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Colloidal Particle Deposition in Turbulent Flow

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ABSTRACT

A theoretical analysis is presented which describes the initial deposition of monodispersed spherical colloidal particles from a steady fully developed turbulent flow onto conduit walls. When the net particle-conduit electrical interaction potential is attractive, particle deposition is shown to be often governed by turbulent hydrodynamics. When the net particle-conduit electrical interaction potential possess a repulsive maximum, particle deposition to first order is uniform and depends solely on electrical interaction effects. The developed theoretical model specialized to orifice deposition with the use of Harwell Flow3D turbulence modelling software qualitatively described the deposition of $0.5\ \mu\text{m}$ silica particles onto glass orifices from an aqueous suspension.

The effect of the electrical double layer on the rate of colloidal particle deposition in laminar flow has been described by Spielman and Friedlander (1), Dahneke (2), Bowen et al. (3) and Bowen and Epstein (4). This article describes the extension of their work to colloidal particle deposition under steady fully developed turbulent flow conditions. This article also reports the results of orifice particle deposition experiments which were conducted to qualitatively investigate the developed theoretical model.

THEORY

The idealized system investigated is one of a dilute suspension of monodispersed spherical colloidal particles flowing through a conduit under steady fully developed turbulent flow conditions. Particles may deposit on conduit walls; however, chemical interactions or reactions between particles or between particles and conduit walls are not considered. Once a particle has been brought to a conduit surface it is assumed to remain there. Under these assumptions, particle deposition is governed by electrical interaction and hydrodynamic particle transport effects which are generally not separable. The primary two electrical interaction effects are the London-van der Waals dispersion forces and electrical double layer interaction forces (4,5). These electrical interaction forces are short ranged forces which are typically of importance for particle and conduit distances of separation of less than 10 particle diameters. Thus, for colloidal particles, the electrical interaction length is typically much smaller than the thickness of the turbulent viscous sublayer, δ . The thickness of δ is of order of the kinematic viscosity divided by the velocity of turbulent eddies characteristic of the flow (6).

The turbulent transport of momentum and matter is typically described by breaking turbulent flow through conduits into two or more regimes with one being a turbulent core region and another being a viscous sublayer region. The transport of momentum and matter is governed by turbulent eddies in the turbulent core. The viscous sublayer is a surface region where turbulent eddies are damped out and molecular transport becomes the dominant transport mechanism. Since turbulent eddies are extremely effective in transporting and mixing matter in the turbulent core, the primary resistance to particle deposition, when the electrical interaction length is much smaller than δ , is transport through the viscous sublayer.

The particle concentration in the viscous sublayer, when electrical interaction effects are considered, is described by the steady diffusion equation in a potential interaction energy field $\phi = \phi(y)$;

$$0 = \frac{d}{dy} \left[D \frac{dC}{dy} + \frac{DC}{kT} \frac{d\phi}{dy} \right] . \quad [1]$$

C is the concentration of particles in the viscous sublayer, y is the direction normal to the surface, D is particle diffusion coefficient, k is the Boltzmann constant, T is the absolute temperature and ϕ is the potential interaction energy between each particle and the conduit wall. Eq. [1] was solved by Spielman and Friedlander (1) to describe particle deposition within a laminar diffusion boundary layer.

Integration of Eq. [1] illustrates that the flux of particles, J(x), at a position x along the surface in the direction of flow is constant through the viscous sublayer. The boundary conditions employed to solve Eq. [1] are at $y = \delta$, the edge of the viscous sublayer, the concentration, C_δ , smoothly approaches the bulk or turbulent core concentration, C_o , by the

logarithmic law of the wall, $C_\delta = J\delta / (10\gamma) \ln(\delta/d) + C_0$ (6). Here γ is the kinematic viscosity and d is the thickness of the turbulent boundary layer. The second boundary condition is at the conduit surface, $y = 0$, the particle concentration is zero. This last boundary condition implies the surface is an infinite particle sink. The flux of particles to conduit walls is obtained from the solution of Eq. [1].

$$J(X) = \frac{C_0 D_\infty}{\delta \left[1 + \frac{\Phi(y)}{\delta} - \frac{1}{10Pr} \ln(\delta/d) \right]} \quad [2]$$

with

$$\Phi(y) \equiv \int_0^y \left(\frac{D_\infty}{D(y)} e^{\Phi(y)-1} \right) dy.$$

Pr is the Prandtl number. D_∞ is the Stokes-Einstein diffusion coefficient evaluated with a friction coefficient of a sphere in an infinite fluid. Dahneke (2) identified that the functionality of the diffusion coefficient ratio, $D_\infty/D(y)$, is described by Brenner's friction coefficient ratio for a sphere moving normal to a surface compared to a sphere in an infinite fluid (7). Eq. [2] can be simplified for large Prandtl numbers which are associated with most liquids, $Pr \approx 1000$.

