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# Triboelectric Effects in Filtration of Small Dust Particles in a Granular Bed

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by an order of magnitude, but at 1000 atm they become comparable.

These data are of course for a temperature far below the critical value. In the critical region one would expect both  $\Delta V$  and  $\partial(\Delta V)/\partial P$  to become much larger, and in view of the rapid changes of volume with pressure, the latter term may become very large indeed. In this case constant-pressure ( $P^r = 0$ ) activity coefficients do not provide a satisfactory solution to the problem of separating the composition and pressure dependencies of liquid-phase properties.

The purpose of this paper is to show how the approximations which attend evaluation of  $\gamma_i(P^r = 0)$  values compromise thermodynamic rigor in the reduction of isothermal VLE data. A general derivation demonstrates that properly evaluated constant-pressure activity coefficients lead to realization of all thermodynamic objectives. However, rigorous evaluation of Poynting corrections for high pressures and in the critical region, where they are significant, requires data not usually available. A possible resolution of this dilemma is offered by recent work of Mathias and O'Connell (1979), who report successful evaluation of pressure-corrected activity coefficients from a statistical mechanical solution theory based on a corresponding states model of direct-correlation-function integrals. Their procedure does not require separation of the pressure dependence from that of composition, and thus does not require evaluation of Poynting corrections.

## Nomenclature

$A^E$  = molar excess Helmholtz function  
 $\bar{A}_i^E$  = partial molar excess Helmholtz function  
 $f$  = mixture fugacity

$\hat{f}_i$  = fugacity of component  $i$  in mixture  
 $\hat{f}_i^0$  = standard-state fugacity of  $i$   
 $G^E$  = molar excess Gibbs function  
 $\bar{G}_i^E$  = partial molar excess Gibbs function  
 $n$  = total moles  
 $n_i$  = moles of component  $i$   
 $P$  = absolute pressure of system  
 $P^r$  = reference pressure  
 $p$  = dummy variable of integration  
 $R$  = universal gas constant  
 $S^E$  = molar excess entropy  
 $T$  = absolute temperature  
 $V$  = molar volume  
 $\bar{V}_i$  = partial molar volume  
 $V_i^0$  = standard-state volume of  $i$   
 $\Delta V$  = molar volume change of mixing =  $V - \sum x_i V_i^0$   
 $\Delta \bar{V}_i$  = partial molar volume change of mixing =  $\bar{V}_i - V_i^0$   
 $x_i$  = mole fraction of component  $i$   
 $\gamma_i$  = activity coefficient of component  $i$  in mixture

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## Triboelectric Effects in Filtration of Small Dust Particles in a Granular Bed

The aerosol filtration efficiency of a packed and fluidized bed of dielectric granules was studied experimentally. A sharp increase in efficiency was observed at the transition from the packed to the fluidized bed mode. Experimental evidence is given which suggests that naturally produced electric charges in the fluidized state (triboelectric effect) may be responsible for this behavior.

An experimental study was performed by Tardos (1977) and Gutfinger and Tardos (1979) on filtration of small particles (aerosols) in packed and fluidized beds of granules. During this research the overall filtration efficiency of the bed of a certain thickness,  $L$ , was measured as a function of carrier gas superficial velocity,  $U_0$ . The overall filtration efficiency  $\eta$ , was computed from

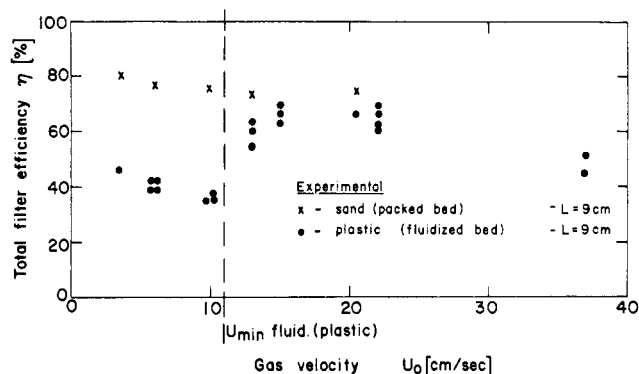
$$\eta = 1 - \frac{n_{\text{out}}}{n_{\text{in}}} \quad (1)$$

