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Studies of the factors controlling the action of hair sprays—III: The influence of particle velocity and diameter on the capture of particles by arrays of hair fibres

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Synopsis—The VELOCITY of an AEROSOL HAIR SPRAY has been determined by measuring the gas velocity within the spray with a PITOT-STATIC TUBE. The velocity rises to a maximum at the centre of the spray cone and falls rapidly with increasing distance from the spray orifice. For a given distance from the orifice the velocity also falls with decreasing pressure of the aerosol pack.

Measurements of CAPTURE and PENETRATION of hair spray droplets into a model ARRAY OF HAIR FIBRES backed by a solid plate representing the scalp have shown that coarse sprays give better penetration than fine sprays. This is in contrast to the behaviour predicted by classical aerosol capture theory and reasons for the observed behaviour are discussed.

INTRODUCTION

This paper is one of a series which describes studies of the factors influencing the action of hair sprays. Previous papers in this series (1, 2) have been concerned with the events occurring after the hairspray droplets

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have been deposited on the hair, and studies of the spreading of hairspray resin solutions on hair (1), and of the adhesion of hairspray resins to hair fibres have been reported (2). In another publication (3) the author has described measurements of the particle size distribution of hair sprays.

The present study is concerned with measurements of the velocity of particles within the sprays, and with the capture of the particles by arrays of hair fibres. It is shown that the capture and penetration of the particles into an array of fibres depends on both the size of the particles and their velocity.

Particle capture by fibre assemblies is generally treated by considering a model system in which a particle-laden gas stream is drawn through a filter composed of the fibres. In experimental studies it is convenient to control as many parameters as possible and monodisperse aerosols, travelling at well-defined air-stream velocities, are captured in a model filter in which fibres of uniform diameter are arranged with a regular interfibre spacing.

In the present study we have not restricted ourselves to such a model system and have studied the capture of actual hair spray particles produced by pressurized aerosol packs. The particles were captured by grids composed of hair fibres arranged in a roughly parallel configuration but without any regular interfibre spacing. In order to characterize the sprays we have measured the mass median diameter of the particles, and assessed the velocity of the particles by measuring the velocity of the particle-laden gas stream with a Pitot-static tube.

THE THEORY OF PARTICLE CAPTURE BY FIBRES

Recently Light (4) has reviewed the forces which determine the movement of an aerosol particle subsequent to the initial velocity imparted by its source. The combined effect of forces such as gravity, drag, inertia, diffusion and electrostatic charges determines the path followed by a particle. For a comprehensive discussion of these forces the reader is referred to this article and we shall only consider here those forces which influence the deposition of hair spray droplets on hair fibres.

As pointed out by Light, the particle size is perhaps the most important variable which is within the control of the formulator and for deposition on small surfaces, such as human hair, the particle diameter should be of the same order of magnitude as the surface dimension.

The particles in hair sprays are generally quite large. The mass median diameters are commonly in the range 60 to about 300 μm, and there is rarely greater than about 10% by weight of the spray with diameters less than 10 μm. For such large particles the forces aiding capture are mainly gravity, inertia and direct interception.

Gravitational settling contributes significantly to the removal of particles in excess of 10 μm from a flowing stream. However, settling is only of importance when the stream is flowing over a horizontal surface and will contribute little to the capture of particles by fibres. Inertial impaction and direct interception are thus the major mechanisms controlling the capture of hair spray particles by hair fibres, and it is useful to consider these more fully in order to define the dependence on the particle diameter and velocity.

First we shall consider inertial impaction. When a particle-laden gas stream approaches an obstacle placed in its path, the gas stream alters its path to flow around the obstacle. Because of its inertia, a particle will not be able to follow completely the flow lines of the gas and may leave these flow lines sufficiently to impact on the obstacle. The probability of collision depends on two parameters (4), the Reynold's number which defines the pattern of the gas streamlines, and its dependence on the stream velocity, and the inertial impaction parameter. The inertial impaction parameter is defined as:

$$P = \frac{d^2 \rho V_0}{18 \eta D} \qquad (1)$$

where d is the particle diameter, V_0 the gas stream velocity, ρ the density of the particle, η the gas viscosity and D the obstacle dimension, which for a fibre is the fibre diameter.

