The Retention of Large Particles in Fibrous Filters

D. C. FRESHWATER and J. I. T. STENHOUSE

Department of Chemical Engineering
Loughborough University of Technology, England

The inertial interception mechanism of particle-fiber collision in fibrous filters is described. The main mechanisms by which particles are retained in filters together with the effect of a number of operating parameters are discussed. The effect of particle size, gas velocity, relative humidity, and filter loading on the retention efficiency of large particles ($> 5\mu$) is investigated experimentally.

The capture of particulate material by fibrous filters has been the subject of a large number of theoretical and experimental studies which have been well reviewed by Davies (*1*). It is normal to consider the behavior of particles with respect to a single fiber within the depth of a filter and to relate this to the overall behavior of the filter using an expression such as that developed by Wong and Johnstone (*2*):

$$\eta_o = 1 - \exp\left(- \frac{4\alpha\ L}{\pi\ d_f} \eta_s \right)$$

where η represents the particle collection efficiency.

Four principal mechanisms, the first two of which are self explanatory, cause particles to collide with fibers. These are Brownian diffusion, electrostatic attraction, interception, or inertia. Interception occurs when a massless particle touches a fiber which is placed normal to the direction of flow purely because of its size. The inertia of a particle may cause it to cut across the fluid streamlines and impinge on a fiber.

In the vast amount of work in the field it has generally been assumed that once a particle touches a fiber it will adhere to its surface. While this is undoubtedly true in the case of particles which have been collected by one of the first two mechanisms mentioned above it is certainly not always the case with particles which have been collected by one of the second two mechanisms. Thus a better way of expressing filter efficiency would be

$$\eta_s = \eta_c \times \eta_R \qquad (1)$$

where η_s is the single fiber efficiency, η_c is the collision efficiency, and η_R is the retention efficiency.

While this paper describes recent work on inertial interception as a combined collision mechanism, the main purpose is to illustrate the importance of particle nonadherence in the field of fibrous filtration. Some of the important parameters which determine particle retention efficiency have been investigated experimentally. The results of these experiments are reported.

PARTICLE FIBER COLLISION EFFICIENCY

Description of Flow Field Due to Inertial Interception

A prerequisite of any particle capture theory is a description of the flow field close to a fiber in the filter mat. The most popular model we have at present is the cellular model which was published by Happel (*3*) and Kuwabara (*4*) in 1959 to describe the flow pattern of a fluid through banks of parallel cylinders and which therefore takes into account the neighboring fibers when applied to a filter.

The Kuwabara model has been applied to the study of the pressure drop through a filter by Kirsch and Fuchs (*5*) and to a theoretical description of the diffusional mechanism by Fuchs and Stechkina (*6, 7*) and Pich (*8*). An approximate method which incorporates the Kuwabara model has been used to describe inertial interception (*9*). The method is applicable at only low levels of particle inertia. The Happel and Kuwabara models have been applied by Harrop and Stenhouse (*10* to *13*) to describe the same mechanism using a more rigorous technique to give results which are not restricted to low inertia systems.

An alternative flow field is that published by Spielman and Goren (*14*) in 1968. They take the packing density into account by solving a combination of the creeping motion equations and Darcy's Law in the proximity of a fiber. This is a development of the technique originally applied by Brinkman (*15*) to the study of sedimenting systems. Dawson (*16*) has determined the efficiency of inertial interception in this flow field: his results are similar in form to those of Harrop and Stenhouse but predict a lower efficiency.

Prediction of Collision Efficiency

The single fiber collision efficiency is determined by computing the critical trajectory of a particle, that is, that trajectory for which the particle just touches the fiber. The finite size of the particle is allowed for in the calculations by adjusting the fiber radius to include the particle radius.

A force balance on a particle results in the following trajectory equations:

$$N_I \frac{d^2X}{dT^2} + \frac{dX}{dT} + U = 0$$
$$N_I \frac{d^2Y}{dT^2} + \frac{dY}{dT} + V = 0 \quad (2)$$

The inertia parameter (N_I) is the ratio of the distance a particle with initial velocity U_0 will travel in a stagnant gas before coming to rest to the fiber radius.

In the Happel or Kuwabara flow fields expressions for the fluid velocity resolutes u and v are so complex that an analytical solution of 2 is not feasible. The equations were therefore expressed in finite difference form and solved using a digital computer. Some of the results of such a computation are shown in Figure 1 (*10*).

