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SELECTING GAS BORNE PARTICULATES FOR MODEL TESTING

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SUMMARY The choice of model scale particulate is limited by materials available and ideal modelling conditions cannot always be met. Computational analysis of important particle trajectories in model and full scale systems is used to determine the model particle scale which will compensate for its actual density so that model particles exhibit a similar response to the gas flow. By suitably scaling the size of the model particulate, it is possible to use any model particulate density. The model particulate can then also represent the mass and volume of particulate accumulations correctly. Criteria for modelling particles in turbulent eddies are also developed.

1 INTRODUCTION

Model tests are often required where particulate fall-out and accumulation [Thomas, 1962; Wilson and Watt, 1974] and the influence of particulate on system pressure drop are subject to uncertainty [Pfeffer et al, 1966; Boothroyd, 1966 and Rose and Duckworth, 1969]. The selection of a representative model particulate is subject to substantial practical limitations due to the limited range of available materials, especially as many particulates are explosive. It is necessary to determine the best modelling criteria for an available model particulate when an ideal model particulate cannot be found. Particular reference will be made here to the modelling of pulverized brown coal conveying systems; the principles, however, may be applied to many other particulate conveying systems.

2 THE MODELLING PROBLEM AND SELECTION OF MODEL PARTICULATE SIZE AND DENSITY

Parameters which govern the behaviour of particulate conveying systems are the particulate and system sizes (d and D), particulate and gas densities (σ and ρ), gas viscosity (μ), gravitational acceleration (g), gas flow speed (U) and particulate mass flow rate (M). Dimensional analysis reduces the modelling requirements to five dimensionless parameters, a possible group being Froude number (U^2/gD), duct Reynolds number ($\rho UD/\mu$), particulate based Reynolds number ($\rho Ud/\mu$), particulate/gas mass flow ratio ($M/\rho UD^2$) and a parameter representing particulate trajectory geometry ($\rho D/\sigma d$), the latter being termed here the particulate response parameter. The restrictions on the model become readily apparent once the model scale and working gas (usually air) are selected, as it is generally important to model the Froude number correctly. This may imply that the full scale duct Reynolds number cannot be achieved in the model, a common aerodynamic modelling problem. Pressure drop effects depend upon the particulate/gas mass flow ratio, and it is necessary to maintain the correct mass flow ratio ($M/\rho UD^2$). Thus parameters over which a choice can be exercised are the particulate size and density. If the particulate Reynolds number is represented properly, then this specifies the size (or more generally, size range and distribution) of the model particulate. It then follows that representation of the particulate response parameter demands a specific particulate density in the model. It is here that practical difficulty arises, because it is not always possible to obtain a particulate of the required density and yet it is important that the particulate response is correctly modelled. The only course available is to vary the size of the model particulate in such a way that the density discrepancy is compensated.

To illustrate the importance of the particulate response parameter, Fig. 1 shows the spatial paths of particles moving with a gas flow which experiences a sudden directional change (such as might occur when passing a set of flow deflecting vanes or a bend in a duct). For simplicity, a constant drag coefficient appropriate to fairly large particle Reynolds numbers has been chosen and the gas has initial and final velocities of (U,0) and (U,V). The trajectories are obtained as numerical solutions of the equation of motion for the particle in the y direction, with time $t = x/U$:

$$\frac{d^2(y/D)}{d(x/D)^2} = 0.75\, C_d \cdot \left(\frac{\rho D}{\sigma d}\right)\left(\frac{V}{U} - \left[\frac{d(y/D)}{d(x/D)}\right]^2\right) \qquad (1)$$

Clearly large particles with low values of the parameter ($\rho d/\sigma d$) show a much slower response to the change of gas motion, and we see that the trajectory form is determined by this parameter. Clearly correct representation of this effect in a model is extremely important.

