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Investigations into Cyclone Dust Collectors

By Professor A. J. ter Linden*

The paper describes experimental investigations made in the mechanical engineering laboratory at Delft, in the field of cyclone separators. These investigations aimed first at determining the most efficient shape of a cyclone, by measuring the effect of a variation of each of its principal dimensions on the efficiency; as a result, a very efficient cyclone shape was developed.

The influence of the position of a cyclone on the efficiency was examined, and a new type of cyclone with curved axis, horizontal gas exhaust, and vertical downward dust outlet was constructed.

The flow of gas and dust inside a cyclone was examined. The static pressure and the three components of the gas velocity at different points in a cyclone were measured with a globe-Pitot tube.

In a cyclone exhausting to atmosphere, a core of low pressure extends over the entire height of the cyclone. Inside this core the flow is very turbulent and unsteady, so that the gas velocities cannot be measured exactly; outside, the pressure is high throughout the remainder of the cyclone.

With the exception of the turbulent area in the centre, the total velocity of the gas deviates only slightly from the tangential component V_t , which increases as the distance from the centre of the cyclone diminishes. The vertical component V_h is directed downwards along the cyclone walls and carries the dust particles to the bunker, and the radial velocity V_r is directed towards the centre in the greater part of the cyclone; but in the very turbulent centre, V_r is directed outwards and V_h upwards.

From these measurements a simple cyclone theory was developed, enabling the approximate calculation of the size of the largest dust particles that may escape a cyclone.

The effect of a variation in the quantity of gas on the efficiency was determined; this effect was small for a well-constructed cyclone.

Efficiencies are given for different sizes of similar shaped cyclones and for various sizes of dust particles. These data enable the selection of a cyclone collector suitable for a particular kind of dust, and the choice of cyclone dimensions for a given efficiency.

A method of measuring the dust content of a gas-flow, by means of a small cyclone, is described.

INTRODUCTION

Before, during, and after the 1939-45 war various experimental investigations were made, in the laboratory of the Technical High School at Delft, in the field of cyclone dust collectors. These investigations aimed at the attainment of a better understanding of the flow of gas in a cyclone, the determination of the most efficient shape of a cyclone, and the determination of the kind of dust for which a cyclone collector might be recommended; only the most important results of these investigations will be briefly described.

Notation. The following symbols are used:—

a_r	Radial acceleration of particle.
d	Diameter of gas exhaust.
g	Acceleration due to gravity.
h	Height of cylindrical part of cyclone.
p_s	Static pressure.
p_t	Total pressure.
r	Radius of a point P .
$r_e = d/2$	Radius at which particle is in equilibrium.
r_0	Radius at which V_t reaches a maximum.
r_p	Radius of point at which V_t is estimated.
s_1	Density of dust particles.
s_2	Density of gas.
A	Width of gas inlet.
B	Height of gas inlet.
D	Diameter of cyclone.

H	Height of cyclone.
Q	Quantity of gas passed through cyclone.
S	Length of exhaust pipe inside cyclone.
V_s	Rate of settling of particle.
V_h	Vertical component of gas velocity.
V_p	Separating capacity of cyclone.
V_r	Radial component of gas velocity.
V_t	Tangential component of gas velocity.
V_{te}	Tangential velocity at the circumference of the cyclone.
β	Inlet angle of gases.
δ	Diameter of dust particle.
η	Efficiency of dust separation of cyclone.
μ	Viscosity of gas.
Δp	Pressure drop of cyclone.

The efficiency for a certain kind of dust (pulverized coal) was checked first under identical conditions. These tests showed that any attempt to increase the efficiency by means of blades, spiral ducts, or any appliance for the purpose of directing the rotating gases, was useless, as it only resulted in the checking of the free rotation of the gases in the body of the cyclone. This rotation, which causes the separation of the dust, is continued in the dust bunker and in the exhaust pipes for the purified gases; but even in these, situated outside the cyclone body, the checking of the rotating gases has an unfavourable influence on the efficiency.

Thus, for instance, a cyclone with a large dust bunker will have a higher efficiency than one whose dust outlet is closed by means of a revolving disk or valve. Similarly, the placing of blades in the gas exhaust pipe in order to decrease the pressure loss in the cyclone, influences the efficiency unfavourably.

It is desirable, therefore, to provide the cyclone with a dust bunker and an exhaust pipe in which the gases can continue their rotation.

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DETERMINATION OF MOST FAVOURABLE SHAPE OF A CYCLONE

As shown in Fig. 9, the shape of a cyclone is determined by the following principal dimensions:—

- (1) Inlet angle of gases, β .
- (2) Diameter of cyclone, D .
- (3) Gas exhaust diameter, d .
- (4) Length of exhaust pipe inside cyclone, S .
- (5) Height of cyclone, H .
- (6) Height of cylindrical part of cyclone, h .
- (7) Width of gas inlet, A .
- (8) Height of gas inlet, B .

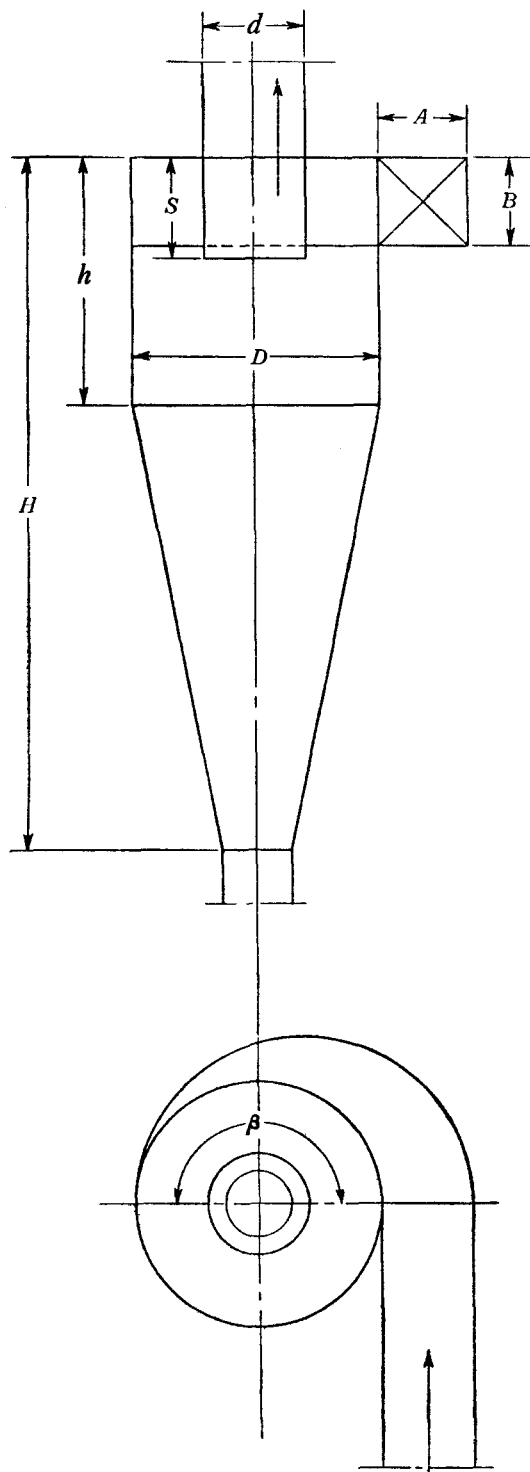


Fig. 9. Principal Dimensions of a Cyclone

In order to investigate the effect of a change in each of these dimensions on the efficiency of the cyclone, the efficiency of a number of cyclone models was measured, each of the above-mentioned dimensions being altered in turn.

From these measurements it appeared that a gradual entry of the gases to be purified into the cylindrical part of the cyclone was essential to obtain a reasonable efficiency. The best figures were obtained with an inlet angle $\beta = 180$ deg. (Fig. 9); further increase of this inlet angle does not raise the efficiency, and makes the construction unnecessarily expensive.

The influence of the dimension S of the gas exhaust pipe on the efficiency is shown in Fig. 10. The efficiency decreases quickly when the value of S becomes too low, the maximum efficiency being reached at $S \approx d$, or $S \approx B$ when $B > d$. The

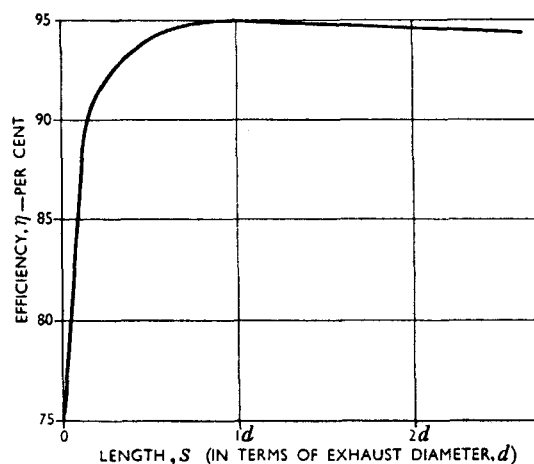


Fig. 10. Influence of Length of Exhaust Pipe inside Cyclone on Efficiency

Cyclone dimensions: $D = 2.25d$, $H = 6d$, and $\beta = 180$ deg.

values obtained from these first two tests, $\beta = 180$ deg. and $S = d$, were maintained throughout the remaining experiments.

Fig. 11 shows the influence of height H of the cyclone on the efficiency. Increase of H improves the efficiency, but raises the initial cost of the cyclone and the space required. The results

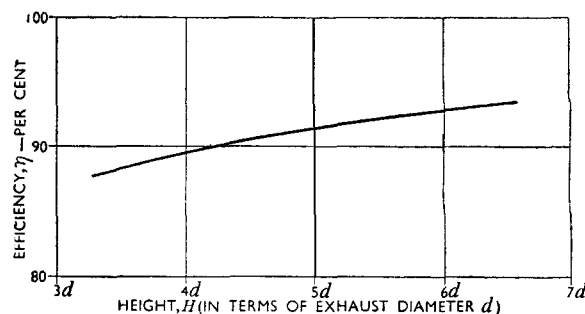


Fig. 11. Influence of Height H on Efficiency

Cyclone dimensions: $D = 2.25d$, $S = d$, and $\beta = 180$ deg.

deduced correspond with the American patent of R. L. Bobbit, in which a height of $H > 3D$ is recommended.

Enlarging the cyclone diameter D also increases the efficiency (Fig. 12), but again at the expense of initial cost and space required. The pressure loss in the cyclone also increases with the enlarging of D .

In order to construct a practical cyclone with a given value of the exhaust diameter d , it is necessary to restrict dimensions D and H to, for instance, $D = 2.5d$ and $H = 6d-7d$.

The dimensions A and B of the inlet duct influence the efficiency to some extent. In general, a broad and not excessively high duct ($A > B$) will increase the efficiency; a practical shape is $A = B$ (i.e. a square inlet). In order to decrease loss of pressure in the cyclone it is desirable to make the cross-sectional

area of the inlet duct ($A \times B$) not much smaller than that of the exhaust.

As a result of these investigations, in the course of which important research work was done by P. J. K. Missel, the cyclone shown in Fig. 9 was constructed. In use with many industrial plants built since 1935, and in the course of many comparative experiments with other existing cyclones, this type has always given favourable results.

The influence of gravity on the dust separation in a cyclone is slight, so that efficiency is almost independent of the position of the cyclone. Experiments have shown that separation remains

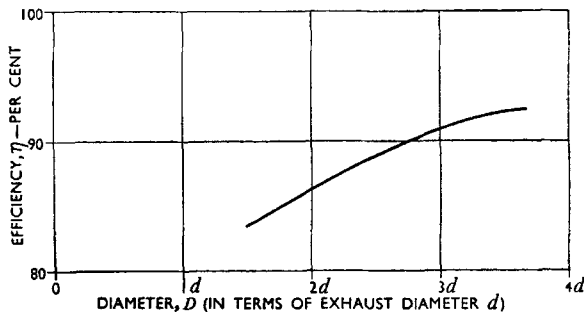


Fig. 12. Influence of Diameter D on Efficiency

Cyclone dimensions: $H = 6d$, $S = d$, and $\beta = 180$ deg.

satisfactory not only in a horizontal position but also even with the cyclone upside-down, with, consequently, the exhaust gases directed vertically downward and the dust carried off upwards from the cyclone.

A good cyclone, therefore, separates the dust satisfactorily in any position. Difficulties may arise, however, with coarse particles of dust, which keep rotating in the conical part of the cyclone and cannot reach the dust outlet. This difficulty may, of course, arise with a cyclone in the normal vertical position, but to a lesser extent.

In order to ensure the maximum removal of dust with the cylindrical part of the cyclone in a horizontal, or nearly horizontal

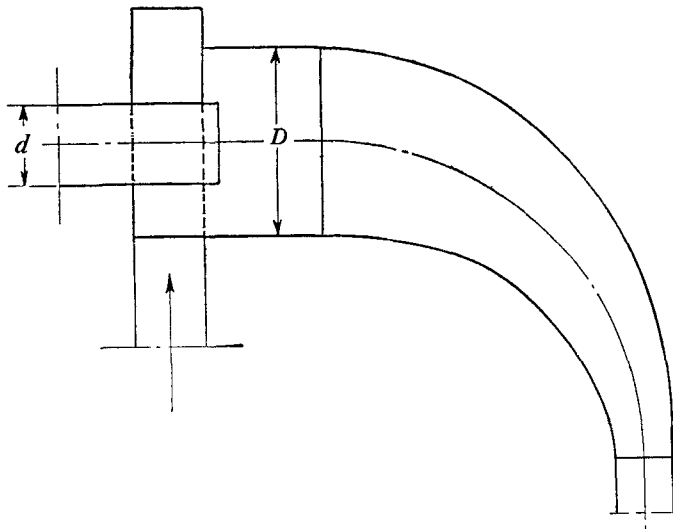


Fig. 13. Horizontal Cyclone with a Curved Axis

position, the dust outlet must pass vertically downwards, and this is only possible with a cyclone having a curved axis (Fig. 13).

Experiments have shown that the efficiency of the curved cyclone is not inferior to that of the straight cyclone; official comparative tests carried out by the German Patent Office in 1939 even showed a slight increase in efficiency with a curved cyclone. In many cases it may be preferable in view of the available space to install a curved cyclone, an additional advantage being that curves in the gas ducts can thus be avoided.

Fig. 14 shows a curved cyclone installed in a workshop of the Netherlands Railways. The cyclone constructions shown in Figs. 9 and 13 have been patented in Great Britain and various other countries.