$$J(X) = \frac{C_0 D_\infty}{\delta + \Phi(y)} \quad [3]$$

Following the notation of Bowen and Epstein (4), the net interaction potential, ϕ , is the sum of the electrical double layer potential, ϕ_{edl} , and the London-van der Waals interaction potential, ϕ_{vdw} . Since particles are of colloidal size, it is reasonable to assume that particle-conduit interactions can be approximated by interactions between a sphere and a plate. Under this assumption, analytical expressions for ϕ_{vdw} and ϕ_{edl} are obtainable. Hogg et al. (8) give the following expression for ϕ_{edl} .

$$\phi_{edl} = \frac{\epsilon a}{4} \{ 2\psi_1\psi_2 \ln \left[\frac{1+e^{-\kappa h}}{1-e^{-\kappa h}} \right] + (\psi_1^2 + \psi_2^2) \ln [1 - e^{-2\kappa h}] \} \quad [4]$$

a is the radius of the spherical particle, h is the distance of separation between the particle and the conduit, ϵ is the dielectric constant, κ is the reciprocal double layer thickness and ψ_1 and ψ_2 are the Stern potentials of the sphere and plate respectively.

Hiemenz (5) gives the following expression for ϕ_{vdw} .

$$\phi_{vdw} = \frac{-A}{6} \left[\frac{a}{h} + \frac{a}{h+2a} + \ln \left(\frac{h}{h+2a} \right) \right] \quad [5]$$

A is the Hamaker constant which typically ranges from 10^{-21} to 10^{-19} J for aqueous solutions.

CASE I- Stern Potentials of Like Sign

The London-van der Waals potential is always attractive ($\phi_{vdw} < 0$). When the Stern potentials are of like sign the electrical double layer potential is either repulsive or attractive depending

upon the specific separation distance and the reciprocal double layer thickness. At small separation distances the electrical double layer potential is attractive. Depending upon the relative magnitudes of ϕ_{vdw} and ϕ_{edl} the resulting total potential energy curve, ϕ , can be repulsive for various distances of separation. When the total potential curve is somewhere repulsive and thus goes through a maximum the integral in Eq. [3], $\Phi(y)$, is much greater than δ . The flux of particles to the surface, in this situation, is governed by electrical interactions in the region immediately adjacent to the conduit surface. $\Phi(y)$ can be represented by an integral to an effective electrical interaction length, δ_{ele} , since δ_{ele} is considered much smaller than δ and the integral evaluated from δ_{ele} to δ is negligible. When this situation occurs, particles deposition is completely independent of the hydrodynamic characteristics of the flow field. Since it has been postulated that electrical interactions are identical at all surface locations, particle deposition is uniform and independent of conduit surface position.

CASE II- Stern Potentials of Opposite Sign

When the Stern potentials are of opposite sign, the electrical double layer potential and thus the net potential is typically everywhere attractive. When the total potential curve is completely attractive, $\phi < 0$, δ is often much greater than the magnitude of $\Phi(y)$. The flux of particles to conduit surfaces under this condition is governed by turbulent hydrodynamic particle transport and specifically particle diffusion through the viscous sublayer. The thickness of the viscous sublayer is a function of the turbulent flow field through the conduit and is thus a function of the conduit geometry. A turbulence model with an appropriate turbulence damping is necessary to evaluate the viscous sublayer thickness.

The viscous sublayer has thus far been loosely used to denote an effective region where both molecular transport of momentum and mass dominate turbulent transport. Depending upon the model of turbulence damping postulated and the fact that most liquids have large Prandtl numbers, the diffusion sublayer thickness, δ_{diff} , is often smaller than the thickness of the viscous sublayer. Under this condition, transport of matter in the outer portion of the viscous sublayer, $y > \delta_{diff}$, is dominated by turbulence. Levich (6) identifies how various turbulence damping hypotheses effect δ_{diff} . If the Prandtl hypotheses of complete cessation of turbulence in the viscous sublayer is adopted, $\delta_{diff} = \delta$. If the Levich model of smooth turbulence damping in the viscous sublayer is adopted, $\delta_{diff} = \text{constant}(\text{Pr})^{-1/4}\delta$. If the turbulence damping model employed by Lin et al. (9) is accepted, $\delta_{diff} = \text{constant}(\text{Pr})^{-1/3}\delta$.