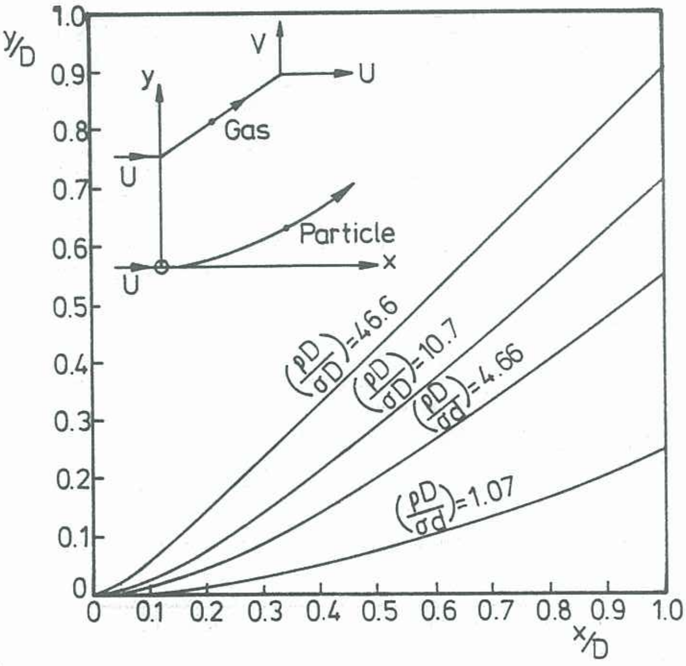

Figure 1 Response of a particle in a gas to a sudden change of gas velocity from Eqn. (1)
Horizontal axis: distance moved in direction of initial gas flow
Vertical axis: distance moved perpendicular to initial gas flow direction
Particle drag coefficient = 0.7, V/U = 1.0

The drag coefficient for a particle may be represented by the empirical relation [see for example, Streeter, 1966]:

$$C_d = \frac{24}{Re_{pr}}\left(1 + 0.13\,Re_{pr}{}^{0\cdot7}\right) \qquad (2)$$

where Re_{pr} is the Reynolds number for particle motion relative to the gas, $(\rho U_r d/\mu)$, U_r being the relative speed of a particle to the gas. Particles are regarded as spherical of equivalent diameter d. To determine the appropriate size of particulate in the model it is necessary to select a critical aspect of the complete flow pattern and to ensure that for this the model system represents the full scale system correctly. For example, where a flow passes through a particulate swirl concentrator or a classifier device designed to reject coarse particles, it is important that the model system should concentrate or reject particles to the same extent as the real systems. Whilst it is not possible to exactly represent particle motions, it will be shown that the deviations in particle path are very small.

The modelling of a pulverized brown coal conveying system using a ¼ scale model and fine fly ash particles to represent the pulverized coal will now be considered. In the full scale system the conveying gas is hot flue gas [see McIntosh, 1976] whilst cold air is employed in the model. If suffix s denotes the full scale system and suffix m the model system, the relevant properties are thus:

$\rho_s = 0.75\ \mathrm{Kg/m^3}$ $\qquad \rho_m = 1.2\ \mathrm{Kg/m^3}$

$\mu_s = 2.05 \times 10^{-5}\ \mathrm{Kg/ms}$ $\qquad \mu_m = 1.83 \times 10^{-5}\ \mathrm{Kg/ms}$

$U_s = 20\ \mathrm{m/s}$ $\qquad U_m = 10\ \mathrm{m/s}^*$

$\sigma_s = 800\ \mathrm{Kg/m^3}$ $\qquad \sigma_m = 1900\ \mathrm{Kg/m^3}$

* to meet Froude number requirement.

The model system Reynolds number is reduced by 0.22 and a similar reduction is likely to occur for the model particulate.

In Fig. 2 are shown two types of particle path in a concentrator which were regarded as critical: Type A is a particle which enters at the wall of the centrebody of the unit on leaving the swirl vanes, and which strikes the outer wall at some distance z_w from that position; Type B is a particle which originates from the same position but passes to the exit plane and enters the concentrated coal flow annulus at radius r_e. All particles at inlet of a particular size would be constrained to move with trajectory A or B as an overall boundary. To represent the fractions of particulate which enter the concentrated fuel annulus flow, it is considered that the above trajectory end points should be made to correspond. On this basis the correspondence between a model particle of size d_m and a full scale particle of size d_s, can be established.

