

1 Gas cleaning at high temperatures: gas and particle properties

J. P. K. SEVILLE and R. CLIFT

1.1 The need for hot gas cleaning

The development of technologies for gas cleaning at high temperatures has been extraordinarily rapid following the pioneering work of the UK/US/German collaborative project at the Grimethorpe pressurised fluidised bed combustion facility in the late 1970s and early 1980s. The long-term needs of the power generators may have driven this early development, but the focus has now shifted to the chemical and process industries. Environmental legislation now being rapidly implemented in most industrialised countries means that their needs are anything but long term! Furthermore, their filtration requirements are at least as challenging as the high-pressure, high-temperature filtration problems which stimulated the early development of the technology.

Table 1.1 gives some examples of applications of hot gas cleaning and their operating requirements. The first group comprises three distinct types of system for electrical power generation from coal, all of which have their own requirements for gas cleaning at high temperatures. In pressurised fluidised bed combustion (PFBC), for example, coal is burned in a pressurised fluidised bed, raising steam within in-bed tubes. The gases from the combustor enter a turbine at typically 10–20 bar and 1100 to 1150 K in order to generate further power and drive the compressor on the air inlet. These gases must be thoroughly cleaned in order to avoid turbine blade damage and there is a thermodynamic advantage in doing this at the operating temperature rather than first cooling the gases, passing them through a conventional gas-cleaning device, and then reheating. As an alternative, longer-term approach to power generation from coal, the fuel is partially or completely gasified and the gases used to fire a turbine (gasification combined cycle). Because turbine entry temperatures are even higher than for PFBC, high generation efficiencies can be achieved, but only at the expense of more thorough gas cleaning, which may include removal of alkali salts derived from the coal (see Chapter 12). For cycles in which the coal is devolatilised or partially gasified, the economics are again in favour of cleaning the gases hot.

In the chemical and process industries and in incineration, the need for gas cleaning is being driven increasingly by the requirements of environmental legislation, which has been directed specifically at particulates, acid gases,

Table 1.1 Summary of potential high-temperature gas filter applications and operating requirements (Lippert)

Application	Operating		Gas environment	Filter device requirements
	Temperature (°C)	Pressure (bar)		
Power generation				
Pressurised fluidised bed combustion	800	10	Oxidising with alkali	Turbine protection; meet environmental standards
Integrated gasification combined cycle	600–800	10–30	Reducing with alkali, H ₂ S	Turbine protection; meet environmental standards, protect sulphur capture beds
Conventional	<700	1	Oxidising	Meet environmental standards; low ΔP
Chemical process				
Metal refining	300–750	1–3	Varied, can be severe	Enhanced product recovery; reduced environmental emissions; resource recovery; energy recovery
Calcination/drying				
Catalytic cracking				
Precious metal recovery				
Incineration				
Hazardous waste	up to 1000	1	Oxidising, containing reactive chemical species	Reduce environmental emissions
Municipal waste				Improve incineration process
Kiln furnaces				Protect downstream equipment

From Lippert (1991).

heavy metal compounds, hydrogen chloride and organic chlorides such as dioxins and furans. The reasons for interest in cleaning gases hot rather than cold are many and various. They include a desire to remain well above acid dew points, improved thermodynamic efficiency, especially where downstream heat recovery is employed, and an improvement in the versatility of the overall process. In cases where the alternative is to cool process gases by dilution with ambient air, there may also be simple economic advantages in filtering the gases hot, because the total power requirement resulting from the filter pressure drop and throughput can be reduced by so doing (Chapter 7). The ability to clean process gases hot also allows the simultaneous removal of gaseous components by 'dry scrubbing' (Chapter 11). A further possible advantage concerns the reformation of chlorinated organics, which is thought to be catalysed by elements of the particulates in the process gases as they are cooled (Dickson and Karasek, 1987); removal of such particulate catalysts should, therefore, prevent emissions of these damaging compounds.

1.2 Gas and particle properties

The selection of materials for construction of gas-cleaning devices is often specific to a particular application. However, the effects of temperature and pressure on gas properties, the consequences for particle motion and the implications for gas cleaning are general. Temperature, pressure and chemical composition can also have strong effects on particle–particle cohesion and on particle–surface adhesion, which affect the performance of gas-cleaning equipment. These effects are to some extent system-specific, but some useful general points can nevertheless be made.

