EFFECTS OF SURFACE PROPERTIES OF COLLECTORS ON THE REMOVAL OF CHARGED AND UNCHARGED PARTICLES FROM AEROSOL SUSPENSIONS

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ABSTRACT

The literature on the adhesion of particles impacting on solid and liquid collectors was reviewed. Different forces or mechanisms affecting collision and adhesion of particles with collectors were described. Good qualitative agreement existed between experiment and theory in the case of solid collectors, although the presence of and variation in surface asperities prevented good quantitative agreement. For liquid collectors, disagreements both theoretical and experimental abounded in the literature on the ability of such collectors to collect non or partially wettable particles. The use of charge on drops in particulate control devices has been shown to greatly enhance the collection of fine particles. However, data indicate that too high a charge may lead to a decrease in efficiencies due to Rayleigh instability of the drops and charge exchange between particles and drops. A program of experimental and modelling studies is proposed to resolve these difficulties in order to be able to optimize control of particulate emissions for fine particles.

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LIST OF SYMBOLS

A	drop radius
A_H	Hamaker constant
a	particle radius
B	particle mobility
C	slip correction factor
D_B	Brownian diffusivity
D_e	eddy diffusivity
D_f	fluid eddy diffusivity
D_p	particle diffusivity
d_{vg}	diffusion coefficient of vapor in gas
d_p	particle diameter
E	electric field
E_c	collection efficiency
E_s	surface energy
e	adhesion efficiency
F_c	capillary force
F_e	electrostatic force
F_{ec}	Coulombic force
F_{edl}	electrical double layer force
F_{el}	electrical force
F_{ext}	external force
F_g	gravitational force
F_i	image force
F_{vdW}	Van der Waals force
f_e	dimensionless radial component
$F_e\theta$	dimensionless angular component
g	gravitational acceleration
h	flattening of sphere
J	particle flux
K_C	Coulombic electrostatic parameter

K_D	diffusiophoretic factor
K_e	dimensionless electrostatic parameter
K_S	Stokes parameter
K_T	thermophoretic factor
k	Boltzmann constant
k_d	diffusion slip coefficient
k_y	sum of bulk mechanical properties of particle and surface
L	characteristic length
ln	natural logarithm
m_g	molecular mass of gas
m_p	particle mass
m_v	molecular mass of vapor
n	particle number concentration
n_i	number of molecules per unit volume for body i
Q	charge on sphere or drop
q	particle charge
R	radius of sphere or tube
r	radial coordinate
S	initial contact area of particle
T	temperature
t	time
U	contact potential difference
U_o	free stream velocity
$\vec{u}$	fluid velocity
V	velocity of drop
V_{12}	interaction energy between two molecules
v_c	critical velocity for particle bounce
v_D	diffusiophoretic velocity
v_F	particle velocity induced by external forces
v_{pn}	minimum normal velocity for particle penetration into drop
v_∞	settling speed
v_S	velocity due to Stefan flow
v_T	thermophoretic velocity
$\vec{v}$	particle velocity
y_c	critical separation resulting in a grazing trajectory

z	distance between nearest surfaces of two bodies
z_o	minimum separation between surfaces
β_{12}	London interaction constant
ε	collision efficiency
ε_a	permittivity of air
$\varepsilon_i(i\xi)$	dielectric constant of material i along the imaginary axis
ε_{im}	collision efficiency due to impaction
ε_{in}	collision efficiency due to particle size
ε_m	weighted mean of static dielectric constant of adhering bodies
π	pi
ϕ	electron affinity
σ	charge density
σ_t	surface tension
ρ	fluid density
ρ_p	particle density
ρ_v	vapor density
η	dynamic viscosity
θ	contact angle
$\hbar\omega$	Lipshitz interaction constant
τ	relaxation time of particle
γ	Euler's constant (= 0.5772$\cdots$)
γ_T	ratio of the thermal conductivities of the fluid to the particle
ν	kinematic viscosity of the fluid

SECTION 1

INTRODUCTION

The amount of suspended particles in the atmosphere has very significant impacts on the environment (NRC, 1980). Variability in the atmospheric aerosol affects the earth's climate through modifications of the earth-atmosphere radiation budget and the availability of condensation and ice nuclei necessary for cloud formation. Adverse biological and material impacts (e.g., sulphuric acid, smog) are caused by the physical and chemical characteristics of the aerosol. Anthropogenic activities (e.g., coal-fired boilers, automobiles) have led to the release of significant amounts of particles into the atmosphere. Increases in the fine (1 μm radius) particle content of the air poses possible serious health hazards because particles in this size range can penetrate into the deepest reaches of the lungs. In addition, visibility is significantly degraded by the presence of minute amounts of fine particles (Friedlander, 1977).

Both natural and anthropogenic sources contribute to the particulate loading of the atmosphere. The former sources are estimated to contribute approximately 2×10^{12} kg/year (Butcher and Charlson, 1972). This total includes wind-blown and volcanic dusts, emissions from natural vegetation such as pollen, spores, pine scents, and sea spray. The latter emissions are primarily from industrial and automobile emissions, and dust from anthropogenic activities such as mining and construction is estimated to be about 3×10^{11} kg/year. Although the relative contribution of anthropogenic sources to total mass loading is small, the effects are significant and largely detrimental. These effects may be localized as in air pollution (e.g., smog) and decreased visibility (haze) or widespread as in acid rain.

The establishment of the National Ambient Air Quality Standards based on the total suspended particulate mass in 1971 has led to a significant reduction in the total mass of suspended particles. Several particulate control devices have been primarily responsible for this reduction in anthropogenic emissions. They include fabric filters, electrostatic precipitators, and scrubbers. These devices are very efficient in removing particles larger than 1 μm radius, which make up the major bulk (mass) of the emissions. However, all these devices have a minimum in collection efficiencies in the particle size range of 0.1 to 1 μm (NRC, 1980). Hence, even though large reductions in the total mass of the emissions have been achieved, the control of fine respirable particles (0.1 to 1 μm radius) has been deficient.

Recent studies have suggested, however, that the collection of fine particles can be greatly enhanced by utilizing electrostatic forces in particulate

control devices (Drehmel, 1977). For example, charging the particles in a spray scrubber increased the efficiency of collection for 0.3 μm particles from 35 to 87% (Pilat, 1975). While there is considerable promise for the use of electrostatic forces for the collection of fine particles, there are a number of serious problem areas. For example, the literature suggests that adhesion forces between the particles being collected and collector surfaces are extremely important for wet collectors. Contradictory evidence exists, however, concerning the nature of this interaction and the role of surfactants in enhancing or inhibiting the collection of fine particles by wetted surfaces. Also, no adequate model exists to explain the observed behavior of a charged or uncharged particle coming into contact with a charged or uncharged droplet.

SECTION 2

SUMMARY AND RECOMMENDATIONS

Optimization of particulate control devices requires a clear understanding of the basic collection process involved. The placement of charge on collection surfaces in particulate control devices shows great promise for the efficient control of fine particulates. However, the processes affecting the adhesion of particles after collision with the collecting surface are not well understood. The particle adhesion problem can be treated as a surface energy problem. The difficulty is in determining quantitatively the contribution of the various adhesive forces. For the case of a solid collecting surface, the major difficulty is in the modelling of surface asperities and deformation of the particles, although good qualitative agreement between theory and experiment has been achieved. Even though further refinements in the theory are foreseeable, the variation of microscopic asperities with different collectors is a major barrier to the particle theory that could give good quantitative results.

Particulate collection by liquid collectors is a substantially different problem. Instead of deformation of the particle, the surface is deformed. In addition, the liquid surface has no asperities. For wettable particles, the primary factors in the adhesion of particles to the liquid surface are capillary forces. For nonwettable particles, other forces can affect particle capture. However, the literature on this area abounds with contradictions in both theory and experiment. The addition of surfactants to the collecting liquid would increase the wettability of the impacting particles and hence would be expected to increase particle adhesion or collection; however, experimental data have not been definitive. In addition, the use of charge to increase collection efficiencies in control devices (e.g., charged droplet scrubbers) has not been as effective as theorized. Formation of a coating of nonwettable particles on the drop surface, Rayleigh instability of highly charged drops, and charge transfer between particles and drop may be contributing factors.

Since the reduction of fine particulate emissions is an important goal, these contradictions in the literature on the collection of particles by liquid collectors should be resolved. To resolve these contradictions and to gain a clearer understanding of the basic collection process, which is needed for the optimization of particulate control devices, the following studies are recommended:

1. Adhesion and Collection Efficiency: Experiments should be conducted to determine the collection efficiency of charged drops (50 to 200 μm radius) falling at terminal velocity for charged and uncharged fine particles

(0.1 to 1 μm radius). The charge on both drops and particles should be varied to study effects of different amounts of charge in relation to Coulomb and image forces. Volatile (water) and nonvolatile (e.g., Dow Corning 200) drops should be used to differentiate phoretic and surface property effects. Hydrophilic and hydrophobic particles should be used to discriminate the effects of wettability on particle adhesion. Effects of particle shape and roughness should also be included. The adhesion efficiency can then be derived from the ratio of the experimental collection efficiency to the theoretical collision efficiency.

2. Wettability: A separate experiment should be conducted to determine the relative wettability of the particles used in the experiment and the effects of size and roughness on wettability. In addition, the net adhesion force acting on a sphere near a drop surface should be measured to help in clarifying the model developed for particle adhesion.

3. Collision and Adhesion Efficiency: For comparison with the data obtained from the above experiments, the collision efficiency of drops for particles should be modelled, taking into account electrostatic Coulomb and image forces, inertial impaction, phoretic forces, and Brownian diffusion. Convective diffusion and trajectory computations should be used to obtain the collision efficiencies with analytical and numerical flow fields. A comprehensive modelling of the dynamics of the impaction process, including the dynamics after coalescence has occurred, should be conducted to determine the important factors affecting adhesion.

4. Charged Particle Collection by Charged Drops: The factors optimizing particle collection should be determined by a study of the effects of charged drop instability and charge transfer between particle and drop on collection.

SECTION 3

ADHESIVE FORCES

ADHESION OF PARTICLES TO SURFACES

The problem of adhesion has been studied by numerous investigators both experimentally and theoretically. Several review papers in this field are available in the literature (Corn, 1966; Krupp, 1967; Zimon, 1969; Visser, 1972; Deryagin *et al.*, 1978). The adhesion of particles to a solid or liquid surface or the "cohesion" of a particle to another is subject to several kinds of forces. These forces include the Van der Waals, electrical double layer, capillary, electrostatic, and gravitational forces. These forces are determined to a large extent by the properties of the adhering surfaces and the surrounding medium. A brief review of the nature and magnitude of these forces will be helpful in determining their relative contributions to the adhesion of particles. The review will concentrate on the problem of interest: particle adhesion to flat or spherical surfaces in air.

Van der Waals Force

Electrical field interactions between or among molecules result in attractive Van der Waals forces. These forces are usually differentiated into orientation, induction, and dispersion forces, which are due to dipole-dipole, dipole-induced dipole, and induced dipole-induced dipole interactions, respectively (Krupp, 1967). For two interacting molecules, the energy of interaction is

$$V_{12} = -\beta_{12}/r^6 \tag{1}$$

where β_{12} is the London interaction constant (London, 1937). For the case of macroscopic bodies, two theoretical methods have been developed for estimating the Van der Waals forces. The microscopic approach entails the estimation of the Hamaker constant for all the interacting molecules in the adhering bodies. The Hamaker constant is given by

$$A_{H12} = \pi^2 n_1 n_2 \beta_{12} \tag{2}$$

where n_1 and n_2 are the number of molecules per unit volume for the two interacting bodies. The macroscopic approach of Lifshitz (1956) treats the Van der Waals forces as the result of the interaction of the fluctuating electromagnetic field in the adhering bodies. The Lifshitz interaction constant is

$$\hbar\omega_{132} = \hbar \int_0^\infty \frac{\varepsilon_1(i\xi) \quad \varepsilon_3(i\xi)}{\varepsilon_1(i\xi) + \varepsilon_3(i\xi)} \times \frac{\varepsilon_2(i\xi) \quad \varepsilon_3(i\xi)}{\varepsilon_2(i\xi) + \varepsilon_3(i\xi)} \, d(i\xi) \tag{3}$$

for two bodies (1 and 2) separated by a medium (3), where $\varepsilon j(i\xi)$ is the dielectric constant of material j along the imaginary frequency axis i (Lifshitz, 1956). In vacuum $\varepsilon 3(i\xi) = 1$ and the Lifshitz interaction constant is related to the Hamaker constant by

$$A_H = 3\hbar\omega/(4\pi) \tag{4}$$

The latter approach is considered to be more accurate since fewer assumptions are used. A comparison shows the Hamaker constants are larger than the Lifshitz constants by about 10-25% (Nir, 1976). Values of the Hamaker constants range from 0.03 180 x 10^{-13} erg (Visser, 1972; Nir, 1976), with 6 180 x 10^{-13} erg for ionic crystals, 14 46 x 10^{-13} erg for metals, 1 100 x 10^{-13} erg for hydrocarbons, and 5 - 45 x 10^{-13} erg for polymers (Visser, 1972).

For two spheres of radii R_1 and R_2 separated by a distance z, the Van der Waals force is given by

$$F_{vdW} = \frac{\partial}{\partial z}\left[-\frac{A_H}{12}\left\{\frac{p}{w^2+wp+w} + \frac{p}{w^2+wp+w+p} + 2\log\frac{w^2+wp+w}{w^2+wp+w+p}\right\}\right] \tag{5}$$

where w $z/(2R_1)$, $p = R_2/R_1$, $R_1 < R_2$ (Nir, 1976). For the case of a sphere of radius R_1 and a semi-infinite slab, the force is obtained from the above equation by taking the limit $R_1/R_2 \to 0$, obtaining

$$F_{vdW} = -A_H R_1/(6z^2) \text{ for } z \ll 1 \tag{6}$$

In general, the Van der Waals force between two surfaces is proportional to $z^{-(m)}$ where m is the power law dependence (Israelachvilli and Tabor, 1973). The above equations are valid for z < 200A. For larger separations, a retardation effect occurs due to the finite time required for the interaction of the electromagnetic fields (Krupp, 1967). The retarded force decreases as $(z)^{-(m+1)}$. This is illustrated in Figure 1 where the force between two mica surfaces was measured for different separations. The power law dependence of the force changes from m to m+1 at about z = 200A.

Electrical Double Layer Force

These forces are due to the contact potential difference between the adhering bodies (Krupp, 1967). The contact potential difference is the difference between the electron affinities of the two contacting bodies, i.e.,

$$U = \phi_1 - \phi_2 \tag{7}$$

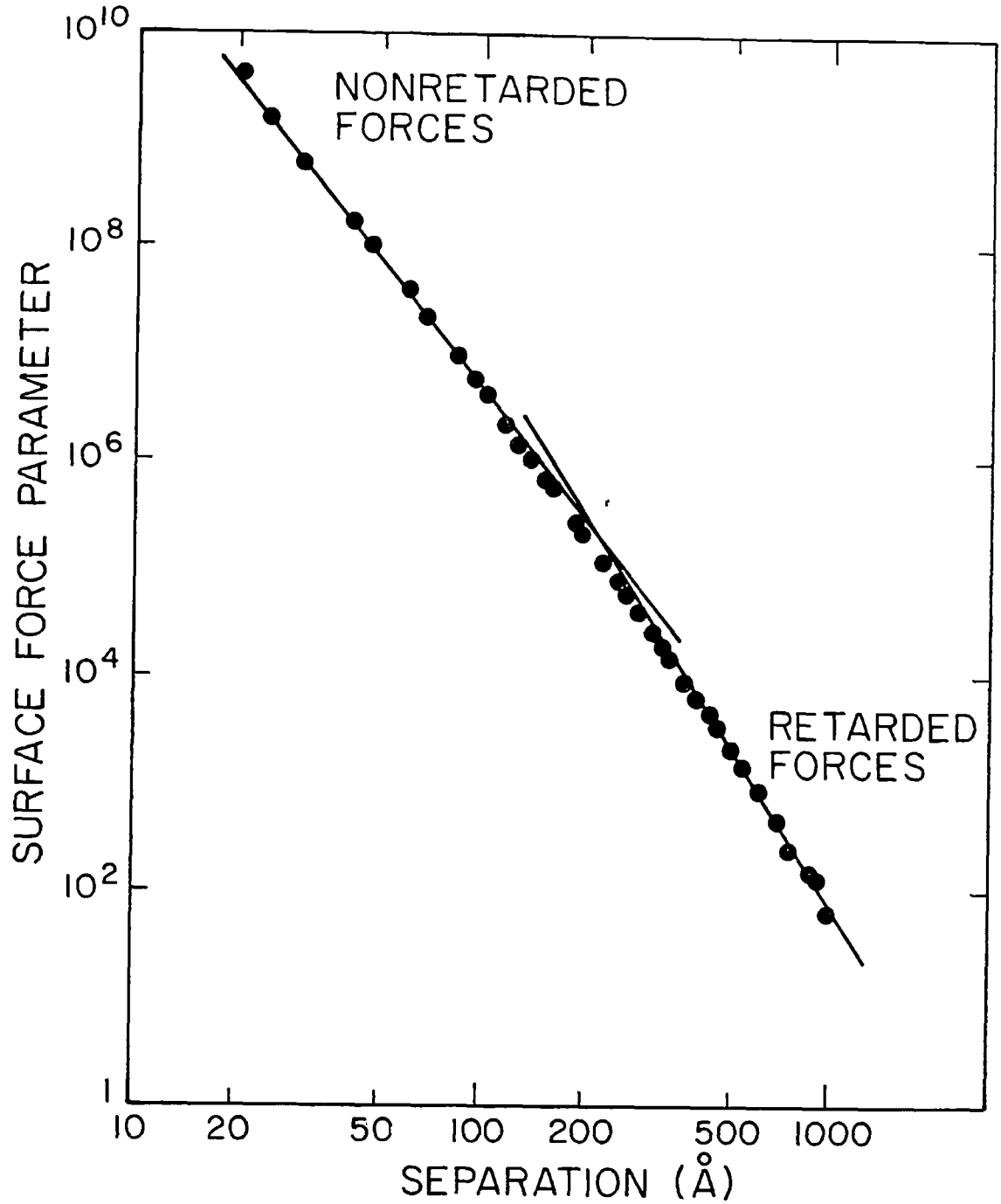

Figure 1. Experimental variation of the force between two curved mica surfaces as a function of separation. The force parameter is such that the slope has a gradient (m+2) where m is the power law dependence of the force (Israelachvilli and Tabor, 1973).