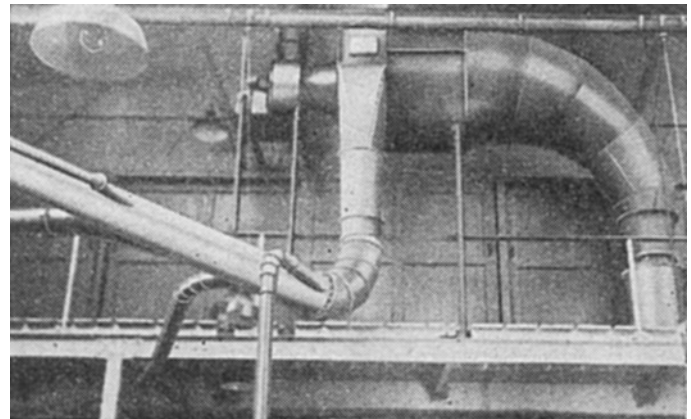


Fig. 14. Curved Cyclone

GAS FLOW IN A CYCLONE

In order to understand fully the functioning of a cyclone, it is necessary to know the course of the gases within it. The gas flow is three-dimensional, so that at any point within a cyclone the velocity can be resolved into three components V_t , V_r , and V_h , these being tangential, radial, and vertical respectively (Fig. 15).

In the laboratory at Delft the gas flow in a cyclone has been measured by H. Mulder, using the globe-Pitot meter of Dr. van der Hegge Zijnen*. With this instrument it is possible to measure the velocity and its direction without noticeably disturbing the flow of the gas.

The results of these measurements are given in Figs. 15, 16, and 17. Fig. 16 indicates the variation of the static pressure p_s and the total pressure p_t at different points in a cyclone. In this case the static pressure at the inlet was 90 mm. (3.54 inches) water gauge, and the gases could escape freely to atmosphere. The cyclone had an airtight bunker, in which a vacuum of 30 mm. (1.18 inches) water gauge was measured.

It appears that, with the exception of a core of low pressure in the centre of the cyclone, the pressure is high throughout the entire cyclone. The core of low pressure extends the full height of the cyclone and may be considered approximately cylindrical, with a diameter of about $0.4d$ (d = diameter of gas exhaust). This low pressure area is continued into the dust bunker, in which it causes a vacuum. If the bunker is not closed hermetically air from the outside will be drawn into it, causing an upward gas current in the dust outlet of the cyclone, which will carry the separated dust with it and thus lower the efficiency. The same defect will occur if the cyclone is constructed without a bunker and is fitted with valves that are not quite airtight.

Figs. 15 and 17 show the variations in the three components V_t , V_r , and V_h of the gas velocity inside the cyclone. With the exception of the highly turbulent area in the centre, the tangential component V_t predominates, so that the total velocity of the gas deviates only slightly from V_t . From the circumference to the centre V_t increases, and attains its maximum at a radius $r_0 \approx 0.65r_e$ (where $r_e = 0.5d$), after which it quickly decreases.

In the cylindrical part of the cyclone the fluctuations of V_t from the circumference to r_0 , can be represented approximately by the formula

$$V_t = \frac{V_{te}}{r_p^{0.52}} \left(\frac{D}{2} \right)^{0.52}$$

where V_{te} is the tangential velocity at the circumference, and r_p the radius of the point at which the gas velocity V_t is estimated. V_{te} does not deviate much from the velocity of the gas in the inlet duct.

* VAN DER HEGGE ZIJNEN, B. G. 1929 Proc. Roy. Academy Amsterdam, vol. 32, No. 5.

In the conical part of the cyclone, V_t increases considerably as the cone becomes narrower, and at the same distance from the axis V_t is considerably greater in the conical part than in the cylindrical part.

The variation of V_t in the cylindrical part corresponds, at least up to radius r_0 , with the values given by Shepherd and Lapple*.

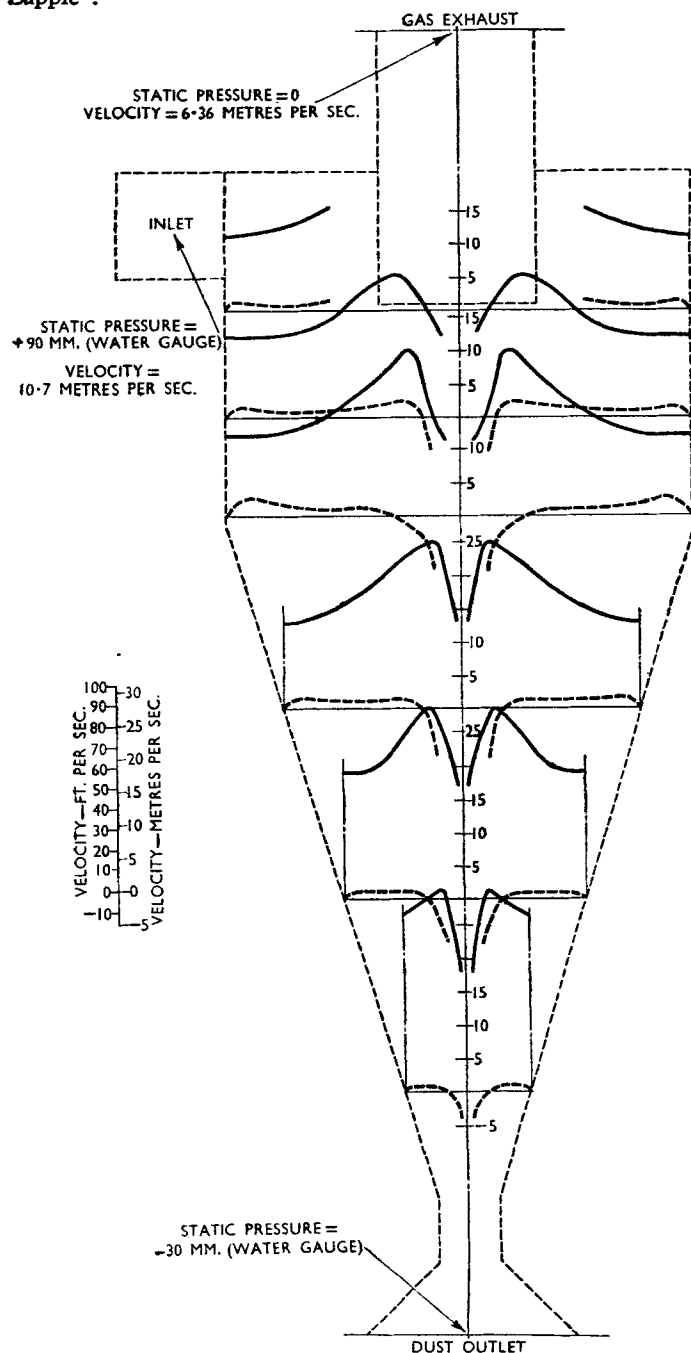


Fig. 15. Variation of Tangential Velocity V_t and Radial Velocity V_r at Different Points in a Cyclone

———— Tangential velocity.

----- Radial velocity.

In the turbulent and disturbed centre of the cyclone, where measurements are difficult to take and consequently are less accurate, the total velocity deviates considerably from the tangential; both radial and vertical velocity components are of importance here. As shown in Fig. 17, the vertical component V_h

* SHEPHERD, C. B., and LAPPLE, C. E. 1939 *Industrial and Engineering Chemistry*, vol. 31, p. 972, "Flow Pattern and Pressure Drop in Cyclone Dust Collectors".

is directed downward along the outer walls of the cyclone, whereas in the remaining part an upward velocity can be observed. The downward flow of gas along the walls ensures the carrying-off to the dust outlet and bunker of the particles that have been flung out to the circumference. Gravity plays a subordinate part in this, as indicated by the satisfactory efficiency of the inverted cyclone.

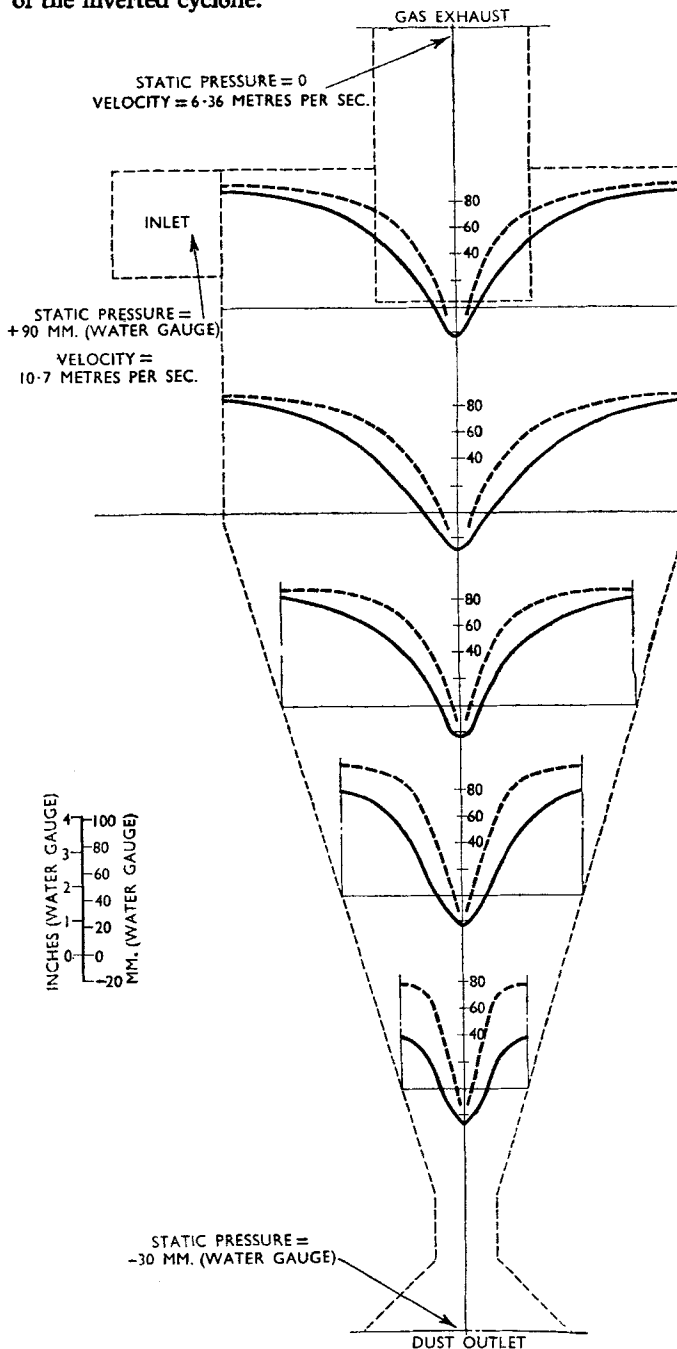


Fig. 16. Total and Static Pressures at Different Points in a Cyclone

———— Static pressure.

----- Total pressure.

The radial velocity V_r is, as might be expected, directed towards the centre throughout the greater part of the cyclone, and shows a tendency to carry the particles to the centre against the action of centrifugal force. In the centre, the radial velocity seems to be directed outwards.

From the variation in velocity indicated in Figs. 15 and 17, it follows that the area in the centre of the cyclone is unfavourable to the separation of particles. A particle in this area will probably

be carried along by the vertical gas currents to the gas exhaust and will consequently not be caught. To attain a high degree of efficiency, the aim should be to keep the particles outside the centre of the cyclone as much as possible, and further, to try to make the tangential velocity V_t , which assists the separation, as great as possible in proportion to the radial and vertical components V_r and V_h , which try to carry the particles in the direction of the exhaust.

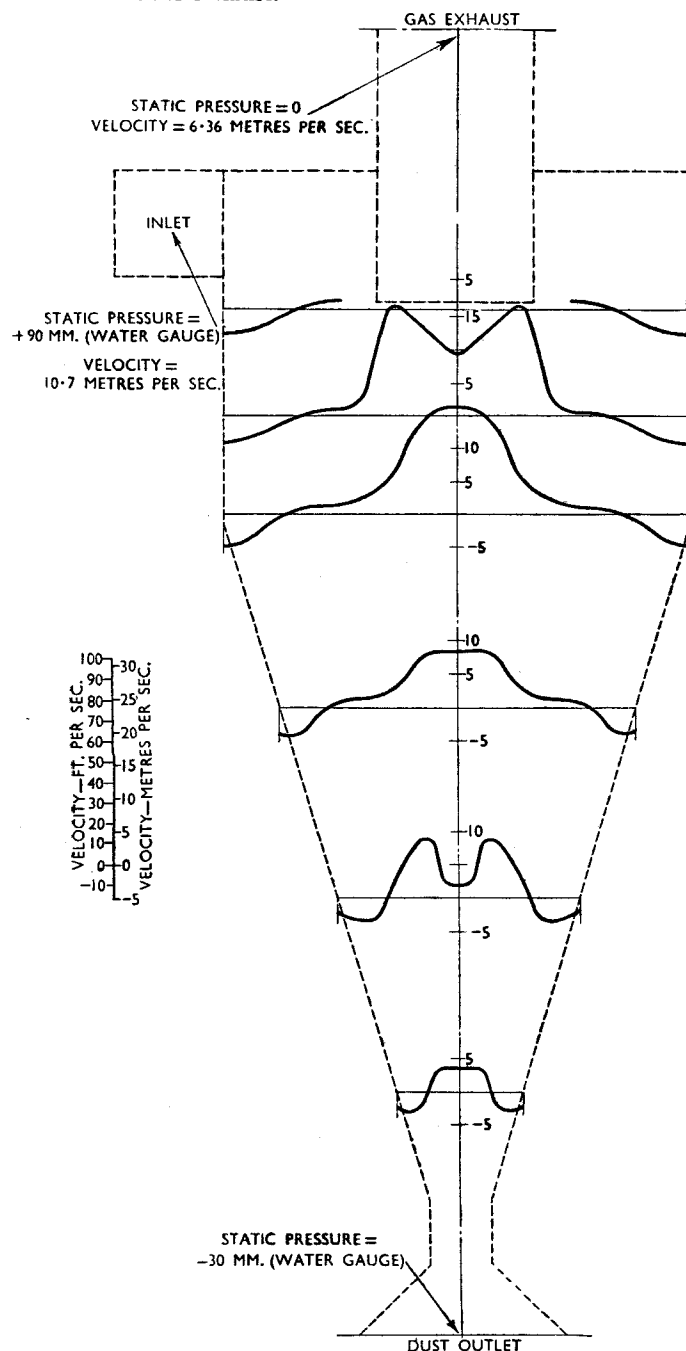


Fig. 17. Variation of Vertical Velocity V_h at Different Points in a Cyclone
 — Vertical velocity.