1.2.1 Gas properties

Over the range of pressures currently conceived as relevant in industrial gas cleaning, departures from ideal gas behaviour are negligible. Therefore, the density of a gas at pressure P and absolute temperature T can be approximated by:

$$\rho_g = \frac{M_w}{V} = \frac{PM_w}{RT} \quad (1.1)$$

where M_w is the mean molecular weight of the gas, V the molar volume and R the universal gas constant. With P in bars, T in K, and ρ_g in kg/m^3 , R is $8.3143 \times 10^{-2} \text{ bar m}^3/(\text{kmol K})$.

Elementary kinetic theory gives a first approximation for the effect of temperature and pressure on gas viscosity. Viscosity is predicted to be

independent of pressure, and proportional to the square root of absolute temperature. In practice, the temperature dependence is usually stronger but, at least over the pressure range of interest here, it can be assumed that pressure has no significant effect on gas viscosity (Reid *et al.*, 1977).

These general conclusions are useful for quick estimates of the pressure drop associated with gas cleaning equipment. For filters in which the Reynolds number of the gas flow is small, e.g. for most fabric and ceramic filters (see Chapters 6 and 7)

$$\Delta P \propto \mu U \quad (1.2)$$

where U is the *actual* face velocity through the filter. Therefore, for constant *volumetric* throughput of gas,

$$\Delta P \propto \mu \propto T^n \quad (1.3)$$

where n is 0.5 or slightly larger (see above). For constant *mass* throughput of gas,

$$\Delta P \propto \mu/\rho \propto T^{(1+n)} P^{-1} \quad (1.4)$$

For devices with high Reynolds numbers, e.g. cyclones or granular bed filters with high face velocity (see Chapters 3 and 9),

$$\Delta P \propto \rho U^2 \quad (1.5)$$

Therefore, for constant *volumetric* throughput,

$$\Delta P \propto P T^{-1} \quad (1.6)$$

while, for constant *mass* throughput,

$$\Delta P \propto \rho^{-1} \propto T P^{-1} \quad (1.7)$$

In addition to these macroscopic properties, the mean free path of gas molecules, λ , is inversely proportional to density, so that

$$\lambda \propto T/P \quad (1.8)$$

For more precise estimates, Beard (1976) recommends a form which is equivalent to

$$\lambda = 3200\mu \sqrt{\frac{\pi}{2\rho_g P}} \quad (1.9)$$

where λ is in μm , μ in Ns/m^2 and P in bars. For air, equation (1.9) becomes

$$\lambda = 215\mu T^{1/2}/P \quad (1.10)$$

with T in K. In view of the dependence of density and viscosity on temperature and pressure, equations (1.9) and (1.10) both imply the form of dependence given by equation (1.8). To indicate typical values, λ for air is $0.069 \mu\text{m}$ at 300 K and 1 bar, $0.32 \mu\text{m}$ at 1100 K and 1 bar, and $0.032 \mu\text{m}$ at 1100 K and 10 bars.

1.2.2 Gas-particle interaction

Many particle removal processes require the particles to migrate relative to the gas, so that the drag of the gas on the particles is of prime interest. The *particle* Reynolds number is defined as

$$Re_p = ud_p\rho_g/\mu \quad (1.11)$$

where d_p is the particle diameter and u the velocity of the particle relative to the gas. In most gas cleaning devices, Re_p remains small. The drag force, F_D , can then be estimated from Stokes' law with a correction to allow for 'slip effects' which arise when the particle diameter is comparable to the mean free path of the gas molecules:

$$F_D = \frac{3\pi ud_p}{C} \quad (1.12)$$

where C is the slip correction factor or 'Cunningham coefficient' defined as,

$$C = \frac{\text{Drag on particle in continuum flow at same } Re}{\text{Drag on particle in presence of slip}} \quad (1.13)$$