For metals, σ, the surface charge density is related to the contact potential by

$$\sigma = \varepsilon_a U/z \tag{8}$$

where ε_a is the permittivity of air. For the case of a conducting particle near a grounded conducting half-space, the attractive force assuming a constant potential difference U is

$$F_{edl} - \pi\varepsilon_a RU^2/z \quad \text{for } z << R \tag{9}$$

Capillary Force

Different substances have varying degrees of affinity for water molecules. Hygroscopic particles have a tendency to absorb water vapor even at relatively low humidities and form a solution on the surface. These particles will be completely wettable with $\theta = 0°$ (see Equation 10). Non-hygroscopic particles can be hydrophilic and have varying degrees of wettability but do not necessarily strongly absorb water. Hydrophobic particles are nonwettable and have little or no affinity for water.

In conditions of high humidity, condensation causes a liquid film to be formed between a hygroscopic particle and the surface. For cases where the adhesion between the particle and surface is small, the presence of the capillary film may dramatically increase the particle adhesion to the surface, especially for hydrophilic surfaces. The adhesive force is given by

$$F_c = 4\pi\sigma_t R \cos\theta \tag{10}$$

where σ_t is the surface tension of the liquid and θ is the contact angle (Zimon, 1969). The presence of the capillary force is shown in Figure 2, where the force of adhesion increased with humidity.

Electrostatic Force

The effect of charges placed on an insulating half-space has been determined by Krupp (1967) to be negligible compared to charges induced by contact potential differences. For the case of a conducting half-space, an opposite charge will be induced on the surface, resulting in the attractive image forces given by

$$F_{el} = Q^2/(16\pi\varepsilon_a(\gamma + \ln(2R/z))^2 Rz/2) \tag{11}$$

where γ is Euler's constant (Krupp, 1967). For nonconducting bodies the force will be smaller and can be approximated by

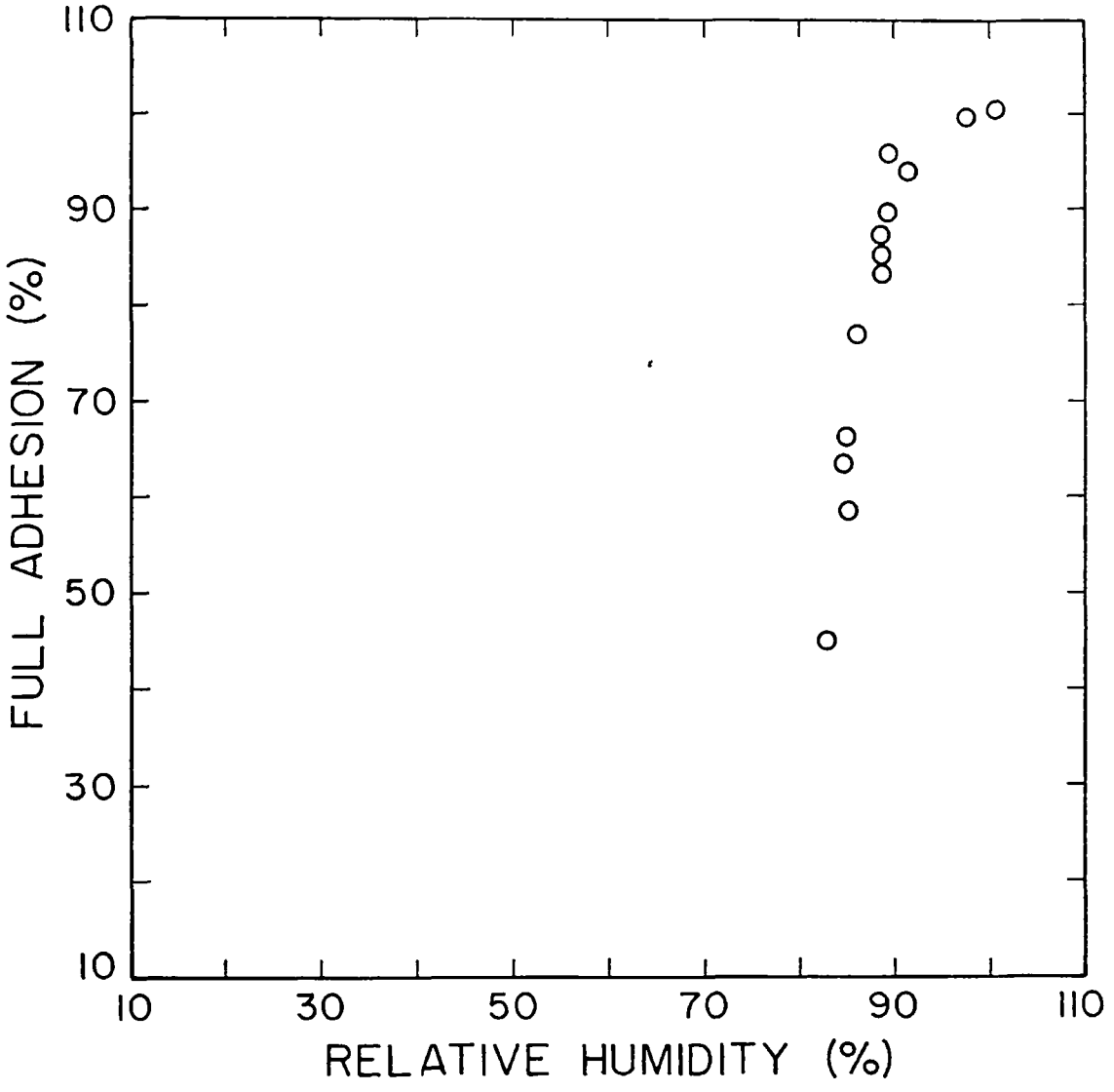

Figure 2. Adhesion of glass spheres to glass slides as a function of relative humidity (Bowden and Tabor, 1954).

$$F_{el} \quad \frac{Q^2}{16\pi\varepsilon_a R\delta} \frac{\ln(1+\delta/z)}{(\gamma+\ln(2R/z)/2)(\gamma+\ln(2R/(z+\delta))/2)} \tag{12}$$

where δ is the sum of the boundary charge density layers of the sphere and half-space (Krupp, 1967). Values range from 0 to 1 μm (Krupp, 1967). For conductors δ is zero and Equation (12) reduces to (11). After contact, the maintenance of this electric force will depend on the resistance of the particle and the contact resistance. For total resistance less than 10^3 ohms, particles will fail to hold their charge (Zimon, 1969).

Gravitational Force

Particles are subjected to the earth's gravitation, resulting in the force given by

$$F_g = -mg = -4\pi R^3 \rho_p g/3 \tag{13}$$

where ρ_p is the particle density. Gravitational attraction between two adhering bodies is much smaller than this force and hence can be ignored.

Other Forces

The forces described above may be termed long-range forces, compared to the short-range nature of such forces as chemical bonding, sintering, diffusive mixing, or alloy formation (Krupp, 1967). Chemical bonding between adherents is a rare occurrence (Krupp, 1967), since the interacting surfaces are usually chemically saturated, e.g., oxide layers. Sintering, diffusive mixing, and alloy formation usually require elevated temperatures. Not much theory or data are available on these forces, and since they are believed to be of no great significance in most adhesion problems (Krupp, 1967), they will not be included in the discussions below.

Relative Importance of Forces

The magnitudes of the Van der Waals, electrical double layer, capillary, electrostatic, and gravitational forces for different particle sizes are shown in Table 1. The values of the Lipshitz constant and contact potential used are in the higher range of values. The particle charge Q corresponds to values obtained by diffusion charging (Liu and Pui, 1977) for particles smaller than 1 μm radius. For larger particles, a saturation charge associated with a field strength of 20 kv/cm is used. A nominal value of 65 dynes/cm for the surface tension of water is used. From Table 1, it is evident that electrostatic forces are significant for particles larger than 10 μm and gravitational forces become significant only for particles larger than about 1 mm. For wettable or partially wettable particles, capillary forces, if present, are dominant. Otherwise, Van der Waals and electrical double layer forces are dominant.

TABLE 1. ADHESIVE FORCES IN MILLIDYNES FOR DIFFERENT PARTICLE SIZES

Particle Radius (μm)	Van der Waals $\frac{\omega R}{8\pi z^2}$	Electrical Double Layer $\frac{\pi\varepsilon_a R U^2}{z}$	Capillary $4\pi\sigma_t R \cos\theta$	Electrostatic $\frac{Q^2}{16\pi\varepsilon_a[\gamma+0.5\ln(2R/z)]^2 Rz}$	Gravitational $\frac{4}{3}\pi R^3 \rho g$
10,000	160,000	43,000	580,000	450,000	8,200,000
1,000	16,000	4,300	58,000	4,500	8,200
100	1,600	430	5,800	45	8.2
10	160	43	580	0.45	0.0082
1	16	4.3	58	7.1×10^{-3}	8.2×10^{-6}
0.1	1.6	0.43	5.8	3.9×10^{-4}	8.2×10^{-9}
0.01	0.16	0.043	0.58	3.0×10^{-4}	8.2×10^{-12}

Values of variables used are: $z = 4 \times 10^{-4}$ μm, $\hbar\omega = 4$eV, $U = 0.5$eV, $\sigma_t = 65$ dynes/cm, $\theta = 45°$, $\rho = 2$g/cm^3, $g = 980$cm/s^2, $\varepsilon_a = 8.84 \times 10^{-12}$, $Q = 1.6 \times 10^{-19}$C x (particle radius/0.01 μm) for diffusion charging ($R \leq 1$μm), $Q = 1.6 \times 10^{-19} \times 500$ x (particle radius/1μm) for field charging ($R > 1$μm), $\gamma = 0.5772$.

Surface Effects

The discussion above has been for idealized smooth solid bodies. In reality, surfaces possess a certain degree of microscopic or macroscopic roughness. The surface roughness will affect the area of contact and, hence, increase or decrease the adhesion. For example, in Figures 3b and 3c, the surface roughness decreases the area of contact of the particle with the surface and decreases the adhesion, whereas the adhesion in Figures 3d and 3e is increased (Zimon, 1969; Tabor, 1977). In addition to roughness, the adhesion is affected by contact deformation between adhering bodies, which increases the area of contact (Tabor, 1977). Figure 4 shows these effects of surface roughness and degree of contact deformation on the adhesion of rubber spheres. The relative detaching force is measured as a function of the center line average of the asperities which is a measure of the roughness of the surface. For a given rubber sphere the force decreases for increasing roughness (decreasing contact area). With a lower value of the modulus the rubber was softer and deformation was greater. Hence, with the increase in contact area, a greater detaching force was needed.

For the case of the adhesion of solid particles to a liquid surface, surface tension and wettability of the particle (Morishima and Kariya, 1978) will be primary factors, while surface roughness of the particle will be secondary. Alternatively, the effects of all the surface forces can be treated together and the adhesion considered as the result of surface energy (Deryagin *et al.*, 1978), resulting in the force needed to detach particles from the surface as $F = 4\pi R E_s$ where E_s is the surface energy.

The measurement of particle adhesion to a flat surface has been achieved by the use of the centrifuge method, where the force of adhesion is determined from the surface. Due to surface asperities (roughness), not all particles will be detached at a given force. However, reasonable agreement between experiment and theory has been obtained for the force required to remove 50% of the particles on the surface (Krupp, 1967), which is shown in Table 2. The data in Table 2 also show the decrease in adhesion when the roughness of the particle increases. A substantial amount of these data on different particles and surfaces has been obtained using this method (Krupp, 1967). Other methods employed gravitation, vibration, electrostatics, or a microbalance (Visser, 1972). However, this type of experiment generally does not give much insight into the more practical problem of determining whether particles will stick to a surface after impact.

ADHESION OF PARTICLES IMPACTING ON A SOLID SURFACE

Recently, there has been substantial research on particle bounce as applied to impactors. Dahneke (1971, 1972, 1973) modelled particle bounce as a function of the elastic deformation of the particle on impact using Hertzian theory on the deformation. Flattening of a spherical particle was found to contribute an additional term to the Van der Waals forces and the adhesive force was given by

$$F = A_H R \left(1 + A_H^2 k_y R/(54\, z_o^7)\right)/6\, z_o^2) \qquad (14)$$

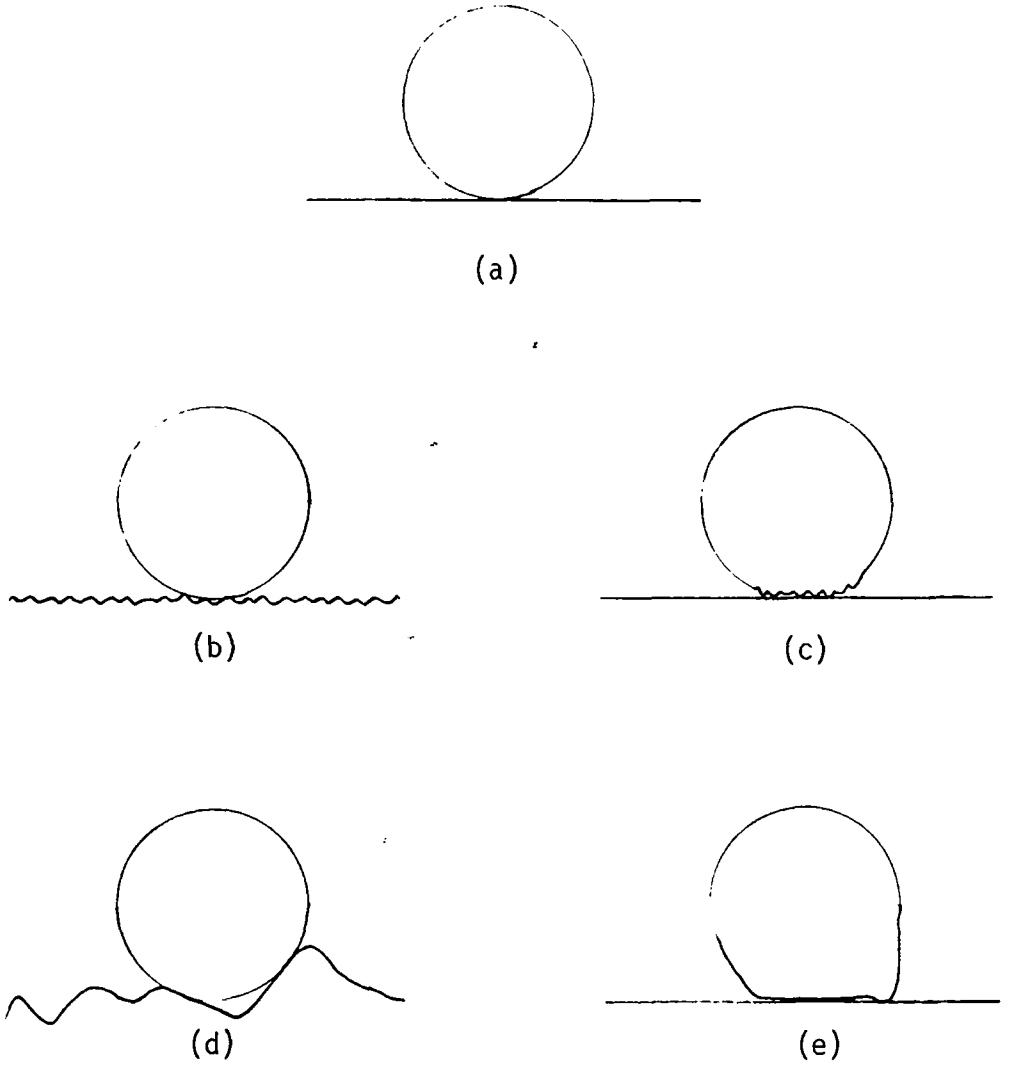

Figure 3. Variation in contact area between particle and surface for different degrees of roughness.

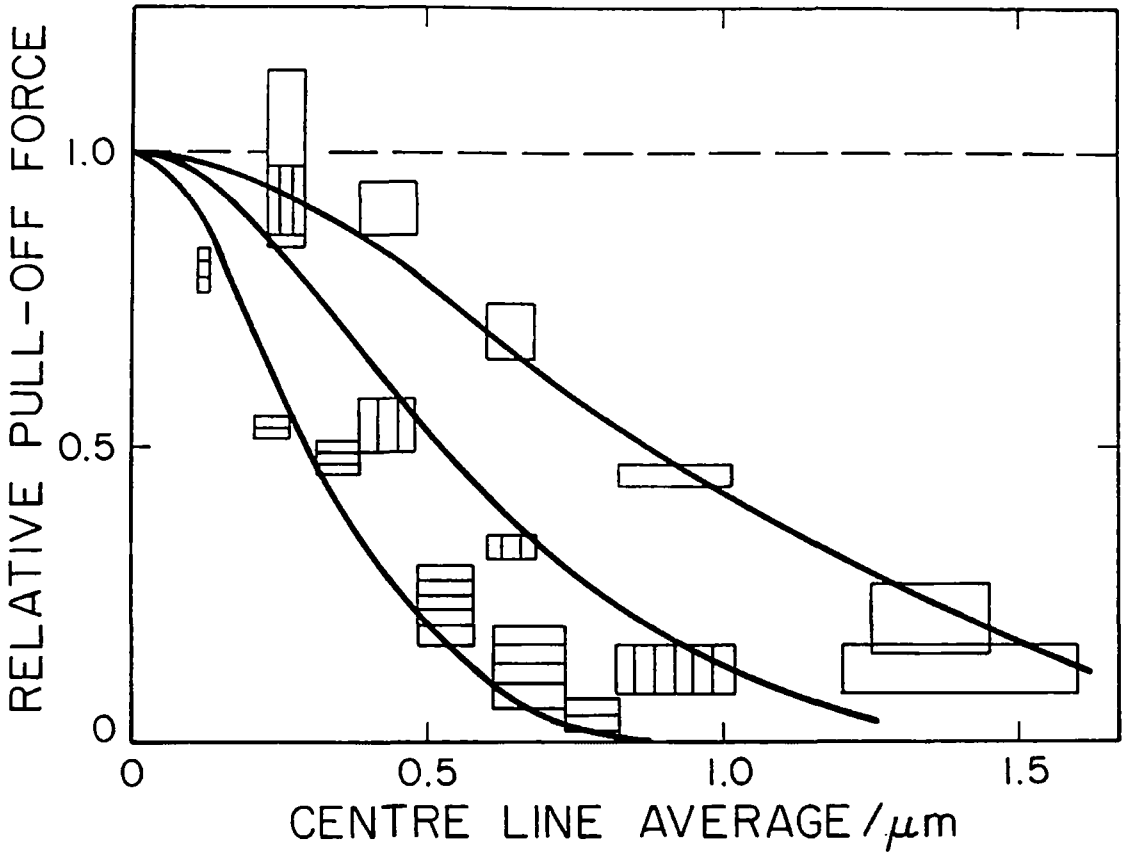

Figure 4. Relative pull-off force for smooth rubber spheres in contact with a flat Perspex surface as a function of the roughness of the Perspex; effects of modulus of the rubber: curve 1, 2.4×10^6 N m^{-2}; curve 2, 6.8×10^5 N m^{-2}; curve 3, 2.2×10^{-5} N m^{-2} (Fuller and Tabor, 1975).