The trajectories of particles were solved by numerical integration from the instantaneous accelerations. The accelerations in the two directions at right angles to the axis of the concentrator are:

$$a_x = \frac{3}{4}\left(\frac{\rho D}{\sigma d}\right) C_d U_r{}^2 \cos\alpha \ , \quad a_y = \frac{3}{4}\left(\frac{\rho D}{\sigma d}\right) C_d U_r{}^2 \sin\alpha \qquad (3)$$

where U_r = relative velocity of magnitude of gas to particle

$$= \left\{(U_g \sin\theta + U_p \cos\phi)^2 + (U_g \cos\theta - U_p \sin\phi)^2\right\},$$

U_g = gas swirl velocity, $\theta = \tan^{-1} y/x$,

$\phi = \tan^{-1} U_{py}/U_{px}$,

and $\quad \alpha = \tan^{-1}\left\{(U_g \cos\theta - U_p \sin\phi)/(U_g \sin\theta + U_p \sin\phi)\right\}$

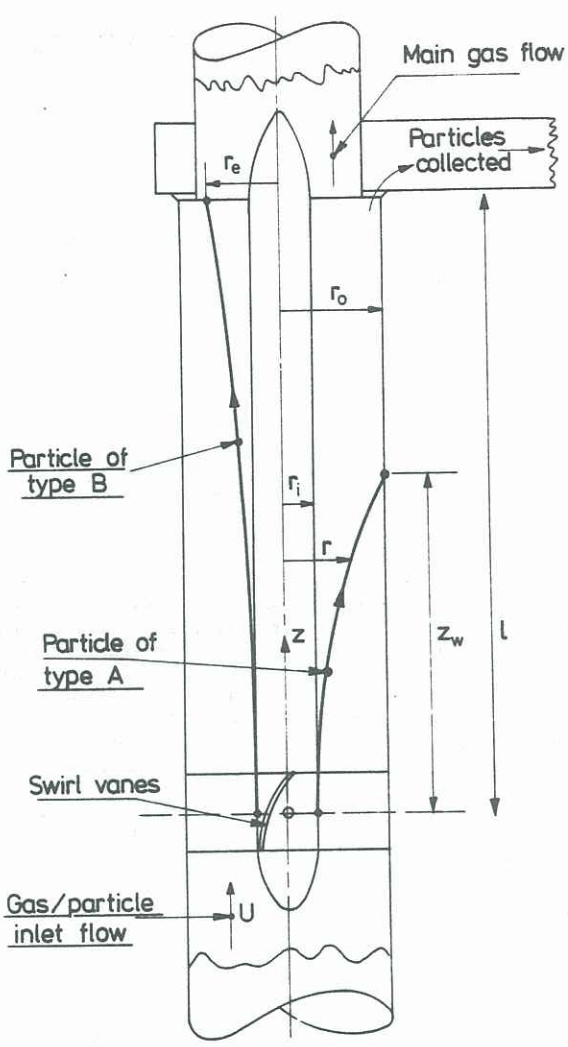

Figure 2 Brown coal swirl concentrator and critical particle boundary trajectories (radial motion only represented in diagram. Particles actually follow spiral paths)

The drag coefficient C_d was determined from Eqn. (2) with $Re_{pr} = \rho U_r d/\mu$. A total of 200 time steps was used to compute the particle trajectory in the total time ℓ/U for the flow particles to pass from inlet to outlet of the swirl concentrator. Particle impacts on the swirl vanes are neglected and the swirl is assumed to commence at the mid plane of the swirl blades.

Fig. 3 shows the variation in trajectory end point locations for each of the three types of trajectory specified in Fig. 2 for both model and full scale systems.

Particles of smallest and largest sizes do not experience strong radial motion and execute motion with a critical trajectory being Type B. At intervening sizes the particles will strike the outer wall and enter the concentrated fuel annulus duct directly (Type A). It is now possible from Fig. 3 to determine what size of model dust particle corresponds to a full scale particle on the basis that they must have the same end points for the critical boundary trajectories. Fig. 4 shows the result obtained by finding corresponding trajecories in Fig. 3 and forms the basis for selecting model particle size.

