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POSSIBLE METHODS FOR REMOVING SMALL AIRBORNE PARTICLES FROM THE FLOW IN THE 5 METRE PRESSURISED LOW-SPEED WIND TUNNEL

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POSSIBLE METHODS FOR REMOVING SMALL AIRBORNE PARTICLES FROM THE FLOW IN THE 5 METRE PRESSURISED LOW-SPEED WIND TUNNEL

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SUMMARY

Because of the size and complexity of the 5-metre wind tunnel, its use raises problems of erosion of wind-tunnel models which have not been encountered with other low-speed facilities. Two methods for removal of small particles have been investigated. They are:

(i) the use of fine mesh fabric screens as filters; and

(ii) by aerodynamic separation at the corners of the tunnel circuit.

(The latter investigation involves the computation of the trajectories of particles in a turning flow.)

The results show that particles smaller than 0.3 mm cannot be filtered out within the practicable pressure drop limitations of the tunnel circuit. However, small particles have a sufficiently high probability of striking the concave surfaces of the corner vanes that if grease or some other retentive material were applied the particles could be quickly removed from the circuit. This latter method is being kept in reserve for the 5-metre tunnel, since physical means such as sweeping and vacuum cleaning have so far seemed to give adequate results. After lengthy shutdowns for maintenance of the 8ft × 8ft tunnel at RAE Bedford, the lower parts of the corner vanes of that tunnel are coated with a suitable grease to remove small airborne particles.

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1 INTRODUCTION

Before the 5 metre pressurised low-speed wind tunnel was completed there was concern that with a civil engineering project of such size and complexity it was unlikely that the tunnel circuit could be cleaned thoroughly enough to ensure the exclusion of all debris and dust. As an example of the necessity for cleaning the circuit, Goodwin, Sage and Tilley[1] have shown that sand particles even as small as 0.02 mm can erode steel and that the erosion increases as the particle size and velocity increase.

In view of the potential damage to the 5 metre tunnel components (*eg* fan blades, cooler) and wind-tunnel models, it was essential that methods for removing small particles from the air flow should be explored. The work described in this Memorandum concerning the removal of small airborne particles was not only applicable to the commissioning of the tunnel but also to its subsequent use, since it is possible that dust will be carried into the tunnel circuit even though all practicable precautions are taken to preclude it.

The two possible ways of restricting the movement of dust particles around the tunnel circuit which have been considered are:

(i) collection of the dust by fine mesh screens;

(ii) aerodynamic separation at the corners of the tunnel with the dust trapped on strategically placed grease bands.

In section 2 the use and location of a fine mesh, fabric screen is discussed together with a description of tests on samples of suitable materials and their effectiveness in filtering out small particles. The aerodynamics and the equation of motion of spherical particles in an air stream are considered in section 3 and a scheme is described for the numerical integration of the equation. In section 4 this scheme is applied when the air flow is turning at the third or fourth corners of the tunnel. The effect of various particle and air stream parameters on the trajectory of particles is studied and the probability of particles passing through the vane system without impinging on the vanes is calculated.

It has to be stressed that the work in this Memorandum is not rigorous, relying as it does on extrapolation, simplified flow models and the assumption that the particles involved can be regarded as spherical. Nevertheless, it is believed that the results indicate the nature of the problems which are liable to be encountered in removing the majority of the dust from the 5 metre wind tunnel air flow.

2 FINE MESH SCREENS

The use of fine-mesh, material screens to collect dust in a wind-tunnel circuit is an established practice (*eg* the 3ft × 3ft transonic tunnel at RAE Bedford). Calculations[2] have shown that the maximum static-pressure drop across a screen which could be tolerated within the power limitations of the 5 metre tunnel is fifteen times the dynamic pressure in the circuit maximum section. At an absolute pressure of 3 atmospheres and a working-section velocity of 95 $m\ s^{-1}$ (the design maximum values) a screen with such a pressure-drop characteristic would sustain a load of 660 kN (approximately 66 tons).

Locations for a screen are limited though somewhere within the circuit's constant area section after the second diffuser but before the rapid expansion is possible (see Fig 1). In this region, the local dynamic pressure (q) is greater than in the maximum section and hence the maximum permissible static-pressure drop is only about seven times the local value of q .

Various materials have been tested in a small wind tunnel over a range of speeds to determine their pressure drop characteristics. The materials were: muslin, scrim, polyester net and two grades of glass fibre mat.

Bradshaw[3] gives an expression for the static-pressure drop (K) across a screen:

$$K = \frac{9(1 - \beta)}{\beta^2 R_e^{0.4}}$$

where β is the open area ratio and R_e is the Reynolds number. The mesh size (ℓ) and thread diameter (d) determine β $\left(= (1 - d/\ell)^2 \text{ for a square mesh}\right)$ and $R_e = \frac{Ud}{\beta\nu}$.

Table 1 shows that the experimentally determined values of K differ from the theoretical values substantially but it must be noted that Bradshaw's work was on screens made of wires rather than fluffy or very non-circular sectioned threads. To verify the results, a sample of a phosphor-bronze screen was also tested and for this the comparison between experimental and theoretical values is better.

Quite clearly, the glass fibre mats are of no use; their pressure-drop characteristics being too large. Also, the polyester net can be discarded since its mesh is so large. Therefore we are left with the possibility of using a screen of either a single or double thickness of muslin or scrim. An estimate of the K-value for a double thickness of scrim can be made using the results of the single and double thickness muslin screens. These values are plotted in Fig 2 and have been extrapolated (using Bradshaw's Reynolds number variation) to Reynolds numbers appropriate to a possible position between the second diffuser and the rapid expansion.

Fig 2 shows that at this Reynolds number either a single or double thickness of muslin or a single thickness of scrim could be used as a screen within the limitations of the tunnel power. The choice between the two materials must therefore be made on the ability of each to obstruct the motion of small particles.

The probabilities of spherical particles of a given radius passing through a single layer of either material *without touching it* have been calculated (assuming the mesh to be regular and square) and the results are presented in Fig 3. This clearly shows that a screen made of the type of muslin tested would hinder the motion of more particles than would one of scrim. However, these probabilities are for particles which do not touch the screen and it is probable that all particles which are small enough to pass through the holes in the screen will do so since it is unlikely that the fabric of the screen could be treated so as to trap any such particle which hits it. In other words, a muslin screen may allow all particles with a diameter less than 0.33 mm to pass through it and even, possibly, some larger ones by deformation of the weave.

The holes in muslin (and scrim) are of irregular shape and size though they are basically square. It is therefore difficult to estimate the filtering efficiency of a double thickness since some areas may act essentially as a single thickness and others as impermeable sheets. However, it is clear that many particles of a much larger size than is desirable can pass through muslin (or scrim) of the type tested.

There are two further problems concerning the use of a dust-collecting screen: the first is that such a screen would approximately double the power required for a given condition in the working section. Secondly, no facility exists on the tunnel structure to suspend a screen sustaining a load up to 660 kN - considerable design effort and structural work would be required to do so.

In conclusion, the disadvantages of using some sort of screen to remove small airborne particles from the air flow of the 5 metre tunnel circuit are great and some other method is preferable. This alternative method must be capable of removing particles smaller than 0.33 mm from the air flow without severely restricting the tunnel performance envelope. One possible method is aerodynamic separation at the third or fourth corner of the tunnel circuit and this idea is examined in the following sections.

3 MOTION OF A SPHERICAL PARTICLE

Although the dust particles introduced into the air stream will not be spherical, it is well established that useful information can be derived from consideration of the trajectories of spherical particles in non-uniform flows at the very low Reynolds numbers involved. The characteristics of the particles are:

radius = a
density = ρ_p
position $\underline{r} = (x, y)$
drag coefficient = C_D

and those of the flow:

density = ρ_A
viscosity = μ
velocity = $\underline{U}(\underline{r}) = (U_x, U_y)$.