TABLE 2. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL ADHESIVE FORCES USING THE CENTRIFUGAL METHOD (Krupp, 1967)

COMPARISON BETWEEN THEORY AND EXPERIMENT

Particle–substrate	*Particle radius R (μm)*	*Order of magnitude of radii of curvature of asperities (μm)*		*Effective radius R′ (μm)*	*Estimated values*			*Adhesive Force (mdyn)*		*Literature on experiment*
					Hardness (dyn/cm²)		$\hbar\bar{\omega}$ *(eV)*	*calculated*	*median measured*	
		Particle	*Substrate*		*Particle*	*Substrate*				
Fe (reduced)–Fe (reduced)	2	0.7	0.1	0.7	10^9	10^9	8	22	20	
Fe (reduced)–Fe (oxidised)	2	0.7	0.1	0.1	10^9	10^9	8	3	4	Bohme *et al.*, 1962
Fe (oxidised)–Fe (oxidised)	2	0.1	0.1	0.05	10^9	10^9	8	1.5	2	
Au–quartz (rough)	3	0.1	0.1	0.1	10^9	10^9	5	3	11	
(smooth)	3	0.1	0.1	3	10^9	10^9	5	96	100	Böhme et *al.*, 1964
Au–plastic films	3	0.1	0.1	0.1	10^9	10^7	2.5	80	100–250	

where k_y is the sum of the bulk mechanical properties of the particle and the surface. Values of k_y range from 0.436×10^{-12} cm^2/dyne for steel to 27.5×10^{-12} cm^2/dyne for polystyrene (Dahneke, 1972). It was concluded that elastic deformation of particles increases the minimum velocity for particle bounce. Dahneke's results were later confirmed by Esmen *et al.* (1978). The fraction of particles that bounced was found to increase with increasing impaction energy, as shown in Figure 5 for uranine particles impacting on a brass plate. Cheng and Yeh (1979) obtained an empirical relation for the critical velocity for particle bounce where

$$v_c < B \times 10^{-6}/(d_p(\rho_p/\rho_*)^{0.5}) \tag{15}$$

where B is an empirical constant having a value between 2.5 and 9.2, d_p is the particle diameter, ρ_p is the particle density, and ρ_* is unity density. Hence for a given impacting velocity, larger particles are more susceptible to bounce.

However, close examination of Dahneke's theory, which ignores electrical double layer forces by Derjaguin *et al.* (1975), has revealed several major inconsistencies. The more rigorous theory put forward by Derjaguin *et al.* shows that the force needed to detach a particle is independent of the deformation, if electrical double layer forces are not considered. The correct expression for the Van der Waals force was found to be

$$F = A_H R/(6z_o^2) + (4R^{0.5}/(3k_y))h^{1.5} \tag{16}$$

where h is the distance between the penetration of an imaginary undeformed sphere, at the same position as the deformed sphere, into the surface and the closest approach of the deformed sphere to the surface. Hence, the dependence of the force of adhesion on the elastic deformation of the particle is unclear. The dependence of the detaching force on the square of the radius of the particle is actually a result of electrical double layer forces, which depend on the area of contact. According to Deryagin *et al.* (1978), the electrical double layer force between a sphere and a flat plane is

$$F_{edl} < 2\pi\sigma^2 S \tag{17}$$

where S is the initial contact area. An examination of this electrical double layer force and the molecular component of the adhesive force shows that the two are comparable. However, the total energy expended to detach particles is an order of magnitude higher for the electrical double layer force, assuming no neutralization, since this force does not decrease as rapidly with separation as the molecular component of the force. The assumption of no neutralization will hold for dielectric or nonconducting particles. Hence, the factors of significance in determining adhesion or particle bounce on solid surfaces are the electrical double layer and molecular forces, the

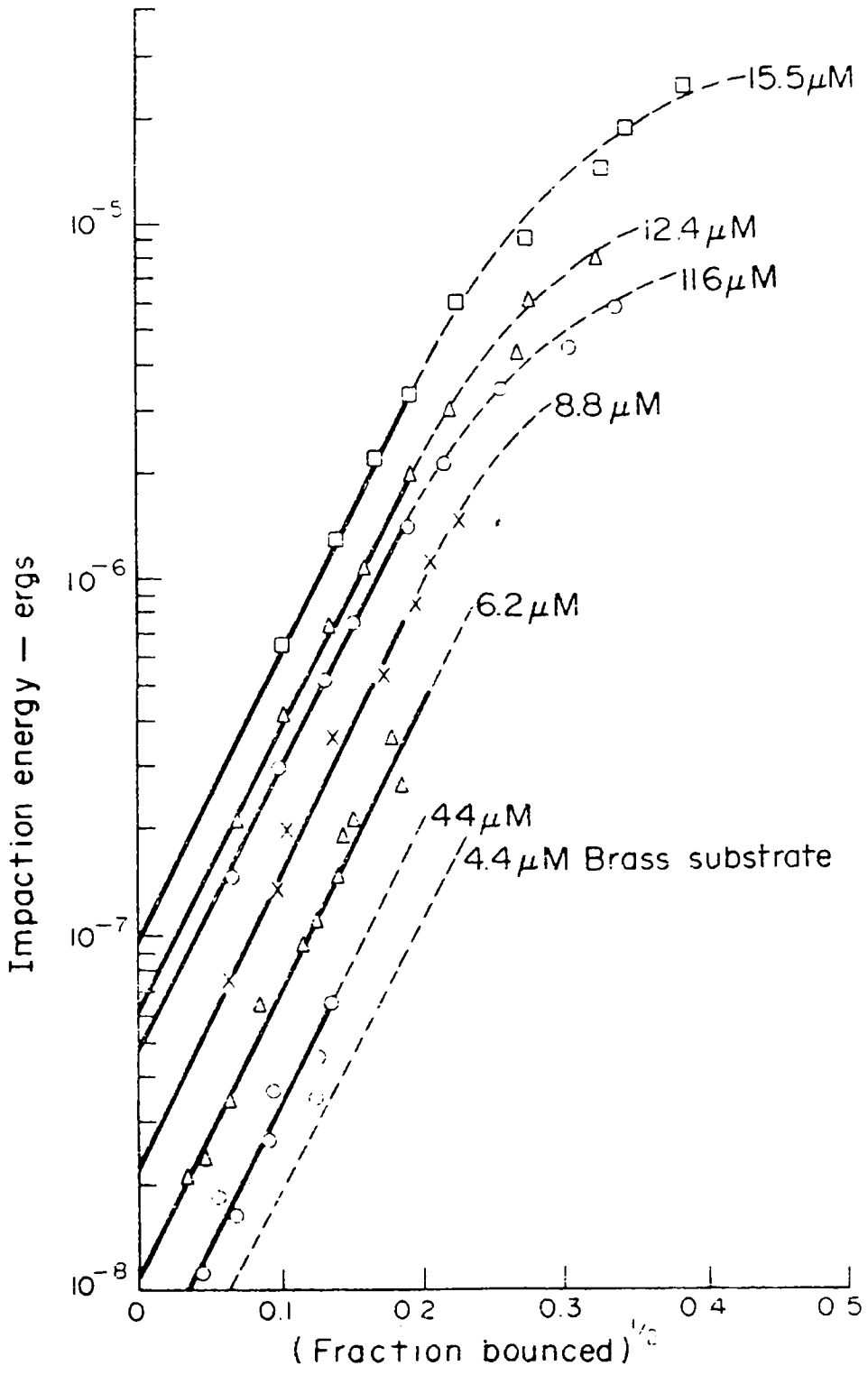

Figure 5. Computed maximum impaction energy and fraction of uranine particles bounced for brass substrate (Esmen *et al.*, 1978).

elasticity or degree of deformation of the particle or surface, the surface textures or characteristics of the contacting bodies, and the velocity of impact.

ADHESION OF PARTICLES IMPACTING ON A LIQUID SURFACE

The process of particle impact on a liquid surface differs considerably from the case for a solid surface. Wettability is the dominant factor, since nonwettable particles may not adhere. Depending on the energy of impact, the liquid surface is deformed considerably. Theory and well-defined experiments on the problem are lacking and contradictions abound in the available literature (Stulov *et al.*, 1978).

The only available measurements on the adhesive force of a liquid drop with different surface curvatures on spheres with varying degrees of immersion into the liquid surface are those of Morishima and Kariya (1978). The force on the particle varied with drop to particle size ratio and contact angle as shown in Figure 6. A larger force was needed to pull the particle from the drop surface for more wettable particles (smaller contact angle). However, this static measurement of the force will not reveal the intricacies of the dynamic process of a particle impacting on the liquid surface.

Deficiencies in Theories on Adhesion of Impacting Particles

Pemberton (1960) treated the problem of the capture of a completely nonwettable particle (θ 180°) impacting on a drop in terms of the ability of a particle to completely penetrate into the fluid. Only surface tension forces were considered, and the particle was assumed to bounce off if complete penetration was not achieved. Different angles of incidence of the particle on the fluid surface were taken into account, and it was found that for complete penetration a particle required a normal velocity to the fluid surface of

$$v_{pn} = (8\sigma_t/(\rho_p d_p))^{0.5} \tag{18}$$

where σ_t is the surface tension of the fluid. McDonald (1963) extended Pemberton's theory to particles with contact angles (θ) less than 180° resulting in

$$v_{pn} = (8\sigma_t \cos(\pi-\theta)/(\rho_p d_p))^{0.5} \tag{19}$$

His computations showed that particles with contact angles less than 90° would penetrate into the fluid. For a completely nonwettable particle (θ = 180°) Equation (19) reduces to (18). Equation (19) shows that a particle with a contact angle less than 180° needs less kinetic energy to penetrate a fluid surface than a completely nonwettable particle. For contact angles less than 90°, v_{pn} is negative. This means that a wettable (θ < 90°) particle need not expend energy to penetrate the drop. Hence, adhesion problems exist only for nonwettable particles with contact angles larger than 90°.

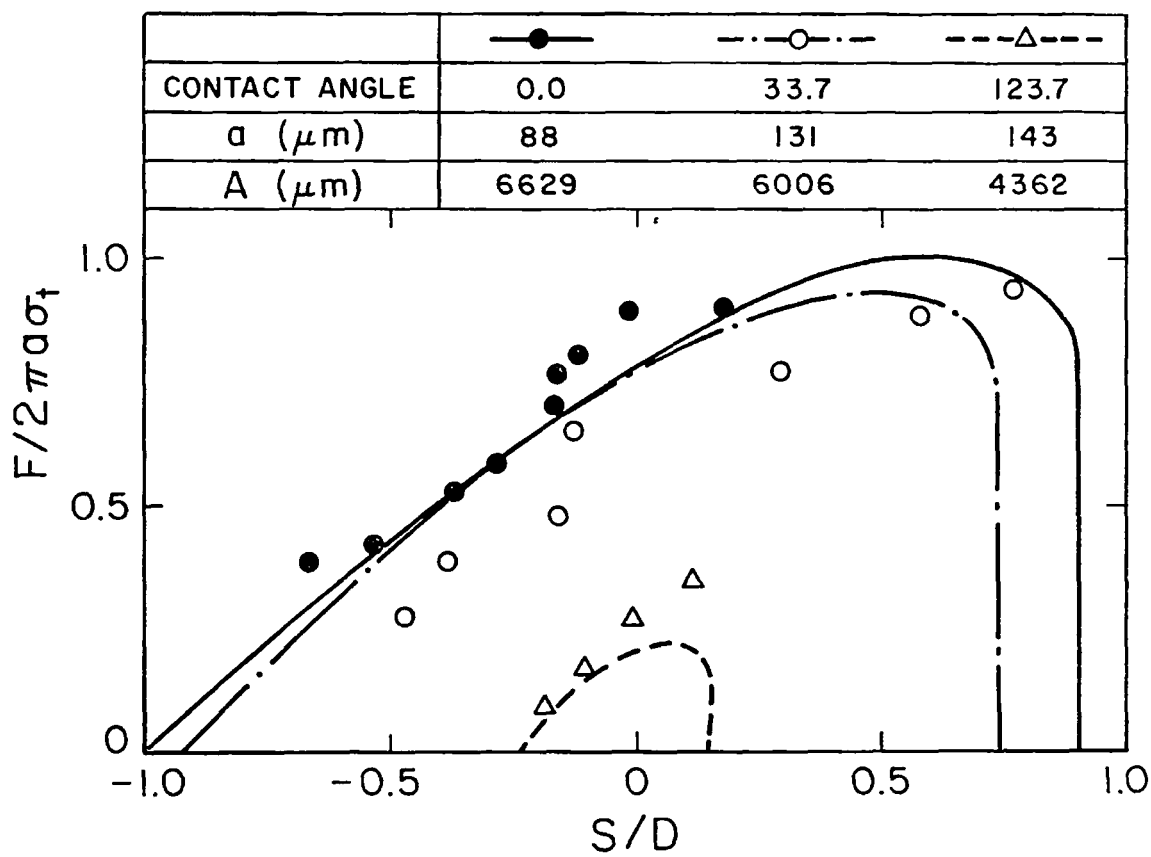

Figure 6. Experimental and calculated values of the force on a particle, nondimensionalized by the surface tension force, as a function of the separation from the drop surface nondimensionalized by the diameter of the particle (Morishima and Kariya, 1978).

The Pemberton-McDonald theory is a rather crude model for predicting particle adherence to a drop and has several deficiencies. Effects not considered by the Pemberton-McDonald theory include the following:

1. For partially wettable particles, some degree of adhesion may occur and the particle may adhere to the surface even if no penetration occurs.

2. The dynamics of the impaction process, such as the viscous interaction of the particle before coalescence with the liquid surface, and the interactions after coalescence, such as processes promoting escape of particles from the surface (reentrainment), are not accounted for.

Allen (1975) modelled the particle surface interactions in terms of the energy of the impacting particle. A captured particle would lose all its energy while a rebounding particle would not. The computations were carried out for particles larger than 10 μm radius. Taking into account viscous interactions, Allen concluded that all particles that did not penetrate into the drop rebounded and that Van der Waals and electrostatic forces were negligible. Emory and Berg (1978) attempted to improve the theory by using the film thinning theory, which has been widely used in predicting drop-drop coalescence (Arbel and Levin, 1977). The particle was assumed to coalesce when the air film separating particle from drop surface thinned to a minimum thickness. Once coalescence occurred, the particle was assumed to be collected by the drop. To determine coalescence, the film thinning time was compared to the particle drop surface interaction time. Results obtained were contrary to the predictions of the Pemberton-McDonald theory. A decrease in surface tension of the liquid by the addition of surfactants led to an increase in the film thinning time. This increase implied a decrease in adhesion efficiency. An increase in the impact velocity led to the same conclusion. The film thinning model depends on the definition of the minimum separation between particle and drop surface when coalescence will occur. This definition has been rather arbitrary, and Emory and Berg (1978) used a value of 5 nm while Jayaratne and Mason (1964) used 100 nm. Another deficiency of this model is that the assumption of particle capture once coalescence has occurred may not be valid since a particle impacting at an oblique angle may coalesce but have enough energy to "tear off" after coalescence. In addition, particles impacting on particles already adhering on the surface may bounce off or cause the adhering particles to escape.

For particles less than 1 μm radius, the net adhesion force that has been neglected in the theories for large particles given above, has to be considered. For hydrophilic or wettable particles, the capillary force is the dominant adhesion force (Table 1). For hydrophobic (partially wettable or nonwettable) particles, the capillary force will be small or even negligible. The dominant force will then be the Van der Waals force. Due to the particles' hydrophobic (nonwettable) nature, the Van der Waals force will tend to be low. Hence, there is a substantial difference of about an order of magnitude in the net adhesion force between the case of a hydrophilic particle and a hydrophobic particle. Particle wettability may then also be a factor in particle adhesion for submicron particles.

The Role of Surfactants in the Collection of Nonwettable and Partially Wettable Particles

The literature on the collection of particles that are not completely wettable abounds with conflicting conclusions and interpretations. The Pemberton-McDonald theory predicted low adhering efficiencies. Experimental works by McCully *et al.* (1956), Oakes (1960), Goldshmid and Calvert (1963), and Allen (1975) confirmed this tendency. The decrease in collection efficiency of hydrophobic particles is shown in Figure 7. For hydrophilic ferrous sulphate (completely wettable) particles, there is relatively good agreement between the experimental data and the theory, whereas the experimental collection efficiency of hydrophobic paraffin wax particles (contact angle 102°) is only about half the predicted collision efficiency values. Agreement with theory was also obtained with particles of methylene blue and water and lower efficiencies were obtained for hydrophobic particles of oil, DOP and talc. However, Weber (1968) observed in his work with glass spheres (10 μm radius) that all spheres with different wettabilities stick on impact on a drop. This inconsistency was explained by Stulov *et al.* (1978), who noted that nonwettable particles adhered to the drop surface on impact and consequently formed a layer on the surface, causing bounce-off of particles impacting later. Stulov's work is not definitive since only particles larger than 5 μm diameter were used. Weber's and Stulov's work indicated that the Pemberton-McDonald theory is invalid. Allen (1975), however, concluded that the layer of particles formed on the drop surface was actually the consequence of particles first penetrating the drop surface and then being brought to the surface, due to the nonwettable nature of the particle and the internal circulation of the fluid inside the drop.