Whilst correspondence of the trajectory end points represents a restricted basis for modelling, the actual

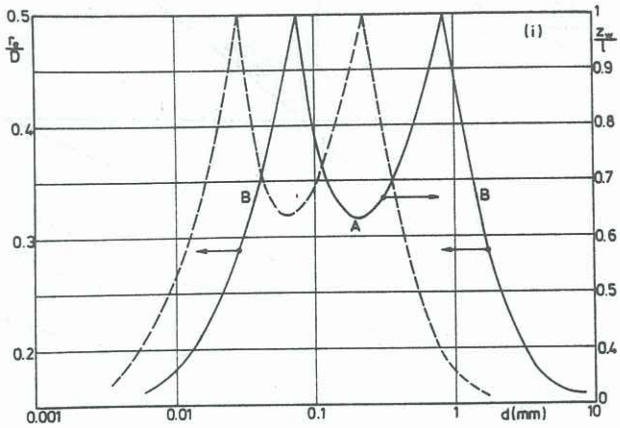

Figure 3 Sizes of particles which follow critical boundary trajectories
(Properties as given in text)
Computed for full scale system: ——— (σ_s = 800 Kg/m^3)
Computed for ¼model scale system: - - - (σ_m = 2400 Kg/m^3)

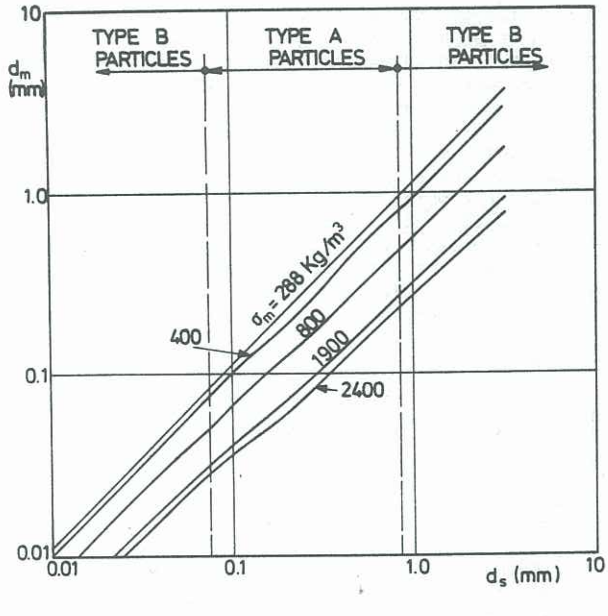

Figure 4 Correspondence between model particle and full scale particle size on basis of identical critical trajectory end points

trajectory shapes in model and full scale systems for corresponding particles show very little difference. This is shown by Fig. 5 for a particle of Type A. The maximum trajectory discrepancy is only 1% of the overall concentrator diameter.

The variation of particle scale ratio from Fig. 4 is shown in Fig. 6 as a function of model particulate density for different full scale particle sizes. It is seen that the requirements for trajectory end point modelling deviate substantially from modelling on the basis of the particle response parameter ($\rho D/\sigma d$) as the model particulate density increases. In fact this parameter is only identical for model and full scale systems when the particle based Reynolds number is also modelled, which in this case corresponds to d_m/d_s = 1.12 and σ_m/σ_s = 0.36 (σ_m = 288 Kg/m^2). However, these ideal particulate model dust parameters can not be used in