Experimental Verification

The most recent experimental work in the field is that of Harrop (*11*) who used model filters to investigate directly the single fiber efficiency. He employed a mono dispersed aerosol of sodium chloride and detected the mass concentration by flame photometry.

Particles of salt in the size range 1.2 to 3.4 μm were used in the experiments at velocities up to 110 cm s^{-1}. It was found that the theoretical predictions underestimate the efficiency at low values of N_I (and hence η_s) and at high values of N_I they overestimate the results (Figure 2). The discrepancy at low N_I is attributed to a fiber Reynolds number effect; since the theory incorporates a solution to the equations of creeping motion it is valid only at very low Reynolds number.

The discrepancy between theory and experimental observation at high values of N_I is almost certainly due to nonretention of particles. Although the fibers were coated with a thin (less than 1 μm thick) layer of adhesion assisting oil, the experimental results indicate that this layer may not have been adequate. The effect of coating the fibers is clearly seen from Figure 3; the single fiber efficiency actually begins to reduce with increase in velocity for the dry fiber. Clearly the particle size is sufficiently large for the retention efficiency η_R to be less than unity. This reduction in retention efficiency which must take the form shown in Figure 4 will cause a maximum in the single fiber efficiency characteristic. This effect of non-adhesion is well known and has been observed many times, notably by Lapple et al. (*17*) who compared the capture efficiencies of solid and liquid particles and by Whitby (*18*). To elucidate the factors which influence this phenomenon an exploratory study has been made and is now described.

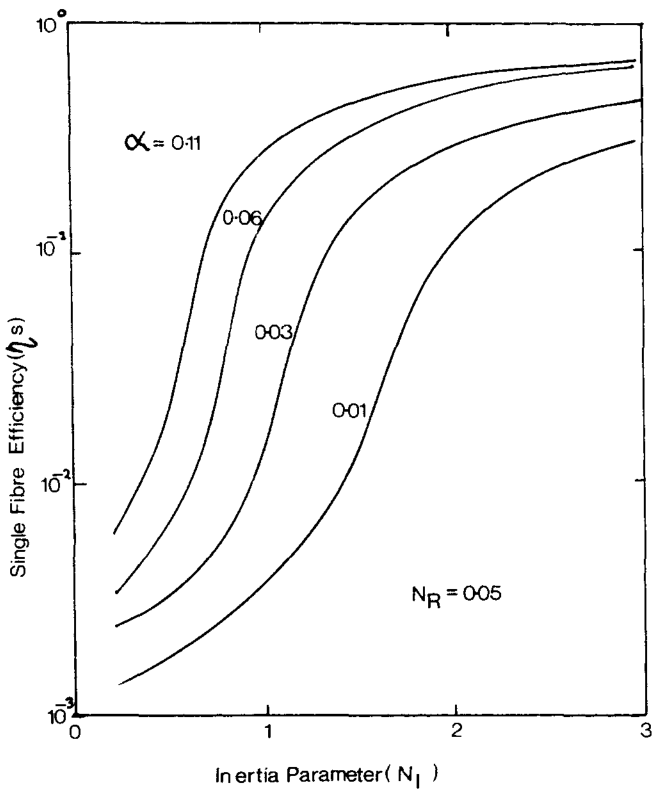

Fig. 1. Theoretical prediction of single fiber efficiency due to inertial interception (*9*).

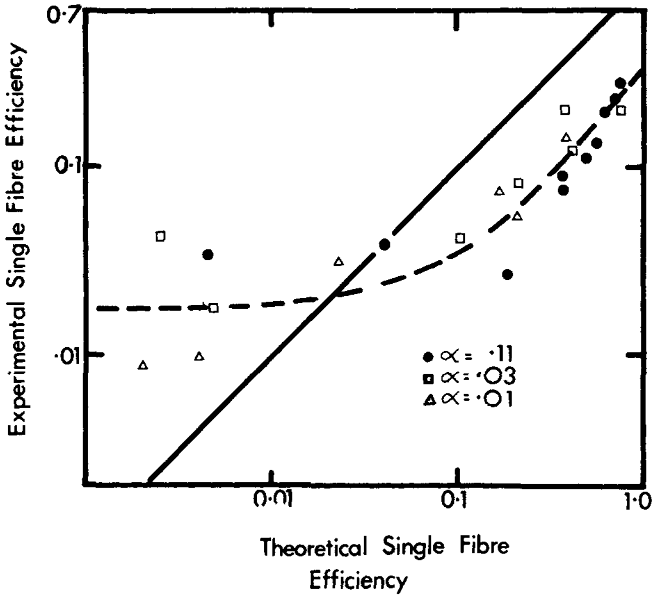

Fig. 2. Comparison of theoretical and experimental results (*11, 13*).