The variation in the pressures and velocities in Figs. 15, 16, and 17, is but to a slight degree dependent on the absolute velocities in the cyclone. It therefore follows that a more general value may be attached to the curves in these figures.

At an arbitrary point P within the cyclone, a particle with a certain rate of settling V_g may be separated, while dust particles with a lower rate of settling will escape with the

gases. Thus the rate of settling V_g controls the value of the flow at P with regard to the separation of the dust particles. This "separating capacity" will be great at the circumference of the cyclone, but slight in the centre. The rate of settling of the particle which can be just caught, may serve as a measure of the separating capacity at a point P in the field of velocity; a low value of V_g points to a greater separating capacity.

A comparison of the separating capacity at various points in the cyclone can be made by injecting known quantities of dust

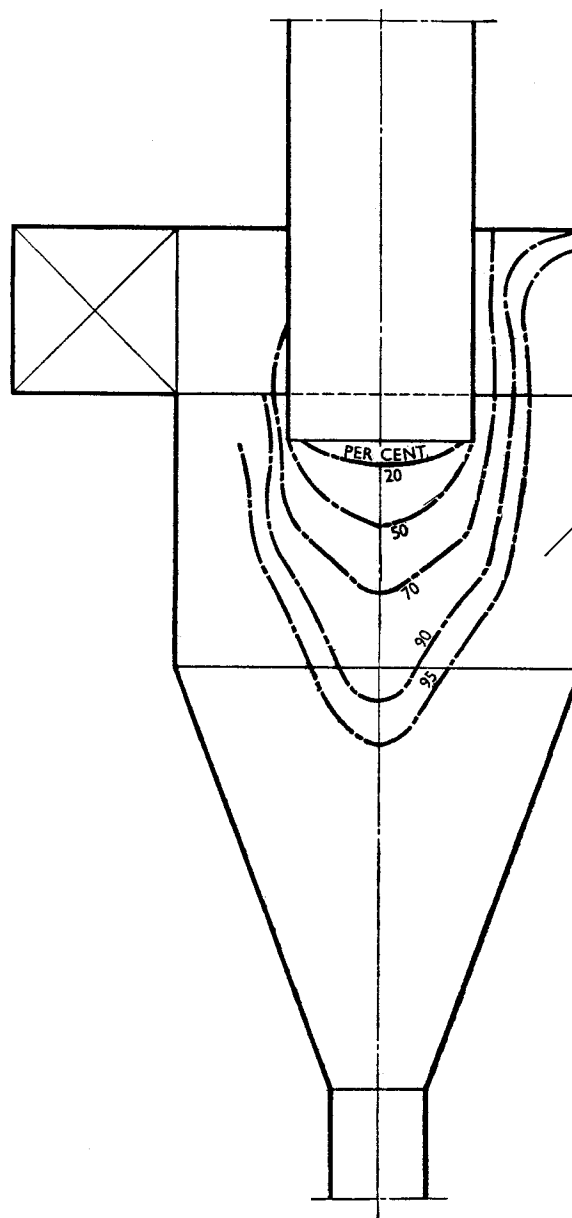


Fig. 18. Efficiency at Various Points of a Cyclone
 Overall efficiency: 95 per cent.

at these points and determining the efficiency. Care should be taken that while injecting the dust the flow should be disturbed as little as possible; this can be achieved by leading in the dust via a small tube to the point required.

Fig. 18 shows the efficiencies obtained during such a test. Powdered coal was used, the normal efficiency for the cyclone in question being 95 per cent. The separating capacity proved to be very slight, especially in the turbulent zone under the gas exhaust, which is to be expected from the results of the measurements of the velocity (Figs. 15 and 17).

The flow of dust through a cyclone may be observed by the use of a cyclone in which the cylindrical part is constructed of glass. Fig. 19 shows an apparatus of this type, and the flow of dust moving downwards in a spiral can be seen clearly. It is noteworthy that the dust drawn in by the cyclone, even though it is spread evenly over the inlet area, immediately forms comparatively narrow bands.

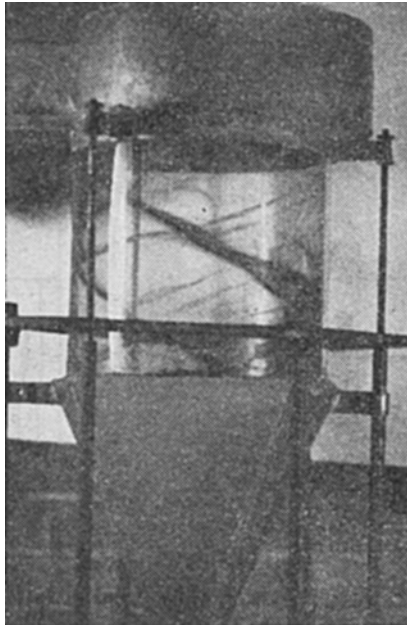


Fig. 19. Flow of Dust through a Cyclone

THEORY OF THE CYCLONE

The flow of gases and dust particles inside a cyclone is too complicated for exact calculation of the efficiency and pressure loss under given conditions. It is possible, however, by the use of simple calculations based on experimental tests, to explain the properties of a cyclone and to estimate the efficiency and pressure loss with an accuracy sufficient for many practical cases.

It is clear that a particle of dust with a rate of settling V_g , may be caught if, on its way through the cyclone, it never reaches a point where the separating capacity V_p is insufficient. It is therefore necessary for the separation of this particle that V_g is larger than V_p . As the paths of the various particles are not the same, it may happen that one with a low rate of settling is separated, owing to the fact that it does not pass regions of low separating capacity; whereas a larger particle with a greater rate of settling may escape, because it was unable to avoid these regions on its way through the cyclone.

Attempts to use a cyclone as a sieve for the separation of coarse and fine dust, are bound to fail, as many fine particles also will be separated with the coarse dust.

To ensure that a minimum number of dust particles reach the regions of low separating capacity, it is necessary to lead them in as near as possible to the circumference of the cylindrical part of the cyclone. A semi-circular inlet duct will serve this purpose; it also follows that a wide and low inlet ($A > B$) is more effective than a high and narrow one.

To calculate the separating capacity at a point P at radius r , with velocity components V_t , V_r , and V_h , the particles are assumed to be spherical and of diameter δ . If they also are assumed to comply with Stokes' law (which is suitable for particles with $V_g < 50$ and > 0.1 cm. per sec. (19.68 and 0.039 in. per sec.)) their rate of settling will be

$$V_g = \frac{\delta^2 g (s_1 - s_2)}{18 \mu} \approx \frac{\delta^2 g s_1}{18 \mu}$$

since $s_1 \gg s_2$, where s_1 = density of particles, s_2 = density of gas (very small in comparison to s_1), g = acceleration due to gravity, and μ = viscosity of gas.

If a particle rotates with the gases, in which case it has a tangential velocity V_t , it must have a radial acceleration $a_r = V_t^2/r$ (see Fig. 20).

If the particle keeps rotating on radius r , this acceleration must be caused by the radial force exerted on the particle by the radial velocity of the gas V_r , and, if Stokes' law is assumed to hold, this acceleration will be gV_r/V_g ; so that the following formula holds good for a particle rotating on radius r :-

$$a_r = \frac{V_t^2}{r} = \frac{gV_r}{V_g} \text{ or } V_g = \frac{grV_r}{V_t^2}$$

Particles with a greater rate of settling can rotate on a larger radius, smaller particles on a smaller radius.

For the points for which $\frac{d(gV_r/V_g)}{dr} > \frac{d(V_t^2/r)}{dr}$, the equilibrium of the rotating particles is stable, and the particles would keep rotating on this radius if they were not carried along by the vertical velocity. With the exception of the centre of the cyclone the equilibrium is stable throughout (Fig. 15).

The formula $V_g = grV_r/V_t^2$ may be considered a mathematical expression for the separating capacity at the point P .

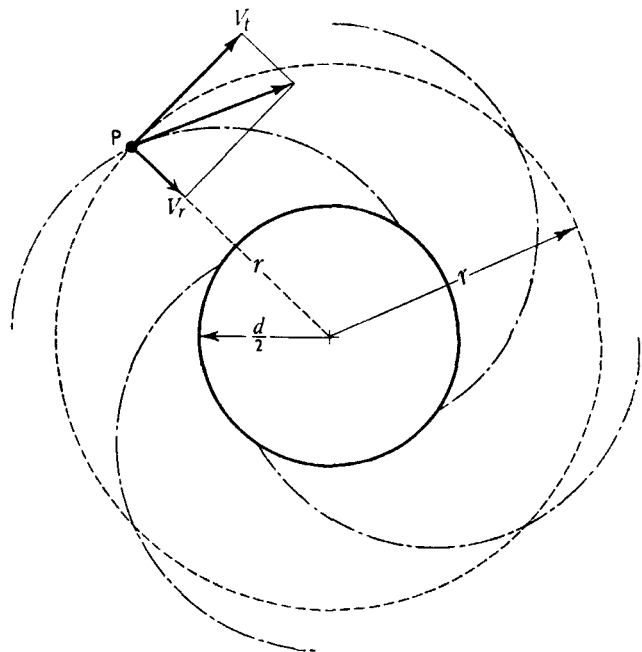


Fig. 20. Flow around the Exhaust of a Cyclone

At the same radius, but at different heights in the cyclone, the value grV_r/V_t^2 is not the same, as is apparent from Fig. 15. This value increases as the distance from the gas exhaust decreases; the separating capacity diminishes, as proved by Fig. 18.

Therefore, the coarsest particles to leave the cyclone will escape from this area beneath the exhaust. To ascertain the rate of settling of these coarser particles, a particle (rate of settling V_g) is taken to be in equilibrium on a radius $r_e = \frac{d}{2}$ in this area (Fig. 20). The following formula then holds good:-

$$V_g = \frac{gr_e V_r}{V_t^2} = \frac{gdV_r}{2V_t^2} \quad \dots \quad (1)$$

Particles with a smaller rate of settling will not attain equilibrium on this radius r_e and will be carried along by the gas to the exhaust. Particles with a greater rate of settling will, on the other hand, rotate on a larger radius and be separated by the cyclone.

Equation (1) represents the maximum value of the rate of settling of the particles that can still escape. From this equation it appears that in otherwise similar conditions (i.e. similar ratio of V_r/V_t^2), the rate of settling of the coarsest particles that can escape is proportional to the diameter of the exhaust d . From

this it follows that the efficiency of a cyclone may be increased by decreasing the diameter of the exhaust.

As, in view of the pressure drop, the velocity of the gas in the exhaust may not be raised too high, it is essential to replace a large cyclone by a number of small ones connected in parallel (multi-cyclone construction).

From measurements taken it appears that the efficiency of a cyclone increases, and the particles that escape become gradually smaller as the diameter of the exhaust becomes smaller. Equation (1) represents this general aspect tolerably well.

Equation (1), however, does not give any indication of the efficiency for particles with a lower rate of settling $V_{g'} < V_g$. Should these particles get into the dangerous zone beneath the exhaust, they will be carried along by the escaping gases. The efficiency will therefore be determined entirely by the number of particles with rate of settling $V_{g'}$, which get into the dangerous zone on their way through the cyclone.

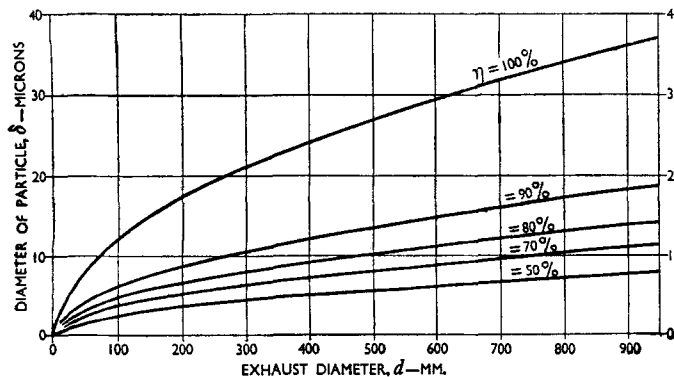


Fig. 21. Influence of Exhaust Diameter and Diameter of Particle on Efficiency

Specific gravity: 1.0; velocity at exhaust: from 5 to 12 metres per sec. (16.40 to 39.37 ft. per sec.).

The variation of efficiency for the finer particles can be determined only by experiment. Fig. 21 shows the results of experiments on the effect of variation of the exhaust diameter and the diameter of the particle.

If, in a cyclone with a different quantity of gas Q , the ratio V_t/V_r should remain unaltered, the efficiency, according to equation (1), would have to become greater with an increase of quantity Q . From Fig. 22, however, which gives the relationship

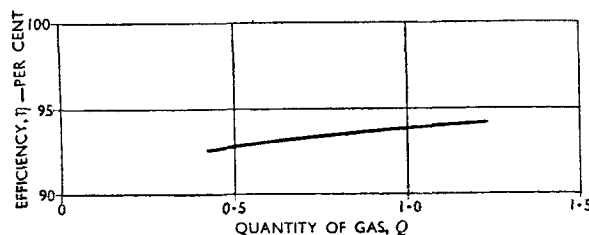


Fig. 22. Effect of Quantity of Gas on Efficiency

between the efficiency η and quantity Q for a given cyclone and a particular kind of dust, it appears that the efficiency will only be influenced to a slight degree by the quantity of gas.

From this it may be deduced that V_r increases more quickly than V_t , so that the proportion V_t^2/V_r does not change considerably with a variation in quantity of gas. As the efficiency does not decrease appreciably for smaller quantities, and even increases for some kinds of dust (with a low specific weight), it is unnecessary to cut out units in a multi-cyclone when the load decreases.

The dust concentration likewise has little influence on the efficiency. With an increasing dust concentration the efficiency will also increase slightly, provided no obstructions occur in the dust outlet. This phenomenon can be explained by assuming that the coarser particles carry the finer ones to the circumference of the cyclone.

APPLICATION OF CYCLONE DUST COLLECTORS

From Fig. 21 it is possible to deduce what efficiency may be expected of a cyclone with a given exhaust diameter for a particular kind of dust.