In developing the theoretical model no distinction was made between δ and δ_{diff} . The model thus rigorously only describes colloidal deposition fluxes under the Prandtl turbulence damping hypothesis. Following the procedure outlined in this article and the turbulence damping forms identified by Levich (6), deposition fluxes are readily obtained for the two mentioned turbulence damping hypotheses. The resulting high Prandtl number solutions, basically are identical to Eq. [3] with a reduced effective length for diffusion. When the Levich turbulence damping hypothesis is adopted, the effective diffusion length in Eq. [3] is reduced from δ to $4/3\delta_{diff}$. If the turbulence damping model of Lin et al. (9) is adopted then the effective diffusion length in Eq. [3] becomes a constant times δ_{diff} .

EXPERIMENT

The primary objective of the orifice particle deposition test was to supply data to qualitatively investigate the theoretical model. A secondary goal of this experimental effort was to determine conditions under which colloidal particles selectively deposit within the orifice throat. Buildup at this location maximizes hydraulic performance degradation. These objectives were accomplished by investigating the deposition of silica particles on glass orifices.

Due to the need for absolute control of suspended particle concentration the wetted perimeter in the experimental apparatus was entirely Teflon, except for the test and flow meter orifices. Silica particles are known not to adhere to, or deposit on, Teflon. The major components in the experimental apparatus were the solution feed tank, pump, orifice test section and flow meter. The feed tank was a Teflon coated 0.11 m³ tank with a Teflon coated lid to prevent the ingress of airborne impurities. During operation the feed tank was stirred by a swirling flow generated by the return flow. Temperature within the feed tank was maintained by a Teflon cooling coil at 28±5°C. A Teflon Thompson-Chemtrex GPT series centrifugal pump was used to circulate test fluid. The mass flow rate through the experimental apparatus, $6.5 \times 10^{-2} \pm 1 \times 10^{-2}$ kg/s, was monitored by measuring the pressure drops across the flow meter and test section orifices. These pressure drops were unaltered by particle deposition.

Orifice Test Section

The test section consisted of a plate glass orifice specimen mounted by means of compressed

O-ring connections to straight runs of larger diameter Teflon pipe. The 0.254 m long upstream straight run of 6.35×10^{-3} m diameter pipe provided a flow-straightening section which assured that the test suspension at entry to the orifice had a well developed turbulent concentration/velocity profile. The orifice itself consisted of a 2.54×10^{-3} m diameter hole drilled through a sheet of plate glass. A cross section of the test orifice is illustrated in Fig.

1. Flow through the test section orifice at a throat velocity of 13 m/s was discharged into a 2.37×10^{-2} m long 4.57×10^{-3} m diameter Teflon discharge plenum before return to the 6.35×10^{-3} m diameter piping system.

To enable deposition to be studied under attractive and repulsive electrical interaction conditions two surface conditions were tested: as-received or a plastic film coating. The as-received glass surface bears a negative charge. A positively-charged surface was obtained by coating orifices with a 80% 2-vinyl pyridine and 20% styrene (2VP/St) plastic film. The method of Utsumi et al. (10) was employed to synthesize the 2VP/St.

The procedure developed to coat the orifices was to place a drop of 2% (wt) 2VP/St in chloroform on the orifice face while it was spinning on a motorized platform. The resulting orifice coating, because of the centrifugal forces acting on the coating liquid, spiralled radially outward on the orifice face and spiralled through the orifice throat. This coating procedure created regions on the orifice face and within the orifice throat which were coated with 2VP/St (positively charged regions) and other regions which were uncoated (negatively charged regions).

Particle Test Suspension

Test particles were uniformly sized 0.5 μm silica particles produced by the procedure of Stöber et al. (11). Bowen and Epstein (4) report the density of 0.5 μm particles produced using the above procedure as 2180 kg/m^3 . Using their density it was possible to generate test solutions of known particle concentration. The particle concentration employed in all experimental runs was 8×10^{14} particles/ m^3 .

Water Chemistry/Zeta Potentials

Test suspensions were prepared using deionized water and neutral electrolyte at the low electrolyte concentration of 3×10^{-4} M NaCl. Experimental electrolyte concentrations were checked at the initiation and completion of experimental runs by conductivity measurements.

Surface Stern potentials were not measured in this experimental work. However, experimental conditions were selected to match the water chemistry conditions used by Bowen and Epstein (4) for which they had measured surface zeta potentials (ζ). The zeta potential of a surface is an accurate estimate of its Stern potential. The zeta potentials of 2VP/St and silica particles measured by Bowen and Epstein for 3×10^{-4} M NaCl are presented in Table 1. Bowen and Epstein did not measure the ζ potential of pure glass surfaces but it is reasonable to assume that these ζ potentials will not substantially deviate from, ζ_{Silica} .