Application of Newton's third law of mechanics gives the equation of motion for the particle:

$$\ddot{\underline{r}} = -\frac{C_D R_e}{24} \frac{9\mu}{2a^2\rho_p} (\dot{\underline{r}} - \underline{U}) \tag{1}$$

where R_e is the Reynolds number of the particle. $R_e = \dfrac{2a\rho_A|\dot{\underline{r}} - \underline{U}|}{\mu}$

$\dfrac{C_D R_e}{24}$ can be approximated[4] by:

$$\frac{C_D R_e}{24} = 1 + 0.197R_e^{0.63} + 0.00026R_e^{1.38}$$

which gives a very good approximation to the experimental data for Reynolds numbers up to 1000. Writing $\dfrac{C_D R_e}{24} = f(R_e)$ and $\dfrac{9\mu}{2a^2\rho_p} = K$, equation (1) may be rewritten:

$$\ddot{\underline{r}} = -f(R_e)K(\dot{\underline{r}} - \underline{U}) \quad . \tag{2}$$

In section 4 it will be seen that in the corner vane system the stream velocity $\underline{U}$ is dependent on $\underline{r}$ and therefore $f(R_e)$ is also. It is therefore necessary to calculate the particle trajectory numerically. The approximations used in this work for the particle velocity and position at time $t + 2\Delta t$ are:

$$\dot{\underline{r}}_{t+2\Delta t} = \tfrac{1}{2}(\dot{\underline{r}}_t + \dot{\underline{r}}_{t+\Delta t}) + \frac{\Delta t}{4}(7\ddot{\underline{r}}_{t+\Delta t} - \ddot{\underline{r}}_t) \quad , \tag{3}$$

$$\underline{r}_{t+2\Delta t} = \tfrac{1}{2}(\underline{r}_t + \underline{r}_{t+\Delta t}) + \frac{\Delta t}{4}(5\dot{\underline{r}}_{t+\Delta t} + \dot{\underline{r}}_{t+2\Delta t}) \quad . \tag{4}$$

These equations were derived empirically using Taylor's theorem to compute a stable particle trajectory.

Substituting from equation (2) in equation (3) enables $\dot{\underline{r}}_{t+2\Delta t}$ to be calculated which when inserted in equation (4) enables $\underline{r}_{t+2\Delta t}$ to be determined.

By suitably defining the starting conditions and the flow field in which the particle is moving, the trajectory can be calculated.

4 PARTICLE MOTION THROUGH CORNER VANE SYSTEM

4.1 Vane geometry and flow model

The corner design in the 5 metre tunnel is copied from that used in the 8ft × 8ft tunnel at RAE Bedford. Each corner is similar with 15 vanes spaced in arithmetic progression. The vanes are made from steel plates with rounded leading edges and chamfered trailing edges. The geometrical details are shown in Fig 4.

The diameter of the 5 metre tunnel section at the third and fourth corners is 11.34 metres (37.2 feet) thus giving the vanes a radius $R = 1.134$ metres (3.72 feet) and $L = 0.83$ metre (2.723 feet). There is a total of 15 free vanes and the gap between the $(r - 1)$th and rth is $0.454 + (r - 1)0.073$ metre along the diagonal.

To model, simply, the flow through such a corner vane system requires a number of assumptions to be made:

(i) the vanes are of zero thickness;

(ii) the flow is inviscid and incompressible;

(iii) all streamlines have the same geometry (which is that of the vane).

Referring to Fig 5a, for a point $\underline{r}_0 = (x_0, y_0)$ on a vane, the flow vector $\underline{U}_{\underline{r}_0} = \left(\frac{y_0 U_\theta}{R}, -\frac{x_0 U_\theta}{R}\right)$ where U_θ is the local stream speed. For a general point $\underline{r} = (x, y)$ within the vane system, $\underline{U}_{\underline{r}} = \underline{U}_{\underline{r}_0}$ when:

$$x = x_0 + \ell/\sqrt{2}, \quad y = y_0 + \ell/\sqrt{2} \quad \text{and} \quad (x - \ell/\sqrt{2})^2 + (y - \ell/\sqrt{2})^2 = R^2$$

whence

$$\frac{\ell}{\sqrt{2}} = \frac{x + y}{2} - \left\{\frac{R^2}{2} - \left(\frac{x - y}{2}\right)^2\right\}^{\frac{1}{2}} .$$

Writing $R_1 = \frac{x - y}{2R}$, $R_2 = \left\{0.5 - R_1^2\right\}^{\frac{1}{2}}$ then:

$$\underline{U}_r = \left((R_2 - R_1)U_\theta , \; - (R_2 + R_1)U_\theta\right)$$

where $\theta = \tan^{-1} \frac{R_2 + R_1}{R_2 - R_1}$.

To determine U_θ , consider two vanes V_{r-1} and V_r as shown in Fig 5b ($AB = DC = S_r$). For all points on AB, $\underline{U} = (U_\infty, 0)$ and on CD, $\underline{U} = (U_\theta \cos\theta, - U_\theta \sin\theta)$. Using the continuity equation for the area bounded by ABCD,

$$U_\infty \cos\frac{\pi}{4} S_r \rho_A = U_\theta \cos\left(\frac{\pi}{4} - \theta\right) S_r \rho_A .$$

Hence $U_\theta = \frac{U_\infty}{\sqrt{2}} \sec\left(\frac{\pi}{4} - \theta\right)$.

It is now possible to calculate the local stream velocity vector for any point within the corner vane system.

4.2 Particle trajectories in corner vane system

Using the integration technique described in section 3 with the stream velocity input as calculated above, the trajectories of some particles passing into the corner vane system have been computed.

Various parametric studies have been undertaken and include variation of particle density, particle radius, flow density and flow velocity. Figs 6 to 9 show some of the trajectories calculated for these studies. Although flow velocity is a variable, the initial particle velocity is the same, 9 m s^{-1}, for all cases. In the figures, the starting point is shown as the leading edge of the upper surface of vane V_{r-1} so that the deflection of the particle can be seen in relation to the vane geometry. The position of vane V_r is indicated by the box in the figures which shows the minimum and maximum vane separations (for $r = 1$ and 15 respectively).

The conclusion which can be drawn from Figs 6 to 9 is that small particle radius and density and large stream density and velocity reduce the deviation of the particle from the streamline on which it entered the corner vane system.

With the intention of examining what proportion of particles could pass through the vane system at the third and fourth corners of the 5 metre tunnel and which could subsequently impinge on a model, more cases were computed with the tunnel velocity and density input at their maximum values ($U_\infty = 21$ m s^{-1}, $\rho_A = 3.675$ kg m^{-3}) and the initial particle velocity put equal to the tunnel velocity (21 m s^{-1})*. The parametric studies suggested that particles of sand ($\rho_p = 2.6$ Mg m^{-3}) bigger than 0.38 mm will all collide with the vanes and for steel ($\rho_p = 7.7$ Mg m^{-3}) the critical size is 0.20 mm.

As sand particles are more likely to pass through the corner-vane system and, therefore, to damage models, the trajectories of such particles of diameter 0.05, 0.125, 0.20 and 0.305 mm were calculated ($\rho_p = 2.6$ Mg m^{-3}). These trajectories are plotted in Fig 10 which shows that the proportion of particles of any size passing through the vane system will vary across the tunnel as the vane spacing increases. Assuming that the particles are uniformly distributed in the air upstream of the vanes, it is possible to calculate the percentage of particles of each size which will impinge on the vane system at the third or fourth corner. This is shown by the solid line on Fig 11. Also shown is the percentage impinging on the corner vanes at both the third and fourth corners (assuming uniform redistribution of particles after the third corner but before the fourth).

Fig 11 shows that particles of diameter less than 0.38 mm have some chance of passing through the corner vane system and for small particles the probability is obviously quite high. If a suitable compound can be found to trap all particles impinging on the concave surfaces of the corner vanes, then the results shown in Fig 11 can be used to estimate the approximate tunnel running times for removal of a given percentage of particles of different sizes. To make this estimate it is necessary to assume that the particles are uniformly redistributed in the air stream (by local turbulence) on each circuit of the tunnel. Given that the air takes approximately 6 seconds to go round the circuit (at maximum

* A calculation showed that a particle of sand of diameter 0.38 mm accelerating from rest reached a speed of 19.95 m s^{-1} (95% of U_∞) in only 0.4 second and in that time travelled approximately 1.7 metres.

speed) the following table gives estimates of the tunnel running time to remove 99% of particles of different sizes by aerodynamic separation at one corner only (the third or fourth).