where,  $n_{\text{in}}$  and  $n_{\text{out}}$  are the aerosol concentrations at the inlet and the outlet of the granular bed. Plastic and sand granules in the diameter range 300–1000  $\mu\text{m}$  and different aerosols such as latex and DOP (dioctyl phthalate) in the diameter range 0.2–2  $\mu\text{m}$  were used in the experiments. The gas superficial velocity was varied so as to obtain both packed ( $U_0 < u_{\text{mf}}$ ) and fluidized bed ( $U_0 \geq u_{\text{mf}}$ ) operating conditions. The procedure and the apparatus used during these experiments are described in detail by Gutfinger and Tardos (1979) and will not be repeated here.

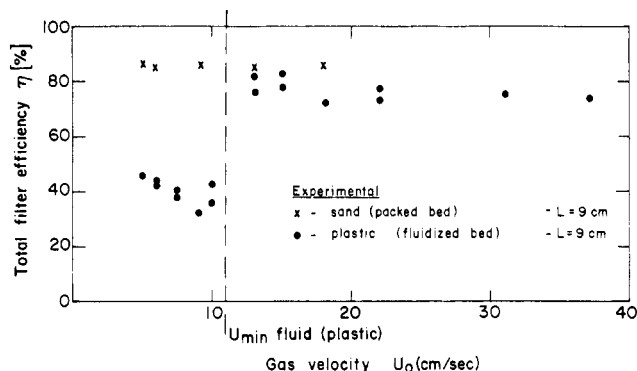
Some typical results are plotted in Figures 1 and 2. Here the overall efficiency,  $\eta$ , is presented as function of

gas velocity,  $U_0$ . Beds of plastic granules (40–50 mesh) and of sand (40–50 mesh) were used to filter latex aerosols (1.01  $\mu\text{m}$  diameter) and DOP droplets (2  $\mu\text{m}$  diameter). The plastic granule bed was operated both below and above the minimum fluidization velocity of the granules ( $u_{\text{mf}} = 11 \text{ cm/s}$ ) while the sand bed being much denser was operated only in the packed bed mode at these velocities.

The striking feature observed in Figures 1 and 2 is that the filtration efficiency of the fluidized bed filter showed a large increase immediately after the gas velocity exceeded the minimum fluidization velocity, strongly suggesting that fluidization caused the dielectric plastic granules to acquire electrostatic charges by contact or frictional electrification. This phenomenon is known as triboelectrification. Further increases in gas velocity above minimum fluidization caused a decrease in efficiency due to the formation of bubbles in the bed and the bypassing of aerosols into the bubble phase. This large change in efficiency observed in the fluidized bed was not found in a packed bed of sand granules run at the same operating conditions. A comparison of Figures 1 and 2 also shows a greater increase in filtration efficiency for the DOP particles than for the latex aerosols. This is probably due to the stickiness of



**Figure 1.** Variation of total filter bed efficiency with superficial gas velocity: beds of sand ( $\epsilon = 0.4$ ) and plastic granules ( $\epsilon = 0.37$ ) of  $360 \mu\text{m}$  mean diameter; latex aerosols of  $1.01 \mu\text{m}$  diameter.



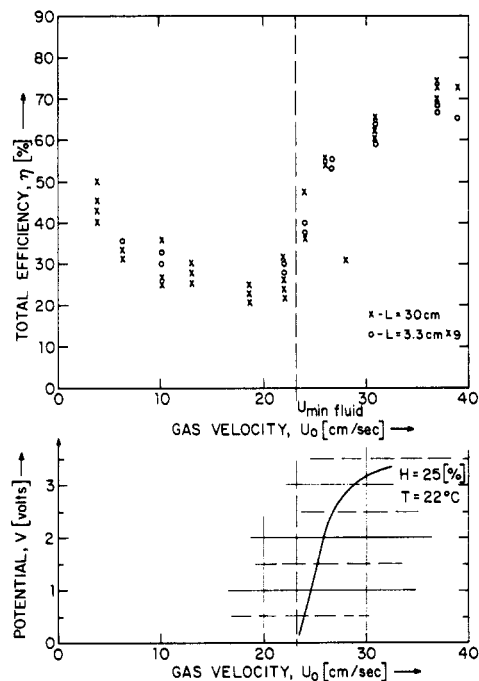
**Figure 2.** Variation of total filter bed efficiency with superficial gas velocity: beds of sand ( $\epsilon = 0.4$ ) and plastic granules ( $\epsilon = 0.37$ ) of  $360 \mu\text{m}$  mean diameter; DOP aerosols of  $2.0 \mu\text{m}$  diameter.