In attempts to increase collection efficiencies, surfactants were used to decrease the surface tension of the drop. Goldshmid and Calvert (1963) and Rosinski *et al.* (1963) observed that collection increased with increases in wettability. In addition, the results of Goldshmid and Calvert (1963) and Montagna (1974) indicated that collection decreased for particles with contact angles less than 90°, contrary to McDonald's (1963) findings. In scrubber studies, Rabel *et al.* (1965), Bughdadi (1973), Hesketh (1974), and Fainerman and Levitasov (1976) obtained positive results. This is illustrated in Figure 8, where the effectiveness of smelter dust removal was measured as a function of pressure drop in the Venturi scrubber used (Fainerman and Levitasov). Significant increases in dust removal were obtained using a surfactant that wetted the smelter dust. A decrease in efficiency was obtained using 0.08% heptyl alcohol, which did not wet the dust. In addition, Woffinden *et al.* (1978) looked at the coalescence delay time of a glass rod with a water drop and the results indicated that surfactants decrease the delay time, promoting adhesion efficiency. However, scrubber studies by Taubman and Nikitina (1956) and spray collection by Hoenig (1977) found insignificant or negative effects on the collection efficiencies. The effect of using a glycerine water mixture (Figure 9) was found to have a negative effect on dust removal by charged sprays (Hoenig). However, the ability of the mixture to wet the dust was not measured. The observed increases in collection efficiencies by the addition of surfactants may be plausibly explained by the increase in wettability of the particles leading to immersion of the particles into the drop and eliminating the formation of a particle layer on

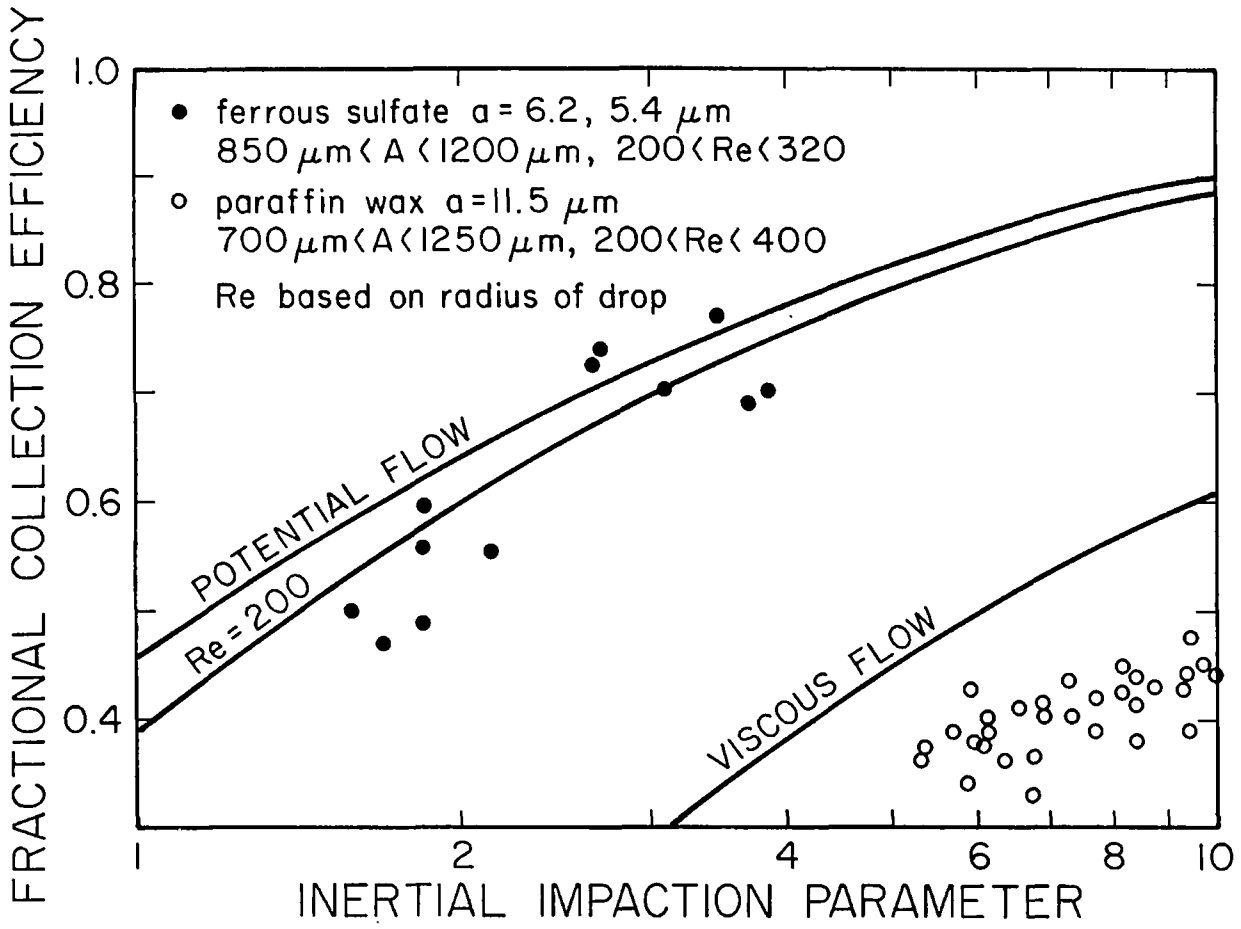

Figure 7. Collection efficiencies for hydrophilic (ferrous sulfate) and hydrophobic (paraffin wax) particles as a function of the inertial impaction parameter (Stokes number). Experimental data are from Allen (1975). Theoretical curves for potential and viscous flow are from Fonda and Herne (1957) and the curve for Re=200 is from Beard and Grover (1974).

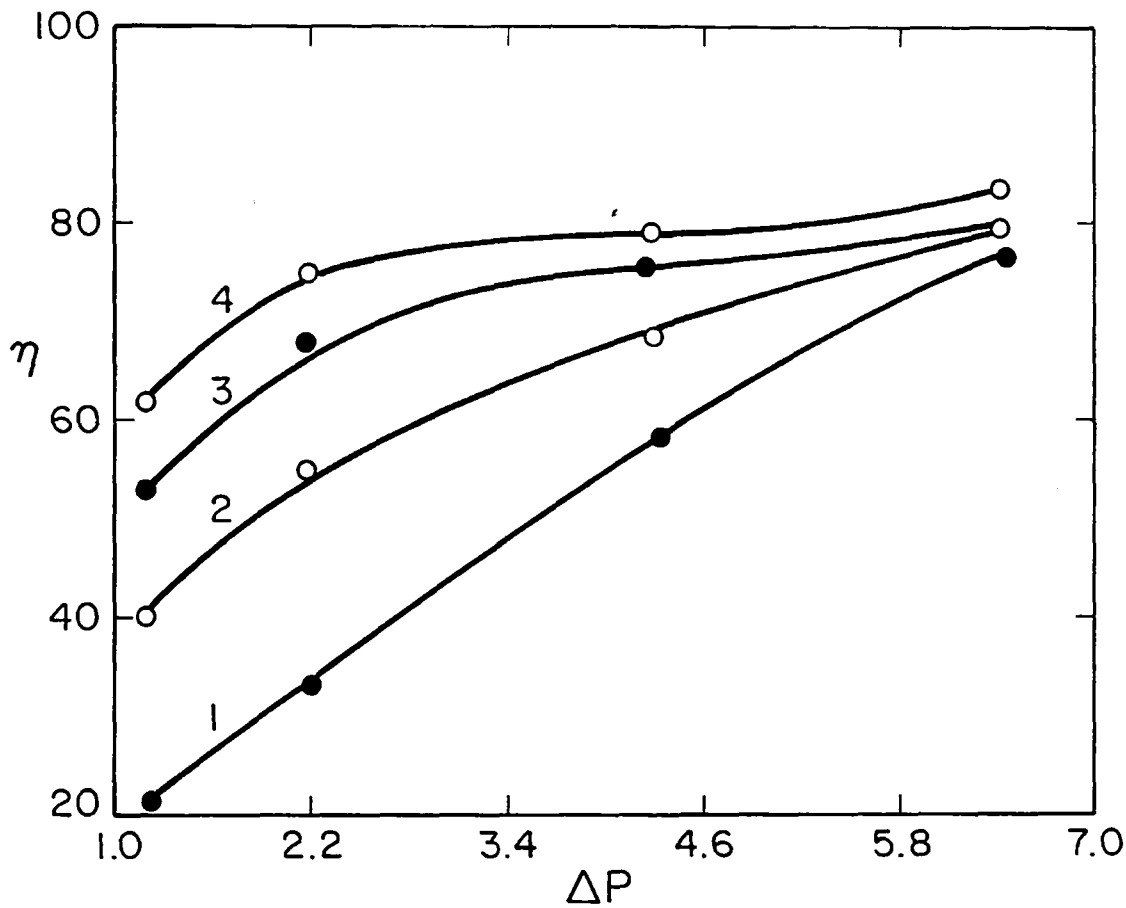

Figure 8. Effectiveness of dust removal, η, as a function of pressure drop, Δp, in a venturi scrubber. 1) 0.08 heptyl alcohol solution, 2) water, 3) and 4) 0.15% and 0.3% oxyethylenated dibutylphenol.

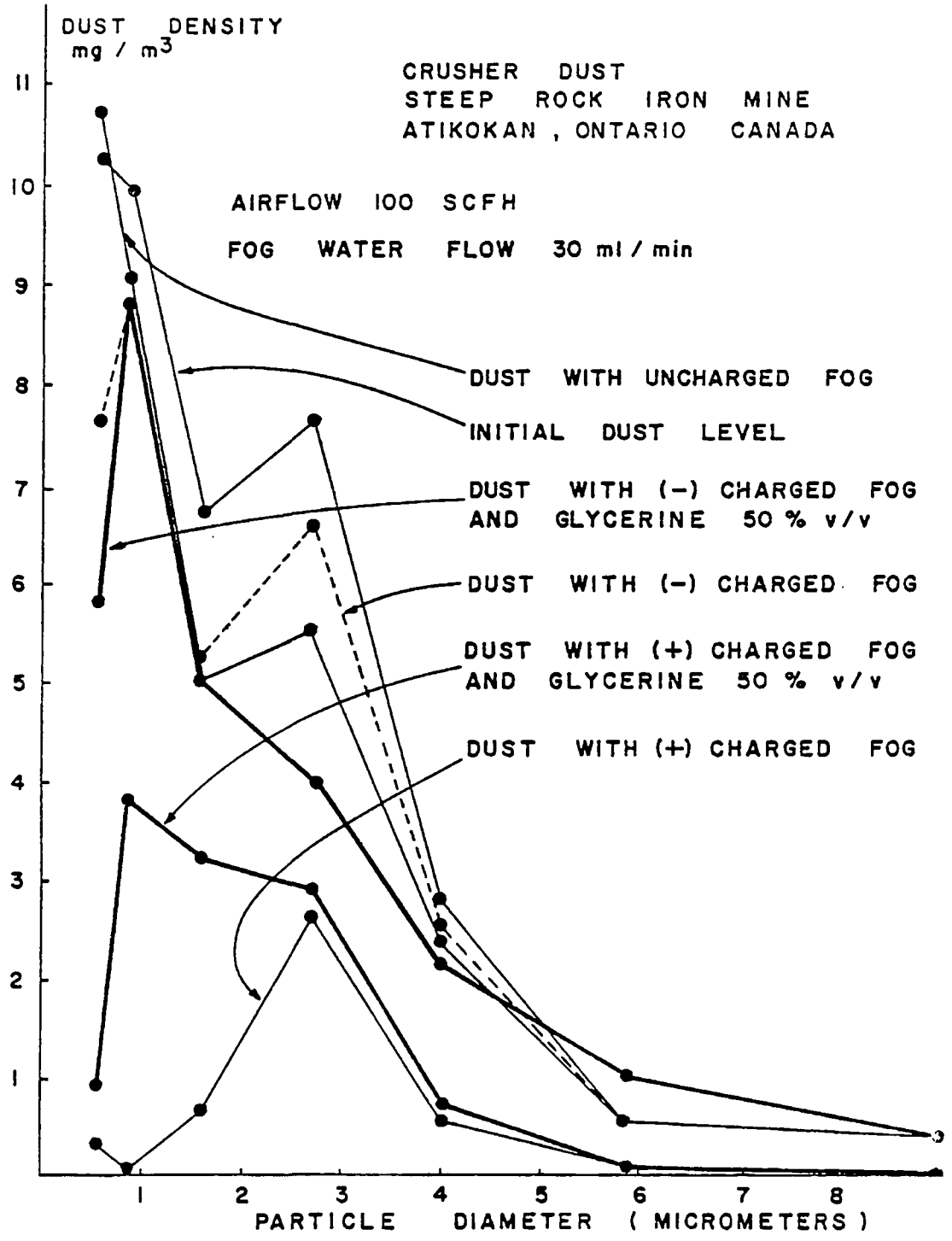

Figure 9. Effectiveness of dust removal by charged fog expressed as dust concentration remaining after passage of fog (Hoenig, 1977).

the drop's surface (Stulov *et al.*, 1978). The observations of negative or insignificant surfactant effects may be the result of the surfactants affecting the size distribution of the drops (Woffinden *et al.*, 1978). However, an understanding of the basic relevant processes based on definitive data collected from well controlled experiments is definitely lacking, especially for fine particles.

SECTION 4

COLLECTION EFFICIENCY

The previous sections reviewed the problems in the adhesion of particles impacting on surfaces. For a thorough comprehension of the process of particles capture by surfaces, the forces or mechanisms that influence the motion of the particles to the surface need to be considered. These forces and mechanisms affect the collision efficiency of the collector for particles, e.g., collecting plates or charged drops in a particulate control device.

The collision efficiency of a collector for aerosol particles is defined as the ratio of the number of particles that collide with the collector to the number of particles passing through the collecting system or swept out geometrically by the collector (drops). For the case of drops, the collision efficiency is

$$\varepsilon = \oint J \cdot ds/(\pi(A+a)^2 Vn) \tag{20}$$

where J is the particle flux, A and V are the radius and velocity of the collector drop, a is the radius of the particle, and n is the particle concentration. For computational convenience, an effective collision area y_c is usually defined as shown in Figure 10, where the separation y_c results in a grazing trajectory. The collision efficiency is then

$$\varepsilon \quad (y_c/(A+a))^2 \tag{21}$$

The collection or capture efficiency, the product of the collision and the coalescence or adhesion efficiency, e, is

$$E_e \quad \varepsilon e \tag{22}$$

METHODS OF COMPUTATION

There are two methods used to compute the collision efficiencies of drops.

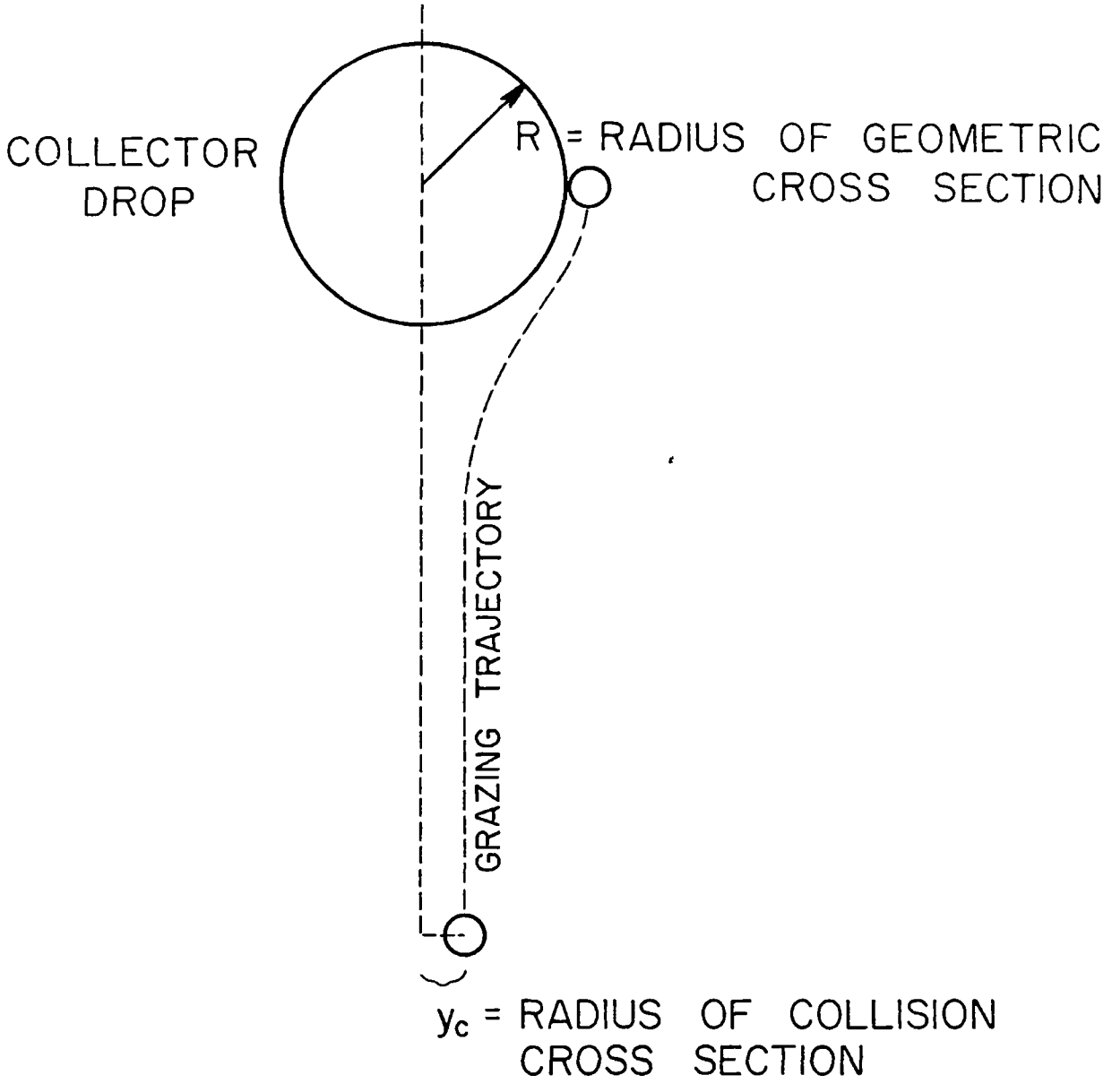

Figure 10. Definition of collision efficiency.