Particle diameter (mm)	Number of tunnel circuits to separate 99% of particles	Approximate time (seconds)
0.025	33	198
0.05	16	96
0.10	7	42
0.15	4	24
0.20	3	18
0.25	3	18
0.30	2	12
0.35	2	12
0.38	1	6

This table shows that during the first $3\frac{1}{2}$ minutes of tunnel running time, the vast majority of particles which can cause erosion[1] can be removed from the air stream. Furthermore, even partial treatment of the vane system (*eg* the part which can be easily reached) should give an acceptable rate of removal of particles. In fact, grease-banding the lower part of some of the corner vanes is already used routinely to clean the circuit of the 8ft × 8ft tunnel at RAE Bedford after the lengthy annual maintenance shutdown.

5 CONCLUDING REMARKS

To remove small particles from the air stream of the 5 metre tunnel two concepts have been investigated, namely: fine mesh fabric screens as filters and aerodynamic separation at the corners of the tunnel circuit.

Within the pressure drop limitations of the tunnel circuit, so as not to stall the fan, a muslin screen seems to be the best choice but it cannot arrest particles smaller than 0.3 mm and does not therefore offer a solution.

The calculations on aerodynamic separation of particles at a corner suggest that if the concave surfaces of the vanes were covered with grease or some other compound capable of retaining particles which impact on them, removal of particles would be very rapid; even partial treatment of the vanes may suffice.

Before the tunnel was run for the first time, the circuit was cleaned by sweeping and vacuum cleaning. The tunnel is now being used for testing models without any method for removing small airborne particles from the flow and there is no evidence to suggest the need to try to remove such particles. ever, a careful watch is being kept on the surface quality of both the leac edges of the models and the fan blades to see if it does become necessary. does, a suitable compound will be applied to the concave surfaces of the va the third or fourth corner of the tunnel circuit.

This method of removal of small particles is used in the 8ft × 8ft tu at RAE Bedford after lengthy shutdowns for tunnel maintenance, where it has found satisfactory to apply a coating of grease to only the lower parts of corner vanes.

Table 1

CHARACTERISTICS OF VARIOUS MATERIALS FOR USE AS A SCREEN

Material	Open area ratio* β	Mean thread diameter d (mm)	Mean mesh size ℓ (mm)	Reynolds number R_e	K Experi-mental	K Theoretical (Ref 3)
Muslin (single)	0.414	0.246	0.576	630	4.31	2.34
	0.414	0.246	0.576	945	4.06	1.99
	0.414	0.246	0.576	1260	3.78	1.77
Muslin (double)	?	0.246	0.576	630	11.38	-
	?	0.246	0.576	945	10.54	-
Scrim	0.477	0.381	1.316	845	4.97	1.40
	0.477	0.381	1.316	1268	4.48	1.19
	0.477	0.381	1.316	1691	4.18	1.06
Polyester net	0.660	0.889	2.515	1426	0.94	0.39
	0.660	0.889	2.515	2138	0.94	0.33
	0.660	0.889	2.515	2851	0.94	0.29
Glass fibre: 101	0.218	0.538†	1.033	1620	62.3	7.70
Glass fibre: 138	0.224	1.440†	2.730	4687	55.8	4.73
Phospher-bronze	0.490	0.254	0.847	545	1.63	1.54
	0.490	0.254	0.847	818	1.56	1.31
	0.490	0.254	0.847	1090	1.49	1.17

* This is a measured value and differs from the theoretical value because of non-uniformity of the weave.

† This is the width of the thread; its thickness is approximately one third this value.

LIST OF SYMBOLS

a	particle radius
C_D	drag coefficient
d	thread diameter of fabric screen
$f(R_e)$	$= \frac{C_D R_e}{24}$
K	static pressure drop coefficient (section 2) *or* $= \frac{9\mu}{2a^2\rho_p}$ (section 3)
ℓ	mesh size of fabric screen
L	length of trailing flap of turning vanes
q	dynamic pressure $\left(= \frac{1}{2}\rho_A U_\infty^2\right)$
r	number of vane (section 4)
$\underline{r}$	$= (x, y)$ position vector
R	radius of turning vane
R_1	$= (x - y)/2R$
R_2	$= \left\{0.5 - R_1^2\right\}^{\frac{1}{2}}$
R_e	Reynolds number
S_r	gap between vanes V_{r-1} and V_r
t	time
Δt	time increment
U_∞	free stream speed
$\underline{U}$	$= (U_x, U_y)$, stream velocity vector
$\left.\begin{matrix} x \\ y \end{matrix}\right\}$	coordinates
β	open area ratio of fabric screens $\left\{= (1 - \frac{d}{\ell})^2 \text{ for a square mesh}\right\}$
θ	angle
μ	viscosity
ν	dynamic viscosity $= \mu/\rho_A$
ρ	density

<u>Subscripts</u>

A	air
p	particle
0	value at a point on a vane
θ	value at angle θ

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2	A.J. Sadler	Private communication
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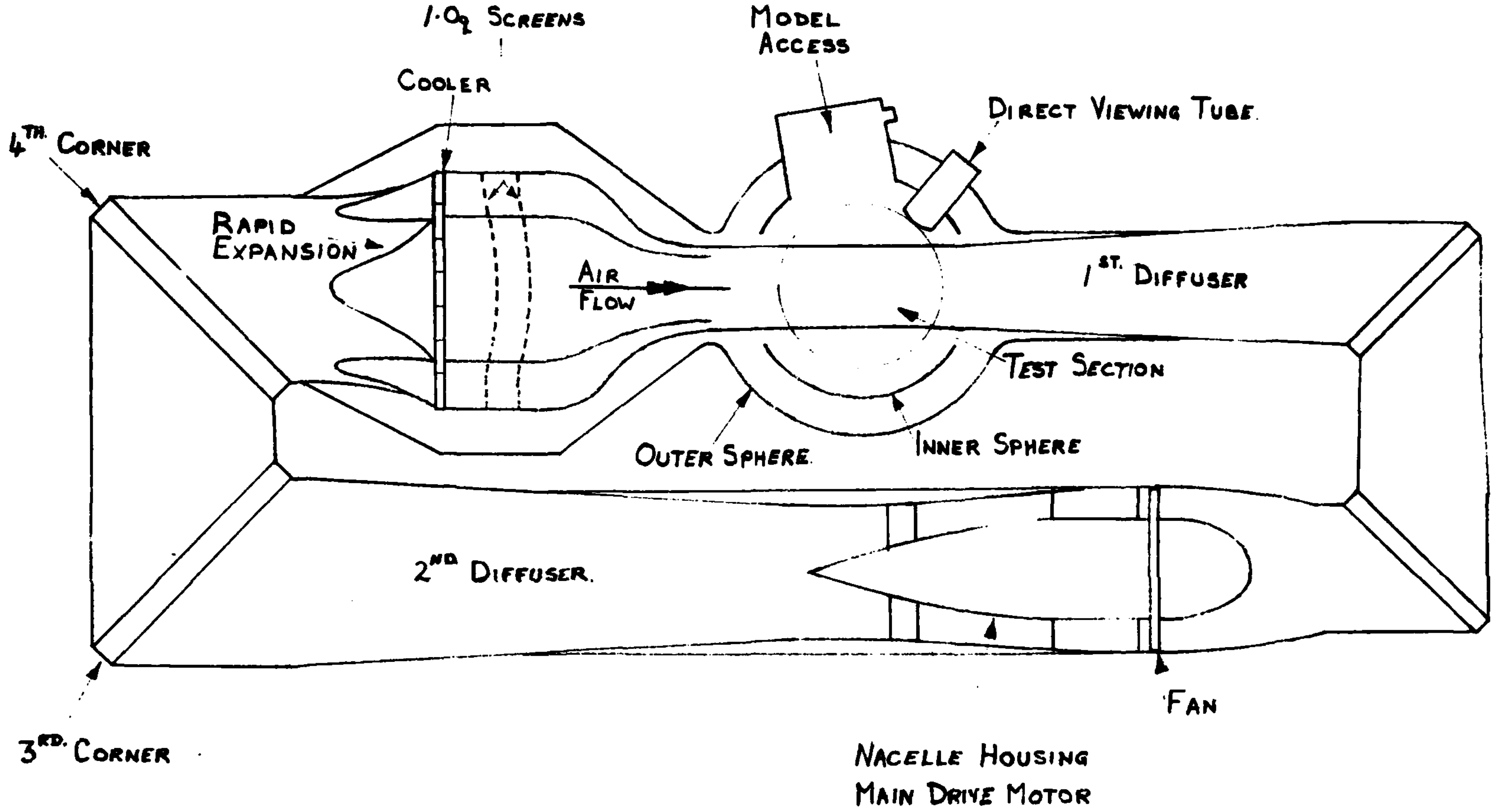