PARTICLE RETENTION EFFICIENCY

When a particle collides with a fiber it tends to be held there by adhesion forces. Opposing these are rebound and drag forces (or both) and the particle will only be retained if the adhesion force exceeds the removal force.

Particle Adhesion Forces

Capillary and van der Waals attraction are generally considered to be the principle adhesion forces in fibrous filters, although in some cases electrostatics may play an important role. In some filters the fiber surface is treated with a layer of oil to assist adhesion. In untreated systems, capillary adhesion may still be the primary adhesion force at high relative humidities due to surface adsorbed water. Obviously van der Waals forces are most important in dry systems. Hamaker (*19*) has given an expression for the magnitude of the van der Waals force and Naidicho and Lavrinenko (*20*) carried out theoretical work on the capillary adhesion forces. It is pertinent to examine the effect which a number of design and operating parameters are likely to have on these forces and hence on the particle retention efficiency in fibrous filters. Some of the important parameters are as follows:

Contact area. Obviously as the contact area is increased the adhesion force will be increased. The contact area will be influenced by such factors as the material properties (that is, hardness), velocity, and angle of impact and particle shape, size, and surface roughness.

Relative humidity. An increase in relative humidity will normally lead to an increase in the adhesion force. The effect of humidity may manifest itself in a number of ways. It may lower the surface hardness of either the particles or the fibers, causing an increase in contact area due to flattening on impact. It is believed in fact that this is the reason for the large reduction in efficiency at low relative humidities observed by Harrop (*11*) (Figure 5). 3.4 μm particles of sodium chloride were fed in a 100 cm s^{-1} air stream to 50 μm diameter stainless steel fibers. The effect is shown to be caused by lack of adhesion since the phenomenon was not apparent when the fibers were coated with a thin film of oil. A similar increase in efficiency with relative humidity was observed by Loffler (*21*) and Durham (*22*).

High relative humidity may give rise to surface moisture which in turn causes capillary adhesion. McFarlane and Tabor (*23*) found that the adhesion force increased rapidly at relative humidities in excess of about 80%. At saturation the force was the same as that observed when a small amount of water was placed between a particle and a plate.

Another possibility is that at high relative humidities the electrical conductivity may be increased, altering the charge distribution in such a way that the long range attractive forces may be increased. Unfortunately, on contact, electrical neutralization will be rapid and enhancement of the adhesion force by electrical attraction will not occur.

Surface Coating Effect. Filters which are used in the collection of material in excess of 5 μm in size are frequently treated with an adhesion assisting oil. Figures 3 and 5 illustrate this effect. There is very little published work on the influence of coating material itself. It is generally accepted that the adhesion force will be proportional to the surface tension; however, there are a large number of other important factors, one of which is the ability of the coating material to wet particles which adhere to the fiber surface. Unless the fluid spreads round the particles it will be effective only in the initial stages of filtration.

Particle Size and Gas Velocity. A high energy of impact resulting from both high velocity and large particle mass will cause an increase in contact area and thus the adhesion force will increase with both particle size and gas velocity. Unfortunately there is a more rapid increase in the removal forces with increase in particle size.

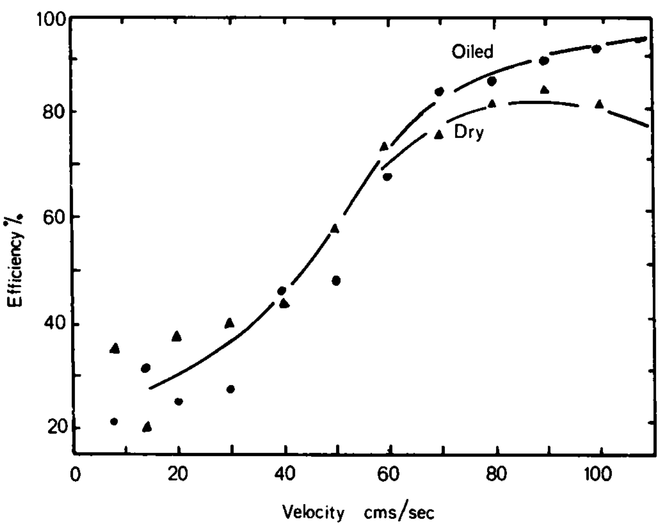

Fig. 3. Influence of fiber oiling on filtration efficiency (*10*).