DOP as compared to latex, which will tend to lower the effect of aerosol reentrainment into the gas.

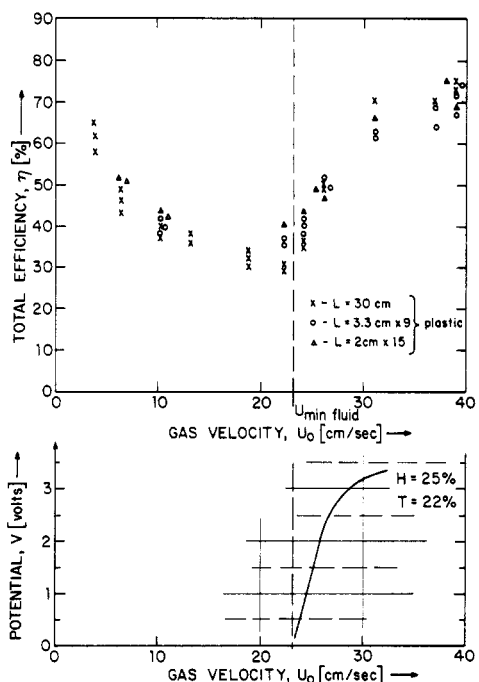
The importance of triboelectrification in fluidized bed filters was described as early as in the mid 1950's by Anderson and Silverman (1958), who found that electric charge is generated within a fluidized bed due to contacts of the fluidized media with conducting surfaces interspersed throughout the media. In one series of tests Anderson and Silverman noted a 12-fold increase in collection efficiency due to the use of electrostatically charged filter media. Recently, Figueroa and Licht (1978) obtained very high collection efficiencies (99% or better) using relatively shallow (9 cm or less) fluidized beds of plastic beads for filtering aerosols in the  $0.5$  to  $2.0 \mu\text{m}$  size range. The high collection efficiencies observed were attributed to the triboelectrification process. Higher collection efficiencies due to triboelectrification were also reported by Balusubramanian et al. (1978) in a spouted bed filter.

In order to further verify whether triboelectrification causes the efficiency increase observed when the bed reaches minimum fluidization conditions, additional experiments were carried out. Overall efficiency ( $\eta$ ) measurements were performed during which  $0.23$ - and  $0.48$ - $\mu\text{m}$  neutral latex aerosols were passed through a  $30$  cm thick granular bed of  $1$ -mm Lucite spheres at velocities below and above minimum fluidization conditions. A spherical nickel probe,  $2$  mm in diameter, similar to one used by Cheng and Soo (1970) and by Duckworth and Chan (1973) in their work on electrostatic charge measurements was introduced in the granular bed and the potential with respect to the ground was measured.

The results are plotted in Figures 3 and 4, as filtration efficiency ( $\eta$ ) and potential ( $V$ ) vs. gas velocity. Three



**Figure 3.** Variation of total filter bed efficiency and electric potential with gas superficial velocity: beds of plastic of  $1$  mm diameter; latex aerosols of  $0.48 \mu\text{m}$  diameter.



**Figure 4.** Variation of total filter bed efficiency and electric potential with gas superficial velocity: beds of plastic of  $1$  mm diameter; latex aerosols of  $0.23 \mu\text{m}$  diameter.

different beds were used: a deep bed  $30$  cm in height and two multilayer beds with the same overall total height. As seen in the figures, the efficiency decreases in the packed bed mode ( $U_0 < u_{mf}$ ) due to the gas velocity increase. This behavior is expected because at these velocities and aerosol size the capture is due mainly to diffusional deposition which decreases with increasing velocity. After minimum fluidization conditions were reached, again a sudden efficiency increase (from about  $30\%$  to  $70\%$ ) was observed. One can also see that the increase in efficiency is similar to that of the potential increase on the nickel probe. This suggests that the natural charge produced on the granules