If a high efficiency for a fine dust is required, it will be necessary to use very small cyclones. This will lead to the application of multi-cyclones, with a great number of units connected in parallel. By employing this construction it is often possible to replace cloth and electro-filters and wet dust collectors; but it is advisable to proceed cautiously, as in many cases the efficiency of the multi-cyclone is considerably lower than that of the small cyclones of which it is composed.

This is more especially to be found with the usual construction in which the cyclones are connected to a common dust bunker. Owing to slight irregularities in the spreading of the gases in the cyclones, there may be differences of pressure in the dust outlets of cyclones connected in parallel (Fig. 15). Thus, vertical gas currents, which will influence the rate of efficiency unfavourably, may arise in the dust outlets of some of these cyclones.

Another drawback, inherent in the application of very small units for high dust concentrations, is the possibility of blocking up the dust outlet, which will allow all the dust supplied to the cyclone to pass out through the gas exhaust. In constructing multi-cyclones it is advisable to take these disadvantages into account.

GUARANTEE OF EFFICIENCY OF CYCLONE DUST COLLECTORS

As the efficiency of a cyclone is to a high degree dependent on the size of grain, a guaranteed efficiency can only be given if the rate of settlement of the particles is fixed. It is correct, therefore, to guarantee the efficiency for a dust with a known rate of settling, or (simpler in practice) to guarantee a complete separation of all dust particles of which the rate of settling (or size of grain) exceeds a certain value.

In view of the nuisance caused in the vicinity of boiler houses, it is desirable, for instance, to demand that the dust separators fitted to grate-fired boilers shall separate all dust with a rate of settling of 0.05 metres per sec. (0.164 ft. per sec.) or more (size of grain $\delta \approx 35$ microns)*. For powdered-coal boilers, where the dust concentration in the smoke gases is considerably greater than for grate-fired boilers, heavier demands must be made, and a 100 per cent efficiency for dust with a rate of settling equal to, or greater than, 0.025 metres per sec. (0.082 ft. per sec.) may, for instance, be demanded. In both cases the height of the stack should affect the demands.

It is unwise to guarantee the total efficiency unless the dust in question has either a constant composition or contains only few very fine grains with $\delta < 10$ microns. If the latter should not be the case, and if the dust contains a considerable percentage of very fine particles, a guaranteed total efficiency is more or less a gamble, as each change in the composition of these very fine particles can greatly influence the efficiency.

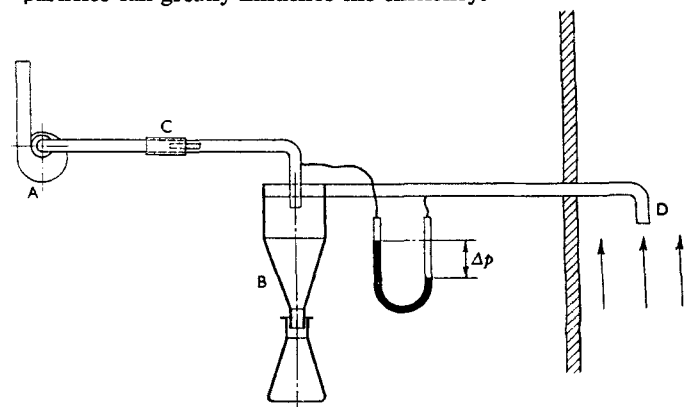


Fig. 23. Cyclone for Measuring Dust Content of a Flow of Gas

A Fan. C Sliding lid.
B Small cyclone. D Open end of suction tube.

* 1 Micron = 1×10^{-4} millimetre = 3.937×10^{-5} inches.

CYCLONE FOR MEASURING THE DUST CONTENT OF A FLOW OF GAS

As follows from Fig. 21, the efficiency of a very small cyclone ($d = 20\text{--}25$ mm. (0.787–0.984 inch)) will be high, and will exceed 99 per cent for nearly all kinds of industrial dust. Dust particles with a diameter of between 3 and 5 microns or more will be separated entirely.

This property of a small cyclone may be used to measure

simply and accurately the dust content of a flow of gas. As shown in Fig. 23, a fan sucks the gases containing dust through a small cyclone, where over 99 per cent of the dust will be separated. The quantity of gas can be deduced from the pressure loss Δp of the cyclone; this quantity can be regulated by a sliding lid, so that the velocity of the gas in the opening of the suction tube will be approximately equal to that in the surrounding flow of gas.

Discussion

Professor C. M. WHITE (London) said that he had been struck by the contrast between the two problems presented in the two papers. In the one case, Professor ter Linden was separating particles, the density of which was as much as 2,000 times as great as that of the fluid carrying them, and yet he encountered the difficulty, seen in Fig. 10, that just a small lip extension for the gas outlet from the cyclone, half a diameter in length, would make all the difference between success and failure, and that was with particles 2,000 times as heavy as the fluid carrying them. The other paper was concerned with fluids, whose difference in density was at the most about 5 per cent. One would expect that in those circumstances there would be no difficulty at all, not in separating them, but in getting them to mix, yet, despite the closeness in density of the two fluids, those fluids refused to mix and were liable to stratify.

Twenty years ago in Germany, Tollmein* gave the first solution for the behaviour of diffusing jets. One of the problems

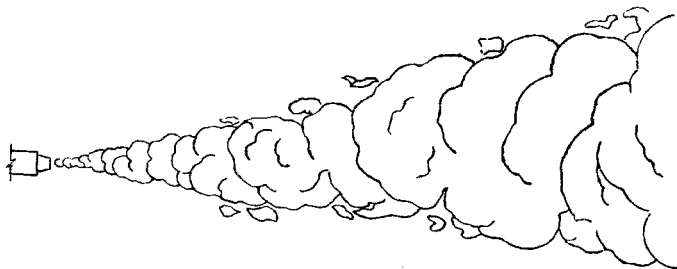


Fig. 24. Dispersing Jet as Observed

he dealt with was a simple jet coming out of a nozzle and diffusing in the way shown in Fig. 24. The general shape of the cloud of the jet was a cone, diverging with an angle of perhaps 28 deg., though the outer boundary of the mixing cone, in the region where the jet was entraining the surrounding fluid, was extremely ragged.

With such an irregular boundary it might seem impossible to get exact numerical results, but if average conditions, rather than the extreme angle of boundaries, were considered precise data could be obtained. For example, the velocity distribution given by Tollmein still held today, and his table showing how the velocity diminished from its maximum at the centre to zero at the sides, held for all fluids and for a wide range of Reynolds numbers; that was plotted in Fig. 25 together with some of the streamlines.

On the centre line the speed fell off in inverse proportion to the distance from the nozzle, and the quantity entrained, which was the important factor in mixing problems, or the total quantity contained by the jet, increased as the speed fell off, because the total momentum remained constant. Thus the relation obtained was of the form

$$Q_{\text{entrained}} = \left(\frac{x}{3d} - 1\right) Q_{\text{nozzle}}$$

If the jet went a distance of about 300 diameters a dilution of 99 per cent could be obtained, which was a very complete

* TOLLMEIN, W. 1926 *Zeitschrift für Angewandte Mathematik und Mechanik*, vol. 6, p. 468.

dispersion, and was probably as good a mixing as could be obtained by any method; but that needed, with a diameter of 1.2 inches, a distance of 30 feet.

A second problem arose in connexion with the process. Unless the mixture could be removed, there might be such a bulk of mixture arriving at the far end of the jet that a cloud of mix would accumulate, and would gradually form a blanket to the jet; that cloud would be re-entrained and would prevent further entrainment of fresh fluid and so set a limit to the dilution obtainable. By providing circulating currents, as the authors of the first paper had done, it was possible to remove the accumulated mix. He thought there were two lines of approach to the problem: either a weak circulating current, just sufficient to remove the mix and allow the mixing to go on wholly by the jet, or, as the authors had done, a very strong circulating current which would itself be sufficient to complete the mixing could be provided, though in that case the power consumed was greater.

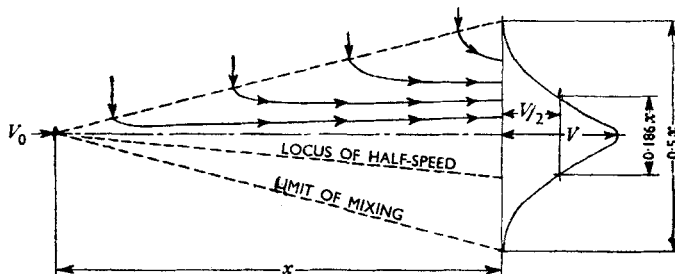


Fig. 25. Mean Streamlines According to Tollmein's Tabulated Values

$$V = V_0 \frac{6.3d}{x}; Q = Q_0 \frac{xd}{2.95}$$

45 per cent of the total flow is within the "half speed" cone.

The problem was more difficult when it came to differences of density. In a jet diffusing from a nozzle of diameter d , there was both the mixing due to the jet which was a function only of x/d , and the distribution of the mix which was chiefly a function of the total volume entering the tank divided by the volume of the tank. There were therefore two possible parameters. The authors, in Fig. 3, used the second of the two multiplied by the ratio of the diameter of the tank over the diameter of the nozzle, but he thought their method of correlation was incomplete and not applicable to other mixing problems. At Imperial College, experimental data had been obtained which would not be satisfied by that type of correlation. According to Fig. 3, the quantity determining the mixing was $\frac{QT}{D^3} \cdot \frac{D}{d}$, but he thought that could be valid only for the particular tank arrangements used by the authors, and then only when both liquids were equal in density.

So far as could be ascertained by experiment, small differences in density did not directly influence the diffusion process, though they certainly controlled the later part of the trajectory of the jet. For example, a heavy liquid, when jetted into a lighter one, mixed with some of it according to the x/d rule, but the mixture fell to the bottom where it formed a discrete layer with

a remarkably tenacious surface which sometimes resisted further mixing.

How resistant such an interface could be was well illustrated by experiments in which a heavy jet was projected obliquely upwards from the bottom of a tank containing two layers. When the jet was not very strong, the interface merely bulged upwards and became wavy, almost as if it were a very thin sheet of rubber, so none of the upper layer was entrained, and any circulating currents were restricted completely to the lower layer.

A stronger jet would pierce the interface and rise into, and mix with the upper layer, though the stream would subsequently curve downwards and re-enter the lower layer through which it might pass completely, sometimes forming a third, more dense, layer at the bottom. Even though such a jet had entered and mixed with the upper layer, it left no momentum there, and the upper layer again remained stagnant.

He thought such experiments emphasized the inhibitory nature of gravitational stratification, and showed how difficult it was to be sure of uniform products from bulk processes.

Dr. R. BEECHING, C.I.Mech.E., said he was particularly interested in the very thorough survey which Professor ter Linden had made of the pressure gradients and the pressures and the velocities in the cyclone. It seemed to him, from Figs. 15, 16, and 17, that the radial acceleration at the centre was against the pressure gradient. It was difficult to tell, in the case of the vertical component of velocity at the centre, whether the pressure gradient was against it or not, but, judging from the scale on the diagram, which was rather difficult to read with great accuracy, it looked as though the vertical accelerations might in places be against the pressure gradient. Probably the explanation of that apparent contradiction was difficulty in measuring pressures in the centre, where there was a great deal of disturbance.

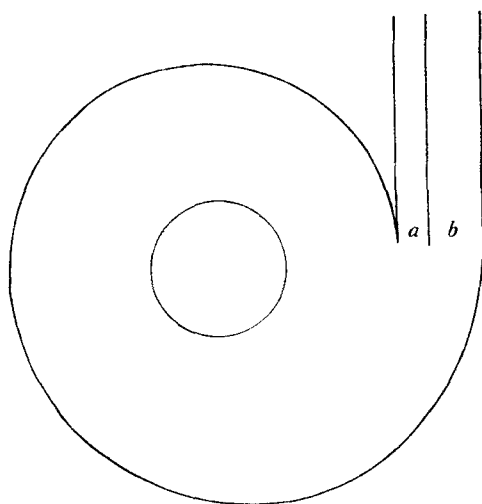


Fig. 26. Transverse Section of Classifying Cyclone showing Arrangement of Gas Inlet

There was one other point in the paper which he thought appeared to be in conflict with generally accepted practice. Usually, he thought, the inlet, which the author marked with the dimensions A and B , A for the horizontal and B for the vertical, was made with B considerably larger than A , and it was generally accepted that it was better that it should be so. The author himself remarked that one should lead the gases in as close to the cylindrical wall as possible. If one were to do that, it seemed better to make A small in relation to B . Perhaps the author would say more about that.

He also thought that, for the purposes of using a cyclone as a sieve, it might be better to use a cyclone which was as shown in Fig. 26: the gas from which separation was required would be injected at a and the other gas at b , so that all the particles would come in over a fairly narrow layer, and would have to separate out through that clear layer. He thought that type of design must have been tried, and he would be interested to hear whether the author knew of such a case.

Dr. HAROLD HEYWOOD, M.Sc. (Eng.), Wh.Sc., M.I.Mech.E., said that he had been connected with some work on the effect of the particle size of dust on small cyclones such as were used for cleaning the air inlet to armoured vehicles. In testing those cyclones, it was found that standardization of the test dust was essential in order to obtain comparative results.

In cyclone-efficiency testing, too often the only figure which was given was the overall efficiency of collection, or the mass efficiency; i.e. the ratio of the weight of dust collected to the weight of dust fed. In fact, however, the vital characteristic of a cyclone was the efficiency with which the different particle sizes were collected; he had termed that the intrinsic efficiency of the cyclone. It was an actual property of the cyclone for given conditions of operation, and the curve would be obtained for a given cyclone by drawing an ordinate on Fig. 21 across the curves at some specific outlet exhaust diameter. The curve which the author gave was a general one; the curve to which he himself was now referring was specific to a particular cyclone. By plotting the intrinsic efficiency up to 100 per cent against particle diameter, a curve of the shape shown in Fig. 27 was obtained.