Fig 1 Layout of 5 metre tunnel circuit

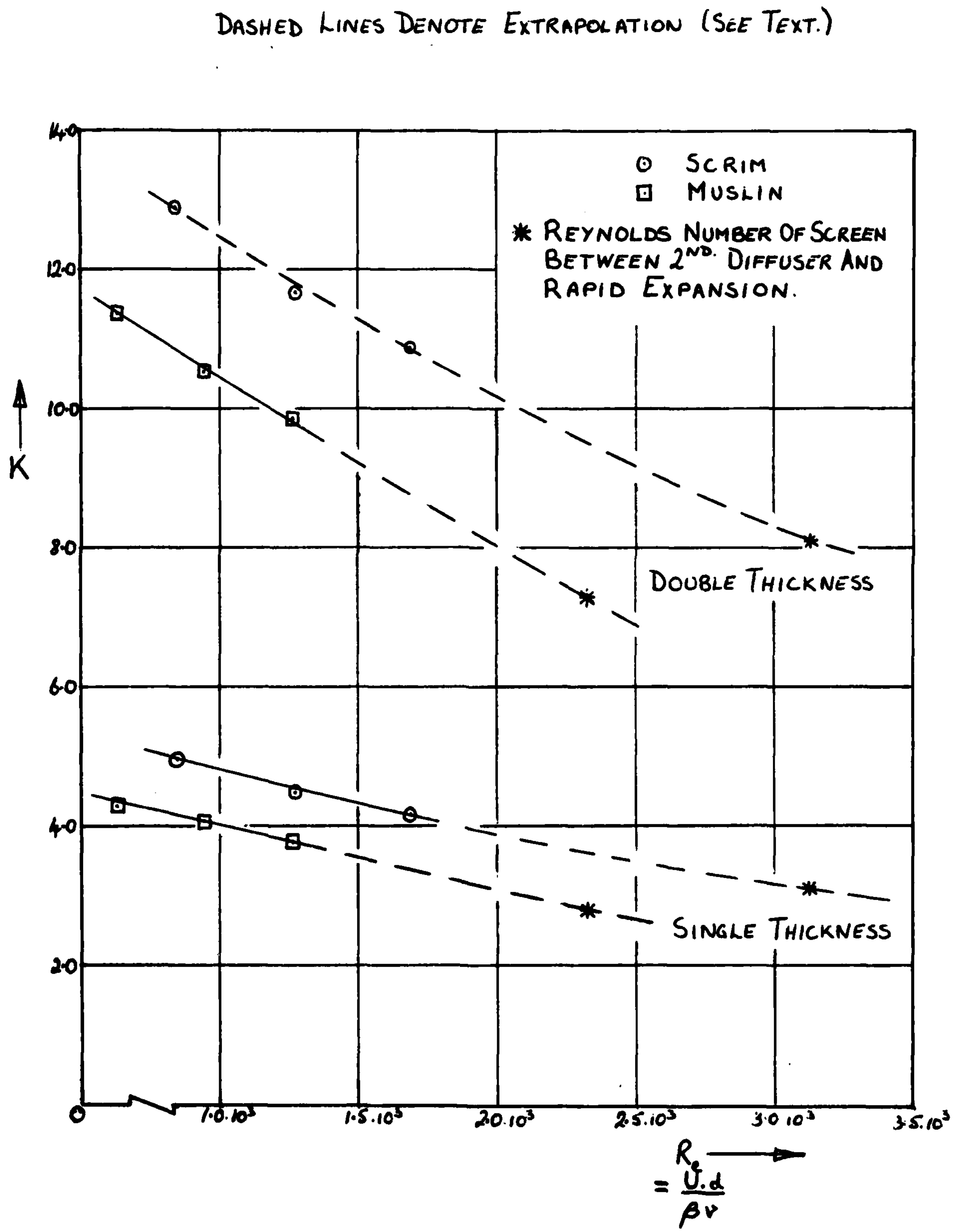


Fig 2 Pressure drop characteristics of materials suitable for a screen

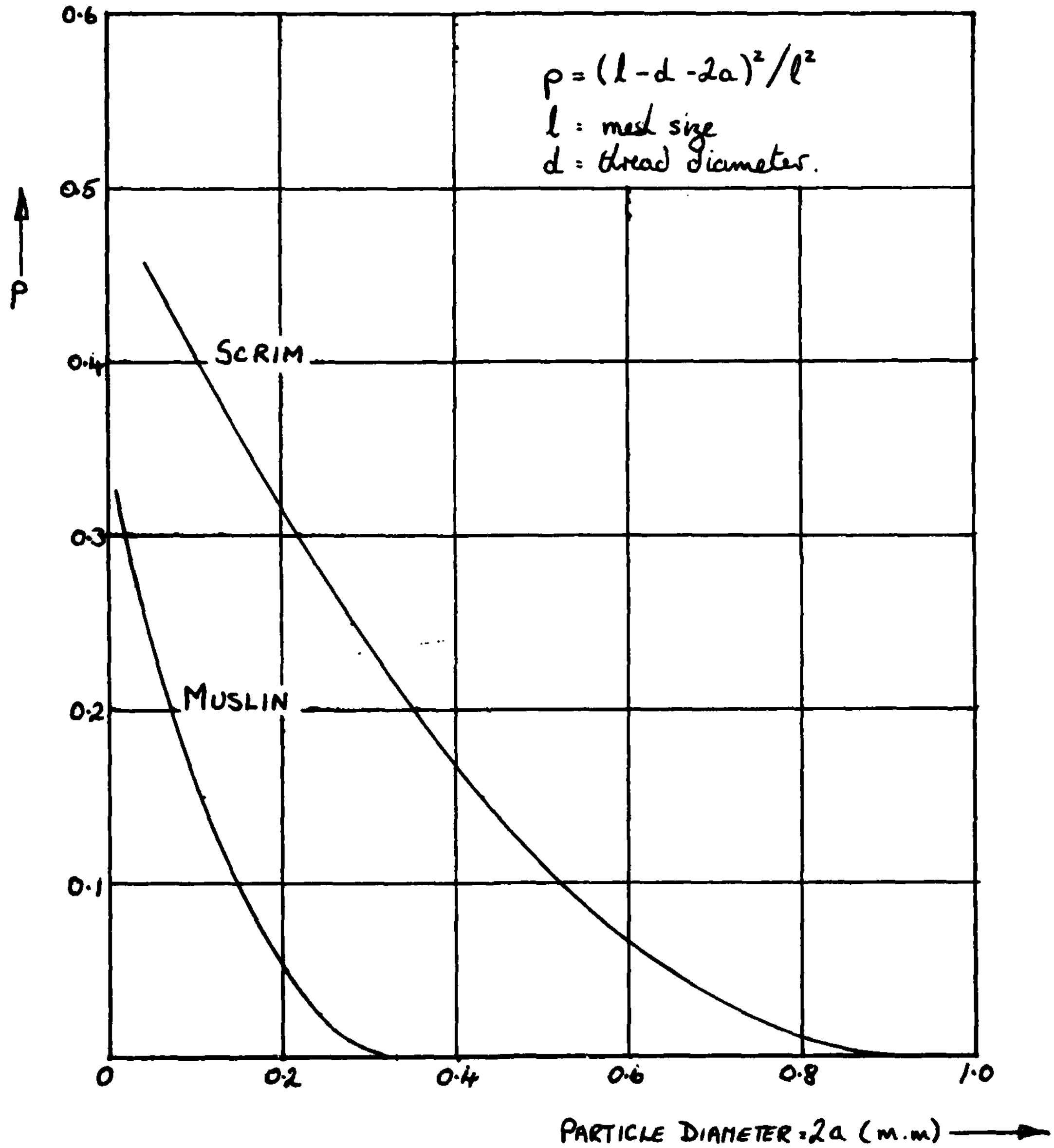
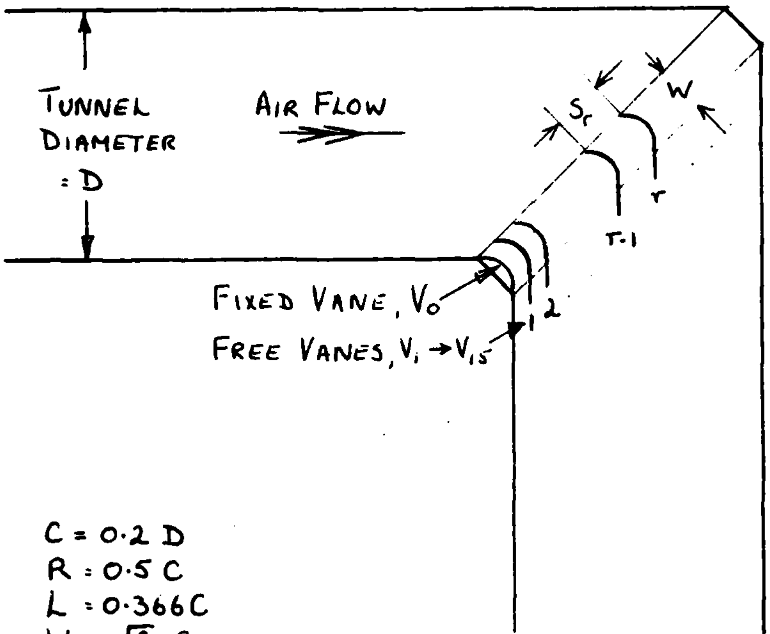