Light (4) has shown how the efficiency of capture may be calculated from the Reynold's number and the inertial impaction parameter. For a hair fibre of 100 μm diameter Light gives the capture efficiencies for particles of various sizes approaching at speeds of 10,100 and 1000 cm s^{-1} (Table 5 of ref. 4). The efficiency increases with increasing particle diameter and velocity and reaches 100% for a 10 μm particle at 1000 cm s^{-1} or a 50 μm particle at 100 cm s^{-1}.

Next we shall consider the contribution of direct interception to the total capture. When the size of the aerosol particles approaches the diameter of the fibres, capture by direct interception becomes significant and increases the capture occurring by inertial impaction. Because of the way in which capture efficiency is defined:

$$\text{efficiency} = \frac{\text{cross-sectional area of stream from which particles are removed}}{\text{cross-sectional area of fibres projected upstream}}$$

it is possible for the total efficiency to be greater than 100%. For example, let us assume that the inertia of all the particles is so great that they continue to travel in straight lines when the streamlines diverge around the obstacle. Then all particles whose centres are within the projected area of the fibre will be captured. In addition those particles whose centres are within a distance $d/2$ of the surface of the fibre will also be captured. The total capture efficiency is then $\frac{D + d}{D}$.

Inertial interception becomes significant for $d/D > 0.1$ and increases with increasing diameter of the particles.

From the foregoing analysis we can see that the capture of hair spray particles by hair fibres can be predicted to increase with increase in both the diameter and velocity of the particles. Conversely, maximum penetration into an array of fibres requires the use of small, low-velocity particles.

EXPERIMENTAL

Measurement of particle velocities in aerosol sprays produced by pressurized packs

The determination of the velocities of particles in an aerosol spray is difficult since there is a distribution of velocity across the spray cone. Particles at the centre of the spray have the highest velocity while those at the outside have the lowest velocity since here the particle-laden gas stream is in contact with the stagnant air of the surrounding atmosphere. We can thus expect a parabolic velocity distribution similar to that shown by a fluid moving through a pipe under laminar flow conditions. The situation is further complicated by local turbulence which is apparent in the spray, particularly on the outside of the cone.

Attempts to measure the particle velocities using a high-speed photographic technique were of limited use, owing to the restricted depth of field, together with the problems outlined above. Instead we eventually chose to measure the velocity of the gas stream carrying the particles rather than the velocity of the particles themselves. The work thus contains the assumption that the particles travel isokinetically with the gas stream. This restriction is probably of little significance when compared with the overall accuracy of the velocity measurements.

The Pitot tube was first described by Henri de Pitot in 1732. Pitot measured velocities by immersing two open tubes to the same depth in flowing water, as shown in *Fig. 1*. The lower opening in one of the tubes was perpendicular to the flow and the rise in water in this tube was taken as an indication of the static pressure p_s of the fluid. The other tube was bent through 90° so that its lower opening faced into the flow direction. The rise in water level in this tube was taken to be an indication of the total pressure p_t, i.e. the sum of the static and dynamic pressures, where the dynamic pressure $\frac{1}{2}\rho_0 V^2$ is the pressure equivalent of the kinetic energy of the flowing stream. The difference in water levels is thus a measure of the velocity of the fluid.

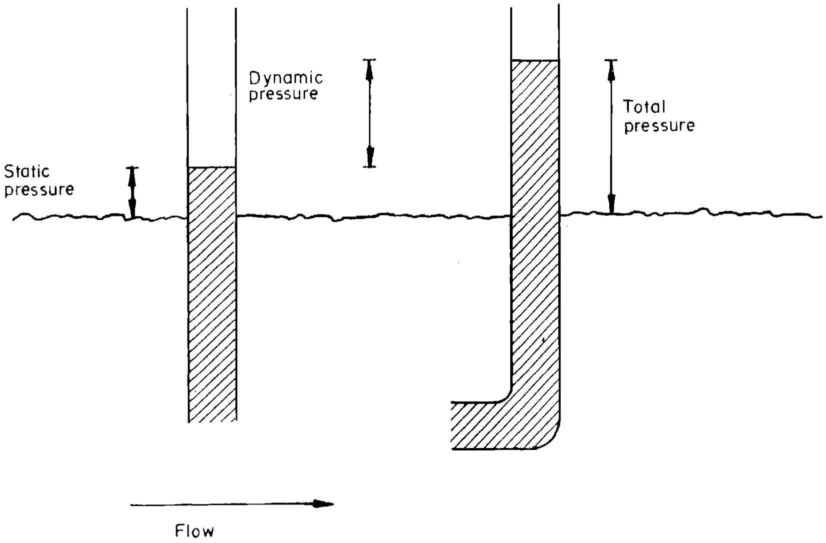

Figure 1. The Pitot-static tube method for measuring the velocity of a fluid stream.