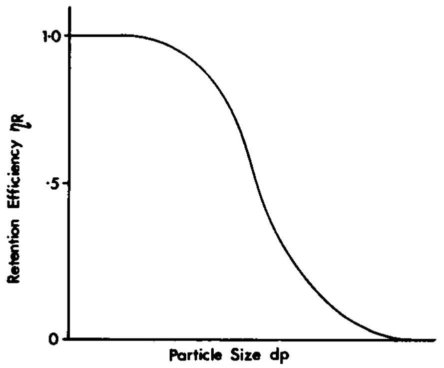

Fig. 4. Characteristics of particle retention efficiency.

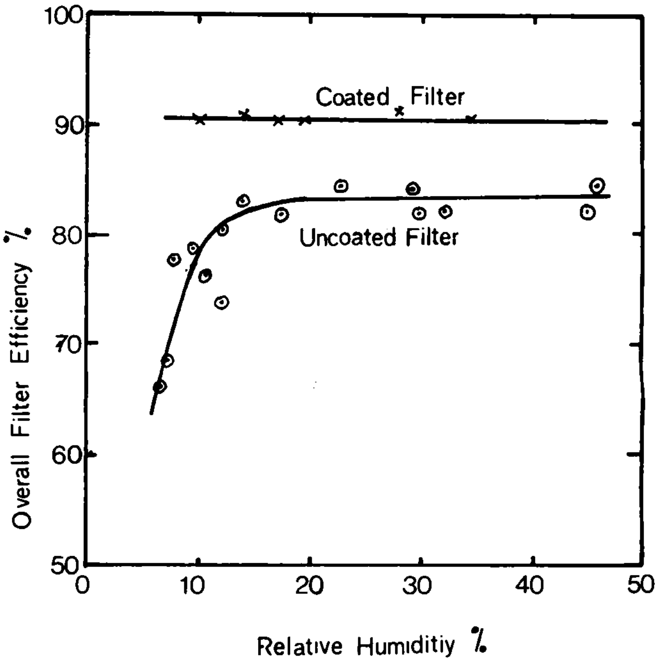

Fig. 5. Influence of relative humidity on filtration efficiency of salt particles (*10*).

Particle Removal Forces

The two principal mechanisms of particle removal are aerodynamic drag ("blow-off"), or simple rebound after impact ("bounce-off"). Secondary mechanisms are bombardment and vibration.

According to Gillespie and Rideal (*24*) particles will "peel off" due to air drag if

$$6\pi \mu V_t > \lambda \left[3\pi E d_p \left(1 + \frac{d_r^2}{6 d_p h} \right) \right] \tag{3}$$

The rebound condition is given by

$$\frac{1}{2} m_p e^2 V_p^2 > \pi E \left[3 h d_p + \frac{d_r^2}{4} \right] \tag{4}$$

Gillespie incorporated Hertz's theory of impact in these expressions to take account of particle deformation and hence increases in contact area ($\pi d_r^2/4$) on impact. The adhesion force in expressions (3) and (4) is that due to van der Waals forces.

Application of these expressions predicts that at low velocities particles will adhere to the fiber surface, as the velocity is increased an increasing fraction will fail to

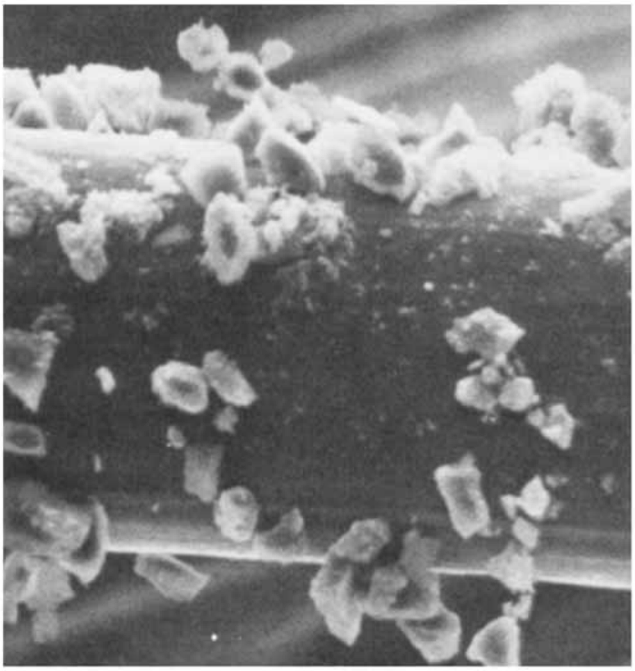

Fig. 6. 5 to 10 μm particles adhering to 50 μm fiber.

stick, but at higher velocities due to an increase in contact area it is possible that the fraction adhering will again increase.