Fig 3 Probability of particle of given diameter passing through screen without impact

Fig 4



$C = 0{\cdot}2\,D$

$R = 0{\cdot}5\,C$

$L = 0{\cdot}366\,C$

$W = \sqrt{2}\,.\,R$

$n = 15 =$ N^{o} OF FREE VANES

$= \dfrac{3{\cdot}2D}{C} - 1$

$S_r = S_1 + (r-1)\Delta$

WHERE

$S_1 = 0{\cdot}2C$

$\Delta = \dfrac{2\sqrt{2}\,D}{n(n+1)} - \dfrac{2S_1}{n}$

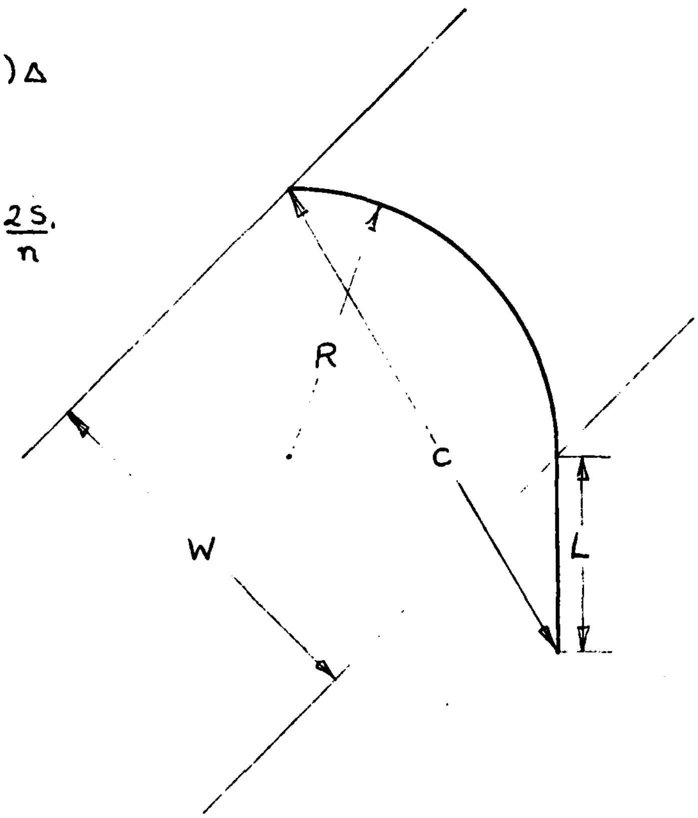


Fig 4 Geometry of the corner vanes

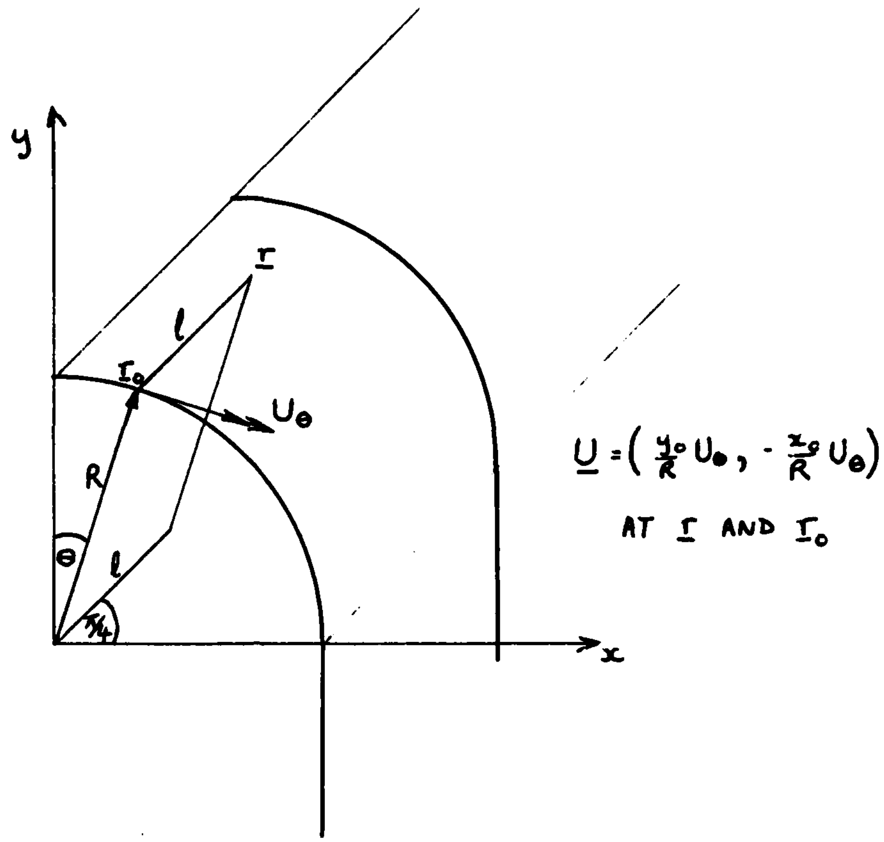