The value of C for a given particle and gas actually depends on the 'accommodation coefficient', i.e. the fraction of gas molecules undergoing diffuse reflection from the particle surface. Clift *et al.* (1978) summarise results which can be used to estimate C if the accommodation coefficient is known. Usually it is not known, and C must be estimated empirically from Davies' (1945) modification of a form proposed by Knudsen and Weber (1911)

$$C = 1 + Kn[2.514 + 0.8 \exp(-0.55/Kn)] \quad (1.14)$$

where Kn is the Knudsen number:

$$Kn = \lambda/d_p \quad (1.15)$$

Equation (1.14) is applicable to spherical particles. Beard (1976) and Clift *et al.* (1978) summarise modifications for non-spherical particles. Some representative values for C are shown in Figure 1.1, taken from Clift *et al.* (1981). It is worth noting that, whereas C only departs significantly from unity for submicron particles at ambient conditions and at elevated pressure, slip effects are significant for particles several microns in diameter at elevated temperatures and ambient pressure (see also Chapter 10).

For Reynolds numbers larger than say 0.1, equation (1.12) is better replaced by the general form:

$$F_D = \pi\rho_g u^2 d_p^2 C_D/8 \quad (1.16)$$

where C_D is an empirical function of Re_p . Of the many forms suggested for $C_D(Re_p)$, that due to Clift and Gauvin (1970) is widely used:

$$C_D = \frac{24}{Re_p}(1 + 0.15Re_p^{0.687}) + 0.42/(1 + 4.25 \times 10^4 Re_p^{-1.16}) \quad (1.17)$$

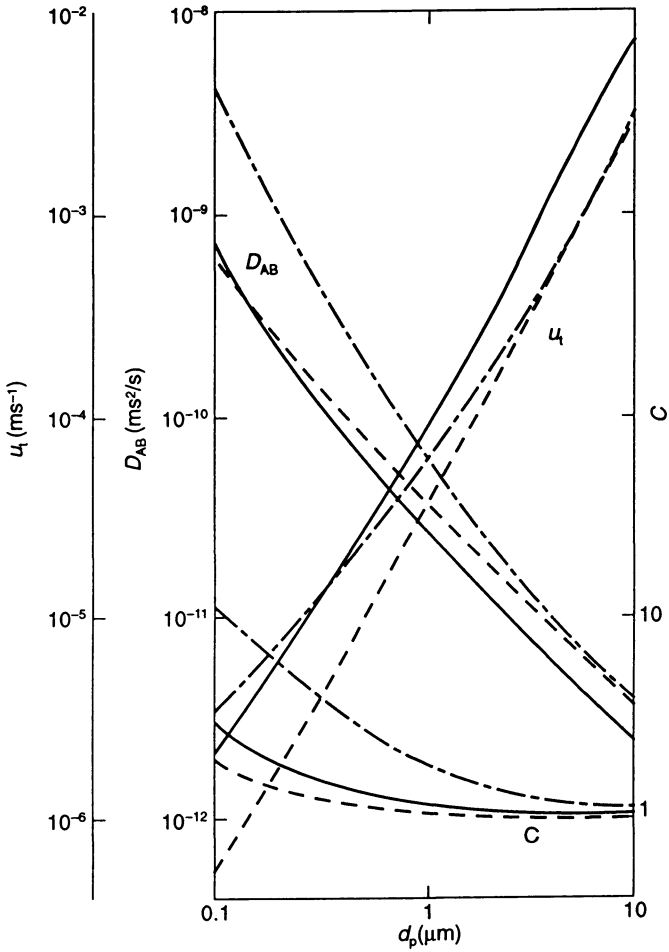


Figure 1.1 Variation of terminal velocity, u_t , diffusion coefficient, D_{AB} , and Cunningham slip correction factor, C , with particle diameter, d_p (Clift *et al.*, 1981). For particles of density 2500 kg/m^3 in air at 300 K, 1 bar (—); 1100 K, 1 bar (---); and 1100 K, 10 bar (-·-·).