Trajectory Method

This method is used for particles with significant inertia, with radii usually larger than about 0.5 μm radius. The trajectory of a particle towards the drop is computed ignoring the small contribution of the particle to the total fluid field. The force balance equation for a particle of radius a in the flow field of the drop is given by

$$m_p \frac{d\vec{V}}{dt} = -6\pi\eta a(\vec{v}-\vec{u})/C + \vec{F}_{ext} \tag{23}$$

where C is the slip correction factor. Starting the particle at an adequate distance away, the trajectory of the particle is integrated numerically, using the external forces on the particle and the flow field of the drop. The collision efficiency is then computed from the critical displacement, y_c, of the particle, which gives a grazing trajectory.

Convective Diffusion Method

With this method, particles must be small enough so that their inertia can be neglected. The efficiency is computed from the particle flux, which consists of a diffusional component, a drift component induced by external forces, and an advection component

$$\vec{J} = -D_p\vec{\nabla}n + n\vec{v}_F + n\vec{u} \tag{24}$$

where $v_F = BF_{ext}$ with $B = C/(6\pi\eta a)$ being the mobility of the particle. The collision efficiency is evaluated using Equation (1) and the continuity equation for the particle concentration

$$\frac{\partial n}{\partial t} = -\vec{\nabla}\cdot\vec{J} = 0 \tag{25}$$

These two methods can be similarly applied to collectors other than spheres such as parallel plate precipitators. The first method is suitable for laminar flow, and the second for turbulent flow where an eddy particle diffusivity can be used. A brief review of the basic mechanisms affecting collection efficiencies will be helpful in determining the dominant forces in a particular system.

COLLISION MECHANISMS

Diffusion

The first term on the right hand side of Equation (24) results from particle diffusion where

$$D_p = D_B + D_e \tag{26}$$

Brownian diffusion, D_B, and eddy diffusion, D_e (from turbulent motion), of the particle contributes to the total diffusion coefficient. The Brownian diffusion coefficient is given by the Stokes-Einstein expression,

$$D_B = BkT = CkT/(6\pi\eta a) \tag{27}$$

where B is the mobility of the particle (Hidy and Brock, 1970).

Eddy diffusivity varies with turbulence intensity. According to Liu and Ilori (1974), particle eddy diffusivity can be expressed as the sum of the fluid eddy diffusivity D_f and a component from the product of the square of the root mean square velocity and particle relaxation time, τ.

$$D_e \quad D_f + v^2 \tau \tag{28}$$

Particles can also be captured by the presence of rear eddies (Beard, 1974; Wang, 1978). For drops, eddies form at about a drop Reynolds number of 20. For Reynolds number over 300, particle capture is impeded by the fast shedding of the eddies.

Electrostatics

The force on the particle near a charged conducting collector sphere due to the electrostatic force can be expressed as

$$F_e = 6\pi\eta a/C(U_o \sum_i k_{ei}(f_e{}^r + f_e{}^\theta)) \tag{29}$$

where U_o is the free stream velocity, k_{ei} are the dimensionless constants resulting from the Coulomb, image, and dipole forces, and $f_e{}^r$ and $f_e{}^\theta$ are the dimensionless radial and angular components, respectively (Nielsen and Hill, 1976). The expressions for the electrostatic parameters are shown in Table 3 (Nielsen and Hill, 1976). The dominant force when both particle and collector are charged is the Coulomb force which is

$$F_{ec} = \frac{Q_q}{4\pi\varepsilon_a r^2} \tag{30}$$

For the case where the collector is a spherical water drop the above equations are also applicable (Davis, 1969).

TABLE 3. DEFINITIONS OF THE DIMENSIONLESS PARAMETERS AND THE VARIATION IN THE RADIAL AND ANGULAR COMPONENTS (Nielsen and Hill, 1976)

e	Force F_e	Description	Parameter[a] K_e	Radial component f_e^r	Angular component f_e^θ
c	Coulombic force	Both collector and particle are charged.	$K_c = \dfrac{CQ_cQ_p}{24\pi^2\epsilon_f R_p R_c^2 \mu U_o}$	$1/R^2$	0
ic	Charged-particle image force	Particle only is charged. Charge separation induced in collector.	$K_{ic} = \dfrac{\gamma_c C Q_p^2}{24\pi^2\epsilon_f R_p R_c^2 \mu U_o}$	$-[R/(R^2-1)^2 - 1/R^3]$	0
ip	Charged-collector image force	Collector only is charged. Charge separation induced in particle.	$K_{ip} = \dfrac{\gamma_p C Q_c^2 R_p}{12\pi^2\epsilon_f R_c^5 \mu U_o}$	$-1/R^5$	0
ex	External electric field force	Particle only is charged. Charge separation in collector induced by external electric field.	$K_{ex} = \dfrac{CQ_pE_o}{6\pi R_p \mu U_o}$	$(1 + 2\gamma_c/R^3)\cos\theta$	$-(1-\gamma_c/R^3)\sin\theta$
icp	Electric dipole interaction force	Neither body is charged. Charge separation in both bodies induced by external electric field.	$K_{icp} = \dfrac{2\gamma_c\gamma_p\epsilon_f C R_p^2 E_o^2}{R_c \mu U_o}$	$-[2(1+2\gamma_c/R^3)\cos^2\theta - (1-\gamma_c/R^3)\sin^2\theta]/R^4$	$\dfrac{-[(2+\gamma_c/R^3)\sin\theta\cos\theta]}{R^4}$

[a]The parameters K_c, K_{ic}, and K_{ip} are identical to K_E, K_M, and K_I defined by Kraemer and Johnstone (1955).

Subscripts f, c, and p relate to air, the collector, and particle, respectively. Q, C, R, ε, μ, U_0, and γ are the charge, slip coefficient, radius, dielectric constant, viscosity, free stream velocity, and polarization coefficient, respectively.

Thermophoresis

Particles in a temperature gradient move down gradient with a thermophoretic velocity which can be expressed as

$$v_T = -K_T(\Delta T/\Delta x) \tag{31}$$

where K_T is a function of the physical and thermal properties of the particles and properties of the fluid (Leong, 1980). The temperature gradient is assumed to be uniform. When the Knudsen number, Kn, which is the ratio of the mean free path of the fluid to the radius of the particle, is much larger than one (free molecular regime)

$$K_T = 15\pi c\lambda/(16\mu_i T) \tag{32a}$$

where c is the mean molecular speed of the molecules, λ the mean free path, and

$$\mu_i = 8 \quad \text{for specular reflection} \tag{33a}$$

$$\mu_i = 8+\pi \quad \text{for diffuse reflection} \tag{33b}$$

In the slip regime, where the Knudsen number is much smaller than one

$$K_T = \nu k_T(\gamma_T + c_t Kn)/(T(1 + 3c_m Kn)(1 + 2\gamma_T + 2c_t Kn)) \tag{32b}$$

where ν is the kinematic viscosity of the fluid, γ_T is the ratio of the thermal conductivity of the fluid to that of the particle, and k_T, c_t, and c_m are the thermal slip, thermal accommodation, and momentum accommodation coefficients, respectively. The values of these coefficients in air are approximately 1.1, 1.6, and 1.2, respectively (Leong, 1980). In the transition regime, where the Knudsen number is of order one, no adequate theoretical formula exists.

Diffusiophoresis

As in thermophoresis, particles have a diffusiophoretic velocity in the presence of a vapor concentration gradient. The diffusiophoretic velocity can be expressed as

$$v_D = -K_D\ (\Delta\rho_v/\Delta x) \tag{34}$$

where the vapor gradient is assumed to be uniform (Leong, 1980). In the free molecular regime for a dilute vapor

$$K_D = D_{vg}/(m_g\ m_v)^{0.5} \tag{35a}$$

where D_{vg} is the diffusion coefficient of the vapor in the gas, and m_g and m_v are the molecular masses of the gas and vapor, respectively (Leong, 1980). In the slip regime

$$K_D = (k_D C/(1 + 3c_m Kn))(m_g D_{vg}/(m_v \rho)) \tag{35b}$$

where k_D is the diffusion slip coefficient and ρ is the fluid density. In the transition regime no satisfactory theory exists. In addition to the diffusiophoretic velocity, there is also a Stefan flow of the fluid due to the diffusion of the vapor. This velocity due to Stefan flow is

$$v_S = -(D_{vg}/\rho)(\Delta\rho_v/\Delta x) \tag{36}$$

Gravity Effect

The settling speed of small spherical particles is given by Stokes law as

$$v_\infty = 2a^2\ \rho_p g C/(9\eta) \tag{37}$$

where g is the gravitational acceleration. Larger particles will have a higher settling speed. For the case of particle collection by falling drops, the effect of gravity is to decrease the relative inertia between particle and drop and hence to decrease the efficiency.

Inertia Effect

Particle velocities are usually different from fluid velocities, due to the inertia of the particle. The inertia can be characterized by the Stokes parameter, defined by

$$K_S = C m_p V/(6\pi\eta a L) \tag{38}$$

where m is the mass of the particle, V, the characteristic of free stream velocity, and L, a characteristic length. For a sphere

$$K_S = C 2a^2 \rho_p v/(9\eta A) \tag{39}$$

For a spherical collector with a << A, the collision efficiency by inertial impaction is given by Rimberg and Peng (1977) as

$$\varepsilon_{im} = (1+0.75\ \ln(2K_S)/(K_S-1.214))^{-2} \quad \text{for } K_S > 1.214 \text{ and viscous flow} \quad (40a)$$

$$\varepsilon_{im} = (K_S/(K_S+0.5))^2 \quad \text{for } K_S > 0.2 \text{ and potential flow} \quad (40b)$$

Interception Effect

If a particle follows the stream lines of the fluid, it will have a collision efficiency due to its size. For the case where the collectors are drops, Rimberg and Peng (1977) give this interception efficiency as

$$\varepsilon_{in} = 1.5(a/A)^2 \quad \text{for viscous flow} \quad (41a)$$

$$\varepsilon_{in} = 3a/A \quad \text{for potential flow} \quad (41b)$$

Sonic Agglomeration

Sonic or acoustic agglomeration is a method for inducing coagulation of particles with high intensity sound waves (Shaw, 1978). Particles smaller than a particular size are set into oscillation by high intensity acoustic vibrations, while larger particles are unaffected. This promotes collision of the smaller with the larger particles. The optimum frequency for agglomeration decreases for larger particles. The sonic agglomeration constant analogous to the coagulation constant is directly proportional to the amplitude of the sonic waves. Depending on the intensity of the acoustic wave, the particle agglomeration can be increased by more than an order of magnitude compared to Brownian coagulation, especially for particle sizes around 1 μm (up to 3 orders of magnitude increase). Details can be found in a recent review by Shaw (1978).

Comparison of Forces or Mechanisms

Collision efficiencies by different mechanisms for different particle sizes for a 100 μm drop are shown in Figure 11, which illustrates the importance of each mechanism. In the estimation of electrostatic collection efficiency, the particle charges used are those attained by unipolar diffusion charging (Liu and Pui, 1977), while the drop charge is about one-tenth the Rayleigh limit for drop stability. For particles less than 2 μm radius, Coulomb attraction is the dominant collision mechanism. Inertia impaction becomes the major mechanism for particles larger than 3 μm. For particles larger than 10 μm, the settling speeds are over 1 cm/sec. Hence, settling is an effective alternate means of removing particles. Gravity has the maximum effect on particle collection by falling drops in the 1 μm radius particle size region. It reduces or even nullifies the effect of interception. However, the absolute effect in terms of efficiency is less than 10^{-2}.

For all practical purposes, Brownian diffusion can be ignored for all the particle sizes shown, and interception can be ignored for particle sizes less than 5 μm. Thermophoretic and diffusiophoretic forces have been shown to be

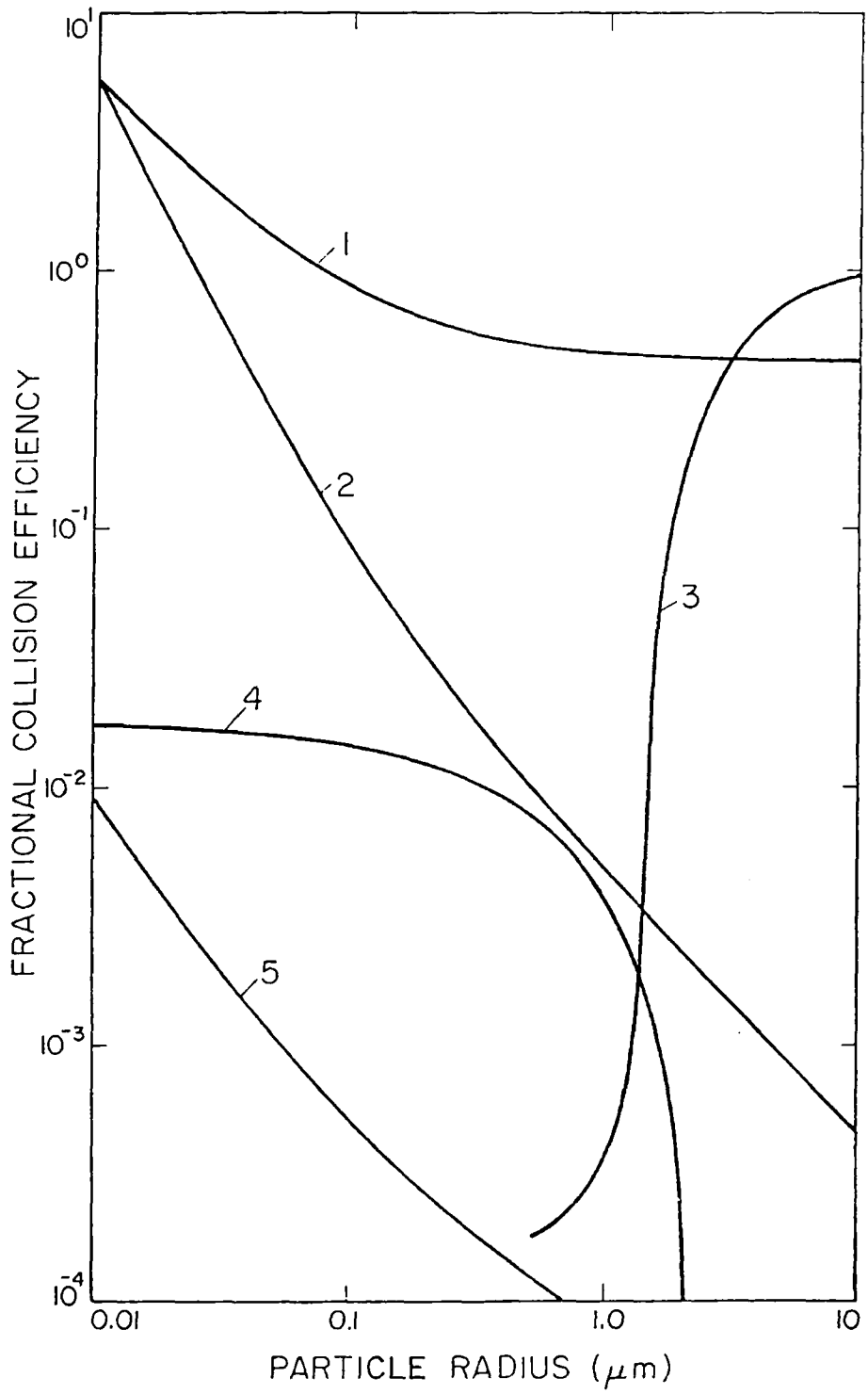

Figure 11. Theoretical collision efficiencies for a 100 μm radius water drop falling at terminal velocity in air. 1) Coulomb force for drop with one tenth Raleigh limit charge and particles charged by diffusion charging only, 2) same as 1) except particles have one electron charge, 3) inertia and interception effects only, 4) thermophoretic and diffusiophoretic forces only, 5) Brownian diffusion only.

insignificant (less than 0.1% in overall collection) in the collection of particles by drops (Pilat and Prem, 1977). In tubes or parallel plate systems, phoretic forces can be significant, depending on the gradients used and the residence time of the particle, e.g., passing a high temperature gas through a cold wall tube (Byers and Calvert, 1969) or condensing steam in the system (Azarniouch *et al.*, 1975). The effect of turbulence, in the case of drops, is about the same order of magnitude as for thermophoresis (Lin, 1976). In turbulent pipe flow, the eddy diffusivity can be several orders of magnitude larger than Brownian diffusion and hence significant in the precipitation of particles on the walls. However, compared to electrostatic forces, these mechanisms are relatively inefficient for fine particles. The effects of acoustic agglomeration would also be insignificant compared to Coulomb forces. In the case of highly charged drops and particles, Kraemer and Johnstone (1955) and Prem and Pilat (1978) have shown that collection efficiencies are over 100%. For neutral particles, a collection efficiency of about 10^{-2} is obtained by image forces for drops charged to the Rayleigh limit (Grover and Beard, 1975). The above comparisons were made for a 100 μm radius drop at the terminal velocity of 0.7 ms^{-1}.

In Venturi-type scrubbers very high drop velocities are used. With a typical velocity of 100 ms^{-1} the collection efficiency from inertia impaction for a 100 μm radius drop using the efficiency equation for potential flow is larger than 0.9 for 1 μm radius particles. However, for 0.1 μm radius particles the collision efficiency is only 0.4. Increasing the velocity by a factor of 10 will only increase the efficiency to 0.5. Hence collision efficiencies can be maximized most effectively by maximizing the Coulomb attraction between particle and drop. For cases where use of water drops may be suitable, acoustic agglomeration offers a viable tool for pretreating fine particles. The larger particles formed after agglomeration can then be removed effectively by other methods.

Comparison Between Theory and Experiment

Numerous experiments have been conducted to measure the collection efficiency of liquid and solid collectors for particles of different size and composition where one or more collision mechanism is operative. For a valid comparison between theory and experiment all collision mechanisms involved have to be identified and extraneous effects modifying the collection efficiency have to be accounted for. These effects include particle non-adhesion and assemblage of collectors instead of single collectors. Formation of a coating of particles on the collector (Wang *et al.*, 1977) can change the collecting characteristics dramatically by changing the size and shape of the collector, as shown in Figure 12. The efficiencies increased as more particles were collected due to the formation of dendrites. Particle bounce-off from the coating may occur (Stulov *et al.*, 1978) and dendritic structures may arise (Bhutra and Payatakes, 1979).