Results

Two experimental runs were conducted at a NaCl concentration of 3×10^{-4} m. The duration of Run 1 was 406 hours and the duration of Run 2 was 340 hours. Deposition results from these experiments were identical in nature and are depicted in the high magnification SEM photographs shown in Figs. (2-5). Three key observations can be made by careful investigation of these figures.

1. Particle deposition on the orifice face is negligible when compared to deposition in the orifice throat.
2. Particle deposition within the orifice throat occurs to a much greater extent on regions coated with 2VP/St than on uncoated regions.
3. Particle deposition in the orifice throat of 2VP/St coated regions is greatest near the orifice face and decreases with position downstream.

Fig. 2 is a collection of SEM photographs of the Run 1 orifice face. Fig. 2A is a low magnification overview of the orifice face illustrating coated and uncoated regions. The 2VP/St coated region is the larger more opaque region around the top portion of the orifice. Fig. 2B is a high magnification photograph of the region marked 1 on Fig. 2A. This region was 2VP/St coated. The top portion of the photograph is the orifice face and the bottom (dark) portion is viewing into the orifice throat. This figure illustrates substantially greater deposition in the orifice throat than on the coated orifice face. Fig. 2C is a high magnification

photograph of the region marked 2 on Fig. 2A. The bottom right of the photograph views the uncoated orifice face and the top left portion views into the orifice throat. This photograph shows negligible orifice face deposition.

Fig. 3 is a series of SEM photographs at increasing magnification of a 2VP/St coated orifice face location from the orifice of Run 2. The top region in each of these figures views into the orifice throat and the bottom of the photograph views the 2VP/St coated orifice face. This figure reiterates the observation noted in Fig. 2 that particles preferentially deposited within the orifice throat.

Unlike Figs. 2 and 3, which are photographs looking normal to the orifice face, Figs. 4 and 5 are photographs looking directly at the orifice throat. Fig. 4 is a comparison of particle deposition onto uncoated and 2VP/St coated regions within the throat of the Run 1 orifice. The photograph in Fig. 4A is of an uncoated throat location and the photograph in Fig 4B is of a coated location. Comparison between the two figures clearly indicates greater particle deposition in 2VP/St coated throat locations. Fig. 4 also illustrates that the surface within the orifice throat is extremely rough and the 2VP/St coating slightly reduces this roughness. This roughness, which was not present on the orifice face, is a direct consequence of drilling the orifice hole.

Fig. 5 is a series of high magnification photographs of orifice throat locations from the Run 2 orifice. Both photographs are of a 2VP/St coated region. Specifically, the photograph in Fig. 5B is of a location immediately downstream of the location shown in Fig. 5A. The top portion of the photograph in Fig. 5A is of the orifice face which has negligible deposition.

Comparison of Figs. 5A and B illustrates that particle deposition on the throat is heaviest near the face and decreases downstream.

EXPERIMENT AND THEORY COMPARISON

The developed theoretical treatment was specialized to describe the orifice particle deposition experiments. A 10^{-20} J Hamaker constant was assumed. Harwell-Flow3D turbulence modeling software was employed to model the turbulent flow through the orifice. Specifically, Harwell-Flow3D modeling software was used to determine the thickness of the viscous sublayer as a function of surface position. The Prandtl hypothesis of complete cessation of turbulence in the viscous sublayer was adopted to calculate the effective diffusion length from the viscous sublayer thickness.

The entrance to the orifice throat was determined as the orifice location with the thinnest viscous sublayer, $36\text{ }\mu\text{m}$. A uniformed flux of 10^{-88} particles/(m^2s) was determined through Eq. [3] for uncoated orifice regions. The particle and conduit had the same Stern potential of -100mV for this situation and upon evaluating Eq. [3], $\Phi(y)$ was noted to be much greater than δ . Deposition thus was predicted to be uniform and independent of hydrodynamic and geometric parameters. This extremely small flux indicates that there should be virtually no particle deposition onto uncoated orifice regions. Figs. 2C (face) and 4A (throat) illustrate negligible particle deposition onto uncoated orifice regions. Thus under a condition in which the theoretical net potential interaction curve has a repulsive maximum, experimental observations are adequately described by theory.