Thus
$$p_t = p_s + \tfrac{1}{2}\rho_0 V^2 \qquad (2)$$
where ρ_0 is the density of fluid and V its velocity.

The instrument used in this investigation combines both tubes in one unit as shown in *Fig. 2*. The pressure differences $(p_t - p_s)$ produced are very small, especially at the lower velocities, and have to be measured on a specially designed inclined manometer. The particular instrument used was

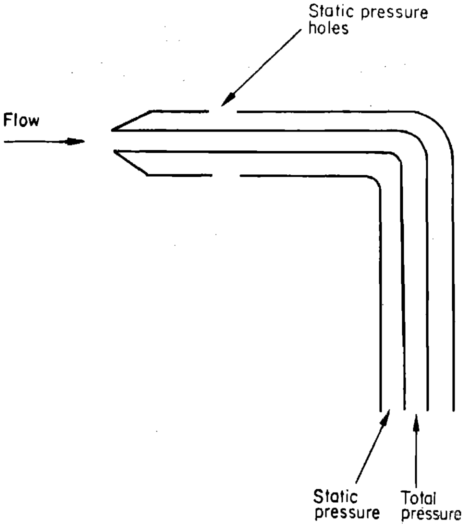

Figure 2. A combined Pitot-static tube.

the 'Portable airflow testing set Mark 4',* incorporating two adjustable limb manometers, each with several different inclinations. The manometer tubes were filled with a red dyed blend of paraffin having a specific gravity of 0.787 at 60°F. The static pressure tube was connected to the top of the manometer and the total pressure tube to the bottom so that only the differential pressure was measured. The scales of the manometer were calibrated in inches of water and an alternative scale was also supplied so that air velocities in ft min^{-1} could be read directly from the instrument.

Pressurized packs were filled according to the specifications shown in *Table I.*

The Pitot-static tube was placed within the aerosol spray cone at a given distance from the atomizing nozzle, and the aerosol button actuated. The

Table I. Details of filling of aerosol cans for velocity measurements

Pressure (kN m^{-2})	Resin-alcohol concentrate (%)	Propellant (%)	*Freon* 11/ *Freon* 12
152	40	60	45/15
221	40	60	35/25
290	40	60	24/36
359	40	60	14/46

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* Airflow Developments Ltd.

Pitot tube was moved within the cone until the maximum pressure was recorded on the manometer. The reading was then noted and the button released. The procedure was repeated at several distances from the nozzle so that the velocities of the aerosol gas stream were obtained as a function of distance from the nozzle. The maximum velocity within the cone was always measured since there is a velocity profile across the cone and a velocity less than the maximum could be obtained, depending upon the position of the Pitot tube.

It was found necessary to wash out the Pitot tube with alcohol after each measurement before the resin solution had time to dry and partially obstruct the gas flow into the tube.

Measurement of the penetration of the hair spray particles into an array of hair fibres

A model filter system was constructed to simulate a mass of hair fibres backed by the scalp. The filter consisted of six separate arrays of fibres which were then placed together. Each array consisted of about 200 hair fibres stretched across a circular brass ring of 47.5 mm internal diameter, and 1.5 mm wall thickness. The fibres were placed roughly parallel, and secured between two rings with Araldite epoxy resin. No attempt was made to obtain a uniform spacing between adjacent fibres. When completed, each array was marked and numbered so that the complete filter could be reproducibly assembled. A sheet of thin aluminium foil, attached across a seventh ring, acted as a back plate representing the scalp. This plate was placed behind the sixth filter stage to leave a 1.5 mm gap. This gap allowed some gas to pass through the filter whilst still maintaining a back pressure amongst the fibres.

Penetration measurements were made in the following way. The filter assembly was dismantled and washed thoroughly with alcohol. After drying to constant weight the individual filters, and back plate, were weighed separately and the whole unit reassembled. A further brass ring was placed in front of the first filter to prevent spray depositing directly on its former, and the spray from an aerosol can, placed at a given distance, was directed at the filter. The unit was dismantled after being allowed to dry. Each part was then reweighed to constant weight, to obtain the weight of resin deposited at each stage.