Robig *et al.* (1978) obtained good agreement between theory and experiment for the collection of 0.02 to 2 μm radius particles by metal spheres for Brownian diffusion interception and inertial capture. The experimental efficiencies of Robig *et al.* are shown in Figure 13 with the theoretical Brownian diffusion collision efficiencies predicted by the convective diffusion theory

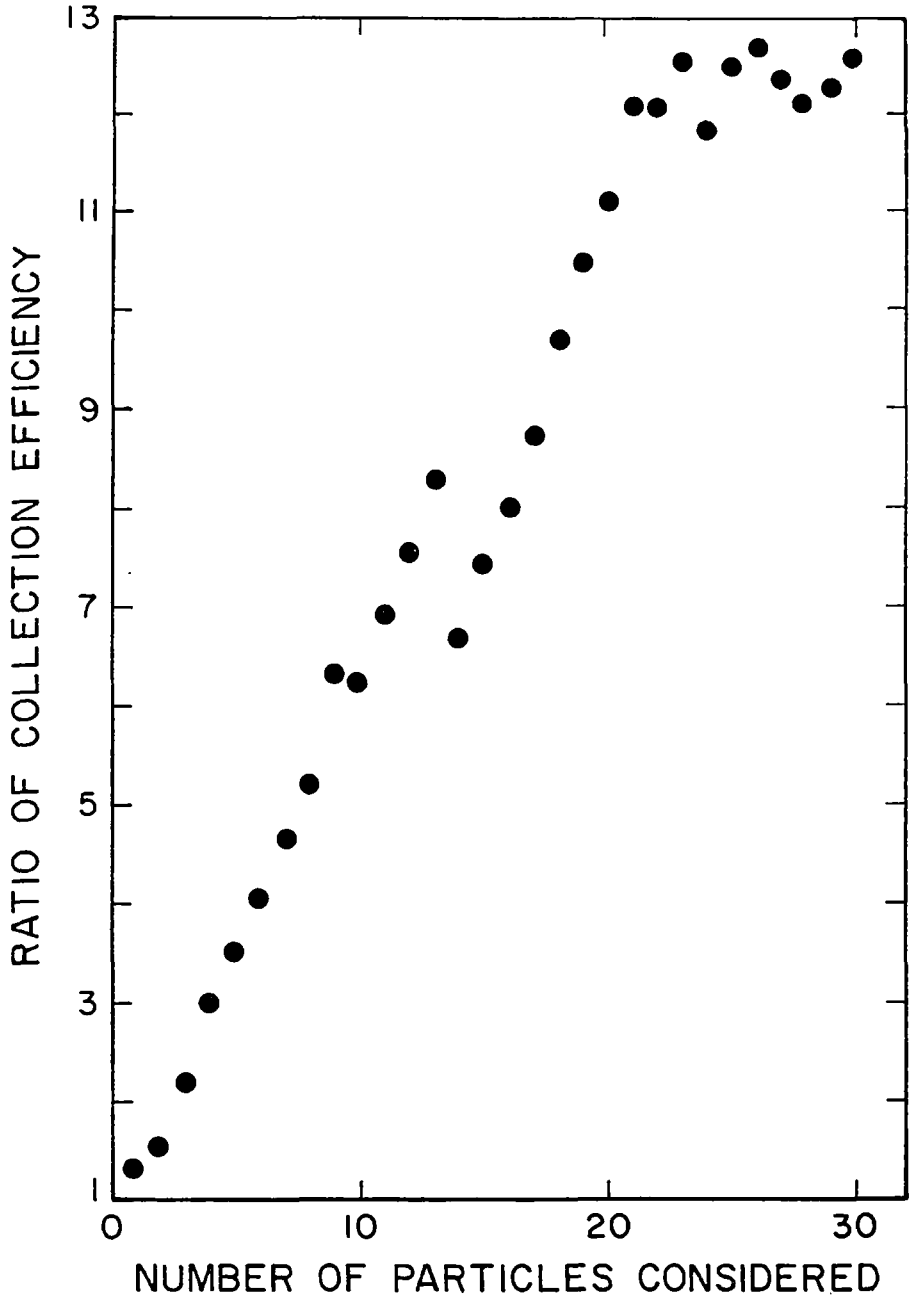

Figure 12. Ratio of collection efficiency taking into account previous particles collected on the collector surface compared to the efficiency computed when the collector surface has no adhered particles (Wang *et al.*, 1977)

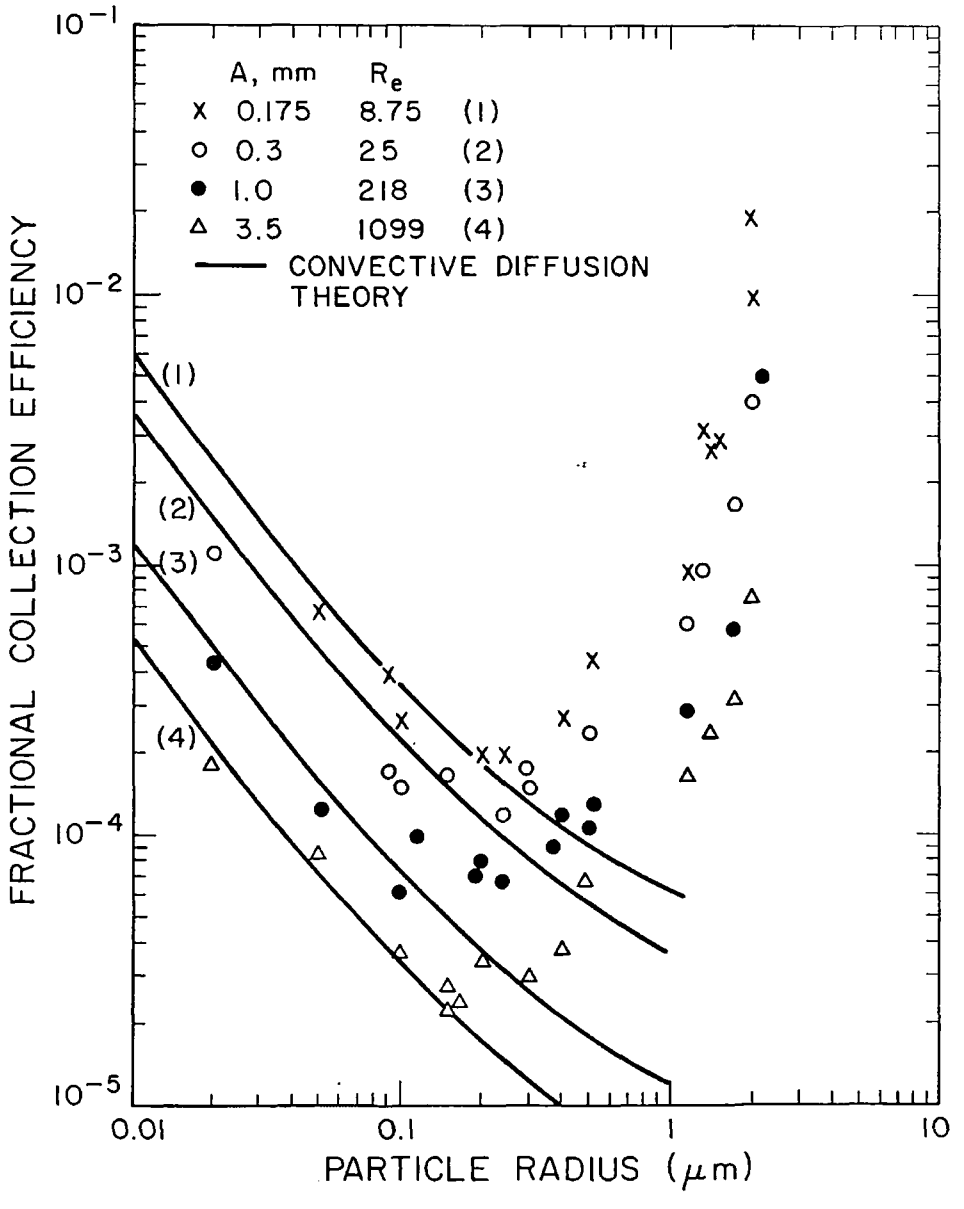

Figure 13. Collection efficiencies of metal spheres by Brownian diffusion, interception and inertial impaction. Experimental data for different drop and particle radii are from Robig *et al.* (1978). Convective diffusion theory is from Wang (1978).

used by Wang (1978). The efficiencies due to interception and inertial impaction are within the bounds predicted by Stokes and potential flow. Confirmation of the theory for interception and inertial capture of particles has also been obtained by several investigators for collection by liquid drops, and cylindrical and spherical shape collectors, e.g., Ranz and Wong, 1952; Goldshmid and Calvert, 1963; Leong, 1980. The good agreement between experiment and theory which included gravitational effects in the 1 μm radius particle size region demonstrates the accuracy of the trajectory method in computing collision efficiencies (Robig *et al.*, 1978; Leong, 1980). For smaller particles where inertia is insignificant and gravity has negligible effect, the convective diffusion method has been proven to be applicable (Robig *et al.*, 1978).

Particle collection by drops due to turbulence has been modelled by De Almeida (1975) and Lin (1976). De Almeida used a stochastic model where the collection was expressed in terms of a probability function. Lin used boundary layer theory for turbulent collection by drops neglecting inertia of the particles. However, no definitive data exist to verify either of the above theories. The increase in particle collection by drops due to rear eddies was shown experimentally by Beard (1974) and Wang (1978) but is less than 1% in efficiency.

Excellent agreement between theory and experiment (Figure 14) has been obtained for electrostatic collection by metal spheres when the Coulomb force is dominant (Robig and Porstendorfer, 1979). Figure 15 shows the data of Kraemer and Johnstone (1955). In contrast to the data of Robig and Porstendorfer there is substantial scatter in these data, probably a consequence of the charge on the particles being not well controlled. The effect of image forces at low drop and particle charge when the Coulomb force was not dominant was also obtained. Image forces were significant only when the collection efficiencies were less than or equal to approximately 10^{-2}. In addition Robig and Porstendorfer demonstrated that all particles that collided adhered with or without a grease layer on the sphere.

In contrast, Lai *et. al.* (1978) found that collection efficiencies of submicron silver chloride particles by liquid drops did not increase monotonically with increasing drop charge but had a maximum value. This suggests that collection by a liquid surface is different than for a solid surface.

For water drops in a nonsaturated environment, thermophoretic and diffusiophoretic forces are present. Leong (1980) obtained significant disagreement between experiment and theory for particle collection by evaporating water drops. The phoretic collection efficiencies did not decrease as rapidly with large particles as theorized. This is shown in Figure 16 where significant collection was obtained for 1 to 2 μm radius particles in contrast to the theory which predicted no collection. His results indicated that the theory used which was derived for uniform vapor or thermal fields may be inappropriate for the nonuniform fields encountered in the vicinity of evaporating drops. Improved theory is difficult due to the mathematical complexities for the case of nonuniform fields. Several experiments have been conducted using water drops with low charge (Coulomb force not dominant) in a subsaturated environment (e.g. Adam and Semonin, 1970; Beard, 1974; Lai, *et al.*, 1978).

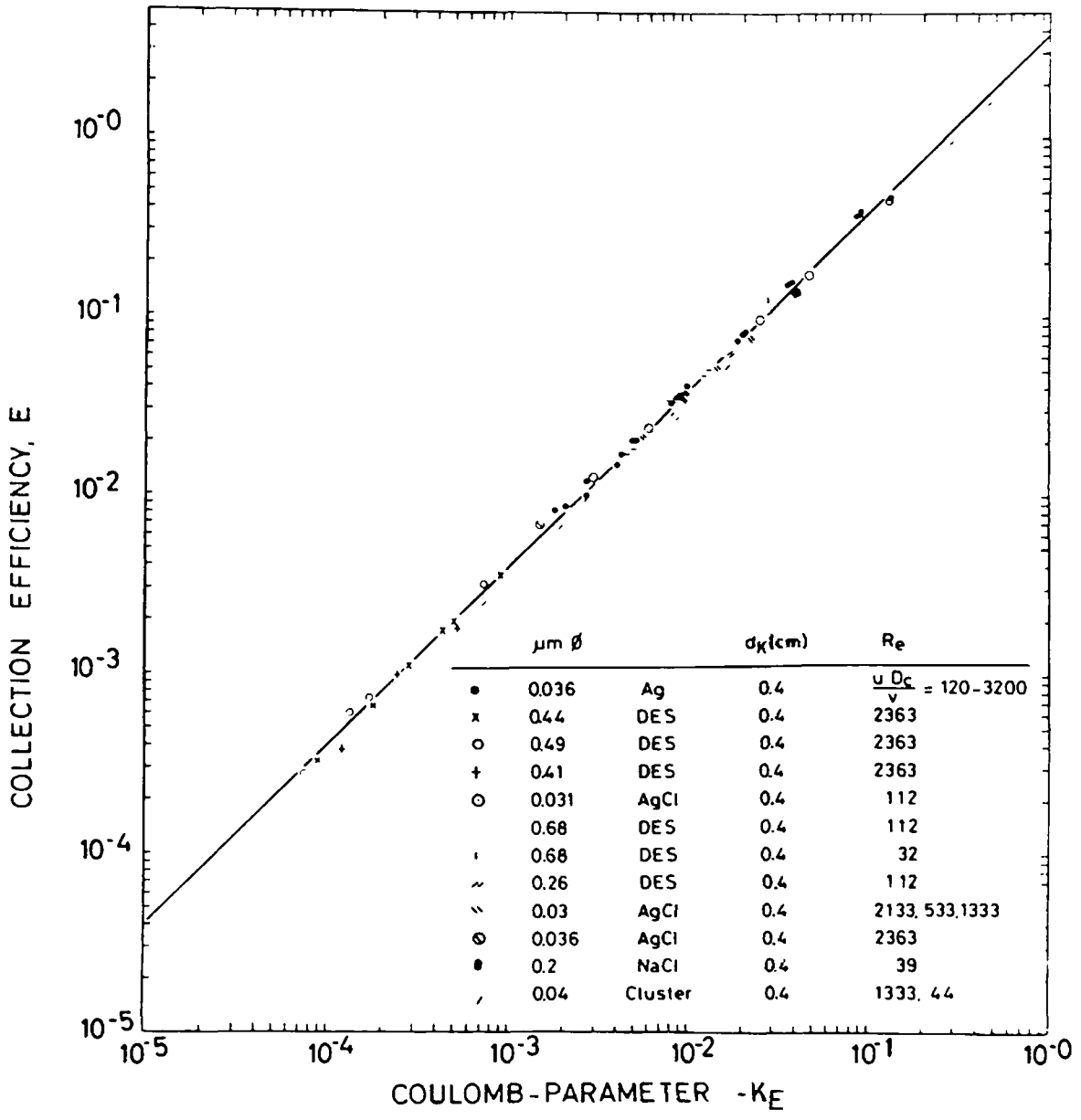

Figure 14. Collection efficiency of charged particles on a charged sphere (Robig and Porstendorfer, 1979).

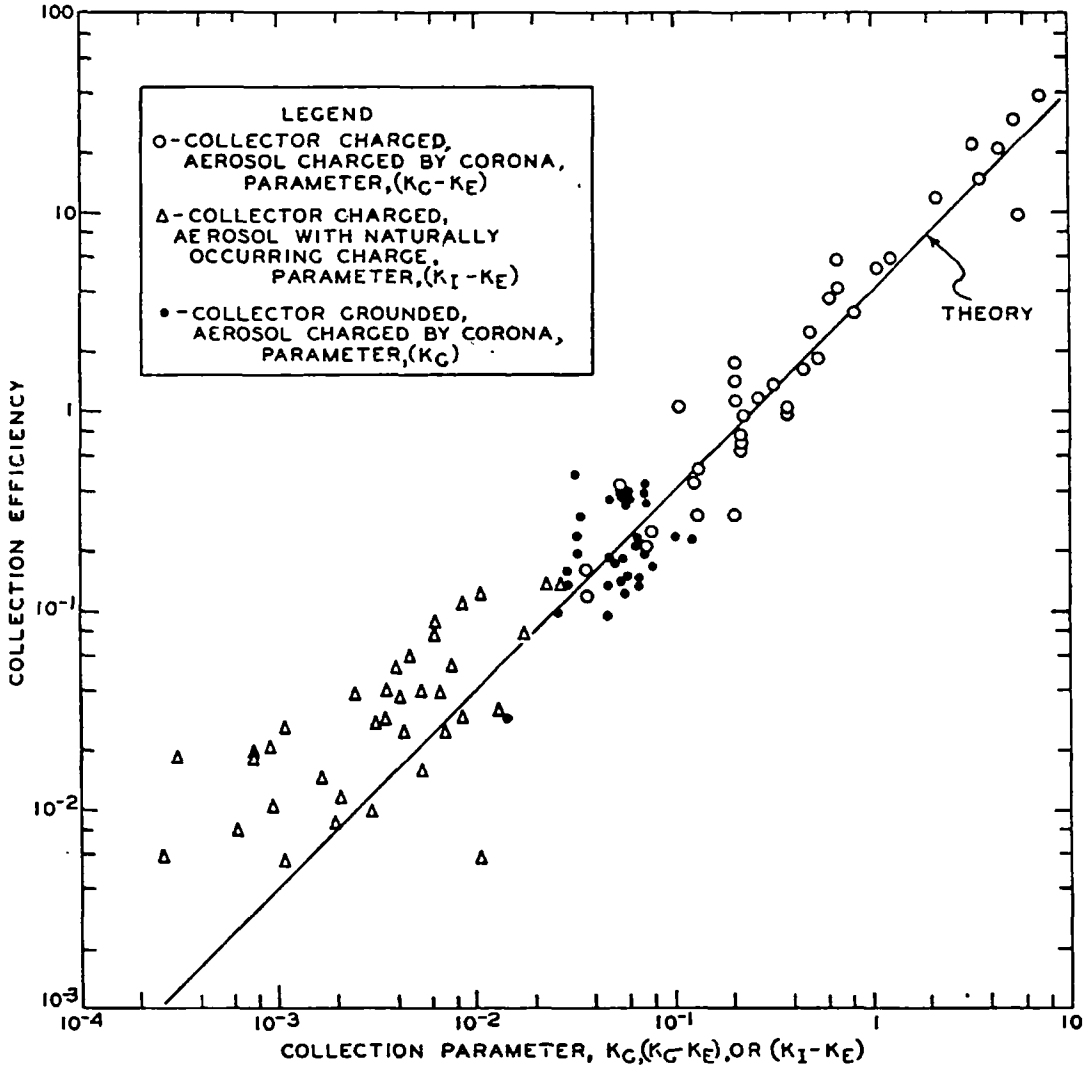

Figure 15. Collection efficiencies of charged particles by charged and uncharged spheres (Kraemer and Johnstone, 1955).