As a general result (see Clift *et al.*, 1978)

$$Kn = \sqrt{\frac{\pi\gamma}{2}} \frac{Ma}{Re_p} \quad (1.18)$$

where γ is the ratio of specific heats of the gas and Ma is the Mach number of the particle. Therefore, if Re_p is not in the range where Stokes' law applies, Kn is very small unless Ma is appreciable, i.e. unless u is significant by comparison with the speed of sound in the gas. This is rarely the case in gas

cleaning equipment so that, if Re_p is sufficiently large that equation (1.16) must be used rather than (1.12), then slip effects can be ignored.

For a particle settling freely under its own weight in a gas, the drag force counterbalances the immersed weight of the particle. For low Re_p the terminal velocity then follows from equation (1.12) as,

$$u_t = Cgd_p^2(\rho_p - \rho_g)/18\mu \quad (1.19)$$

where ρ_p is the particle density. Normally $\rho_p \gg \rho_g$, so that equation (1.19) can be written

$$u_t = Cg\rho_p d_p^2/18\mu \quad (1.19a)$$

Representative values for u_t are shown in Figure 1.1 for particles of density 2500 kg/m^3 . In the absence of slip effects (i.e. at elevated pressure), $u_t \propto \mu^{-1}$ or, from the previous section, $u_t \propto T^{-1/2}$ approximately. Therefore, increasing temperature, through its effect on gas viscosity, increases fluid-particle drag, reduces settling velocity and generally makes removal of particles from gas more difficult. The effect of pressure is smaller and acts through the slip correction, so that it is only significant for particles typically smaller than about $1 \mu\text{m}$ (see Figure 1.1). In general, the effect of increasing pressure is again to make particle removal more difficult. Electrostatic precipitators can be an exception to this rule because of the effect of pressure on the electrical properties of the gas (Chapter 10). Increasing the pressure, within the range of interest here, widens the gap between the corona-starting and sparkover voltages. Therefore, the effect of increased drag on the particle at high pressure and high temperature may be compensated for, or even overcome, by increasing the electrostatic field intensity.

In certain types of filter, the Brownian diffusivity of particles in the gas is of concern. This is usually best evaluated by the Stokes–Einstein equation (see Clift *et al.*, 1981):

$$D_{AB} = Ck_B T/3\pi\mu d_p \quad (1.20)$$

where k_B is Boltzmann's constant, $1.380622 \times 10^{-23} \text{ J/K}$. Taking $\mu \propto T^{1/2}$ as before, for a given particle size,

$$D_{AB} \propto CT^{1/2} \quad (1.20a)$$

so that Brownian diffusivity increases with increasing temperature. Pressure again has a much weaker effect, through the slip correction factor C : increasing pressure decreases D_{AB} . Some typical values are shown in Figure 1.1.

1.2.3 Particle–particle interaction

Whereas the effects of temperature and pressure on hydrodynamic properties are predictable, as outlined above, the effects on the forces between particles are much less predictable. Nevertheless, interparticle forces are important in

most gas cleaning operations. In fabric and ceramic filters (Chapters 5–8) the permeability of the filter cake and the cleanability of the filter depend critically on the cohesion between particles and on the adhesion of particles to the filter medium. In granular bed filters (Chapter 9), whether a cake forms and the structure of the deposit – even whether the filter is effective – depend on the strength of interparticle forces. Some particulate collection devices, particularly electrostatic precipitators and barrier filters, rely on the collected particles to form large agglomerates which have high terminal velocity and are, therefore, removed easily from the gas when detached by mechanical action.

Interparticle forces are generally system-specific because they are strongly dependent on the properties of the particle surface. To take the specific example of fly ash from coal combustion, sodium and potassium sulphates can condense onto the surface of the particles (by reactions considered in Chapter 12). The resulting surface layer causes the fly ash to sinter at temperatures several hundred degrees below the softening or fusion points indicated by standard tests. This kind of behaviour is at present very difficult to predict *a priori*. The sections which follow provide a simple introduction to the more general types of interparticle forces which may arise.

