A direct method for studying particle deposition onto solid surfaces

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Abstract: An experimental technique has been developed to study the deposition of colloidal particles under well controlled hydrodynamic conditions. The deposition process is observed under a microscope and recorded on video tape for further analysis. Fluid flow conditions in the experimental set-up were determined by numerical solution of the Navier-Stokes equations. Mass transfer equations were solved numerically (taking into account hydrodynamic, gravitational, electric double layer, and dispersion forces) for the stagnation point region. Also, some analytical solutions are presented. Deposition has been studied of 0.5 μm polystyrene latex particles on cover glass slides used as collectors. From an analysis of the shape of the coating density vs. time curves and independently from the distribution of the particles on collector surfaces, it was found that one particle is able to block an area of about 20 to 30 times its geometrical cross-section. The initial flux of particles to the collector for a given salt concentration was found to depend strongly on the method of cleaning the collector surface. In general the flux and the escape of particles to and from the collector surface are sensitive to the interaction energy at small separations. The direct method of observing particle deposition and detachment could lead to important insights into the nature of particle-wall interactions at near contact.

Key words: Particle deposition, stagnation point flow collector.

I. Introduction

The process of coating solid surfaces by colloidal particles is strongly affected by the hydrodynamic conditions prevailing in the vicinity of the solid surface. Particles deposited on the surface as a result of capture in a primary energy minimum have a finite probability of escape from the surface because of their thermal motion or random forces in case of turbulent flow [1, 2]. Hence coating is in general a dynamic process. The flux of particles towards a solid surface (often referred to as collector) depends on the concentration distribution of particles which depends on the fluid flow field in the vicinity of the collector. Theoretical calculations show that very close to the collector surface the particle concentration may exhibit a maximum, especially when a secondary minimum exists [3, 4].

In commonly used methods of studying particle deposition the prevailing hydrodynamic conditions are changed when the surfaces with deposited particles are examined. This happens e.g. when surfaces are rinsed and dried after an experiment in order to prepare them for microscopic observations. Also, observing the deposition of radioactively traced colloidal particles may cause experimental problems due to the fact that it is difficult to distinguish between deposited particles and slowly moving ones close to the wall.

Information about the behaviour of particles very close to the wall is of great practical and theoretical importance because existing theories describing particle-wall interactions in colloidal systems are only approximate. This is because continuum theory at short particle-wall separations breaks down and because the influence of microroughness becomes an essential factor. As yet only qualitative models exist explaining the origin of the tangentional forces which keep particles at a fixed position on the surface after deposition, despite the hydrodynamic forces exerted on them. As was noted in [5], allowing for particle mobility in the primary minimum region can have a large effect on the coating density and on the kinetics of coating.

These phenomena can best be studied in systems in which the deposition process can be directly observed in the original flow field. The aim of this paper is to present a method which allows a direct observation of
the deposition process as well as some experimental
data obtained with this method. A convenient collector
that is often used in experimental and theoretical
studies of deposition of colloidal particles is the
rotating disk [6-9]. Its major advantage is that for this
system the diffusion boundary layer thickness is
constant. A disadvantage is that during an experiment
the disk moves which makes it very hard to directly
observe the deposition process. The thickness of the
diffusion boundary layer is also constant for a stagna-
tion point flow.

This paper describes a method for studying particle
deposition in a stagnation point flow. Such a system
has the same advantages as deposition on a rotating
disk, but it has the additional advantage that the
collector surface is stationary and, when transparent,
deposition can be observed directly by microscopic
means. In order to produce a stagnation point flow we
constructed a cell consisting in essence of two plates,
the lower one having a circular hole to which a circular
tube was connected. A flow through this tube creates a
stagnation point flow near the upper surface facing the
tube exit.

The organization of this paper is as follows. In
section II we describe the flow field in the cell,
obtained by a numerical solution of the Navier-Stokes
equations. After presenting the general solution, it is
shown that near the stagnation point the flow is a true
stagnation point flow, the strength of which depends
on the mean value of flow velocity and cell dimen-
sions. In section III we make theoretical predictions of
mass transfer rates in stagnation point flow. In section
IV the experimental procedure is described in detail
and in section V results of deposition experiments are
presented and discussed.

II. Fluid flow field

(a) General solution

The flow due to a jet spreading out over a plane
surface has been discussed by Glauert, who derived an
expression for the velocity components of an axisym-
metric wall jet [10]. However this expression breaks
down for distances close to the stagnation point, a
region in which we are primarily interested. Because
of this we cannot use the results in [10] to analyze data
on colloidal particle deposition. In order to describe
the hydrodynamic conditions near the collector sur-
face accurately, we have to solve the fluid flow
equations numerically. Figure 1 shows in detail the
geometry of the system. The radius of the tube is
denoted by \( R \) and the distance between the top and
bottom plate by \( h \).

We assume that the fluid is incompressible and
Newtonian and we restrict ourselves to laminar and
steady flow. The governing equations are the Navier-
Stokes and the continuity equations. Due to symme-
try of the system it is convenient to introduce the
vorticity \( \omega \) and the stream function \( \psi \), which are
defined (in dimensionless form) by:

\[
\omega = \frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r} \tag{1}
\]

\[
v_z = \frac{1}{r} \frac{\partial \psi}{\partial r}; \quad v_r = -\frac{1}{r} \frac{\partial \psi}{\partial z}. \tag{2a} \tag{2b}
\]

The cylindrical coordinates \( z \) and \( r \) are non-dimen-
sionalized by the tube radius \( R \) and \( v_z \) and \( v_r \) with
respect to the average velocity \( U \) at the exit plane
\( z = h \) (plane II). Substituting (1) and (2) into the
Navier-Stokes equation results in a system of two
non-linear elliptic equations:

\[
\bar{\omega} = \frac{1}{r^2} \left[ - \left( \frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial z^2} \right) + \frac{1}{r} \frac{\partial \psi}{\partial r} \right] \tag{3}
\]

\[
r^2 \left[ \frac{\partial}{\partial z} \left( \bar{\omega} \frac{\partial \psi}{\partial r} \right) - \frac{\partial}{\partial r} \left( \bar{\omega} \frac{\partial \psi}{\partial z} \right) \right] - \frac{1}{Re} \left[ \frac{\partial}{\partial z} \left( r^3 \frac{\partial \bar{\omega}}{\partial z} \right) + \frac{\partial}{\partial z} \left( r^3 \frac{\partial \bar{\omega}}{\partial r} \right) \right] = 0 \tag{4}
\]

Fig. 1. Geometry of stagnation point flow cell. Fluid moving
upward in tube of radius \( R \) enters between two flat plates I and II, a
distance \( h \) apart. The stagnation point, located on the axis of
symmetry and plane I, is the origin of a cylindrical coordinate
system \( r, z \) and \( \phi \) (\( \phi \) not shown).