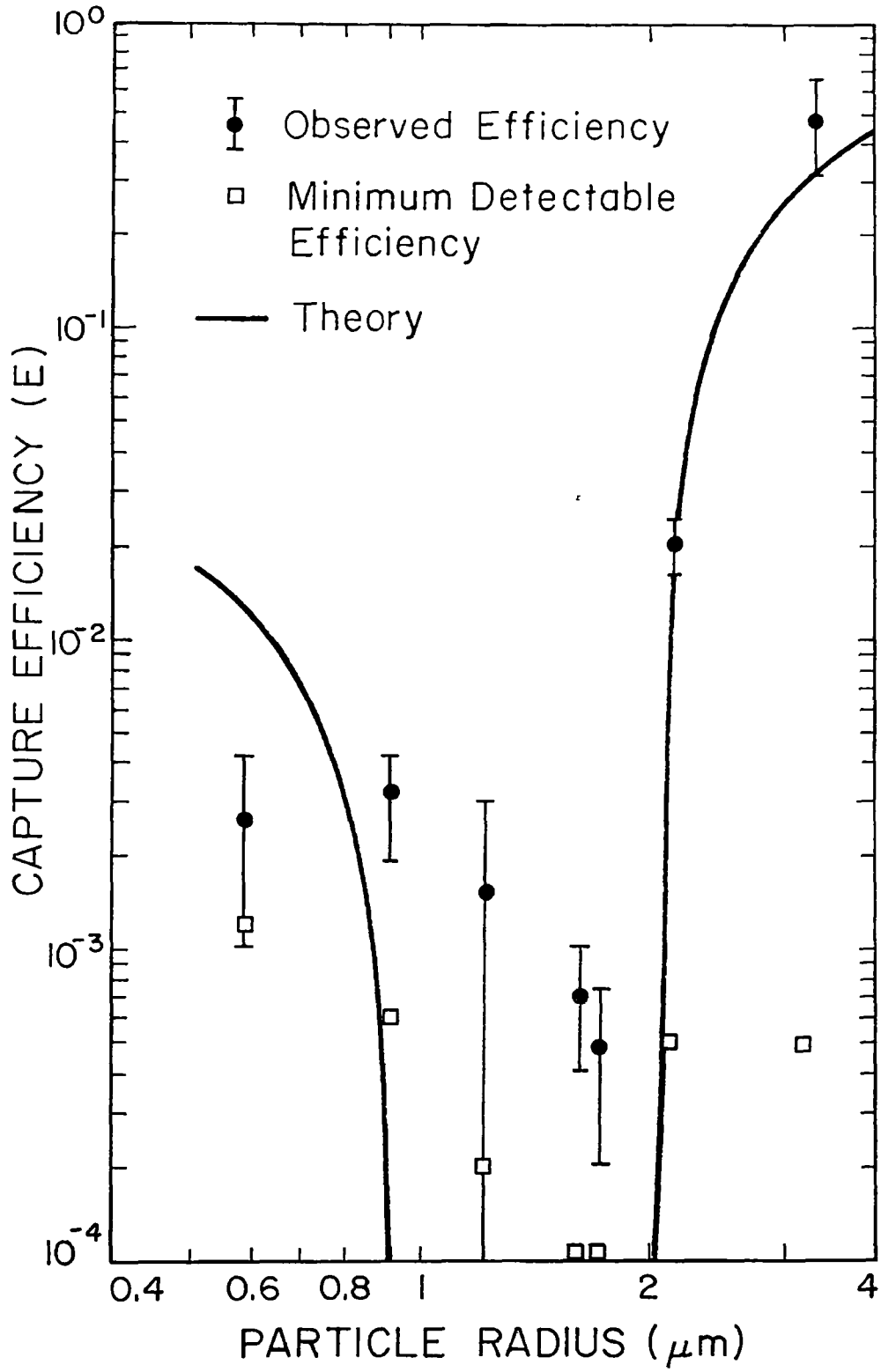

Figure 16. Collection efficiencies of manganese hypophosphite particles by a 66 μm radius drop (Leong, 1980).

Significant disagreements were obtained due to omission of phoretic forces in the theory or the lack of measurement of charge on the particles.

The theory has been adequate in predicting particle collection efficiencies larger than 10^{-2} when extraneous effects are negligible. This range of efficiencies higher than 10^{-2} is usually the result of inertia capture for particles larger than 2 μm radius and Coulomb attraction for smaller particles. In this region of minimum collection efficiencies between 0.1 and 1 μm radius, good agreement between theory and experiment is difficult for efficiencies less than 10^{-2}. Contributing factors include experimental errors and inexact theory. For the purpose of particluate control, the most efficient collection mechanism is Coulomb attraction. Hence, collection by highly charged drops and particles will be examined in detail in the next section.

PARTICLE COLLECTION BY CHARGED DROPS

With charge collection as the dominant particle collection mechanism, the collision efficiency for particles with negligible inertia by charged drops can be computed as follows. The particle flux to the drop surface is given by Equation (24), where

$$J_{A+a} \quad nv_F = nBF_C = -CQqn/(24\pi^2\eta a\varepsilon_a(A+a)^2) \tag{42a}$$

where B is the electrical mobility of the particles. For a << A

$$J_{A+a} = J_A = -CQqn/(24\pi^2\eta a\varepsilon_a A^2) \tag{42b}$$

Since the drop is falling through the aerosol cloud at a velocity u >> v, the particle concentration n is relatively constant. Hence, the collision efficiency is computed using Equation (1)

$$= 4\pi A^2 J_A/(\pi A^2 un) \quad -4K_C \tag{43}$$

where K_C is the Coulombic electrostatic parameter.

Limits in Charged Particle Collection

Kraemer and Johnstone (1955) showed that single collector collision efficiencies of over 1000% can easily be achieved by the adequate charging of collector spheres and particles. Even with a value of the single collector efficiency of 160% in the penetration formulae for electrostatic scrubbers (Calvert *et al.*, 1978) and charged droplet scrubbers (Pilat, 1975), the overall theoretical efficiency values obtained are over 99.9%. However, in practical applications, overall collection efficiencies attainable are well below 99%. For example, in electrostatic scrubbers (Calvert *et al.*, 1978) charging of the particles increased the collection efficiency of collection for 0.5 μm radius particles from about 80 to 90%. Pilat (1975) obtained an increase from 35 to 87% for 0.3 μm radius particles in a charged droplet scrubber in which both the droplets and the particles were charged. The efficiencies obtained for both the above cases are significantly below the theoretical efficiencies (greater than 99%) for fine particles. These theoretical values, however, did not take into account the particle-drop surface interactions which

may lead to nonadhesion and hence lower efficiencies. This will be especially true for nonwettable particles where particle nonadhesion may occur. Nonwettable particles tend to form a coating on the drop surface and this increase bounces off and reduces effective electrostatic collection of particles. Another consideration is that the maximum negative charge that a hydrodynamically stable drop can possess is defined by the Rayleigh limit (Rayleigh 1882, Hendricks and Schneider, 1963) which is given by

$$Q^2 \quad 64\pi^2 A^3 \varepsilon_a \sigma \tag{44}$$

Above this limit, drops become unstable and charged droplets are ejected (Abbas and Latham, 1967). For positively charged drops corona discharge occurs before the Raleigh limit is reached. If drops are produced with negative charge near the Rayleigh limit, evaporation in the low humidity environment of particulate control devices will decrease drop size and cause instability. Hence, maximization of the charge on the drops may not maximize collection efficiencies. In addition, the maximum charge is controlled by the surface tension. Decreasing the surface tension may help in particle adhesion, but collision efficiency may be decreased.

Charge neutralization of charged particles by a highly charged drop may also decrease the expected collection efficiency. Lai *et al.* (1978) found that collection efficiencies for drops increased with higher charge to a maximum value and then decreased for still higher charged drops for relatively uncharged 0.24 μm radius particles. The decrease in efficiencies was attributed to charge transfer to the particles that came close to the drop for a drop charge above a certain limit. The particles were possibly either neutralized or acquired a charge of the same sign as the drop. Hence, the electrostatic attraction of the particles to the drop would decrease or even be reversed, leading to lower efficiencies. This explanation seems plausible considering that a charged particle may induce an opposite charge on the drop, increasing the charge density on the surface of the oppositely charged drop. If this increase is large enough to cause a local Rayleigh instability charge transfer may occur. In addition, the decrease in efficiencies occurred at a lower drop charge density for a smaller drop. This is in agreement with the trend for Rayleigh instability. However, the charge on the particles was not measured by Lai *et al.* and the limited data do not conclusively define this effect of charge transfer. In contrast, no decrease in efficiencies was found when the charge on a metal sphere was increased (Kraemer and Johnstone, 1955; Robig and Porstendorfer, 1979) to much higher than that used by Lai *et al.* Also, good agreement with theory and experiment was obtained, indicating no adhesion problems for metal spheres.

SECTION 5

PROPOSED STUDIES

EXPERIMENTAL STUDIES

Adhesion Efficiency

Figure 17 shows the schematic of the proposed experiment to determine the adhesion efficiency of different wettability particles to charged drops. Widely spaced charged or uncharged drops of uniform size are generated and fall through a cloud of monodispersed charged or uncharged particles at a known temperature and humidity. The drops are collected at the bottom of the chamber and analyzed for the mass of particles collected determining the collection efficiency. For highly charged drops and particles, the dominant collision mechanism is the Coulomb charge attraction. Robig and Porstendorfer (1979), using a metal sphere, determined that no particle bounce-off occurs in electrostatic collection and excellent agreement was obtained between Coulomb attraction theory and experiment. Hence, the adhesion efficiency will be determined by the ratio of the measured collection efficiency of the charged drop to the computed collision efficiency. The theoretical collision efficiency is easily obtained by measuring particle and drop charge and size since electrostatic collection is independent of the flow regime. Drop sizes from 50 to 200 μm radius which correspond to sizes in scrubbers will be used. Particle sizes tested will be in the 0.1 to 1 μm radius range, where collection efficiencies are minimum.

Effects of the addition of surfactants to the drops, the use of drops of volatile (water) and nonvolatile (oil) liquids, and particles with different wettability and physical characteristics (shape and roughness) will be studied. Ionic (e.g., alkyl sulfates and sulfonates) and nonionic (e.g., aliphatic, lauramide and coconut amide) surfactants will be used to determine their efficacy. For proper control, pure surfactant compounds will be used initially. Later, commercial preparations will also be applied.

The main components of the experiments (Figure 17) will be the aerosol generator, aerosol conditions system, chamber, particle concentration detector, hygrometer, charge detectors, and drop generator. Each component is described below.

Aerosol Generator

Particles which are nonwettable or partially wettable are insoluble in water. The Sinclair-LaMer type of generator is suitable for the generation of this type of particles. The technique involves vaporization of the material and subsequent condensation to form the required particle. This method of

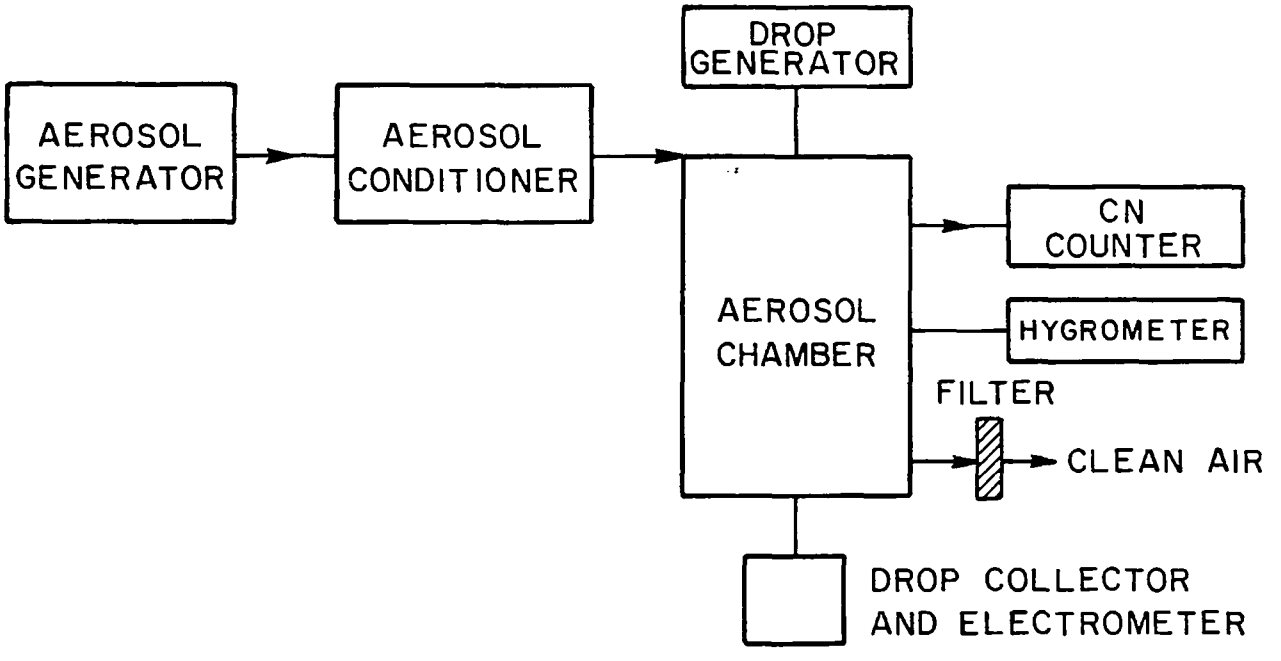

Figure 17. Experimental design for determining adhesion efficiency of particles to drops.

generation and its variations are readily available in the literature, e.g., Kerker, 1975. Figure 18 shows an outline of the aerosol generating system which can produce both insoluble particles and soluble particles.

Aerosol Conditioning System

The aerosol conditioning system will enable the selection of an aerosol of a specified size, charge, and concentration. The system (Figure 19) will consist of an electrostatic aerosol classifier (TSI 3071), a corona charging device, a humidifier, and a dilution control. The classifier produces a monodisperse aerosol with singly charged particles from a polydispersed source. Size is selectable and monodispersity is 5% of mean size. Independent sizing will also be carried out with electron microscopy. A monodisperse aerosol is necessary to differentiate any effects of size on the adhesion efficiency. The corona charging device will be used to increase the charge on the aerosol particles for examining effects of increased charge. The humidifier will provide humidification of the aerosol for studying humidity effects on the adhesion efficiency. Aerosol concentration can be decreased by the addition of clean dilution air.

Drop Generator

An Abbott-Cannon type drop generator (Abbott and Cannon, 1972) will be used to generate 50 to 200 μm radius drops. Uniform drops in a wide range of sizes can be produced at a specified rate. The size of the drops produced can be measured by a microscope after collecting the drops in a dish filled with silicon oil (Wang, 1978). Drops can be charged to approximately the Rayleigh limit by induction charging and the individual charge measured by an electrometer.

Aerosol Chamber

Figure 20 shows an outline of the aerosol chamber. The aerosol is introduced continuously near the top of the chamber and flows out near the bottom. This continuous flow method does not have the disadvantage of the closed chamber method, where the particle concentration decreases with time due to losses by coagulation or diffusion to chamber walls. Slight positive pressure in the collector and drop chambers will prevent contamination. A condensation nuclei counter (CNC) will monitor the particle concentration continuously. Temperature and humidity will also be monitored continuously by a hydrometer. An electrometer connected to the conducting cup will monitor the charge on each drop collected.

Particle Wettability

Present theories and experiments indicate that the primary effect on particle adhesion to a liquid surface is the wettability of the particle. Hence, to characterize the effects of particles with different physical or chemical properties on the adhesion efficiency, the wettability of the particals used needs to be determined. In addition, the surface tension of the fluid will also be required. Surfactants will be used to vary (lower) the surface tension of water.

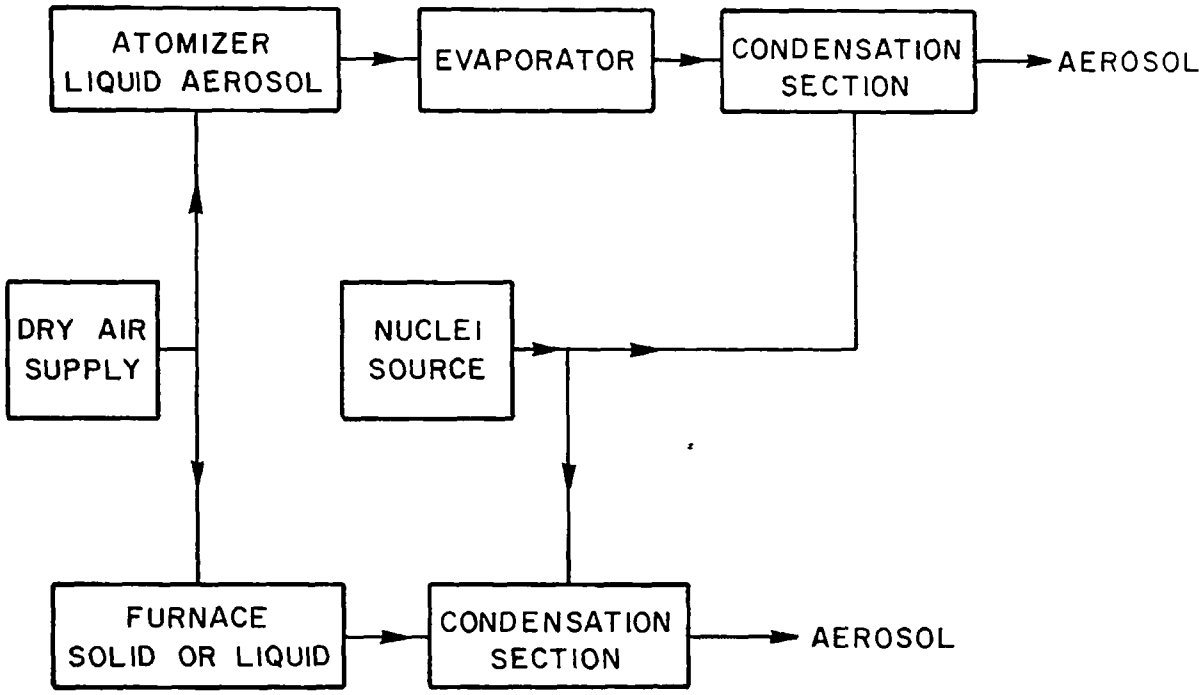

Figure 18. Aerosol generating system.