Orifice particle deposition fluxes calculated through Eq. [3] for various 2VP/St coated orifice locations are depicted in Fig. 6. The particles and conduit surfaces had different sign Stern potentials for this situation and when evaluating Eq. [3] it became apparent that δ was larger $\Phi(y)$. Thus for this condition, deposition was controlled theoretically by Brownian diffusion through the viscous sublayer. The deposition fluxes noted in Fig. 6 are initial particle deposition fluxes since the net surface potential becomes more repulsive and theoretical deposition fluxes are reduced as negative Stern potential particles deposit onto the orifice surface. For experimental comparison, the theoretical net deposition after 350 hours is approximately 25 particles/ μm^2 when the initial maximum deposition flux, 1.9×10^7 particles/(m^2sec), is assumed constant. This calculated net deposition is a surface coverage ≈ 6 times greater than a monolayer coverage, 4 particles/ μm^2 .

Fig. 6 illustrates that the greatest orifice particle deposition occurs theoretically at the entrance to the orifice throat and decreases with downstream throat locations. This figure also demonstrates that particle deposition is expected to be less on the orifice face than in the throat. Qualitatively similar results were experimentally observed. Fig. 5 gave experimental evidence that particle deposition within a 2VP/St coated orifice throat was heaviest at the entrance and decreased downstream. Figs. 2B, 3 and 5A illustrate greater deposition on the orifice throat compared to the face. The theoretical model using Harwell-Flow3D turbulence modeling software predicts a gradual decrease in particle deposition flux within the orifice throat and predicts roughly a 40% greater deposition flux in the orifice throat than on the face. Experimentally, a gradual decrease in particle deposition was observed within the orifice throat. However, only slight deposition was observed on the orifice face. One possible explanation for this deviation is that when theoretically modeling the flow through the orifice,

all surfaces were assumed to be of uniform roughness. In contrast, experimentally it was observed that the orifice throat was rougher than the face. The effect of roughness is to increase the turbulence and thus decrease the viscous sublayer thickness and therefore increase particle deposition. Therefore, the inclusion of roughness would tend to improve the quantitative agreement between theory and experiment. It should be emphasized that experimental evidence indicates that roughness is not the key parameter which governs preferential particle deposition within the orifice throat. Fig. 4A illustrates negligible particle deposition on a rough uncoated orifice throat region. In contrast, deposition was observed on smoother 2VP/St coated orifice throat locations, Fig. 4B.

CONCLUSIONS

The developed analysis can be employed to describe the initial deposition of colloidal particles from a dilute suspension flowing through a conduit under turbulent flow conditions when the electrical interaction length is much smaller than the thickness of the diffusion sublayer. Typically, when the conduit and particles are of Stern potentials of like sign and the net potential curve possess a repulsive maximum, deposition to first order is uniform and controlled entirely by electrical interactions. In contrast, when conduit and particles are of different sign Stern potentials, deposition is often independent of electrical interactions and described solely by Brownian diffusion through the diffusion sublayer. In this situation, an appropriate turbulence and turbulence damping model is required to determine the thickness of the diffusion and viscous sublayers as a function of conduit geometry.

The presented theory, employing Harwell-Flow3D turbulence modeling software qualitatively

describes experimentally observed particle deposition onto 2VP/St coated and uncoated glass orifice regions. Negligible particle deposition was observed on uncoated regions where the theoretical net electrical interaction potential has a repulsive maximum. The theory also appears to qualitatively explain differing extents of particle deposition observed within the orifice throat and on the orifice face. Quantitatively, the theory may over predict particle deposition on the orifice face. An experimental condition was determined in which silica particles preferentially deposited within the orifice throat. The theoretical net electrical interaction potential, determined from second hand measurements of experimental properties, is always attractive for this experimental condition.

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Table 1. Surface Zeta Potentials from Fig. 5 and Run III-4 of (4).

[NaCl]	$\zeta_{2VP/Si}$	ζ_{Silica}
$3 \times 10^{-4} \text{ M}$	32 mV	-100 mV

Fig . 1 Orifice Cross Section

* all dimensions are in meters

Fig.2. Orifice Face Run 1

(A) overview (18x)

(B) position 1 2VP/St coated (2,500x)

(C) position 2 uncoated (2,000x)

Fig. 3. Orifice Face Run 2

(A) 500x

(B) 2,000x

(C) 10,000x

Fig. 4. Orifice Throat Run 1

(A) uncoated (2,100x)

(B) 2VP/St coated (2,000x)

Fig. 5. 2VP/St Coated Throat, Run 2

(A) near face (1,800x)

(B) downstream (1,900x)

Fig . 6 Orifice Particle Deposition Fluxes
for 2VP/St Coated Locations

Symmetry Plane

Location	Flux [particles/ (m ² sec)]
1	1.2×10^7
2	1.5×10^7
3	1.9×10^7
4	1.7×10^7
5	1.5×10^7
6	1.2×10^7
7	1.2×10^7
8	1.2×10^7

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