Van der Waals forces. All intermolecular forces are essentially electrostatic in origin, although they manifest themselves in such different ways that subclassification has become common. For a more extensive and very readable review of the subject, the reader is referred to *Intermolecular and Surface Forces* by Israelachvili (1991). In general, it can be shown that the force of adhesion, F_{ad} , between two spheres of radii R_1 and R_2 is given by

$$F_{ad} = 4\pi\gamma R_1 R_2 / (R_1 + R_2) \quad (1.21)$$

where γ is half the van der Waals energy needed to separate two surfaces from contact to infinity. For $R_1 = R_2 = d/2$, therefore,

$$F_{ad} = \pi\gamma d \quad (1.22)$$

Real particle surfaces are, of course, rough, and the radii of the asperities may determine the van der Waals force. Fine particles may act as spacers between the larger particles and, therefore, reduce the forces between them, or they may fill in gaps and thus increase the interaction force, depending on their relative size.

Real particles are not rigid and will deform elastically and/or plastically at the contact point, even under zero external load. The effect of elastic deformation is relatively small. For plastic deformation, the total interaction force must include a term for the extended contact area.

From the calculations leading to equation (1.21), it is apparent that the total interaction energy for two bodies almost in contact is dominated by the interactions between the *surfaces* of the bodies, the so-called ‘screening’

effect. In fact, the interaction energy is determined almost entirely by the two surface layers of depth equal to the surface separation. Therefore, thin layers of, for example, oxide, or adsorption of gases may have a strong effect on the observed interparticle force.

Liquid bridge forces. If the surface of a particle has a film of mobile liquid, then at points of contact with other particles and surfaces ‘liquid bridges’ will form. It will also be the case that if the partial pressure of some suitable vapour in the surrounding gas is sufficiently high, condensation will occur at points of contact. Again, the result is the formation of a liquid bridge. The static capillary force between two particles is the sum of three terms: the axial component of the surface tension force at the solid–liquid–gas interface, the force owing to the reduced hydrostatic pressure in the bridge itself and the buoyancy force resulting from the partial immersion of each particle. The buoyancy term and the distortion of the shape of the bridge by gravity can be neglected if the particle size is less than about 1 mm. Fisher (1926) was the first to show that the total capillary force at contact between equal spheres of radius R under conditions of perfect wetting is

$$F_c = \frac{2\pi R\gamma}{1 + \tan(\beta/2)} \tag{1.23}$$

where γ is the liquid surface tension and β is the ‘half-angle’ of the bridge (Figure 1.2). The derivation of this result is considered by Seville *et al.* (1997).

Equation (1.23) predicts an increase in the magnitude of F_c for a decrease in the size of the liquid bridge (represented by β) until a maximum value is reached at zero liquid content. Although careful laboratory experiments, such as those of Cross and Picknett (1963) and Mason and Clark (1965), reproduced this trend down to very low liquid volumes, this behaviour is nevertheless the opposite of what one would intuitively expect, i.e. wetter powders commonly appear stronger than drier ones (until the capillary state is reached, at which point the strength is reduced). Pietsch (1968) attempted to resolve

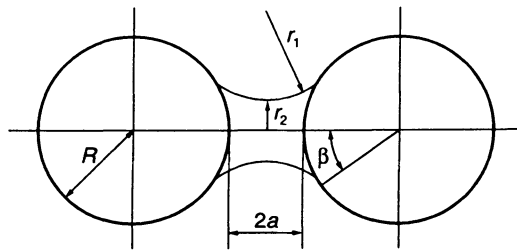


Figure 1.2 A liquid bridge between equal spheres (perfect wetting); a = self-separation.

this apparently paradoxical conflict between theory and experimental result by suggesting that all real contacts are rough and that an effective sphere separation, a , should be included in the theory. The predicted total capillary force then shows a maximum at a certain value of β (Seville *et al.*, 1997). Other contact geometries, such as cone-on-plate, show an interparticle force which increases with the quantity of liquid in the bridge (see, for example, Coughlin *et al.*, 1982).

Electrostatic forces. Most aerosol particles carry some electric charge and very large charges may accumulate either accidentally, in working of stone for example, or deliberately, as in electrostatic precipitation. For coarser particles, electrostatic charges are frequently generated in transport and handling and if not properly controlled may lead to electrical discharges and the very real danger of powder explosions (see, for example, Palmer, 1990). Four types of electrostatic force are distinguished below and illustrated in Figure 1.3.