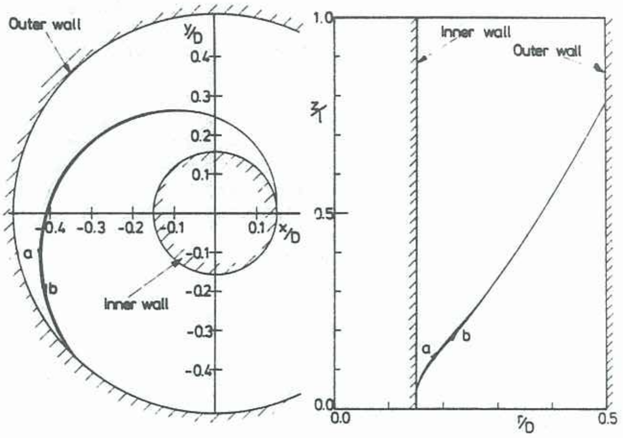

Figure 5 Comparative particle trajectories
(Example shows trajectory of Type A, d_s = 0.100 mm, d_m = 0.0423 mm, $(\rho D/\sigma d)_s$ = 14.06, $(\rho D/\sigma d)_m$ = 5.59)
(a) Model
(b) Full scale system

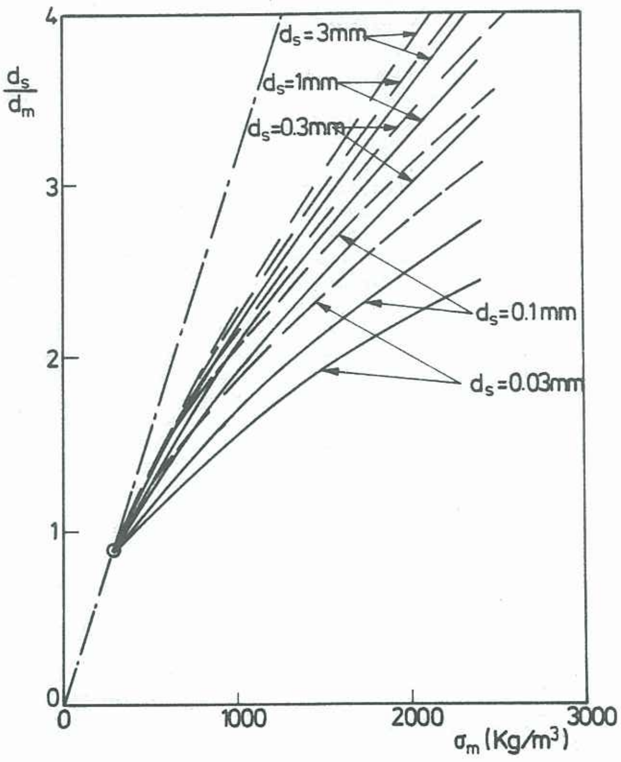

Figure 6 Particle scale ratios required to simulate critical trajectories in model for varying dust density
Solid lines: by matching of computed trajectories
Dashed lines: by Eqn. (3)
Chain dashed lines: on basis of trajectory response parameter ($\rho D/\sigma d$)
⊙: ideal modelling of particle Reynolds number and particle response parameter ($\rho D/\sigma d$)
(d_s/d_m = 0.893, σ_m = 288 Kg/m^3, σ_s = 800 Kg/m^3)

practice in a ¼ scale model test for a pulverized brown coal concentrator if no suitable and safe particulate of that low density can be located. Thus it may be necessary to use a particulate of $\sigma_m = 1900\,\mathrm{Kg/m^3}$ and d_m/d_s in the range 1/2.5 to 1/3.5 (depending upon absolute particle size). It was found that certain types of fly ash met these criteria satisfactorily.

It might be thought that a simpler basis for establishing appropriate model particulate size and density could be found, as the method so far described involves detailed numerical solution of particle motions. From Eqns. (2) and (3) such a simpler approach would require maintaining the product ($C_d \cdot \rho D/\sigma d$) at the same value in model and full scale systems. That is:

$$\left\{\frac{\mu}{\rho U d}\left(1+0.13\left(\frac{\rho U d}{\mu}\right)^{0\cdot 7}\right)\frac{\rho D}{\sigma d}\right\}_m = \left\{\frac{\mu}{\rho U d}\left(1+0.13\left(\frac{\rho U d}{\mu}\right)^{0\cdot 7}\right)\frac{\rho D}{\sigma d}\right\}_s \quad (4)$$

where the velocity U is the characteristic reference velocity (the swirl velocity in the present example of a concentrator). Fig. 6 also shows curves established on the basis of Eqn. (4), the results being determined by iteration for the model dust size (d_m) in Eqn. (4). It is seen that this approach results in model particle sizes which are up to 30% larger than those determined by matching of computed trajectories. The discrepancy arises from matching particle responsiveness at only one speed, the reference speed U, whilst trajectory computations have in effect obtained the best all round particle responsiveness taking account of the actual relative velccities which occur. It is concluded that this simpler approach is not adequate.