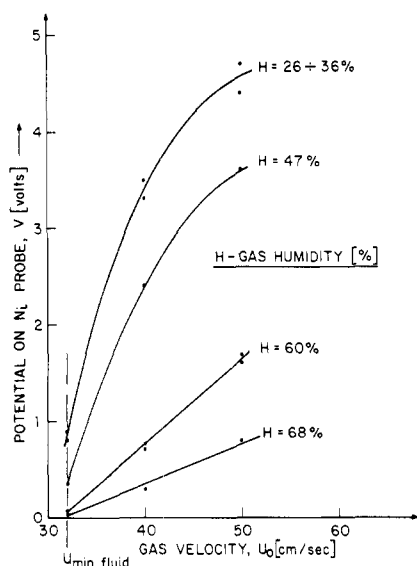


Figure 5. Variation of measured electrical potential on the Ni probe with gas superficial velocity and with gas humidity as a parameter.

by the fluidization process may be the cause for the observed enhancement in the filtration efficiency.

In order to show the effect of other factors on the triboelectric effect, additional electric potential measurements using the nickel probe were made. A sand bed consisting of 70% 18–30 mesh and 30% 20–25 mesh was fluidized by running at higher velocities (30–60 cm/s) and the potential measured by the nickel probe was plotted against gas velocity for different gas humidities,  $H$ , in Figure 5. As can be seen, the potential is strongly humidity dependent and increases sharply after the minimum fluidization velocity is exceeded.

The potential measured by the nickel sphere in a granular bed gives a qualitative indication of the magnitude of the charge on the granules but does not give the charge actually present on the granules' surface. This is due to the fact that the number of granules which hit the probe per unit time in a fluidized bed cannot be computed

because the granule flow pattern around the sphere is completely unpredictable. Further effort is needed to measure this charge using other experimental methods. The authors are presently working on this problem as well as on a theoretical analysis which should predict the effect of triboelectrification on granular bed filtration efficiency.

### Nomenclature

$H$  = relative gas humidity  
 $L$  = filter bed thickness  
 $n_{in}$  = aerosol concentration at filter inlet  
 $n_{out}$  = aerosol concentration at filter outlet  
 $T$  = gas temperature  
 $u_{mf}$  = minimum fluidization velocity  
 $U_0$  = superficial gas velocity  
 $V$  = potential

### Greek Letters

$\eta$  = overall filtration efficiency  
 $\epsilon$  = granular bed porosity

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## The Use of the Corresponding States Principle for Mixtures Containing Polar Components

It is shown that the Corresponding States Principle and its extensions using shape factors can be used for the calculation of critical states of mixtures containing polar components. The results show that the van der Waals one-fluid model works well for such mixtures and that a nonlinear pseudocritical rule for the critical compressibility factor may be useful in extending other methods of calculation, such as those employing equations of state, to mixtures containing polar components.

### Introduction

An extended form of the corresponding states principle using shape factors (Rowlinson and Watson, 1969) has been used with considerable success for the calculation of vapor-liquid equilibria (Gunning and Rowlinson, 1973; Mollerup, 1975), saturated liquid densities (Mollerup and Rowlinson, 1974), and critical and azeotropic states (Teja and Rowlinson, 1973; Teja, 1975) of mixtures of nonpolar components. It is shown here that the method can also be used for mixtures containing polar components (such as ammonia and hydrogen sulfide), at least when the components of the mixture do not differ too greatly in size.

A brief outline of the method is given and the reasons why it can be applied to polar components are discussed.

### The Corresponding States Method

Two pure substances  $i$  and  $o$  are defined to be in corresponding states if the configurational Helmholtz energy of substances  $i$  at temperature  $T$  and volume  $V$  may be obtained from the configurational Helmholtz energy of substance  $o$  at temperature  $T/f_{ii,o}$  and volume  $V/h_{ii,o}$  as follows

$$A_i[T, V] = f_{ii,o} A_o[T/f_{ii,o}, V/h_{ii,o}] - RT \ln h_{ii,o} \quad (1)$$

where the subscripts  $ii,o$  signify a property of  $i$  relative to