Fig 5a

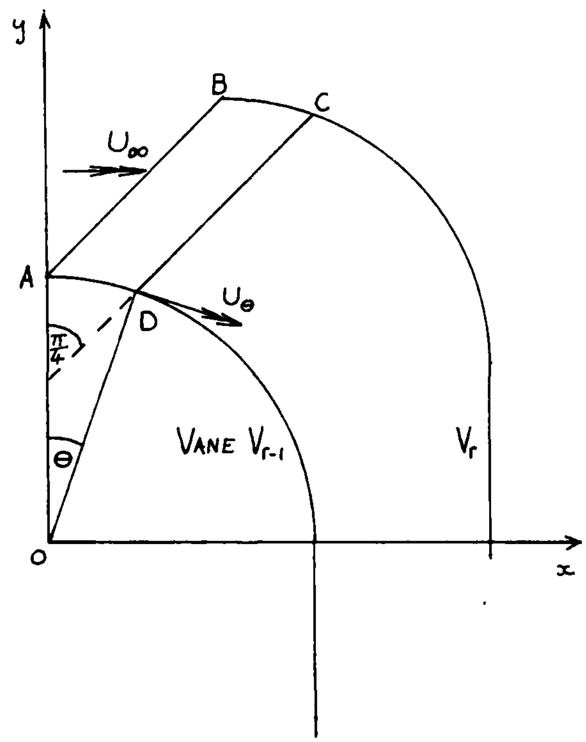


Fig 5 b

Fig 5a&b Nomenclature for flow model at corner vanes

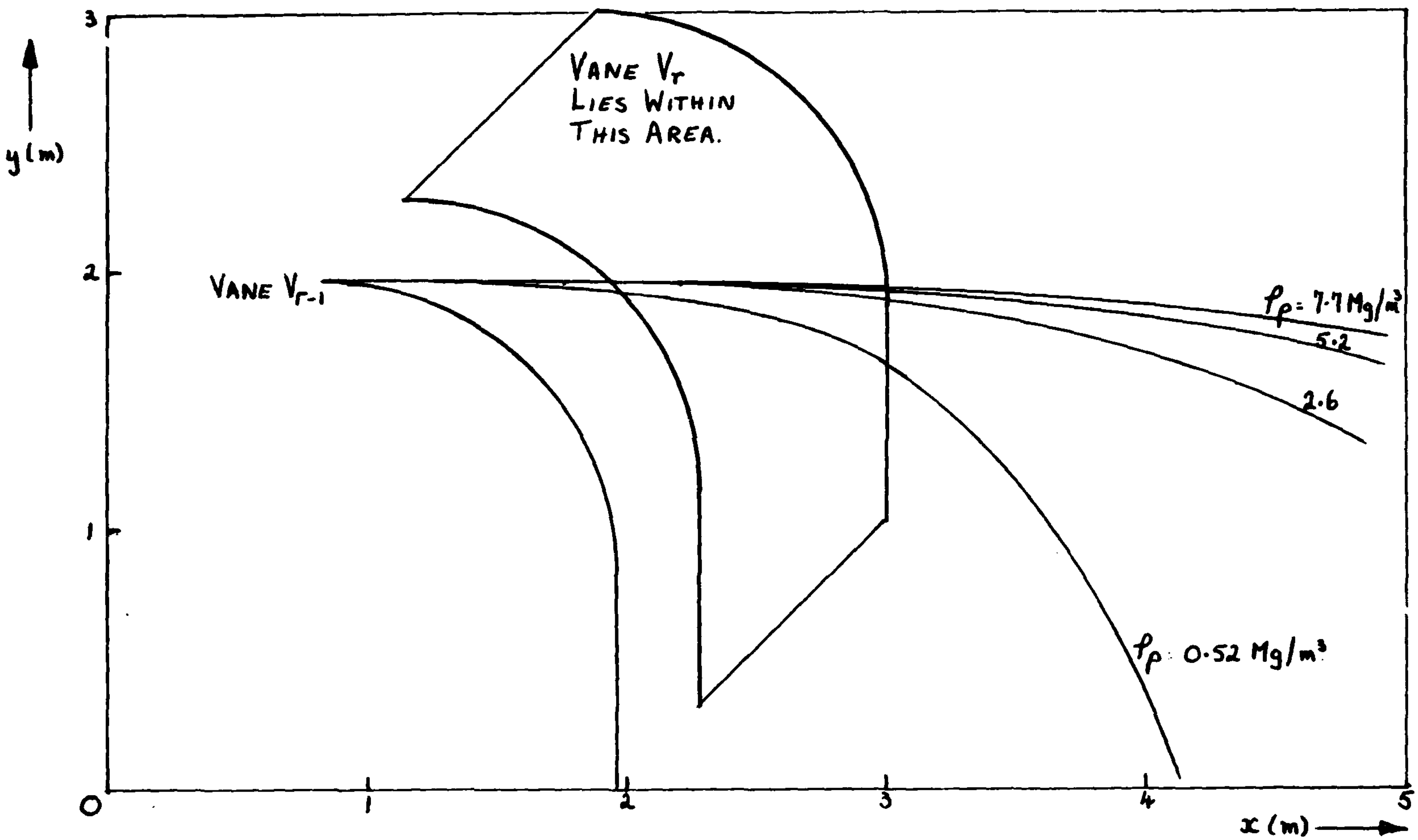


Fig 6 Variation of particle trajectory with particle density
$a = 1.2$ mm, $\rho_A = 1.225$ kg m^{-3}, $U_\infty = 15.2$ m s^{-1}

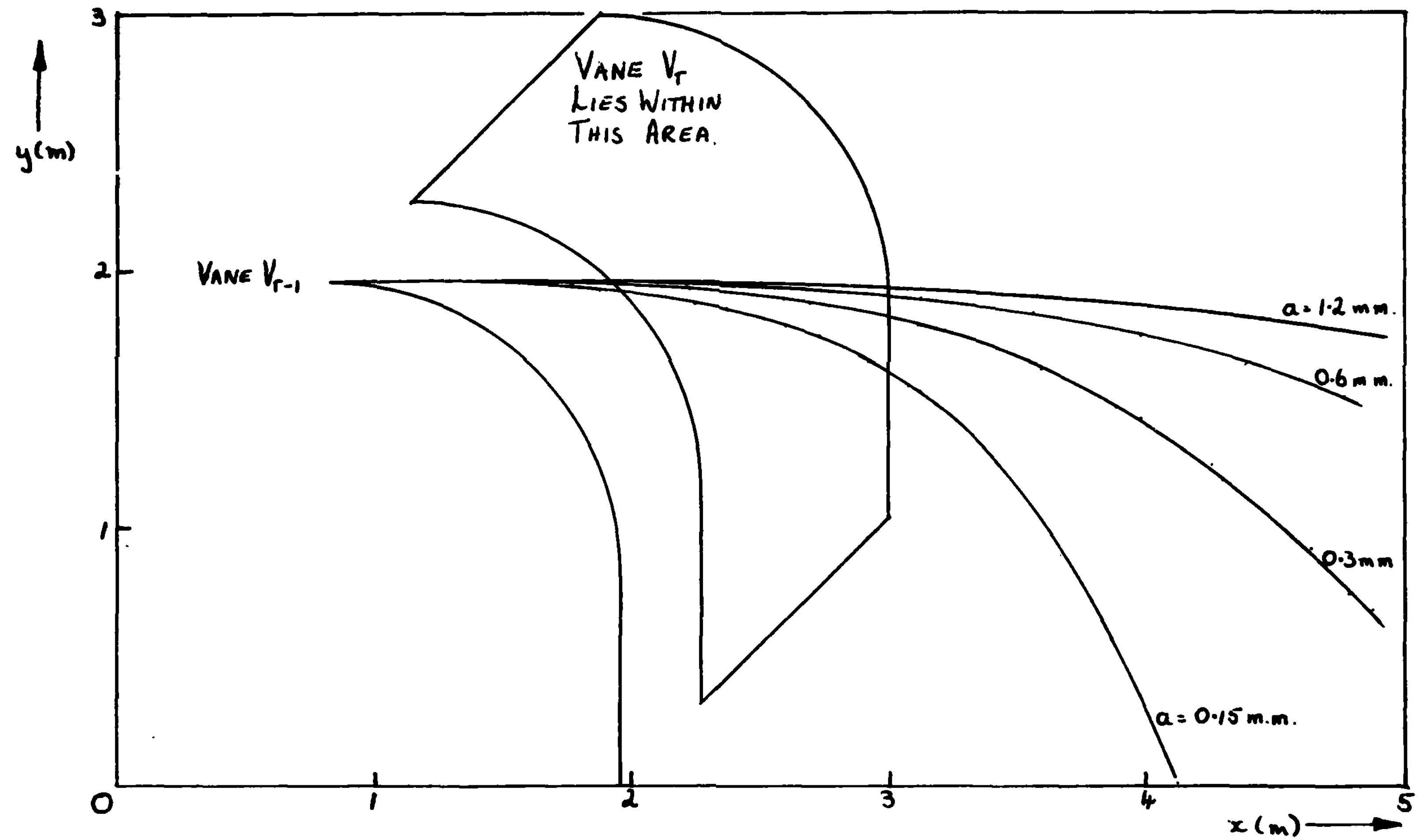


Fig 7 Variation of particle trajectory with particle radius
$\rho_p = 7.7$ Mg m^{-3}, $\rho_A = 1.225$ kg m^{-3}, $U_\infty = 15.2$ m s^{-1}