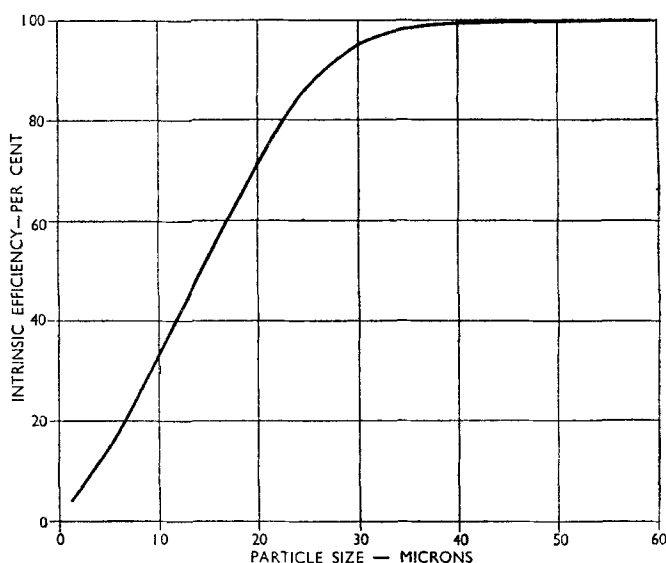


Fig. 27. Variation of Intrinsic Efficiency with Particle Size

To calculate both the mass efficiency and the intrinsic efficiency curve for a cyclone, it was necessary to determine the three weights of dust involved: the weight fed to the cyclone, the weight collected, and the weight which was passed. It was also necessary to know the size distribution of the particles composing those three weights. It was difficult in practice to obtain all that information from an installation which was working in a factory or installed in a boiler plant. If two of the weights only were known, say, the weight of dust fed and the weight of dust collected, and the weight of dust passing was obtained by difference, there was a liability to considerable error unless the experiments had been made with very great care.

For example, to raise an efficiency from 98 to 99 per cent meant that the effectiveness of the cyclone as regards preventing the passage of dust had been doubled, and in the latter case only half the amount of dust was passed as compared with the former; yet it would be very difficult to measure the weight of dust fed and the weight collected to within ± 0.5 per cent, so that without complete data there was a liability to serious error.

It was theoretically possible to obtain the mass efficiency and intrinsic efficiency if one knew the size analyses of the three dusts, but again, unless the sampling had been of the highest degree of accuracy, the resulting calculation would be greatly affected by any errors, and in practice it was necessary to know at least two weights and two particle size distributions to calculate the complete characteristics of the cyclone. Which four quantities out of the six were selected for measurement depended, of course, on the circumstances. If the cyclone was an experi-

mental one, arranged under test conditions, the weight of the dust fed could be measured, but if it was in an installation extracting dust from a boiler plant the weight of dust fed was not, of course, so easily measured.

One feature in testing small cyclones he had not seen mentioned in any publication, and it complicated the interpretation of the test data, namely, the degradation which occurred when friable dusts were fed through the cyclone. There could be an actual grinding effect as the dust passed through, and the result would be to give more than 100 per cent efficiency of collection on certain sizes: more fine dust could be collected from a small cyclone than was fed into it, and that could only be due to degradation of the feed. That point should be borne in mind in cyclone tests, because while the phenomenon was obvious if the efficiency exceeded 100 per cent, it was not so apparent at lower efficiencies, and false conclusions might be drawn.

The author referred to the difficulty of obtaining a clean size cut with a cyclone. That was a very disappointing feature in some respects, because there was a great industrial demand for a powder material graded between two definite sizes, say, 20 and 60 microns. He asked if the author thought there was any possibility of improving or altering the design of cyclones so that they could be used in that way, to give definite cuts.

Wing Cdr. T. R. CAVE-BROWNE-CAVE, C.B.E., R.A.F., M.I.Mech.E., said he was particularly interested in Professor ter Linden's paper, because it gave so much information as a result of practical tests with an apparatus which probably differed very much from the theoretical ideal. He thought that the vortex which existed inside the cyclone was a free vortex, in which the product $v \times r$ was constant, and that did perhaps explain the reason for the violent turbulence in the centre. It seemed to him that the reason that the centre region conditions departed so very greatly from theory was that the velocity gradient between adjacent layers was there very high, and the viscosity of the gas was comparatively great and hence the flow broke down altogether.

If one did not lose any considerable amount of energy near the axis it would be perfectly practicable to incorporate an "inverse" cyclone to recover most of the energy, and thereby almost double the effective pressure drop through the cyclone. So far as he knew, no attempt had been made to recover the rotational energy in the central core; that probably indicated that there had been so much violent turbulence in the centre that the energy was not worth using.

Reference was made in the paper to the speed at which small particles would settle, and that, of course, was the speed at which the centrifugal acceleration was capable of overcoming the inward flow. The speed of settlement of a very small particle which came under the influence primarily of viscosity was, by Stokes' formula, quite different from the speed with which a comparatively large particle would settle, and it would be interesting to know whether, in practical problems of dust separation, one was entirely within the Stokes region as distinct from the normal aerodynamic region. With very small particles, the difficulty of separation would presumably increase with the temperature, because the viscosity of the gas increased rapidly with temperature. On the other hand, if the conditions were aerodynamic rather than viscous, then the speed of settlement would increase as the temperature increased.

Dr. G. W. C. ALLAN, B.Sc., A.M.I.Mech.E., said that the paper on the mixing of petrol was very interesting, particularly because the literature dealing with mixing in general was very sparse. The authors very rightly dealt with the expression in equation (3), the criterion connecting the mixing time of the model with the full-scale tank. That expression, where the model was of length unity and the tank of length L , was an expression of a velocity gradient in the two vessels, and was the criterion of mixing time, but, as Professor White pointed out, in the Tollmein formula the expression for the gradient across the jet section was a complicated one, involving the square of that gradient. He asked whether that did not cast doubt on the adequacy of the reasoning leading up to equation (3).

He had had experience in designing mixing vessels in the

chemical industry where, in order to obtain a velocity gradient, the recommendation was to use a relatively broad, shallow vessel, with a paddle of corresponding shape.

There was a strong geometrical similarity between the authors' tank and jet and a pulverized fuel jet in a large combustion chamber. Neither required violent mixing as it was known in chemical engineering.

The obvious difference between the two processes was that the authors were dealing with free liquids with no film resistance, whereas coal particles being gasified had a film resistance which reduced the rate of mass transfer in combustion. Secondly, in the tank tests the end point was approached asymptotically, as in Fig. 3, but a pulverized fuel chamber finished with either an excess of air or unburnt carbon in the ash. It was probable that combustion in pulverized fuel chambers had stagnant layers, as described by the authors, which probably interfered with agitation, although, as far as he knew, that point had never been noticed.

The pulverized fuel burners were very simple, as shown in Fig. 28, with a large chamber with vertical tubes and a burner.

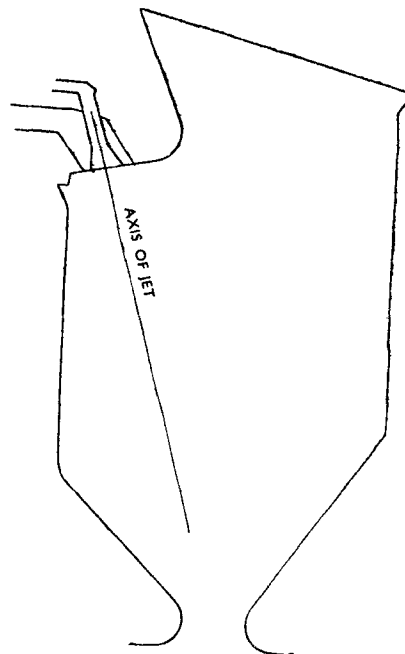


Fig. 28. Combustion Chamber

One firm provided for additional mixing by putting in tangential burners in the way shown in Fig. 29; those reacted with one another at the point where the jets were becoming rather feeble.

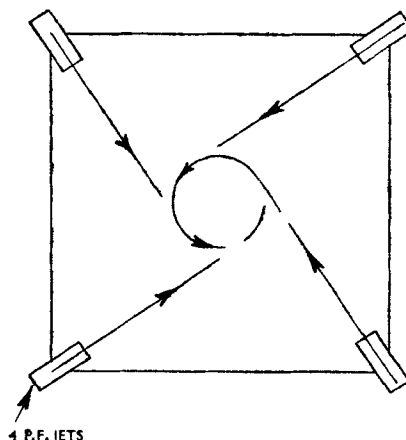


Fig. 29. Plan of Corner-fired Pulverized-fuel Combustion Chamber

Mr. I. M. DAVIDSON, B.Sc. (Farnborough), said that in connexion with the hindrance of free rotation of the gases by the use of vanes to control the swirl or to remove it, he would have expected an attempt to remove the swirl to produce that result, because the cascade would be a compressor cascade, operating under very adverse conditions; but he did not understand why it would not work for the inlet cascade, because that corresponded to a simple reaction turbine cascade, and even with flat vanes instead of aerofoil-shaped blades a fairly high efficiency should be obtained.

Professor ter Linden gave sizes of particles for which Stokes' law was followed within the cyclone, and he would be interested to know whether those figures were meant to apply for atmospheric conditions; he thought that the criterion for the applicability of Stokes' law was the Reynolds number, there being an upper value of about 1.0 and some lower value at which intermolecular slip occurred. The Reynolds number included not only the diameter of the particle but also its slip velocity in the air and the kinematic viscosity of the air.

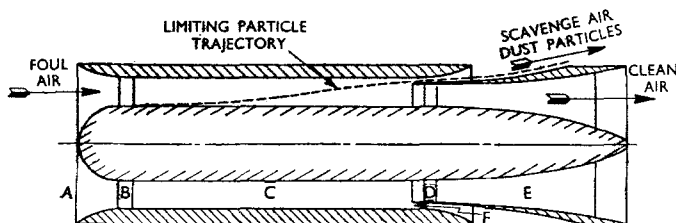


Fig. 30. The Free-vortex Dust Separator
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The author had shown that if the outlet diameter d of a cyclone was decreased, for given velocities and the same geometrical system (apart from that change) there was a decrease in the size of the smallest particle which could efficiently be separated. That could be thought of in terms of the centrifugal field strength in the cyclone; in addition, Wing Cdr. Cave-

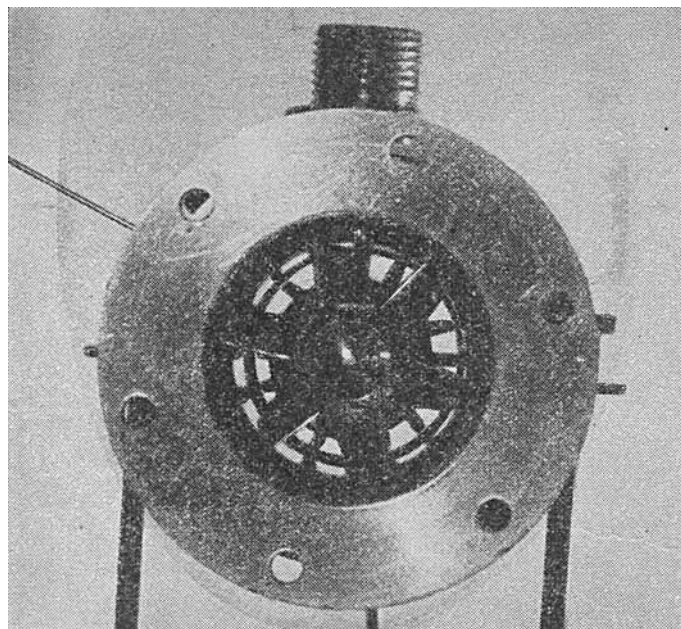


Fig. 31. Experimental Laboratory Model
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Browne-Cave mentioned the very turbulent region in the core. From those two considerations he thought that a logical process would be to develop a straight-through type of cyclone without any reverse flow. If there was no turbulent core one would have small losses, and therefore could use a higher velocity and so get a greater centrifugal field strength.

Fig. 30 illustrated that point. Such a cleaner would have an annular shape. The limiting particles would be centrifuged along the broken line, and the swirl would be removed again at the outlet. It would seem that such a cleaner could be made much more compact than the orthodox type of cyclone. He asked if the author had considered such a design, or done any research upon it.

Fig. 31 showed an experimental model of a cleaner of that type. There was very little blockage of the flow through the unit. Such models had been run with velocities as high as 700 ft. per sec. in the cleaner, and centrifugal field strengths up to 150,000g, and at those field strengths a limit had been found at which the natural rate of turbulent diffusion of the dust in the air was such that it counteracted the centrifugal component. That limit occurred, for particles with a specific gravity of one, about the size of 3-5 microns. The size of such a cleaner was roughly indicated by the fact that it would appear that for the same pressure loss as a normal cyclone it would fit in the exhaust duct of the latter.

Mr. C. PAYSANT (London) said that in the formulae given by Professor White, and in those from the body of the paper, no allowance was made for viscosity. That might be all right for blending motor spirits or aqueous solutions, whose viscosities were relatively equal and constant (each in its own category), but he asked if it were true for blending viscous oils such as fuel oil, which might consist of oils of widely differing gravity and viscosity.

The work of Professor White and other authorities showed that the flow of a fluid through a rough pipe was ultimately dependent on a "boundary Reynolds number" or similar function which embodied viscosity as one of the variables. A jet of liquid forcing its way through a plastic (or possibly a viscous) medium, would entrain and mix that medium, surely, by virtue of a roughness of this pseudo-pipe—i.e. some viscosity function at the boundary of the jet. He did not feel qualified to pursue that argument, but he wondered whether the authors were justified theoretically in taking the Froude number as a criterion of similitude.

The inclination of the jet had been chosen on an arbitrary basis, but its value was taken into account in the mixing formulae. He wondered if there was an optimum inclination for viscous or plastic fluids such as fuel oils.

The height of the jet above the tank bottom was deducted from the total height in the formulae so as to give a height of which mixing, time, etc., are functions. Thus, it could be construed that by placing the jet at the top of the tank, little or no energy would be required for mixing. It would perhaps be more correct to calculate the energy requirements from the total height to the liquid surface.

He asked whether the authors had any views as to how high the jet would need to be to avoid disturbing the lower portion of the contents of the tank. There was often more cause to leave the settlings undisturbed in tanks containing viscous oils than in those containing motor spirits; and the slower, less vigorous agitation of the older blending methods did often provide that compensation for their inefficiency.

Finally, it would be interesting to hear whether the authors had any further information on double layers than that devoted to the subject in the paper. The paper stated that "should stratification occur, it may be quicker to transfer the denser layer to another tank and then reintroduce it through the mixing jet". That was a possible procedure, but it might call for a lot of tankage.

Mr. J. COOPER, A.M.I.Mech.E., said that reference was made in one part of the paper to the quantity of gas passing through the cyclone. He asked whether there was some relationship between the diameter of the cyclone and the quantity of gas with which the cyclone had to deal.