Several different types of spray were used. These were produced by varying both the actuator button and the internal pressure of the aerosol pack. Details of the various combinations used are listed in *Table II*.

Table II. Summary of actuators and products examined in penetration experiments

Actuator	Type	Orifice diameter (cm)	Pressures (kN m^{-2})
Precision 2-piece	Swirl chamber	0.045	145–372
PKN-38	Swirl chamber	0.040	152–372
	Mechanical break-up	0.075	165–359

The results of the penetration experiments were analysed in the following way.

Consider that in time t a total of (N_0)g of spray approaches the first filter. A fraction Δx of the particles will be removed by the fibres in the first filter, so that the weight collected will be $(N_0)\Delta x$, and the total weight passing to the second stage will be $(N_0)(1 - \Delta x)$. Assuming that a further fraction Δx is removed at each subsequent stage, the weight penetrating the second filter is:

$$N_0(1 - \Delta x) - N_0 \Delta x(1 - \Delta x) = N_0(1 - \Delta x)^2 \qquad (3)$$

and the weight penetrating filter number y is:

$$N = N_0(1 - \Delta x)^y. \qquad (4)$$

The initial weight, N_0, is obtained by summing all the weights captured on the individual filters together with that on the back plate, assuming that no material escapes through the gap between the final filter and the back plate.

From equation (4) we obtain the penetration at any stage y:

$$\text{penetration} = \frac{N}{N_0} = (1 - \Delta x)^y \qquad (5)$$

$$\therefore \log \frac{N}{N_0} = y \log (1 - \Delta x). \qquad (6)$$

Thus a plot of log $\frac{N}{N_0}$ against filter number y should be linear and the slope will be a measure of the overall penetration of the spray into the filter.

RESULTS AND DISCUSSION

Velocity measurements

Figure 3 shows that the velocity of an aerosol spray varies with the distance from the actuator and with the pressure of the aerosol pack. The results shown are for pack pressures of 152, 221, 290 and 359 kN m^{-2} and for a *Precision Standard* RTBU type actuator. The hair spray formulation consisted of 5.6% crotonic acid/vinyl acetate copolymer in IMS with a product/propellant ratio of 40/60, the propellant being the particular mixture of *Freon 11* and *Freon 12* required to give the desired pressure.

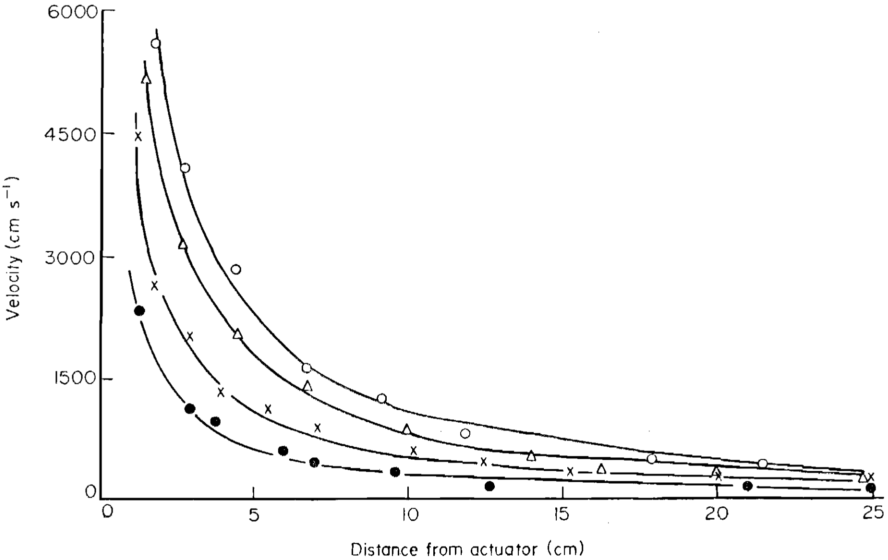

Figure 3. Variation of velocity of aerosol sprays with distance from the actuator. Experimental points: O, 359 kN m^{-2}; △, 290 kN m^{-2}; X, 221 kN m^{-2}; ●, 152 kN m^{-2}.