These equations relate what are essentially equilibrium conditions. However these mechanisms must be considered under dynamic conditions. Larsen (*25*) and Loffler (*21*) measured "blow-off" velocities experimentally. They both found that once a particle sticks to a fiber, the velocity required to blow it off greatly exceeds that used in practice. Further measurement of removal forces confirmed that once a particle has become attached to a fiber surface the forces it will encounter in normal filtration are not likely to be sufficient to remove it. It follows therefore that the particles which are not retained must be removed virtually as soon as they touch the fiber by a combination of "bounce-off" and "blow-off" aided by the impulse force tangential to the point of contact. The main problem, therefore, is not to retain already deposited particles but to offer adequate adhesion to the particles at first contact with the fiber surface.

It will be obvious from the above discussion that the conditions of adhesion in fibrous filters are complex and that the parameters affecting these are numerous and complex in nature and some of them will be time-dependent.

It would seem, therefore, more realistic to investigate the dynamic processes in filtration by studying the filter retention efficiency rather than to study the collision efficiency and adhesion forces independently. Two simple experiments were designed to investigate some of the main parameters which determine the retention efficiency of a filter.

EXPERIMENT

To obtain a qualitative picture of the system, a photographic study was made of fibers on which particles had been deposited. This was then followed by an exploratory quantitative analysis.

Photographic Analysis

Particles of AC test dust in the size range 5 to 10 μm were ıptured on a 50 μm diam stainless steel fiber. The air velocity ;ed was 250 cm s^{-1}. The fibers were then photographed using scanning electron microscope.

Some typical S.E.M. photographs are shown in Figures 6 ıd 7. They show that the contact area between particle and ber is in fact extremely small and frequently of a secondary ature, namely between ultra-fine particles about 0.1 μm in ze and the fiber and particles.

Almost all experimental work on fibrous filters has been conərned with clean filters. However, as pointed out earlier, ltration is a dynamic process in which the state of the filter self is continually changing. Therefore tests were carried out ı which the dust loading was increased until a layer several articles thick was collected.

Fig. 7. Close-up of 5 μm particles on 50 μm fiber.

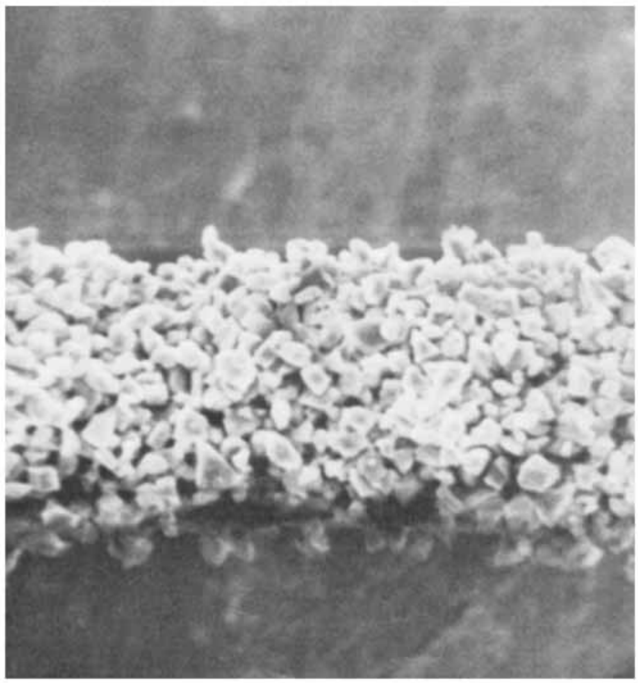

Fig. 8. Multilayer packing of 5-10 μm particles.