He inquired whether the author had experimented with different air entry velocities and different quantities of solids entrained in the air. That was a most important point in industry where cyclones were used in conjunction with grinding plants, and the only medium moving up the cyclone was the air, plus a certain amount of dust; the majority of the products were

conveyed away from the bottom of the grinder. That was particularly true with cereal grinding or mills where some of the dust ejected from the cyclone would pass through a 150- or 200-mesh B.S. screen.

It was often necessary to put the cyclone in a position where it complied with the Factory Acts, particularly when it was used in conjunction with a grinding plant, as it then became part of a system in which an explosion could be conveyed from the grinder. Sometimes that meant taking the cyclone some distance up a building. He asked if the author had any experience of the effect of a delivery leg, 30 or 35 feet long, and whether a long exhaust pipe from the top of the cyclone would give a chimney effect.

Finally, he asked if the cyclone of the given dimensions would function in conjunction with a pneumatically operating plant, i.e. where the outlet side was connected to a vacuum pump, as in the pneumatic handling of seed. In all industrial cyclones for handling cereals and grains, it was essential that the cyclone should recover the maximum amount. Otherwise the dust was slung on the roof, and that incurred heavy expense in cleaning. It would also be interesting to know whether the author had had any experience of connecting cyclones in series. In the paper there was mention of them in parallel, but he asked if the series working of cyclones had been attempted to recover the extra 5 per cent.

Dr. G. A. HANKINS, Wh.Ex., M.I.Mech.E., said that he thought the first paper was a particularly good example of dimensional analysis and a model experiment applied to a practical engineering problem.

In connexion with Reynolds numbers, much experimental work had been done in large wind tunnels and those results had been applied to aircraft design, while the Froude number—i.e. the ratio of the inertia forces to gravitational forces—had been investigated on ship models in tanks 100 feet long. Yet in the paper one had the application of those same principles, the use of the Reynolds number and the Froude number, applied to a practical engineering problem using very simple apparatus.

The authors did not give an illustration of their apparatus in the paper. It was merely a piece of concrete pipe about 5 feet in diameter, placed vertically on the floor of the laboratory, in conjunction with one or two pumps. He thought that in the actual full-scale job there were certain columns inside the tank, and those were reproduced in the model by small rods.

Mr. I. M. D. HALLIDAY (Sheffield) said that the first paper was of considerable interest to the iron and steel industry, because it showed that a study of flow patterns and scale models could be employed to predict the behaviour of full-scale plant. During the last two years an intensive study had been made by a British steel Company of the flow patterns in open-hearth furnace models, using water as a medium and aluminium powder or air bubbles as visualizers. After even a preliminary study, it became evident that the patterns were so complex that they were almost incapable of interpretation without some preliminary elementary type of background.

A study of the flow patterns in simple geometrical shapes, such as circles, semi-circles, rectangles, and ellipses, did not appear to be recorded in the literature, and hence they had worked out a large number using shallow perspex dishes with bakelite powder as the visualizer. As a result of those studies, a number of generalizations had been made which greatly simplified the interpretation of the patterns obtained in the more complex models.

Figs. 32 and 33 showed the patterns obtained when a jet was shot across an equilateral triangle into one corner and along the axis of an ellipse, respectively. In the first case a shallow triangular dish was used, and a small water jet introduced through one of the sides. The jet had a typical angle of expansion and the reaction effect of the two walls occurred with a stagnation point in the corner; entrainment could be observed on the sides of the fast flowing jet. The point where the fluid left the tank had little effect on the pattern; and the flow path was extraordinarily steady over a wide range of Reynolds numbers.

In the second case, the experiment was of the same type, but the shape was now an ellipse. The jet was projected along the

major axis, and take-off was at both sides, the result being an unstable or oscillating condition; the jet would for one moment sweep to one side and almost wholly leave the tank through the opening on that side, whilst no flow at all would leave by the

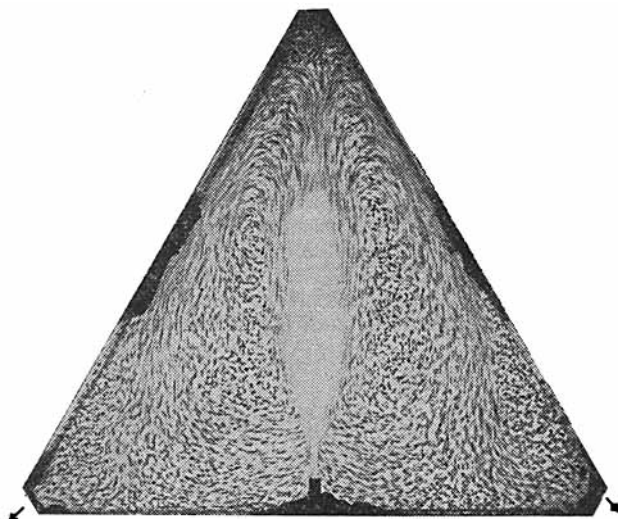


Fig. 32. Flow Pattern produced by a Jet in a Shallow Dish of Triangular Shape

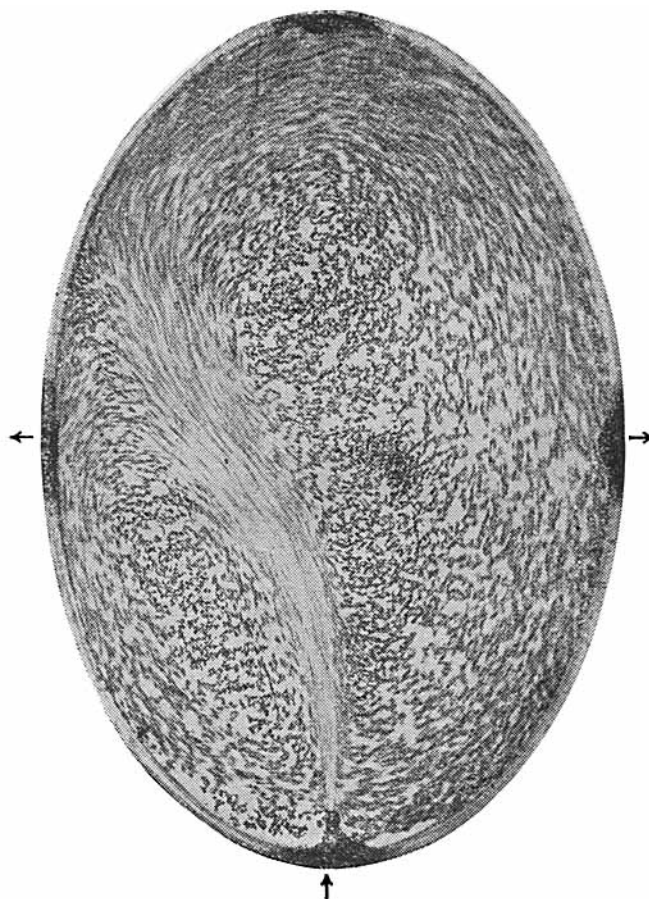


Fig. 33. Flow Pattern produced by a Jet in a Shallow Dish of Elliptical Shape

opening on the other side. That, however, occurred only momentarily, and immediately afterwards the jet swung across until it took up the same position on the other side. The features associated with this flow were again entrainment on both sides, but conditions never balanced.

In both these and all other patterns studied, recirculation was shown to be the dominant factor. That helped considerably in explaining the recirculation always observed in models of open-hearth furnaces, and which more recently had also been

shown to exist in full-scale 80-ton steel-melting furnaces. In the latter case the visualization was achieved by the use of blocks of wood and balls of pitch placed on the banks or allowed to float on the top of the slag.

Communications

Mr. C. CAILLE (Winterthur) wrote that the problem of creating an artificial circulation in polluted lakes with a shortage of oxygen in the deeper layers involved similar considerations to the mixing of fluids in large tanks. It had been proposed* to create a vertically ascending current of 3-4 ft. per sec. by a propeller, located at the deepest point of the lake bottom and having a diameter of about one-tenth of the lake depth at that point. Because of the extremely flat shape of lake basins, as compared with tanks, mixing of the upper and lower layers was obtained only over a relatively small area. However, the cold water at the bottom flowed to the propeller continuously owing to its greater specific weight and was raised to the surface, where it absorbed oxygen from the air. An experimental arrangement was planned for a small lake in Switzerland.

Mr. W. F. CAREY, M.Eng., M.I.Mech.E., wrote that Professor White had called attention to the manner in which a turbulent jet could assist mixing by setting up a circulation. If such a jet was directed along the axis of a cylinder, the type of circulation set up was that illustrated in Fig. 34, where large volumes of

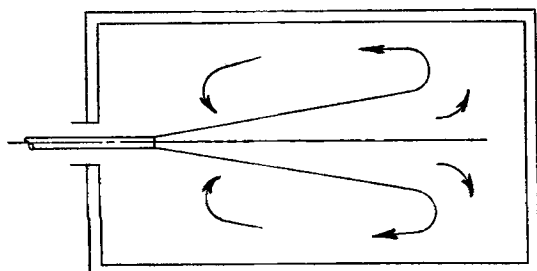


Fig. 34. Flow Pattern of Jet in Cylinder

fluid were continually being recirculated and drawn into the jet. If the original volume flowing in the jet was V , it could be shown that V volumes would be entrained for each $6\frac{1}{2}$ jet diameters, so that at distances 6.5, 13, and 19.5 jet diameters the flow was $2V$, $4V$, etc., see Fig. 35.

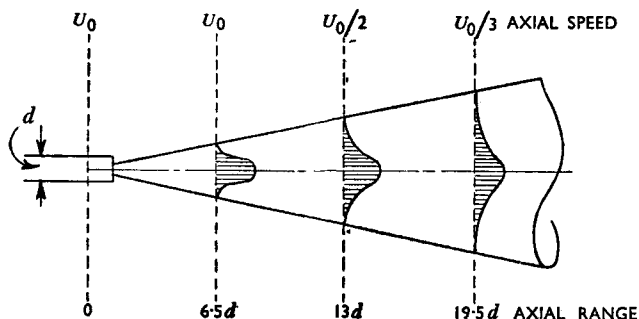


Fig. 35. Flow Pattern of Open Jet

If, therefore, the tank were rearranged so as to inject the same volume of fluid at the same pressure through multiple instead of single jets, it would follow that the multiple jets, being smaller, would entrain more liquid than the large single jets of the same total flow. For instance, four small jets with a

* 1946 Zur Gewässer-Reinigung durch Seewasser-Umwälzung, Schweizerische Bauzeitung, vol. 128, pp. 204-207.

capacity equal to one large one would entrain twice the amount of liquid, assuming that the flow patterns were arranged so as not to interfere with each other. It might, however, be questioned whether a jet gave the type of flow most favourable for mixing. His own experience with mixing hot gases so as to produce a uniform temperature for drying had drawn his attention to the value of splitting a stream into two halves which were then caused to impinge on each other, see Fig. 36. That had also

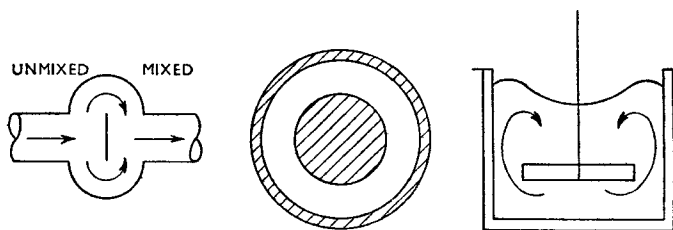


Fig. 36. Mixing by Splitting

Fig. 37. Annular Baffle

Fig. 38. Paddle Stirrer

led to the development of an annular type of baffle (Fig. 37), which had proved very useful for mixing dust before sampling.

The authors drew attention to the inefficiency of "the normal spider", but they did not give particulars of its design, nor did they discuss the type of flow pattern which resulted from its movement.

Many mixers in chemical plants comprised a stirrer at the base of a cylindrical vessel (Fig. 38); such a paddle acted as a pump and gave rise to a flow pattern of the type shown. That type of flow pattern might be expected to be effective because the liquid was spread out in a large number of turbulent jets and also mixed by impingement at the centre. Large numbers of such mixers were employed in chemical plants. He asked whether the authors considered the orthodox stirring equipment referred to in their paper was badly designed, or whether they considered it was wrong in principle.

Mr. W. F. CAREY, M.Eng., M.I.Mech.E., and Mr. C. J. STAIRMAND (Billingham) wrote that they had been associated with various investigations to improve the efficiency of cyclones for the last ten years. As Wing Cdr. Cave-Browne-Cave had pointed out, the flow in cyclones would be that of the free vortex, but it had to be corrected for the effects of wall friction and viscosity which had two main effects:—

(a) The tangential spinning speed $V \propto \frac{1}{\sqrt{R}}$ whereas in the

free vortex $V \propto \frac{1}{R}$.

(b) The rate of spin of the vortex might be either greater or less than the inlet velocity, being regulated by the balance between the frictional torque and the amount of angular momentum of the fluid flow.

It had been shown that by adding the changes in head due to (1) inlet momentum, (2) centrifugal effects, and (3) exit loss, it was possible to estimate the theoretical pressure loss in any cyclone. That relation had been checked by experiments on models and full-scale cyclones and had given reasonable agreement. For cyclones of the proportions normally encountered in practice the change in velocity when passing from the inlet duct to join the vortex did not exceed ± 10 per cent. In such

cases the pressure drop across the cyclone could be expressed as $\left(4\frac{R_1}{R_2}-1\right)$ inlet radius velocity head + 2(exit pipe velocity head), where one velocity head equalled the head of fluid necessary to generate a velocity V , i.e. $\frac{\rho V^2}{2g}$ in consistent units; and the pressure loss which corresponded to the velocity head of air (density 1/13.3 lb. per cu. ft.) flowing with velocity V ft. per sec. equalled

$$\frac{1}{13.3} \times \frac{V^2}{2g} = \frac{V^2}{855} \text{ lb. per sq. ft.}$$

and R_1 = mean inlet radius of entering gases.

R_2 = mean radius of exit vortex = $\frac{1}{2}$ radius of exit pipe.

In developing that expression it was found experimentally that none of the devices mentioned in the literature were capable of recovering any of the exit energy and that the condition which best satisfied the dynamics at the axis was to consider that a central core (radius 0.56 of the exit pipe) rotated at constant angular speed and was surrounded by a free vortex modified by friction as already described.