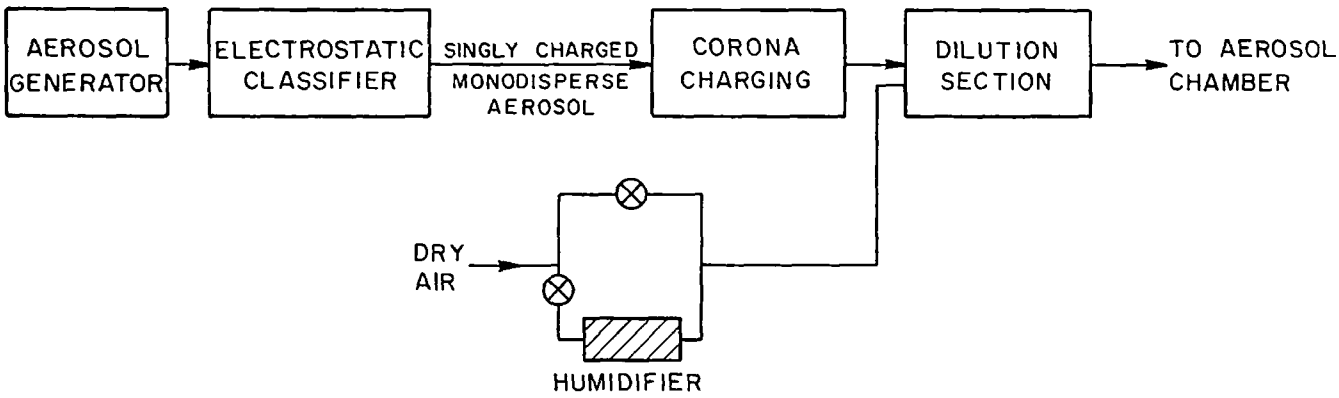

Figure 19. Aerosol conditioning system.

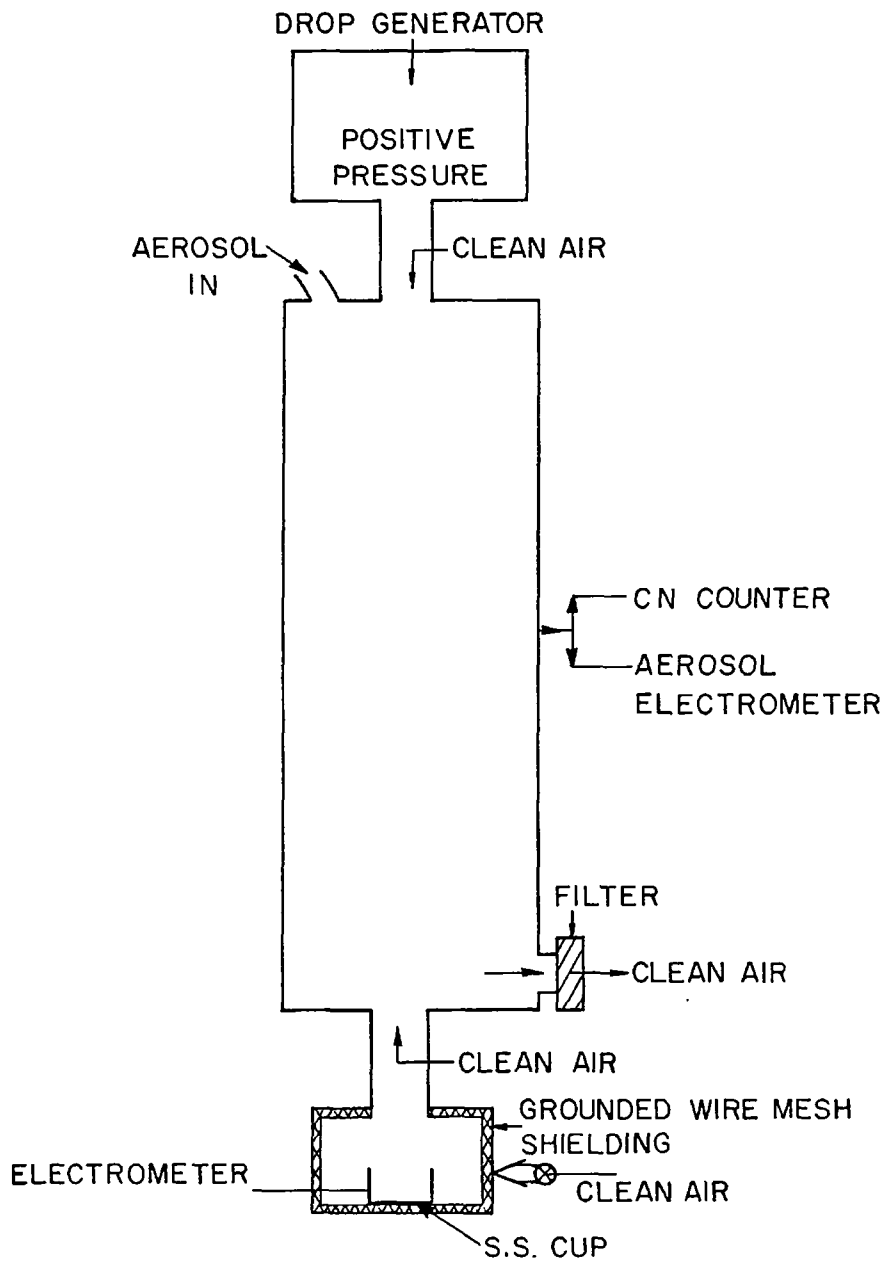

Figure 20. Aerosol chamber design.

Contact Angle

Direct measurements of the contact angle involve the interaction of a liquid drop with a flat substrate or the interaction of the sphere with the liquid. The latter method is the appropriate one for the case of particles impacting on a drop. The particle sizes of interest are in the micrometer and submicrometer range. However, due to engineering limits, spheres with diameters larger than approximately 100 μm only are available. Hence, the experiment will be done with "large" spheres and the effects will be inferred for the particle sizes of interest.

Spheres of metals, plastics or glass of various sizes are readily available. Figure 21 illustrates the experimental technique for the determination of the contact angle which is obtained by direct observation through a magnifying lens. Resolution can be achieved by adequate enlargement of a photographic print. The following effects on the contact angle will be examined.

1. Surfactants: A range of surface tension values, obtained by the addition of surfactants to the water, will be used.

2. Roughness or asperities on sphere surface: Different degrees of roughness measured by height and spacing of asperities will be studied. The roughness will be mechanically or chemically (etched) produced.

3. Electrical charge: Effects of charge on the contact angle will be studied by placing different potentials on the liquid and sphere.

In addition, following the method of Morishima and Kariya (1978), the forces needed to push the sphere into or pull the sphere away from the fluid will be determined with the above parameters. The results will be useful in checking the theory developed for particle adhesion.

Wettability

The primary concern is with nonwettable and partially wettable particles. Wettability can be measured in terms of the contact angle. However, for most substances a smooth sphere is impossible or extremely difficult to produce. An alternate method of determining the relative wettability is by the rate of rise of the liquid up a compacted bulk of the powder of the material used to generate the particles (Weber, 1968; Glowiak and Kabsch, 1972). The contact angle can be inferred (estimated) by reference to the rate of rise for a powder of known contact angle such as glass, taking into account the effects of size, shape and roughness obtained from the contact angle experiment. Figure 22 shows an outline of the simple apparatus needed.

MODELLING STUDIES

Adhesion of Particles Impacting on a Drop

All previous studies (Pemberton, 1960; McDonald, 1963; Allen, 1975; Emory and Berg, 1978) have considered only the case of particles impacting

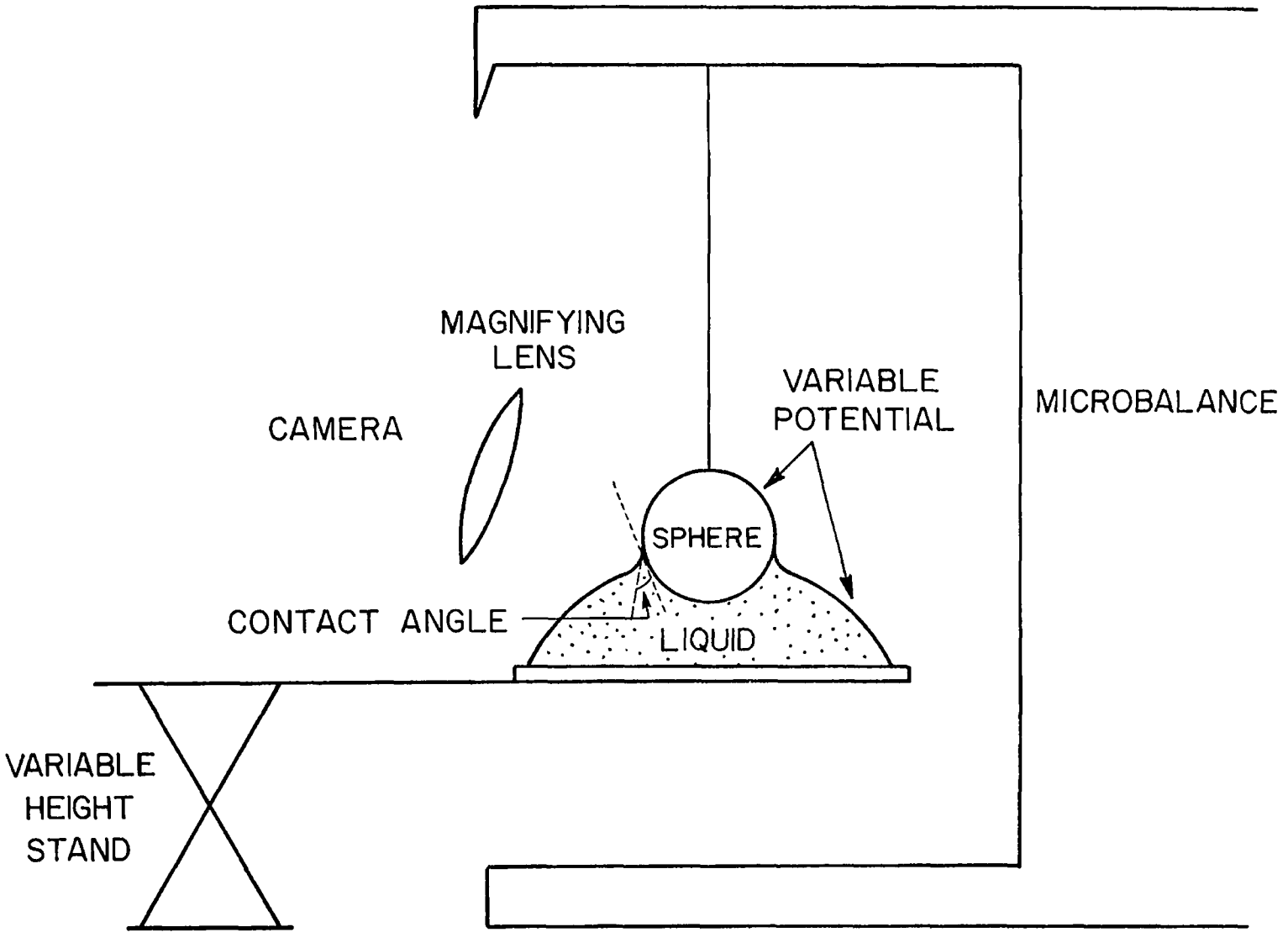

Figure 21. Experimental design for determining contact angle of sphere.

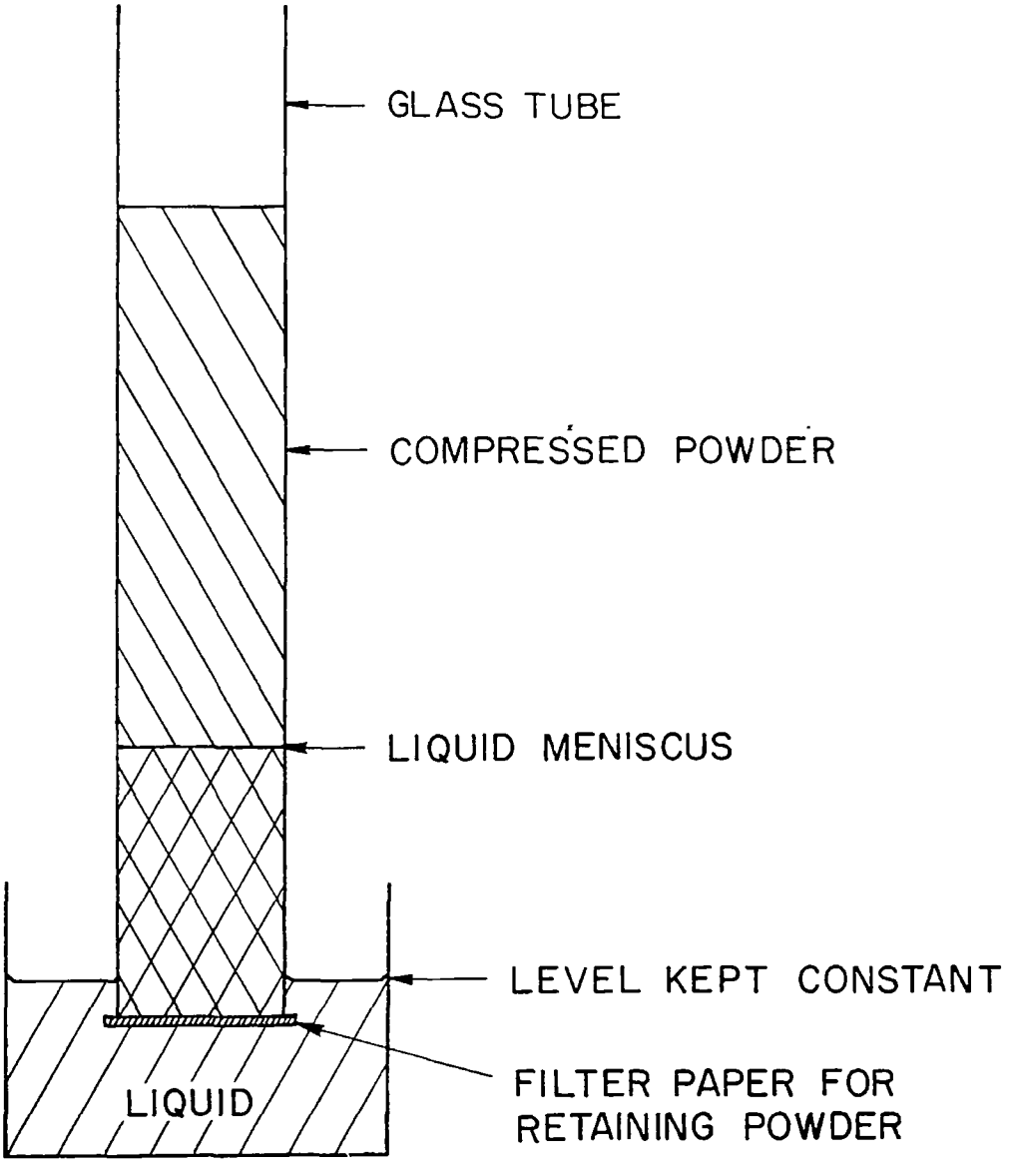

Figure 22. Experimental design for determining wettability of powder.

normally on a flat liquid surface. Particles were assumed to adhere once coalescence occurred. These theories have been found to be inadequate in light of experimental findings of Weber (1968, 1969) and Stulov *et al.* (1978).

Particles impacting on drops have different angles of impact. Particles on a grazing or near grazing impact may have enough inertia to escape after coalescence. The dynamics of the particle after coalescence has occurred may be the decisive factor in determining if the particle adheres. Factors which may affect coalescence include the shape of deformation of the liquid surface, the curvature of the liquid surface (Morishima and Kariya, 1978), the condition of the particle or liquid surface (presence of contaminants), electrical charges, and short range forces (Van der Waals, double layer forces). A thorough analysis of the significance of the possible forces and conditions and the modelling of more comprehensive dynamics of the particle-surface interaction will be conducted to resolve the contradictions existing. In addition, the proposed well-controlled experiments will yield data which will verify the validity of the model.

Collision Efficiency

To characterize the data obtained from the above proposed experiments, the collision efficiencies of drops for particles will be modelled taking into account all significant mechanisms promoting particle capture. Electrostatic forces, inertial impaction, phoretic forces interception effects and Brownian diffusion will be treated. Convective diffusion and trajectory computations will be carried out to obtain the collision efficiencies in Stokes and potential flow. Numerical flow fields available in the literature will also be used.

Limiting Factors in Particle Collection by Charged Drops

Previous studies, e.g., Kraemer and Johnstone (1955) and Prem and Pilat (1978), have indicated that increasing the drop and the particle charges will increase collection efficiencies. However, these works did not consider the effect of charge on drop stability. A maximum in drop charging exists due to the Raleigh limit (Hendricks and Schneider, 1963) for a hydrodynamically stable drop. Due to the decrease in drop size by evaporation, a drop generated at the Raleigh limit will become unstable and eject highly charged droplets. Hence, the effects of maximizing the drop charge on the particle collection characteristics are not clear. A theoretical study will be carried out to determine the conditions which maximize particle collection.

RESULTS AND/OR BENEFITS EXPECTED

The proposed studies will provide the following results:

1. Clarification and documentation of the various mechanisms affecting the adhesion of particles impacting on drops.

2. Determination of the adhesion efficiency of nonwettable, partially wettable, and wettable particles impacting on drops.

3. Elucidation of the role of surfactants in the collection of non-wettable, partially wettable, and wettable particles.

4. Determination of the parameters for maximizing the collection of charged particles by charged drops.

The results obtained will enable optimization of the collection efficiency and operating costs of particulate control devices utilizing wet surfaces as collectors, e.g., electrostatic, Venturi, or charged droplet scrubbers and electrostatic precipitators with wet walls. Especially important is the maximization of the fine particle collection efficiencies.

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