The effect of coating the fibers with glycerol is shown for comparison in Figure 12. The overall efficiency is now an increasing function of velocity. Clearly in this case

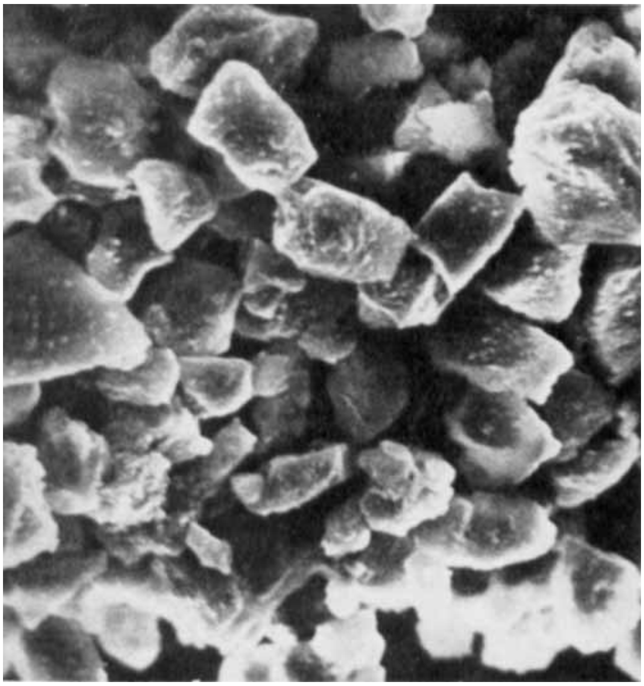

Fig. 9. Close-up of particles in multilayer packings.

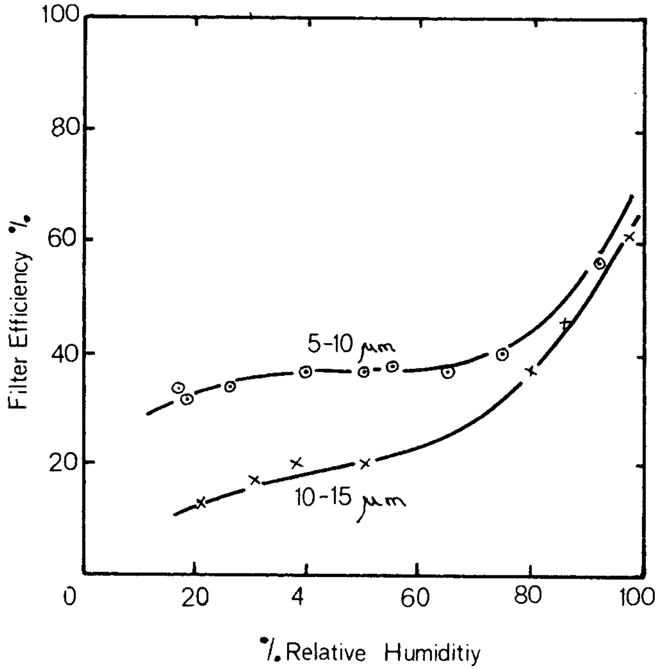

Fig. 10. Influence of relative humidity on the filtration efficiency of fractions of A.C. dust.

Figures 8 and 9 show the phenomenon of multilayer packing. These photographs emphasize that under high loading conditions, that is, when the filter is no longer clean, the cohesiveness of the dust (which is strongly influenced by such factors as size, size distribution, humidity, etc.) must be of paramount importance in determining the retention capabilities.

Quantitative Analysis

A gravimetric technique of filter testing was used. A model filter consisting of a 10-cm. depth of stainless steel knitmesh in a 4-cm. diameter light metal tube was employed. A polydispersed test dust (AC fines) with a mass median Stokes diameter of 7 μm was fed at a constant rate to the filter. The dust was dispersed using a shearing field as described in BS 1701. The overall efficiency of capture was determined by weighing the filter before and after filtration. Reproducibility was better than $\pm$ 1.0%. The grade efficiency for each test was obtained by comparing the size analysis of the dust captured in the filter with that of the feed material. This was accomplished by washing the dust from the filter and analyzing it using a Bound-Brook photosedimentometer.

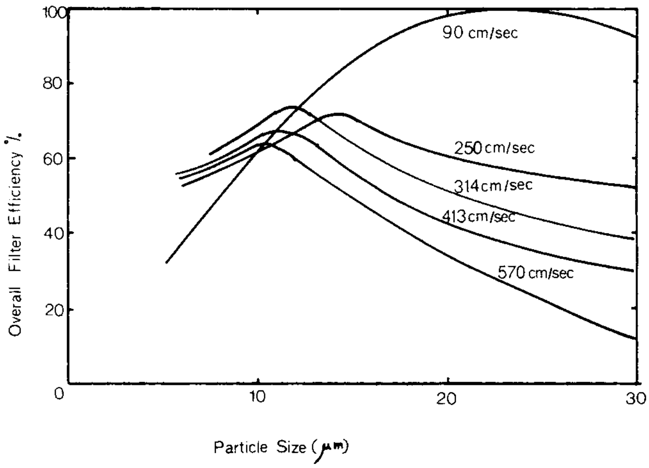

Fig. 11. Grade efficiency curves for coarse filters.