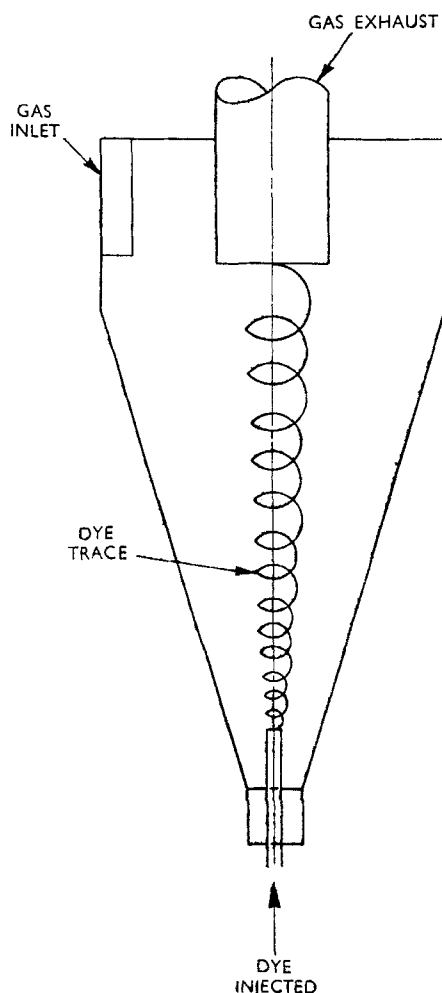


Fig. 39. Experiment with Water Cyclone

If precession currents (already mentioned by Wing Cdr. Cave-Browne-Cave) that might be supposed to move at, say, 10 per cent of the speed of the main axial spin and normal to it, were superimposed a flow pattern in substantial agreement with that given in Professor ter Linden's Figs. 8, 9, and 10 would be obtained.

There was a simple experiment which could be performed with a small celluloid cyclone filled with water; if whilst water

was flowing through the cyclone in the normal fashion a small stream of dye was introduced at the base, a column of dye formed right up the centre of the cyclone the outer portions running clear, as shown in Fig. 39. It was inferred that the column represented the central core in which the inward drift was zero, and in that case it would be expected to carry a gradually increasing flow as it approached the exit, being formed fairly uniformly by fluid as it rose up the axis.

They were also interested in the practical performance of small diameter cyclone dust collectors. Professor ter Linden referred to the danger of assessing the performance of a nest of small cyclones from that of a single unit; they agreed with that warning but there was the greater danger of assessing the performance of a small diameter cyclone on theoretical grounds, or even by extrapolation from that of a larger cyclone. The error was largely associated with the degree of bouncing of the coarser particles. Experiments by the writers, hitherto unpublished, had shown conclusively that particles larger than about $60-80\mu$, initially separated, could bounce from the walls of the cyclone and reach the "danger zone" near the exhaust. That was probably the reason for the drop in efficiency of small diameter collectors at higher gas throughputs.

Thus, whilst theoretical considerations showed that small diameter cyclones had important advantages, those advantages had not yet been fully established, particularly as regards removal of the larger particles. It would be of interest to know the type of experiments carried out by Professor ter Linden to check the curves given in Fig. 21. Examination of the figure suggested that an experimental curve for a cyclone with a particular exhaust diameter had been extrapolated in terms of the "separating capacity" at various radii. If that was so, it neglected the experimentally established fact that the smaller diameter cyclones were subject to re-entrainment and bouncing.

Mr. R. H. B. FORSTER, B.Sc. (Eng.), A.M.I.Mech.E., wrote that it had been recognized for a long time that the efficiency of collection of a cyclone increased with decrease in size, and the important dimension had usually been understood to be the diameter of the cyclone. The author had, however, pointed out that it was a reduction in the diameter of the gas outlet which had the biggest effect in improving efficiency and that alteration of the main diameter had, in fact, the reverse effect. That contention would probably not go unchallenged, and he personally knew of certain cyclones in which the outlet diameter had been deliberately made as great as possible and yet a high efficiency had been obtained.

In the paper there was no mention of the effect of variation in the height, h , of the cylindrical part of the cyclone, and it would be of interest if that could also be stated.

He had made some experiments a few years ago with the object of determining velocity and pressure distribution in several designs of cyclone. The measuring apparatus was crude compared with that used by the author but the results clearly confirmed the diagrams given in the paper. Fig. 40 showed a typical curve of tangential velocity distribution, that had been plotted on a log base to facilitate determination of the power of r . At values of r less than $0.7r_0$ measurements were difficult, but the points were roughly represented by $V/r = \text{constant}$, which corresponded to a forced vortex. At values of r greater than $0.7r_0$ the relationship $V/r^{0.5}$ held approximately.

Although that relationship had been put forward by several experimenters he knew of no published theoretical explanation, and he would be interested if the author could explain why the powers should be 0.5 and 1.0, since the latter corresponded to a free vortex.

In Fig. 17 the vertical velocity in the centre of the cyclone was in an upward direction. In the tests which he carried out with a cyclone having a relatively large diameter of outlet there was a slight downward component over the central region where a forced vortex held. It was found possible to block about half the outlet area by means of a disk without affecting the pressure drop through the cyclone.

The author stated that provision of blades in the gas exhaust pipe, in order to decrease the pressure loss, influenced the efficiency unfavourably. He himself had been concerned with certain tests in which that was not found to be the case: with a

certain type of dust the efficiency of 95 per cent was unaffected by the fitting of the vane, but the pressure drop through the cyclone was reduced to nearly half. The vanes were carefully designed so as to give no shock at inlet to the exhaust pipe, the correct angle being determined from a knowledge of the horizontal and vertical components of gas velocity at that point. The passages were designed to transform the velocity energy

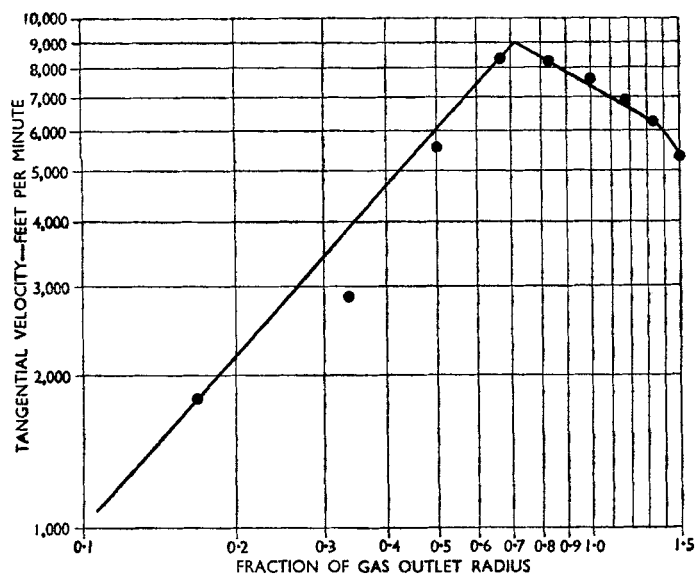


Fig. 40. Variation of Tangential Velocity with Radius of Cyclone

gradually to pressure energy and it was found that about 90 per cent of the energy in the rotating gases could be recovered without affecting the collecting efficiency.

The pressure drop, H , without vanes in the outlet was found to vary with $Q^{2.25}$ where Q was the gas flow rate. When vanes were fitted H became proportioned to $Q^{1.5}$.

He had attempted to plot the flow pattern of the gas from the extensive series of the tangential, radial, and vertical velocities given by the author. The radial velocity in Fig. 15 was unfortunately not completed in the central portion of the top curve. It appeared that in the portion omitted, the velocity must change to a very high outward flow if continuity of flow was to be maintained, and, therefore, a secondary circulation such as indicated in Fig. 41 must hold.

The area of the cylindrical surface of diameter AB and length AC in Fig. 41, scaled about thirty-one times the inlet area, and as all the radial velocities indicated over that cylindrical surface in Fig. 15 were directed inwards, either the mean velocity must be $1/31$ of the inlet velocity, or there must be a very violent outward flow at the point not shown.

That was further indicated by the high vertical velocity at the base of the outlet which showed about 2.4 times the inlet flow rate rising up at that point, i.e. about 140 per cent was recirculated through the cylindrical area represented by BE in Fig. 41.

Tests which he had made by inserting wool streamers on the end of a piece of wire seemed to confirm a secondary circulation similar to that indicated.

Many of the cheaper type of commercial cyclone had the upper portion constructed as a cylinder of the same diameter as the top of the cone. The gas was admitted through a rectangular port and very bad shock conditions existed. That could be seen from a transparent cyclone: the dust descended in a spiral for about three-quarters of the circuit, but when it came in the vicinity of the inlet port, it suffered a severe kick upwards and some of the dust particles might be thrown into the dangerous central region.

A gradual transformation over 180 deg., such as occurred with the author's spiral design of inlet, allowed the gas to flow gently over the lip of the cone and avoided the violent shock of the simpler design.

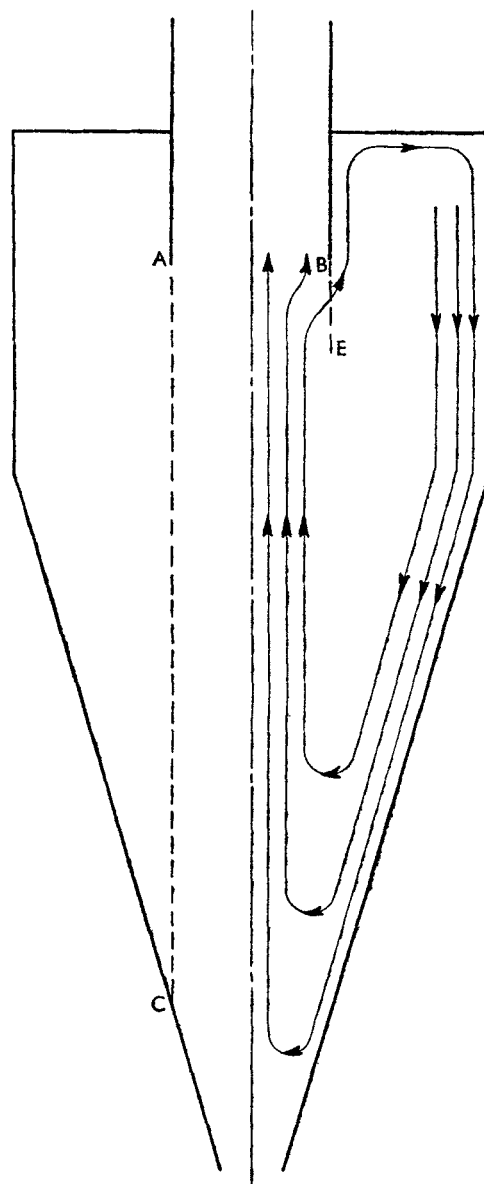


Fig. 41. Secondary Circulation Showing Outward Flow and Recirculation over the Zone BE

Dr. A. H. LECKIE, B.Sc. (London), wrote that the results of Professor ter Linden's experiments appeared to conflict with some of the previously accepted views on cyclones, based on the work of Rosin and his colleagues*. Rosin considered a tangential velocity only, based on the initial entry velocity, and also calculated the movement of particles in the upper part of the cyclone only, i.e. within the annulus defined by the outer cylinder and inner exit tube. Professor ter Linden, on the other hand, had studied mainly the field of the cyclone below the exit duct. Rosin's method of calculation might be summarized as considering a particle with a tangential velocity V , which was a function of the entry velocity, and calculating its outward radial movement under the opposing forces of centrifugal action and viscous resistance according to Stokes' law. If it reached the cyclone wall before the bottom of the exit duct, separation was considered effective. In that way the diameter of the smallest particle which could be separated could be calculated, and, from a knowledge of the size distribution of the dust, the maximum separation efficiency which could be effected. That treatment ignored the radial movement of the gases; presumably Rosin considered such radial movement to be negligible within the annulus above the bottom of the central exit tube.

* ROSIN, RAMMLER, and INTELMAH 1932 Z.V.D.I., vol. 76, p. 443.

Rosin's method of calculation indicated that a small cyclone diameter, giving increased centrifugal force, and a tall, narrow entry section, which, for a given area of entry section, started the particles off in the cyclone already near to the wall, were to be favoured. Since the bottom of the exit tube had to extend well below the lower edge of the entry section, those principles demanded cyclones of small diameter and considerable height; in practice such cyclones gave very good results. It would be interesting to have the author's comments on the method of calculation used by Professor Rosin and his colleagues, and on whether the differing views on diameter and entry section were dependent on whether the calculations were based on the cyclone field above or below the bottom of the exit tube.

Mr. A. D. MACLEAN, B.Sc. (Eng.), M.I.Mech.E., wrote that previous methods of mixing fluids were in general of three types:—

(a) Those in which the contents of a tank were continuously drawn off from the bottom and returned through a swing pipe or a distributing system of perforated pipes or troughs placed so that the return stream was distributed fairly evenly over the liquid surface in the tank. The second fluid was introduced into the return stream on its way to the tank and circulation was continued until the specified degree of homogeneity was obtained. That method did not involve great turbulence so that the pump horse-power was not high, but it took a long time so that the energy expended per mix was considerable and the throughput of the tank and associated equipment as a mixing system was low.

(b) Those in which a system of upward pointing jets was provided over the tank bottom. With that method the two fluids were first introduced through the normal pipe inlet into the tank. The contents were then circulated through the jet system which was specifically designed to create turbulence and not a quiet pattern. The horse-power involved was inevitably very high and the time to reach homogeneity was also high so that the energy expended was very great, again with a low throughput factor.

(c) Those in which mixing was secured after the components had been filled into the tank by means of immersed mechanical stirrers designed and positioned so as to induce a mixing pattern. Where applicable that method was found to be more economical than (b) and about the same as (a), but considerably less so than that described by the authors.

He had been closely connected with the problem described by the authors in their paper; that problem fell into two parts, namely, where to introduce the tetraethyl-lead, and how to mix the tank contents. They had not primarily been concerned with the time of mixing, provided it was not greater than by conventional means, but with establishing that adequate mixing was obtained. The results showed not only that the method would work, but also that it would take less power and shorter time.