Figure 4 shows the velocity profile across the spray cone for the same aerosol packs. These measurements were taken at a distance of 50 mm from the actuator by placing the can on a turntable calibrated in degrees. In each case the aerosol button was initially lined up with the Pitot tube by eye, and the position was taken to be zero degrees. Velocity measurements were then taken on each side of this zero.

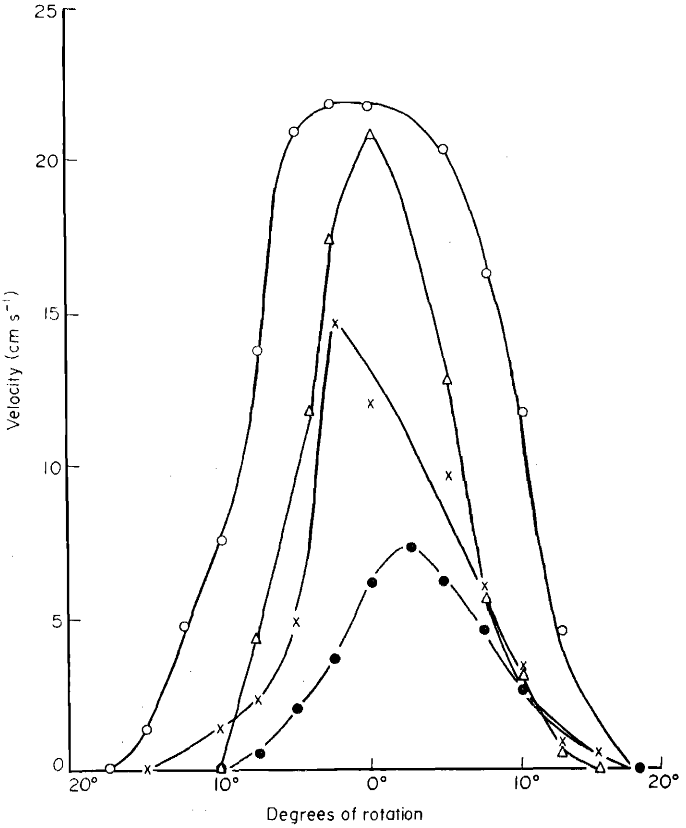

Figure 4. Velocity profile across spray cone 5 cm from the actuator for a *Precision* Standard RTBU actuator. Experimental points: O, 359 kN m^{-2}; △, 290 kN m^{-2}; X, 221 kN m^{-2}; ●, 152 kN m^{-2}.

Figure 3 shows that the velocity is very high close to the actuator and falls rapidly with increasing distance from the actuator. For the high pressure packs (290 and 359 kN m^{-2}) the velocity 10 mm from the orifice is of the order of 6000 cm s^{-1}. At 250 mm the velocity falls to betweeen 100 and 500 cm s^{-1} depending on the pack pressure. The velocity profiles across the spray cone (*Fig. 4*) show that the velocity rises to a maximum at the centre of the spray cone. Both figures show that the maximum velocity in the cone increases with increasing pressure of the aerosol pack.

Figure 5 shows the velocity profile across the spray cone for a 221 kN m^{-2} pack fitted with a *Precision* two-piece actuator.

From a knowledge of the diameter of the actuator orifice and the discharge

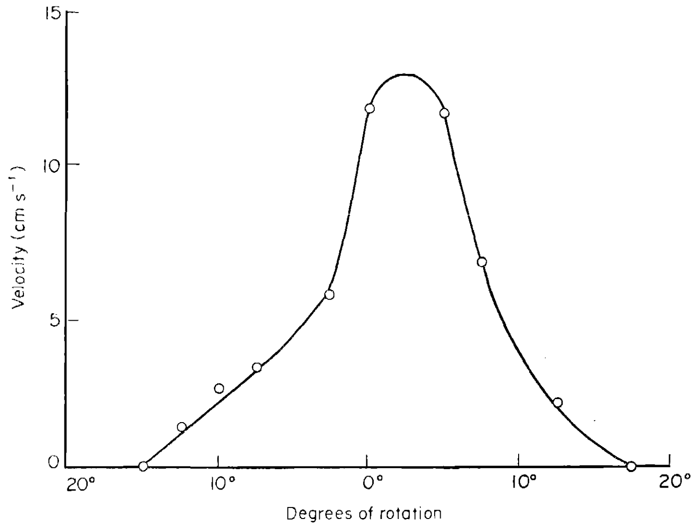

Figure 5. Velocity profile across spray cone 5 cm from the actuator for a *Precision* 2-piece actuator. The pressure was 221 kN m^{-2}.