Space charge forces. Each particle in a cloud of charged particles is affected by its interactions with all other particles. If, as is often the case, all particles have like charge, this will result in mutual repulsion. The effect is generally only of importance at high charge levels and high mass loadings, as in

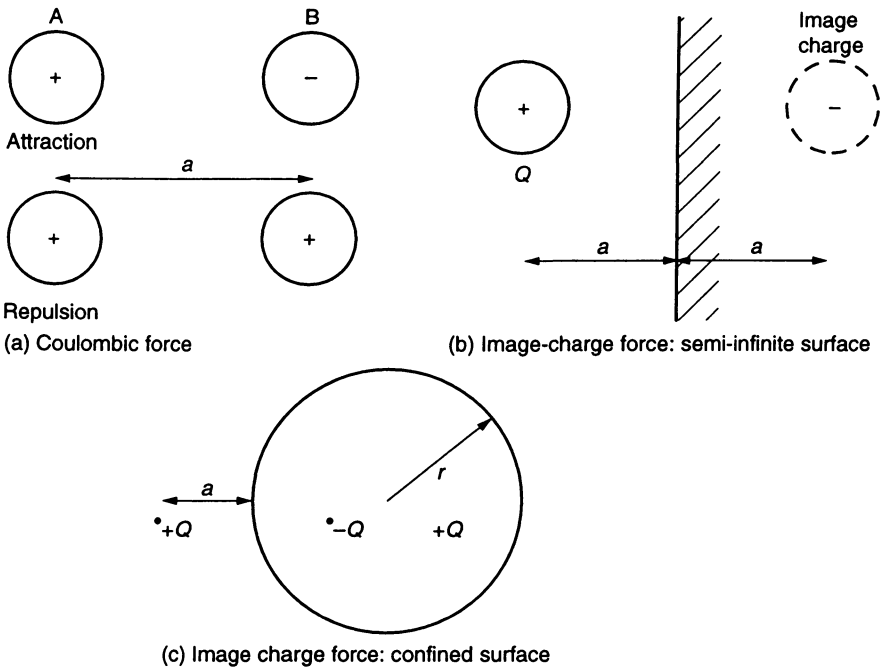


Figure 1.3 Three types of electrostatic force (Seville *et al.*, 1996).

electrostatic precipitation. The maximum electrical field which can be sustained in air as a result of space charging is about 3×10^6 V/m, the breakdown strength of the gas; this same limit effectively curtails the maximum charge which particles can carry.

Coulombic forces. If two particles are charged, as in Figure 1.3a, the force between them is given by

$$F_E = \frac{-Q_A Q_B}{4\pi\epsilon_r\epsilon_0 a^2} \quad (1.24)$$

where Q_A and Q_B are the total charges on the two particles, separated by a centre-to-centre distance a , and ϵ_0 and ϵ_r are the permittivity of free space and the relative permittivity, respectively. F_E is, therefore, positive in attraction.

Image-charge forces. When a charged particle approaches a surface, it induces an 'image charge' in the surface, as shown in Figure 1.3b. For a charged particle and a semi-infinite surface, the attraction is the same as if there were a second particle of opposite sign on the other side of the interface. For a conducting surface,

$$F_{IC} = \frac{Q^2}{4\pi\epsilon_r\epsilon_0(2a)^2} \quad (1.25)$$

If the neutral surface is limited in extent, the strength of the image-charge force depends on the extent of *charge separation* within it, so that

$$F_{IC} = \frac{Q^2}{16\pi\epsilon_r\epsilon_0 a^2} \left[1 - \frac{a}{(a^2 + r^2)^{1/2}} \right] \quad (1.26)$$

Therefore, if $r \ll a$, the image-charge force is negligible, because little charge separation is then possible. In filtration applications, it is, therefore, generally more effective to charge the aerosol, which can then induce an image charge on the much larger collecting fibre or particle, than to charge the collecting surface alone and attempt to induce an image charge in the aerosol. (It would be better still to charge both to opposite sign, but this is usually difficult to arrange.)

It is worth noting in this context that electrostatic forces are often important in filtration up to the first contact between the aerosol particle and the collecting surface, but are seldom responsible for holding the aerosol particle in place thereafter, because the stored electrical charge can usually leak away through the contact. In other words, electrostatic charges can be responsible

for deflecting a particle trajectory but can seldom hold the particle against a surface, unless that surface is an insulator.