Fig 8

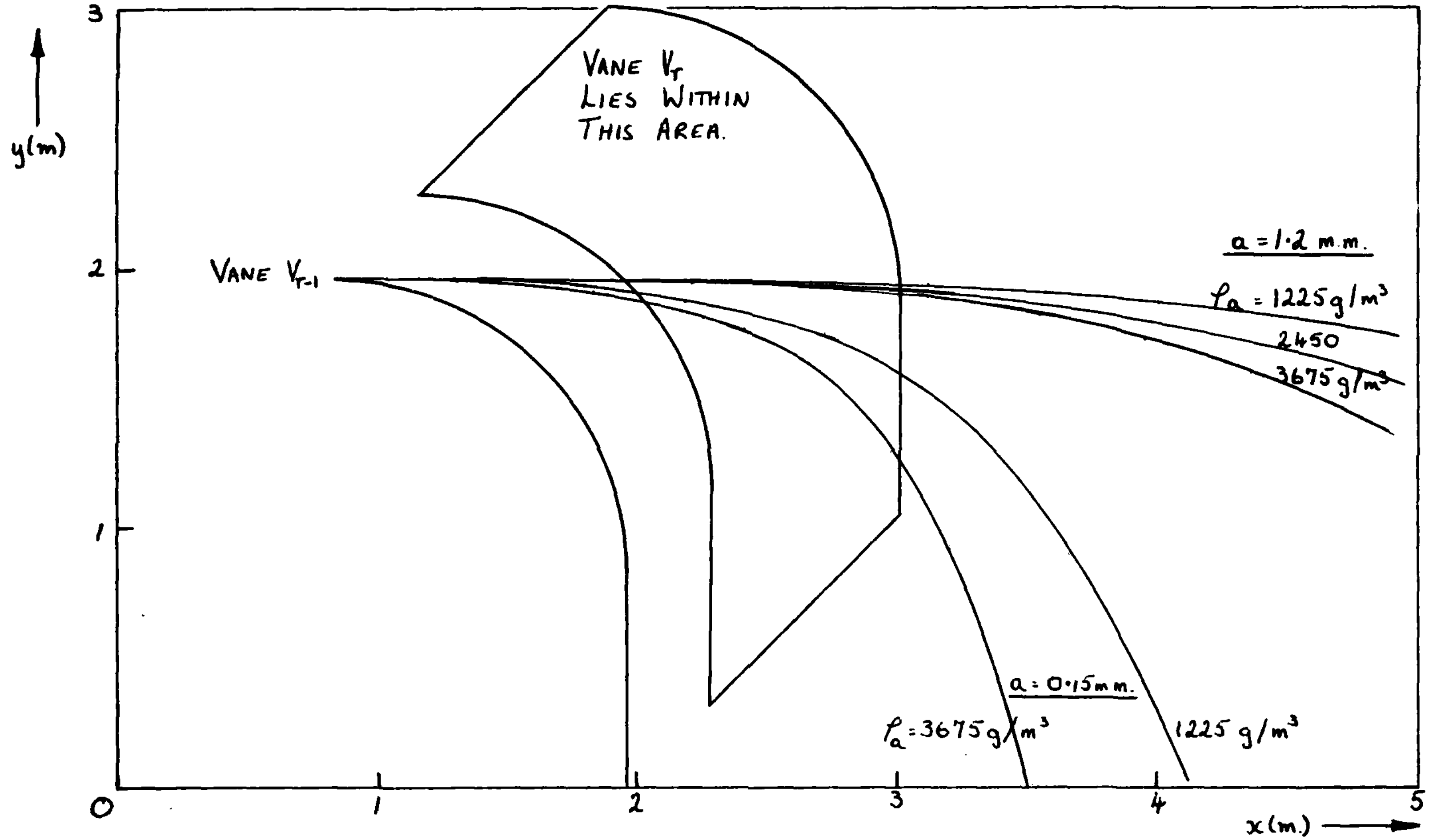


Fig 8 Variation of particle trajectory with air density

ρ_p = 7.7 Mg m^{-3}, U_∞ = 15.2 m s^{-1}, a = 1.2 mm and 0.15 mm

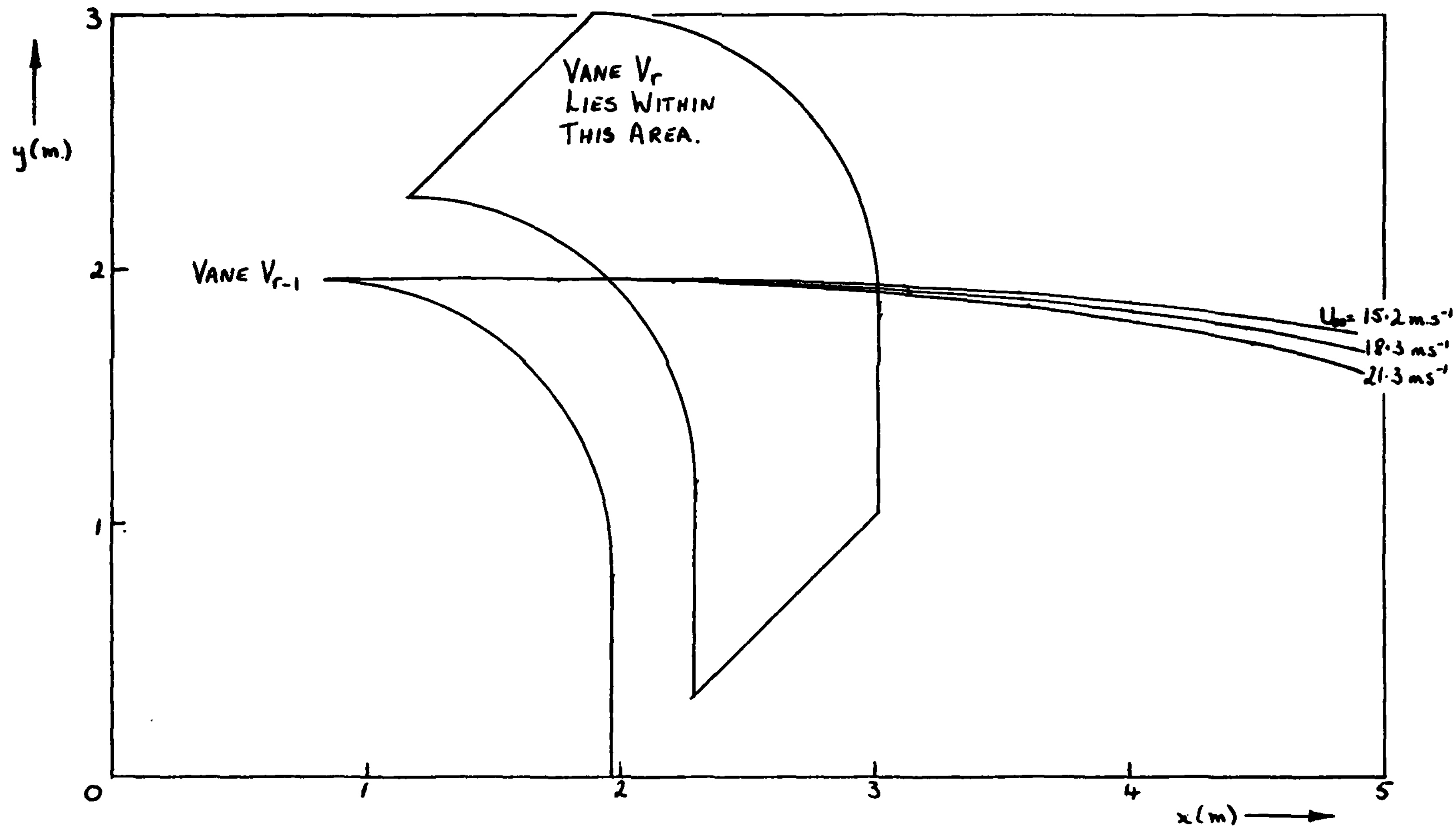


Fig 9 Variation of particle trajectory with wind velocity
$a = 1.2$ mm, $\rho_p = 7.7$ Mg m^{-3}, $\rho_A = 1.225$ kg m^{-3}