rate of the aerosol it is possible to calculate the discharge velocity of the sprays. *Table III* shows data for the *Precision Standard* actuator which had an orifice diameter of 0.041 cm. The formulation density was taken as 1.1 g cm^{-3}. The final column of *Table III* shows the values of the maximum velocity of the sprays at a distance of 20 mm. The measured velocities are several times greater than the calculated values. This evidence suggests that the product does not emerge from the can as a continuous jet but as a mixture of liquid and propellant gas. The expansion chamber which precedes the atomizer probably allows partial evaporation of propellant before the

Table III. Comparison of calculated and measured discharge velocities for the standard RTBU actuator

Pressure (kN m^{-2})	Discharge rate (g s^{-1})	Calculated velocity (cm s^{-1})	Measured velocity 2 cm from orifice (cm s^{-1})
152	0.92	645	1700
221	1.03	722	2600
290	1.11	778	3900
359	1.15	806	5200

product enters the orifice. The product then leaves the actuator in a partially atomized condition as a mixture of gas and liquid. The mixture has a lower overall density and consequently higher discharge velocity.

Penetration measurements

Penetration measurements were made with sprays produced by aerosol packs fitted with swirl chamber actuators of the *Precision* two-piece and *Aerosol Research* PKN 38 design and with a conventional mechanical break-up actuator with an exceptionally large orifice diameter of 0·75 mm. Each actuator was used with aerosol cans packed with 5.6% crotonic acid/vinyl acetate copolymer in IMS with a product/propellant ratio of 40/60, and with mixtures of *Freon 11* and *Freon 12* to give pressures ranging from about 138 to 359 kN m^{-2}.

A series of experiments was performed with the model fibre array at a distance of 150 mm from the actuator.

The results for the series of experiments are shown in *Fig. 6* where the data is presented as plots of log N/N_0 versus filter number.

In general linear plots, as predicted by the theoretical analysis, are obtained. Deviations occur for the poorly atomized sprays produced by the mechanical break-up button with 0.75 mm orifice diameter at the lower pressures. These sprays are jet-like and the capture theory breaks down since capture of individual droplets is no longer the controlling mechanism.

Figure 6 shows certain trends which can be seen by simple inspection. The sprays produced by the 0.75 mm orifice diameter mechanical break-up actuator were more penetrating than those produced by either of the swirl chamber actuators at equivalent pressures. Furthermore, for a given type of actuator the penetration generally increases with decreasing pressure of the aerosol pack. Both of these observations indicate that coarse sprays, containing large droplets, are more effective in producing penetration into the array of fibres. This is directly opposite to the effects expected from theoretical consideration.

Direct comparison of the penetration plots allows a ranking order of penetration to be obtained. This order is shown in *Table IV*.

Particle capture theory predicts that the efficiency of capture increases with increasing inertia of the particles, that is with increasing diameter and velocity of the particles. Our data, on the other hand, indicate that this condition does not apply for particles encountered in aerosol hair sprays. Thus the coarser the spray the more penetrating it proves to be.