RESULTS AND DISCUSSIONS

Effect of Relative Humidity

The relative humidity was varied between 15% and 90% (Figure 10). The close resemblance of the efficiency characteristic to the water adsorption isotherm is in agreement with the findings of Zimon (*26*) on the effect of humidity on the adhesion force. Above 80% RH the mechanism is most likely to be that of capillary adhesion. All subsequent tests were completed at 35 to 55% RH.

Effect of Particle Size and Gas Velocity

Typical grade efficiency curves for a filter are shown in Figure 11. It can be seen that after the maximum in the curve is reached the efficiency falls off rapidly with increase in particle size. As would be expected in this regime, where nonadhesion is the most important mechanism, the efficiency is also a decreasing function of gas velocity. The effect is perhaps seen more strongly in Figure 12 which shows the effect of velocity on the total mean efficiency.

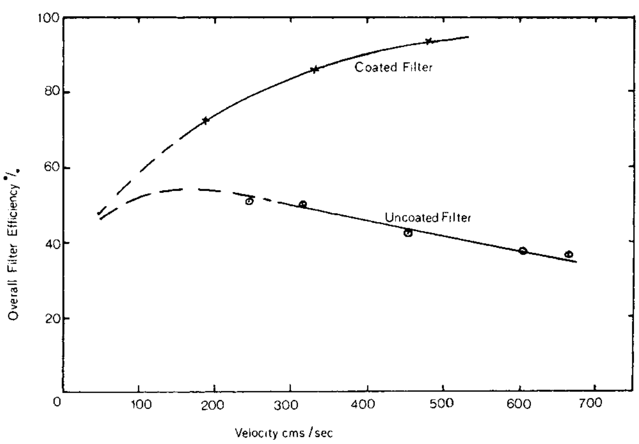

Fig. 12. Effect of velocity on filtration efficiency of A.C. fine dust.

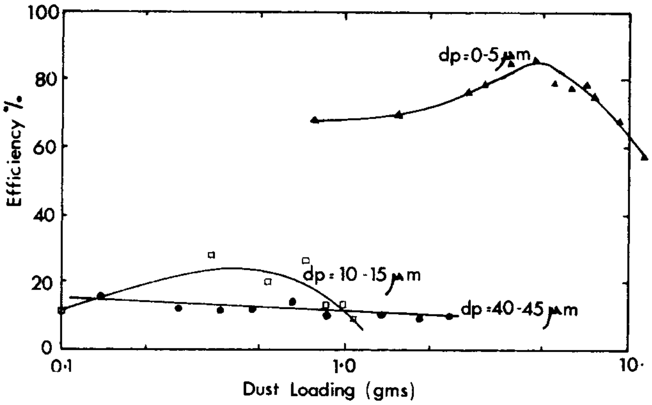

Fig. 13. Effect of dust loading on filtration efficiency.

adhesion is effective and the overall efficiency is controlled by the collision efficiency.

Effect of Dust Loading

The influence of dust loading was investigated using model filters similar to those described in the first part of this paper. The dust used was narrow sized cuts obtained using a "zig-zag" classifier. Some of the results are shown in Figure 13.

As particles build up in a filter it would be expected that the collection efficiency will increase initially. However the retention efficiency is affected by loading in two ways. First the surface for adhesion is changed as the particles build up. Second the agglomerates which build up on the fiber are because of their size subjected to a much greater air drag and are more likely to be removed.

The effect of both of these mechanisms is clearly illustrated in Figure 13. The maxima are obviously caused by their interaction.

CONCLUSIONS

The result of this work confirms that the discrepancy between experimental and measured filter efficiencies can be described by a simple equilibrium model.

The concept of retention efficiency is shown to be useful and measurements of this has shown it to be affected by relative humidity, gas velocity, particle size, and filter loading. Only some of the parameters which affect the system have been mentioned in this paper; there are many others, such as material properties, particle and fiber shapes, size distribution etc. which will have an important bearing on the efficiency and holding capacity of a filter. Clearly there is a need for a considerable amount of work in this field especially on the behavior of air filters themselves. It is hoped, however, that this paper has helped to clarify an extremely complex situation.