Computations of particle trajectories have also been carried out in an array of turbulent eddies of the type proposed by Townsend [1976]. The critical parameter is here taken as the time (T) for the particle to leave the array. Fig. 7 shows the variation of this time (TU/D) with response parameter ($\rho D/\sigma d$) and Reynolds number ($\rho U d/\mu$). Calculations were for a 10 × 10 array of eddies of alternating rotation with maximum speed U in the eddies and overall array size D × D. The eddies decayed from the array centre at a rate $\exp(-0.3\,r/d)$, r being the radial distance from the array centre. Particles were released at zero speed at $x/D, y/D = 0.01$ in the centre eddy. The diagram shows that there is an increase of particle Reynolds number with trajectory parameter for equivalent motion in the array, and lines of constant TU/D can be used as a basis for modelling equivalence by ensuring that model and full scale conditions lie on the same curve in the diagram. For a specific model particle density, variation of size (d) produces a hyperbola on Fig. 7, the intercept with the appropriate time curve giving the required model particle size.

4 CONCLUSIONS

Where available particulate materials do not satisfy the ideal requirements for the representation of particulates such as pulverized brown coal in a model, an alternative to the ideal model particulate size and density must be found. It has been shown that computational simulation of critical particle trajectories in model and full scale systems can form the basis for determining an approximate modelling criterion based on the end points of these trajectories. The remaining sections of the trajectory are found to be closely similar when only the end points are exactly matched. The required scale ratio deviates from that which would be required if only the response parameter ($\rho D/\sigma d$) were modelled. Modelling based on the product of drag coefficient at nominal particle Reynolds number and response parameter ($C_d \times \rho D/\sigma d$) also showed significant deviation from the requirement based on trajectory computations up to 30% in model particle size for a given density. It was concluded that trajectory computation and matching forms the most accurate selection method for model particulates.

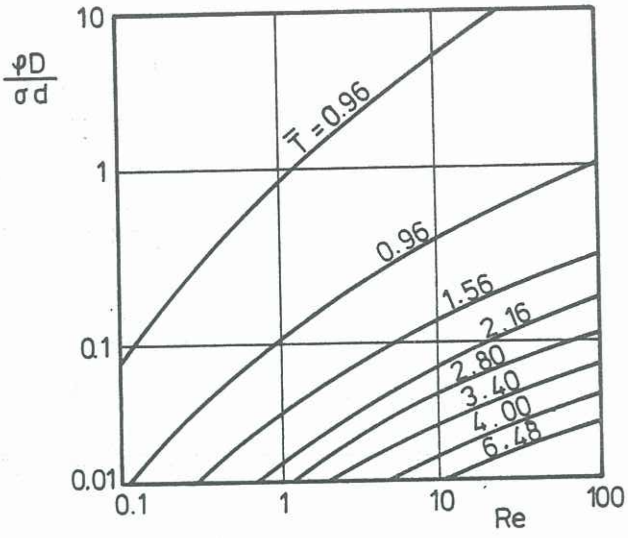

Figure 7 Modelling of particles in array of turbulent eddies
(Time to reach outer edge of array, $\bar{T} = TU/D$)

If the interaction between flow and an accumulated heap of particulate occurs, it may be desirable that the mass and size of the heap be correctly represented. Selection of an appropriate model particulate density to represent accumulated particulate masses and volume can be accommodated using the method described to size the model particulate such that it has the correct response to the gas. Thus, whereas matching of particulate Reynolds number and response parameter leads to the selection of a coarse low density ideal model particulate for which accumulations of particulate of given size would have an undesirably low mass, the use of a higher density, fine size model particulate would closely represent both the mass and volume of accumulations of particulate as well as its responsiveness to the gas motion.

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