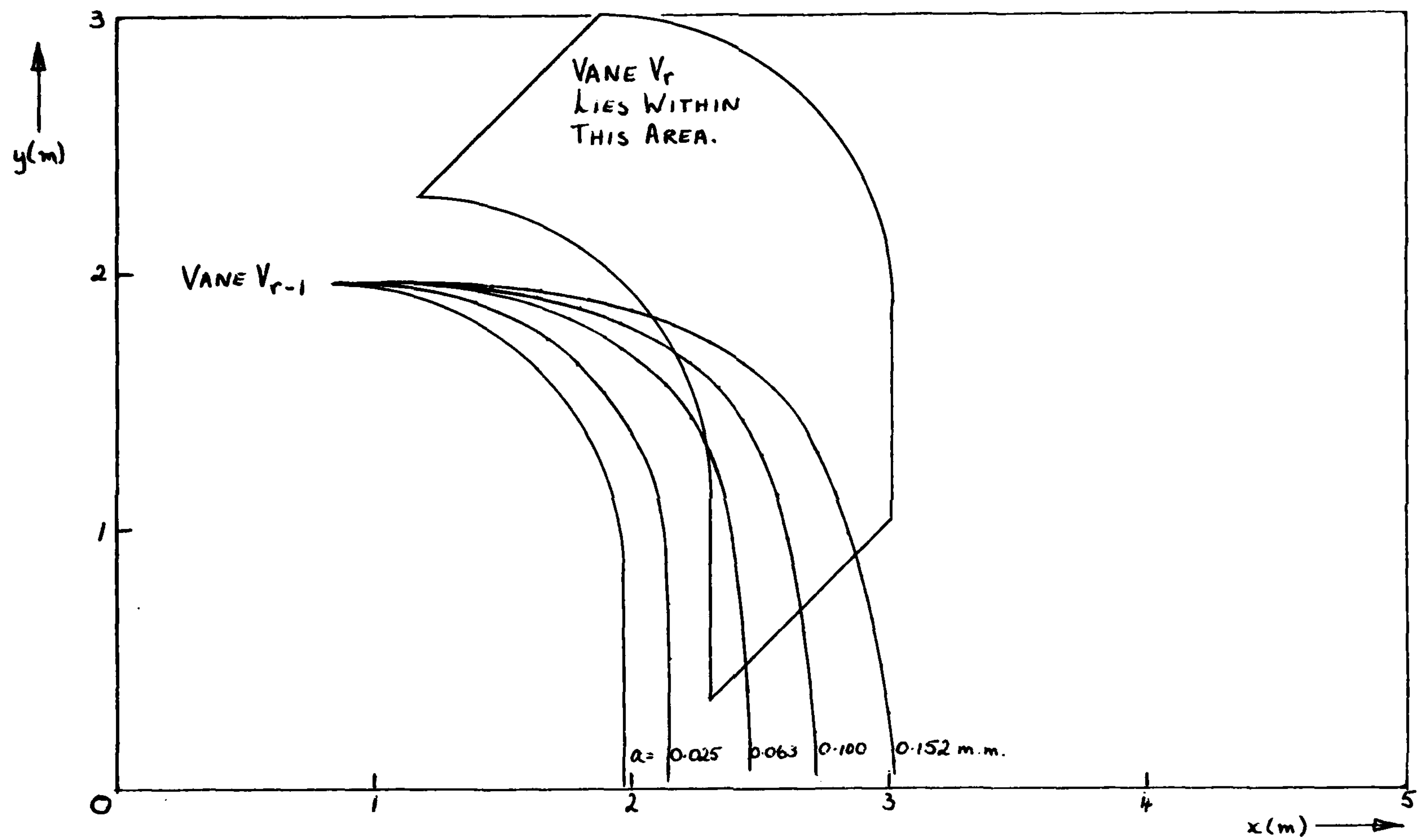
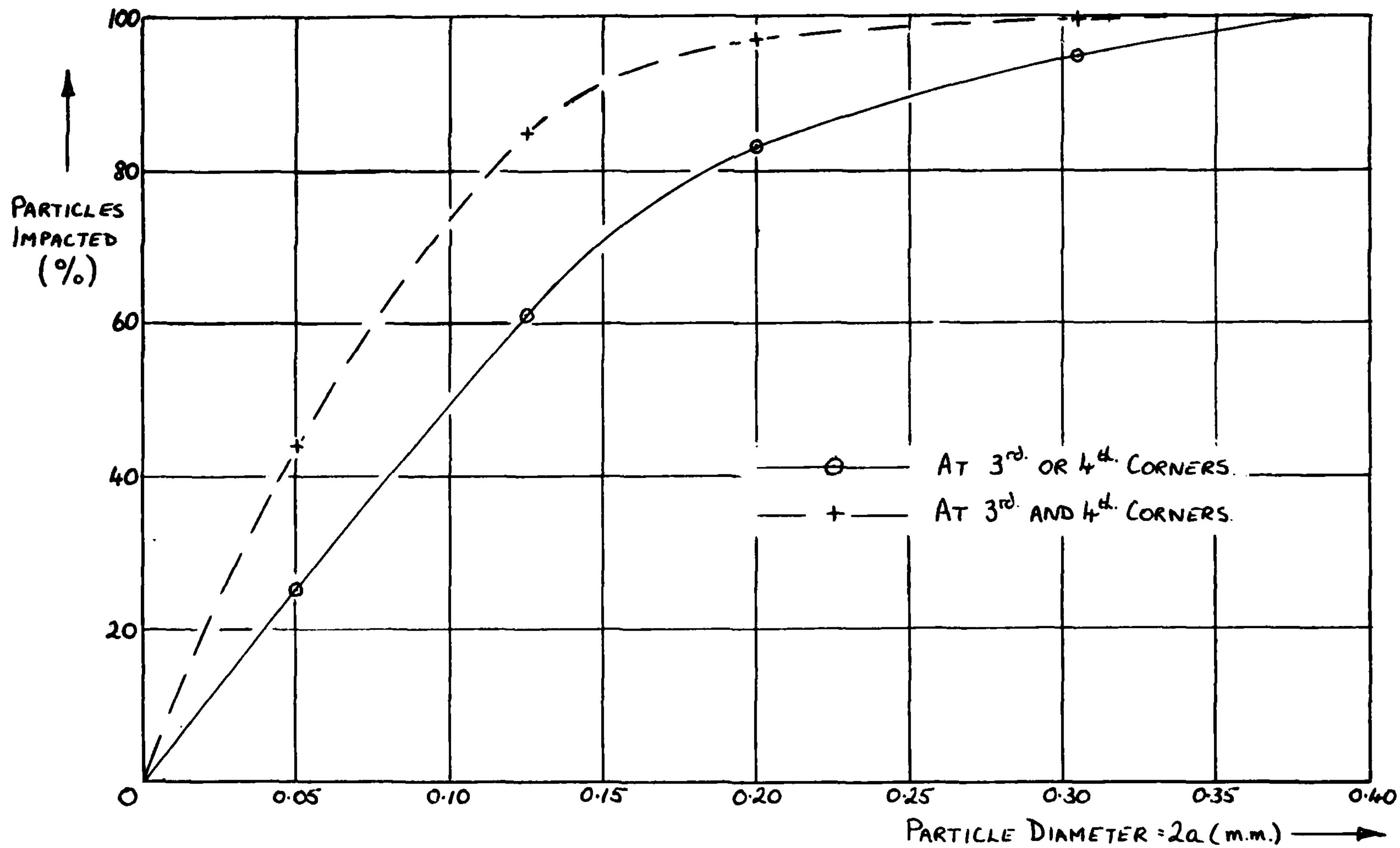


Fig 10 Trajectories of particles with density $\rho_p = 2.6$ Mg m^{-3}, $U_\infty = 21$ m s^{-1}, $\rho_A = 3.675$ kg m^{-3}


100
80
60
40
20
0
PARTICLES IMPACTED (%)
0·05
0·10
0·15
0·20
0·25
0·30
0·35
0·40
PARTICLE DIAMETER = 2a (m.m.)
AT 3rd. OR 4th. CORNERS.
AT 3rd. AND 4th. CORNERS.

REPORT DOCUMENTATION PAGE

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17. Abstract Because of the size and complexity of the 5 metre wind tunnel, its use raises problems of erosion of wind-tunnel models which have not been encountered with other low-speed facilities. Two methods for removal of small particles have been investigated. They are (i) the use of fine mesh fabric screens as filters and (ii) by aerodynamic separation at the corners of the tunnel circuit. (The latter investigation involves the computation of the trajectories of particles in a turning flow.)

The results show that particles smaller than 0.3 mm cannot be filtered out within the practicable pressure drop limitations of the tunnel circuit. However, small particles have a sufficiently high probability of striking the concave surfaces of the corner vanes that if grease or some other retentive material were applied the particles could be quickly removed from the circuit. This latter method is being kept in reserve for the 5 metre tunnel, since physical means such as sweeping and vacuum cleaning have so far seemed to give adequate results. After lengthy shutdowns for maintenance of the 8ft × 8ft tunnel at RAE Bedford, the lower parts of the corner vanes of that tunnel are coated with a suitable grease to remove small airborne particles.

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