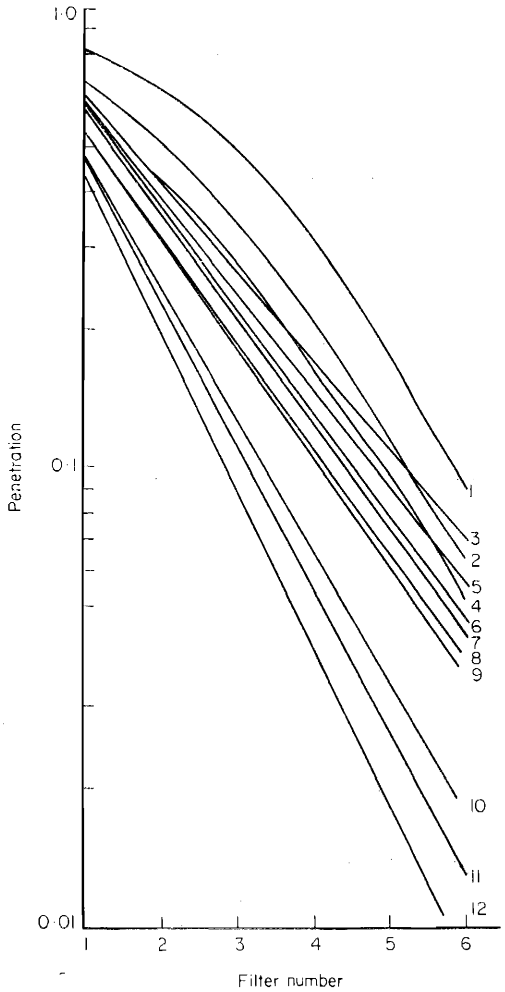

Figure 6. Penetration of hair spray droplets into model fibre array, placed 15 cm from the actuator.

Actuator	Pressure ($kN\ m^{-2}$)	Actuator	Pressure ($kN\ m^{-2}$)
1. Mechanical break-up	165	7. *Precision* 2-piece	214
2. Mechanical break-up	262	8. *Precision* 2-piece	283
3. *Precision* 2-piece	165	9. *Aerosol Research* PKN 38	234
4. Mechanical break-up	303	10. *Precision* 2-piece	372
5. *Aerosol Research* PKN 38	165	11. *Aerosol Research* PKN 38	303
6. Mechanical break-up	359	12. *Aerosol Research* PKN 38	372

Table IV. Penetration of sprays into model filter placed 150 mm from actuator

Ranking order	Actuator/ pressure (kN m^{-2})	d (μm)	V (cm s^{-1})	$d^2 V$ (cm^3 s^{-1})
1	MBU/165	1000	200	2.00
2	MBU/262	500	400	1.00
3	P2P/165	270	200	0.146
4	MBU/303	121	450	0.066
5	PKN-38/165	75	400	0.023
6	MBU/359	81	600	0.039
7	P2P/214	225	400	0.203
8	PKN-38/283	160	200	0.051
9	P2P/234	100	450	0.045
10	P2P/372	60	600	0.022
11	PKN-38/303	80	450	0.029
12	PKN-38/372	63	600	0.024

To investigate the dependence of penetration on the inertia of the particles more fully, it is necessary to consider both the velocity and the dimensions of the particles. If a particle is projected into still air with an initial velocity V cm s^{-1}, and if the particle motion subsequently obeys Stokes law, then the distance travelled by the particle before coming to rest is known as the 'stop distance' and is given by:

$$\text{'stop distance'} = 307\, d^2 \rho V \qquad (7)$$

where d is the particle diameter in cm and ρ is the particle density in g cm^{-3}. The quantity d^2V is a measure of the inertia of the particle.

Since the velocity and size of the particles within each spray both follow a distribution it is not a simple matter to calculate an inertia value which can be rigidly applied to each spray. Perhaps the best that can be hoped for is to use some average value of particle diameter and velocity for each spray. This may be done conveniently with respect to the particle size by calculating the mass median diameters of the sprays from particle size distribution measurements as shown previously (3). It is much more difficult to obtain an average velocity for each spray and the best that could be obtained in the present study was to measure the maximum velocity of the spray at a distance of 150 mm from the actuator. The values of the mass median diameter and maximum velocity for each spray are listed in *Table IV* together with the calculated values of d^2V. It can be seen that the general trend is for the penetration to decrease with decreasing values of d^2V. A more quantitative picture can be obtained by considering actual values of the penetration. For example *Fig. 7* shows the penetration N/N_0 after the fourth filter, plotted against d^2V. The values of d^2V are plotted on a logarithmic scale because of the large range of values encountered (200–20 000).

