal of all particles applied to them. When such filters are not producing efficient removal, the chemistry of the system (α) should be changed. A great variety of destabilizing chemicals is currently available for this purpose. Examples include hydrolyzing metal salts [e.g., salts of Al(III) and Fe(III)] and natural and synthetic polymers which may be organic or inorganic. These latter materials can be cationic, anionic, or nonionic and can contain one or more of several types of functional groups. These chemicals probably enhance attachment in filtration by adsorption to produce charge neutralization and (or) bridging. These destabilization mechanisms have been shown to be effective in many coagulation processes (e.g., Stumm and O'Melia, 1968; Black et al., 1965; Hahn and Stumm, 1968). As in full-scale coagulation processes, the type and optimum dosage of chemical for filtration can be determined using jar tests. The wide diversity in the chemicals available should provide adequate means for filtering such substances as bacteria, viruses, the colloidal calcium phosphate precipitates often produced in tertiary treatment for phosphate removal, and organic biocolloids present in secondary effluents, in addition to the clays and metal hydroxide flocs which are filtered in conventional water treatment plants.

To a first approximation, the removal efficiency of a packed-bed filter is independent of the applied concentration of particles (Equation 4). Here a significant difference arises in comparing coagulation and filtration processes. The detention time required to achieve a given degree of aggregation in coagulation depends upon the concentration of particles to be aggregated. Consider, for example, a water containing 10,000 viruses per milliliter and no other colloidal particles. Using Smoluchowski's analysis for perikinetic flocculation, 200 days would be required to halve the initial particle concentration even if all the virus particles were completely destabilized ($\alpha = 1$). Furthermore, the resulting aggregates would still be too small to be removed by gravitational settling. The removal of viruses within a reasonable detention time in coagulation processes requires the presence of a large number of other colloidal particles or enmeshment in a voluminous precipitate of metal hydroxide. This suggests that filters can be effectively used in water treatment to remove colloidal particles present in dilute but objectionable concentrations; prior coagulation is not required, but a destabilizing chemical must be added to the filter influent. Such processes could save capital costs and some chemical operating costs, but would require close operating control.

Unlike the quality of the filtrate, the head loss developed during filtration is very dependent upon media size, filtration rate, and the concentration of particles to be filtered. The ability of polymers to enhance attachment in filters requires that conventional filters be redesigned to provide larger pores. Multimedia beds, radial beds, moving beds, or other modifications are required. For example, it seems plausible that direct filtration of secondary effluents could provide both long filter runs and efficient removal if upflow filters with depths in the order of 4 ft and media having a size of about 1.5 mm were used at filtration rates in the order of 5 gpm/ft^2.

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