ACKNOWLEDGMENT

The authors wish to thank the U.K. Science Research Council for their financial support and Mr. M. Burrows, Mr. T. Gleave, Mr. D. Mould, and Mr. A. Grimley who helped carry out the experimental work.

NOTATION

d_p, d_f = particle and fiber diameters
d_r = diameter of contact between particle and fiber
E = energy of adhesion
e = particle coefficient of restitution
h = minimum distance of separation between particle and surface
m_p = mass of particle
N_I = inertia parameter, $d_p^2 \rho U_0 / 9 \mu d_f$
t = time
T = dimensionless time, $t U_0/d_f$
u, v = x and y gas velocity resolutes
U_0 = main stream velocity
U_t = tangential velocity of particle
V_p = normal velocity of particle
U = u/U_0 dimensionless velocity
V = v/U_0 dimensionless velocity
x, y = Cartesian coordinates
α = filter packing density (volume fibers/volume filter)
η_c = collision efficiency
η_o = overall filter efficiency
η_R = retention efficiency
η_s = single fiber efficiency
λ = constant
μ = gas viscosity
ρ = particle density

LITERATURE CITED

1. Davies, C. N., (ed.), *Aerosol Science*, Academic Press, New York (1967).
2. Wong, J. B., and H. F. Johnstone, Univ. Illinois, Engineering Experimental Station Tech. Report 11 (1953).
3. Happel, J., *AIChE J.*, **5**, 174 (1959).
4. Kawabara, S., *J. Phys. Soc. Japan*, **14**, 527 (1959).
5. Kirsch, A. A., and N. A. Fuchs, *Ann. Occup. Hyg.*, **10**, 23 (1967).
6. Fuchs, M. A., I. B. Stechkina, *ibid.*, **6**, 27 (1963).
7. Kirsch, A. A., N. A. Fuchs, *ibid.*, **11**, 299 (1968).
8. Pick J., *Czech. Chem. Comm.*, 3721 (1964).
9. Stechkina, I. B., A. A. Kirsch, and N. A. Fuchs, *Ann. Occup. Hyg.*, **12**, 1 (1969).
10. Harrop, J. A., J. I. T. Stenhouse, *Chem. Eng. Sci.*, **24**, 1475 (1969).
11. Harrop, J. A., Ph.D. thesis, Loughborough Univ. Technology, England (1969).
12. Stenhouse, J. I. T., and J. A. Harrop, *Chem. Eng. Sci.*, **25**, 1113 (1970).
13. ———, and D. C. Freshwater, *Aerosol Science*, **1** (1970).
14. Spielman, L., and S. L. Goren, *Environ. Sci. Technol.*, **2**, 279 (1968).
15. Brinkman, H. C., *Appl. Sci. Res.*, **A1**, 27 (1967).
16. Dawson, S. V., D.Sc. thesis, Harvard Univ., Cambridge, Mass. (1969).
17. Lapple, C. E., R. J. Stasny, and T. E. Wright, "High Velocity Filters," Tech. Rpt. 55-457, Wright-Patterson Air Force Base, Ohio (1957).
18. Whitby, K. T., *Am. Soc. Heating Refrig. Air Cond. Eng. J.*, **7**, 55 (1965).
19. Hamaker, H. C., *Physica*, **2**, 1058 (1937).
20. Naidicho, Y. V., and O. A. Lavrinenko, *Soviet Powder Met. Metal Ceram.*, **10**, 831 (1965).
21. Loffler, F., Ph.D. thesis, Univ. Karlsruhe, Germany (1965).
22. Durham, J. F., R. E. Harrington, and D. L. Harmon, "Influence of Relative Humidity on Filtration Resistance & Efficiency," 63rd Annual Am. Inst. Chem. Engrs. Meeting, Chicago (1970).
23. McFarlane, J. S., D. Tabor, *Proc. Roy. Soc.*, **A202**, 224 (1950).
24. Gillespie, T., and R. Rideal, *J. Colloid. Sci.*, **10**, 281 (1955).
25. Larsen, R. T., *Am. Ind. Hyg. Assn. J.*, **19**, 265 (1958).
26. Zimon, A. D., *Kolloid Zh.*, **15**, 315 (1963).

Manuscript received July 23, 1971; revision received March 9, 1972; paper accepted March 9, 1972.