In principle, the magnitude of an electrostatic force can be calculated using equations (1.24) to (1.26) but, in practice, the electrostatic charge is very difficult to measure (Coury *et al.*, 1991) and even more difficult to predict *a priori*. Three mechanisms can contribute to charging a solid aerosol particle: static electrification (tribocharging), diffusion charging and field charging. *Static electrification* depends very much on the specific materials involved and can be quite unpredictable. *Diffusion charging* results from the Brownian motion of ions and particles and, therefore, does not require an external electric field. *Field charging* results from the movement of unipolar ions in a strong electric field. The charge acquired is proportional to the square of particle diameter in field charging and to particle diameter in diffusion charging; as a result, field charging is the dominant mechanism for particles larger than about 1 μm (Hinds, 1982). Further consideration of particle charging is given in Chapter 10.

By way of example, for fly ash particles from fluidised bed combustion redispersed for filtration testing using a tribocharging feeder, the charge level was found to be about $10 \mu\text{C}/\text{m}^2$ (equivalent to about 200 excess electrons for a 1 μm particle; Coury *et al.*, 1991). From equation (1.24), with $\epsilon_r = 1$ (air) and $\epsilon_0 = 8.9 \times 10^{-12} \text{C}^2/\text{Jm}$ and assuming that the two particles considered have equal and opposite sign,

$$F_E = 8.8 (d^2/a)^2 \quad (1.27)$$

At its maximum, $a = d$, so that

$$F_{E,\text{max}} = 8.8 d^2 \quad (1.28)$$

This is compared with the magnitude of the other interparticle forces below.

Comparison of the magnitude of interparticle forces. Theoretical interparticle forces for single-point contact between equal spheres (in air) are plotted as functions of particle diameter in Figure 1.4, with single particle weight plotted for comparison. It is clear that, in general, capillary forces, if present, will make the largest contribution to interparticle force at contact, followed by van der Waals forces and electrostatic forces. For perfect point contact, under the conditions selected here, these forces exceed single particle weight for particles below about 1 mm in diameter. In practice, however, contact is never perfect; if asperity contact is assumed, particles above about 200 μm are virtually free of all interparticle force effects except for capillary forces.

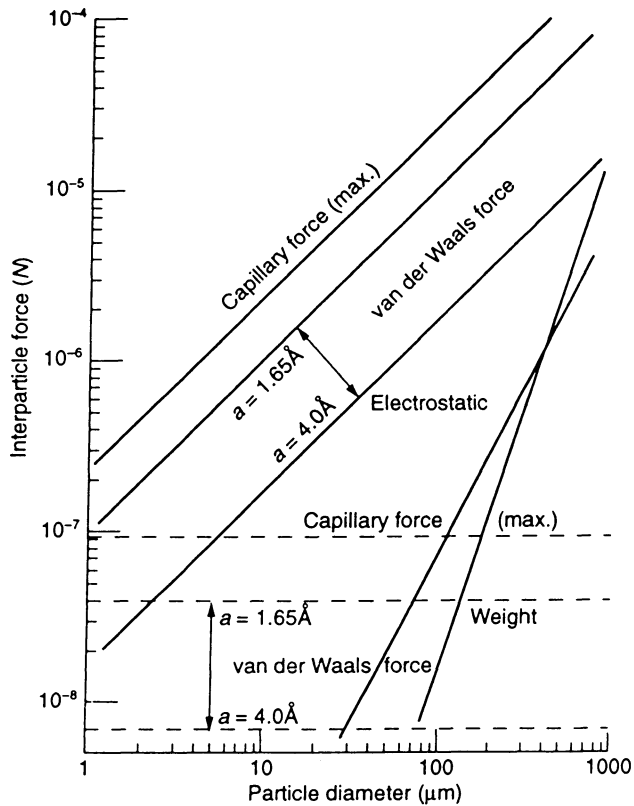


Figure 1.4 Comparison of the magnitude of interparticle forces ($1 \text{ \AA} = 0.1 \text{ nm}$) (Seville *et al.*, 1996).

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