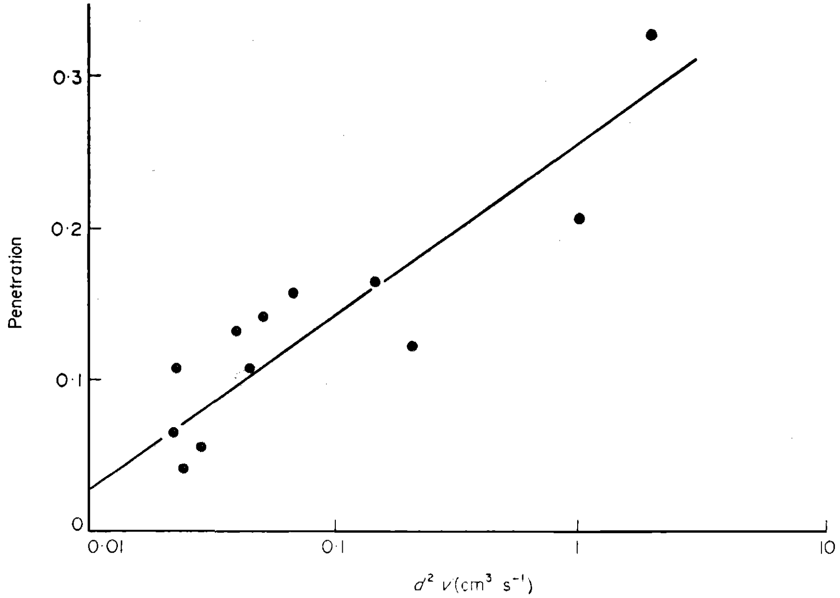

Figure 7. Dependence of the penetration through the first four filters on the product d^2V.

From our experiments we thus find that the theory of capture of aerosol particles does not apply for the capture and penetration of hair spray droplets in arrays of hair fibres. With these systems the greater penetration of coarse sprays is apparently due to the much larger inertia of their particles, which is in turn mainly due to their larger diameters.

There are at least two effects which may be responsible for the observed behaviour. Firstly, since the fibre array is backed by a solid plate representing the scalp the particle-laden gas stream will not be able to pass right through the array. The gas flow lines will be deflected around the array, carrying with them the smaller particles. The larger particles will be able to leave these flow lines more easily and enter the array of fibres. Particles which enter will then travel through the array mainly due to their own inertia since the gas within the array will probably be stagnant. The higher the inertia of the particles the further will they be able to penetrate. This effect will also be shown on the head. Many of the smaller particles will be deflected away by the gas flow around the head and only the larger particles, or the smaller particles at the very centre of the spray, will be deposited on the hair.

The second effect which could produce greater penetration of the larger particles is incomplete capture of the particles by the hair fibres. The aerosol capture theory assumes that those particles which contact a fibre are completely captured, but it is very likely that large high velocity particles might shatter on impact with the fibres, producing several smaller droplets which penetrate further into the array. Only a fraction of the initial droplet is retained at the first impact. This effect would become of greater significance when the particles approach or become larger than the diameter of the fibres, a condition which exists for many of the sprays studied.

CONCLUSIONS

Measurement of the velocity of aerosol sprays using a Pitot-static tube to measure the velocity of the gas stream rather than the actual particle velocity have shown that there is a velocity distribution across the spray cone. The velocity rises to a maximum at the centre of the cone and this maximum falls off with increasing distance from the actuator, and with decreasing pressure of the aerosol pack for a given distance from the actuator.

The capture of hair spray droplets by arrays of fibres backed by a solid plate representing the scalp does not agree with the behaviour predicted from classical aerosol capture theory, that is that the fine sprays containing small droplets would be more penetrating than coarse sprays. In practice it has been found that coarse sprays are more capable of achieving penetration into the fibre array.

It has been found that the penetration increases with increasing value of the product d^2V where d is the mass median diameter of the aerosol spray, and V is the maximum velocity of the spray at a distance of 150 mm from the actuator. This was the experimental distance used between the actuator and the fibre array and corresponds approximately to the spraying distance used by the consumer.

The observed capture behaviour can be explained in terms of the greater inertia of the larger particles which is necessary to carry the particles into the array of fibres. Normal aerosol capture experiments use a filter which is open at both ends so that the gas stream and the particles can flow right through. Larger particles are then more efficiently captured by a combination of the inertial and direct interception mechanisms. When the array of fibres is backed by a solid plate most of the gas stream will be deflected around the front of the array. Small, low inertia particles will tend to follow the gas flow lines and any particles which do enter the array will travel only a small distance before losing their remaining inertia since the air within the array will be largely stagnant. Large particles will leave the gas flow lines much more easily to enter the fibre array and will then travel further because of their greater inertia.

A second factor which could help to achieve greater penetration with larger particles is splitting of droplets on impact with hair fibres. This splitting is liable to be greater the greater the particle inertia. The droplet fragments so produced are then capable of further penetration into the array.

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