There was one point in the paper concerning Fig. 5 upon which he would like further confirmation. In order to overcome the Froude effect the nearer the jet was to pointing vertically upwards the better, but to initiate the pattern the jet required a horizontal velocity component. He had employed an empirical rule, namely, $\tan \phi = 3H/D$ where H was the height and D the diameter of the tank. That in effect reversed the proportions $\frac{1}{3}$ diameter and $\frac{3}{4}$ diameter given in Fig. 5, and enabled a somewhat lower velocity to be used. He asked if there was any experimental objection to that method. A possible reason for the arrangement given in Fig. 5 was to safeguard conditions when blending with the tank only partly filled.

Mr. B. V. POULSTON, B.Sc., A.M.I.Mech.E., wrote that the term "efficiency", used in comparing the performance of different cyclone dust collectors, was defined as the ratio between the weight of dust separated from the gas per unit volume and its initial dust content. He thought that definition might cause confusion in the application of collectors to practical separation problems, because it did not account for the associated energy loss. In many types of separator, that took the form of pressure drop in the fluid stream, with or without additional expenditure of heat or electrical energy.

In many proposed applications, such as those involving power gas, the pressure drop was a vital consideration, and any additional energy absorption detracted from the total output.

It was therefore suggested that a non-dimensional performance factor of a general nature be sought, to include both the effectiveness of the separating device and the energy expenditure.

He realized that the mere removal of solid matter from a mass of fluid entailed the expenditure of energy, which in aerodynamic separators had to come from the gas itself. There would also be a loss, due to the kinetic energy of the removed particles, if that energy was useful in any case.

The performance factor might, by analogy with the thermodynamic conception of efficiency, take the form:—

$$\text{Performance factor} = \frac{\text{"Inevitable" energy needed to remove the separated dust}}{\text{Actual energy loss}}$$

If an ideal separator such as a perfect semi-permeable membrane or a perfect settling tank was imagined, the minimum or "inevitable" energy required to agglomerate the dust particles would depend upon the dust content of the fluid. The performance factor could then be written:—

$$\frac{\text{Extraction efficiency} \times \text{"inevitable" energy based on total dust content}}{\text{Actual energy loss}}$$

An approximate analysis of the idealized case indicated that the "inevitable" energy loss was a function of a variable of the form $\frac{\mu MQ}{\delta_m^2 S_1}$ in the notation of the paper, where M was the weight of dust in 1 cu. ft. of fluid presented to the separator, and δ_m some mean particle diameter.

A suitable "pressure drop" factor for cyclones might therefore be of the form:—

$$\frac{\mu MQ}{g \delta_m^2 S_1 X} / \text{pressure drop } (\Delta p),$$

where X was a characteristic dimension of the separator.

However, since it appeared to be more difficult in practice to separate the smaller particles than the larger ones, it might give a fairer comparison if an estimate, $\delta_{\min}$, of the minimum particle size separated were used instead of δ_m . Also, for generality, a "power" ratio might be more useful than a pressure drop ratio, of the form:—

$$\frac{\mu MQ^2}{g \delta_{\min}^2 S_1 X} / \text{actual power used in separator}$$

It was therefore suggested that a factor be considered of the form:—

$$\text{Performance factor} = \frac{\text{Extraction efficiency} \times \left(\frac{\mu MQ^2}{g \delta_{\min}^2 S_1 X} \right)}{\text{Power used in separator}}$$

Dr. K. W. RIZK (Cambridge) wrote that the authors' approach to the problem of mixing fluids was such that their results could be applied directly by the designer without an intimate knowledge of fluid dynamics.

The authors' remarks that the colorimetric method of measuring the composition of the flow was unsuitable and that an electric method employing electrodes was adopted for their tests were particularly interesting. Methods of recording the instantaneous composition of streams were of importance in the study of scavange flow in two-stroke engines by means of scale models employing water. In Cambridge, the method of measuring the conductivity of a saline solution had been tried, but a slight time lag existed between the change in concentration and the current passing through the electrodes. The probable explanation of that phenomenon was that the electric current through the solution, and therefore the voltage drop, depended instantly on the supply of ions in the immediate vicinity of the electrode. The concentration of salt solution in the boundary layer surrounding the electrodes might be substantially different from that in the main stream, and not until homogeneity had been reached could a true measure of the concentration be recorded. By careful design of the electrodes the time lag could be reduced. While that effect might be negligible in comparison

with the maximum rate of change in sizes of models encountered in the authors' tests, it was a serious drawback in models involving higher velocities of flow.

A colorimetric method had been developed and successfully used on water models with the injection of a dye solution to record the instantaneous composition of the flow.

It consisted of a probe in which a beam of light was made to traverse a gap past which the mixing liquids flow, and subsequently fall on a photo-electric cell suitably coupled by a D.C./A.C. amplifier to a cathode-ray tube. Only the sensitive end of the probe was inserted into the cylinder. The unit could be calibrated and was capable of recording extremely rapid changes within the cylinder. If made in a sufficiently small size relative to the cylinder it did not affect the flow appreciably.

Mr. H. FOSSETT and Mr. L. E. PROSSER, in reply to the discussion and communications, emphasized that the paper was a record of experiments on a model of an original idea for jet mixing applied to a fairly typical oil tank, and of the confirmatory full-scale results; although it was interesting to speculate on the internal mechanism of the process they did not feel there was, as yet, sufficient experimental evidence on which to base an adequate theory. Recently published American theoretical work had demonstrated the danger of speculation without practical experiments: it had led to the erroneous conclusion that the total quantity to be circulated through the nozzle was greater than the amount actually required.

The suggestion made by Professor White that the process could be regarded as involving two stages, namely the mixing in the diverging jet and the provision of circulating currents, was useful since it stressed the importance of avoiding corner pockets. Alternatively, the flow pattern could be regarded as a continuously diverging jet of indefinite length which was merely deflected, and possibly divided, by the tank boundaries. In that way there was no difficulty in visualizing the 30-foot length of jet, mentioned by Professor White, curled into the 15-foot diameter tanks listed in Table 4.

Professor White had drawn attention to the fact that the criterion used in Fig. 3 was equivalent to the ratio of the total injected volume to the tank volume divided by the ratio of the nozzle diameter to the tank diameter. Although that was presumably significant, the reason for the adoption of the non-dimensional

time scale of $T \sqrt{\frac{D^2}{\rho Q U}}$ followed directly from the simple reasoning given in equations (1), (2), and (3): the relationships between the full-scale quantities and those in a dynamically similar model were true for all geometrically similar installations, provided the flow patterns were similar. That implied that there was no scale effect due to differences of viscosity, density, or linear scale; and that fact was confirmed by the tests over a wide range of Reynolds number given in Table 1 and Fig. 3. It was reassuring to learn that Professor White confirmed that small density differences did not directly influence the diffusion process, although as they had shown, stratification could occur unless there was sufficient vertical momentum.

Mr. G. W. C. Allan had pointed out that the criterion $\frac{\sqrt{\rho Q U}}{D^2}$ was also a velocity gradient. That, however, had the dimension of T^{-1} and could therefore only be used to the first power to give a non-dimensional number when multiplied by time.

Mr. C. Paysant had mentioned the effect of viscosity, and it was perhaps desirable to draw attention to the results given in Table 1 and Fig. 3, which showed that there was no evidence of any failure to mix down to at least a Reynolds number of 4,500. Although model tests had not been made at lower values, some of the full-scale tests with thick oils were probably lower, and indeed it was difficult to see how even a laminar jet could fail to diverge and entrain fluid. The mixing process for oils of widely differing viscosities might be different, but it would be a simple matter to carry out model tests at the same Reynolds number to determine that, if it were of sufficient importance. They were of the opinion, however, that there would be no material difference in behaviour, and that was perhaps confirmed by the practical success of the mixing of a very viscous additive of fairly high density to lubricating oil.

Mr. Paysant was correct in assuming that if the nozzle were placed near the top of the tank the excess head required to prevent stratification would be negligible, but, as shown in Fig. 8, a reasonable head would still be required to give the desired value of $\sqrt{\rho Q U}$ if an excessively large diameter nozzle were to be avoided. Normally the nozzle was placed near the bottom to allow for mixing in a partially filled tank. No data was available on the necessary height of the jet above the tank bottom in order to avoid disturbing the lower portion of the contents, but if the lower portion were a stratified layer of greater density it was probable that the jet, if inclined upwards, would have little effect below its own level.

Dr. G. A. Hankins called attention to the stark simplicity of the war-time experimental set-up, which they had delicately refrained from illustrating. Although it was perhaps gratifying to record that the N.P.L. fire pump had served a useful if illegitimate purpose, it was sincerely to be hoped that more adequate and convenient hydraulic experimental facilities would be available in future.

The principle of using a number of smaller jets, referred to by Mr. W. F. Carey, could result in uneven distribution, as mentioned in the paragraph on "Further Improvements".

The "normal spider" they had referred to in the paper was of the perforated distributing pipe system, as mentioned by Mr. Maclean. Models of the "normal spider" system and a system of inclined troughs were tested and found to give very slow mixing.

They considered that there was insufficient factual knowledge of the mechanism of mixing for them to put forward an opinion as to whether any particular method was wrong in either principle or design, but they did ask for further full scale, or scientifically controlled model tests.

There appeared to be no objection to using a larger angle of inclination of the nozzle. The reason for the relatively low angle they had used was, as correctly inferred by Mr. Maclean, to avoid any chance of the jet breaking through the surface of a partially filled tank with the consequent risk of electrostatic discharge and possible fire.

It was interesting to learn from Dr. Rizk that a quick acting colorimetric method of measuring concentration had been developed at Cambridge; it might be preferable to adopt such a method in any future work.

Professor A. J. TER LINDEN wrote in reply that the gas velocities in the highly turbulent core of a cyclone could not be measured accurately, as both the direction and the magnitude varied continually.

He agreed that the tangential velocity in the cylindrical part of the cyclone could be approximately described by

$$V_t/r = \text{constant, from } r = 0 \text{ to } r = 0.65r_0,$$

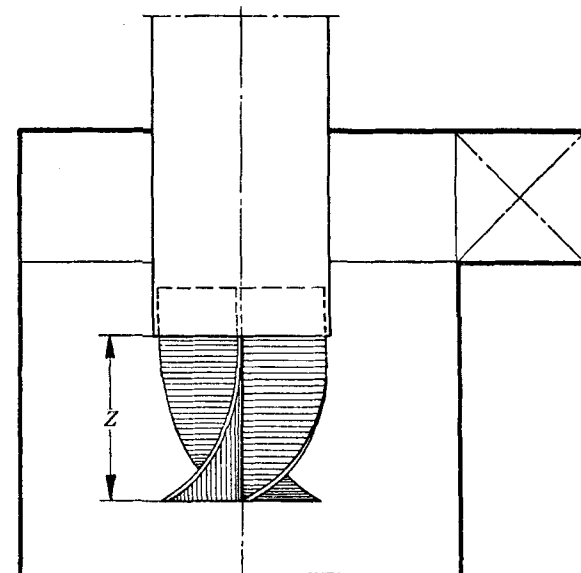


Fig. 42. Exhaust Pipe Fitted with Guide Vanes

and by

$$V_r \sqrt{r} = \text{constant from } r = 0.65r_0 \text{ to the circumference}$$

In the conical part of the cyclone, the radius, r_s , at which the flow broke down decreased gradually: at the breaking point of the flow the gas velocity was between two and two and a half times the gas velocity at inlet. He did not know of an exact theoretical explanation of the gas flow.

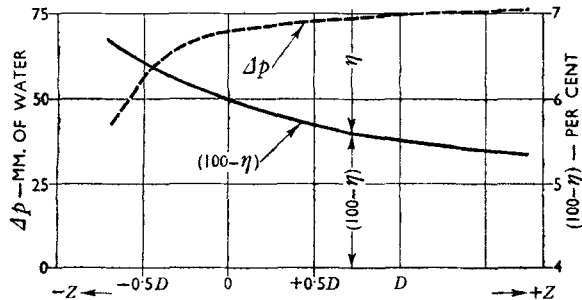


Fig. 43. Effect of Position of Guide Vanes on Pressure Loss (Δp) and Efficiency ($100-\eta$)

A considerable amount of the rotational energy of the gases in the exhaust could be recovered by fitting guide vanes, as in Fig. 42. His experience was contrary to that of Mr. Foster in that he had always found that the collection efficiency decreased when guide vanes were fitted in the exhaust pipe. The position of the vanes, shown by Z in Fig. 42, influenced both the pressure loss, Δp , and the efficiency, η (see Fig. 43).

The negative values of Z in Fig. 42 corresponded to positions of the vanes when they were partly under the bottom of the exhaust; normally the vanes were fitted in the position $Z = 0$.

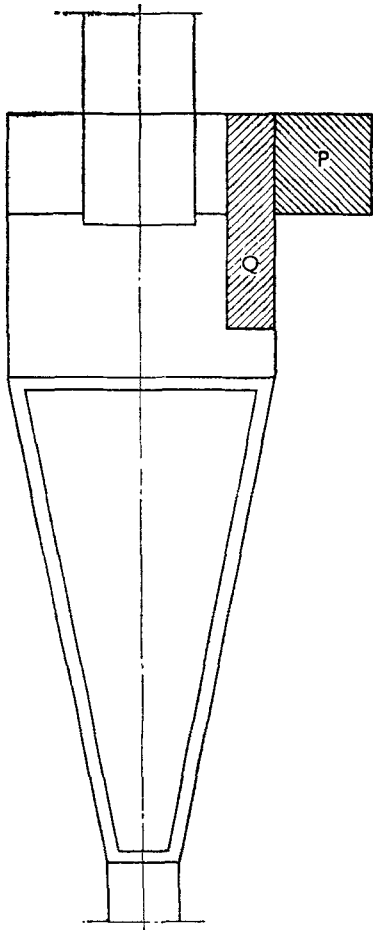


Fig. 44. Different Inlet Surfaces for Cyclones

Under the same load conditions, the cyclone working without vanes had a pressure loss of 80 mm. water gauge and an efficiency of 95 per cent.

To avoid any difficulties that might arise in measuring the pressure loss, owing to variations of the pressure in the exhaust pipe, a cyclone having a free exhaust to the atmosphere was used: the difference of the pressure in the inlet pipe and in the atmosphere was considered to be equal to the pressure loss in the cyclone.

He also had found, as Mr. Foster had done, that for cyclones with relatively large exhaust pipes ($d > 0.5D$) there was a downward gas flow. However, for cyclones with a small exhaust pipe ($d < 0.5D$), a downward flow could not be ascertained.

The flow in the central area directly below the bottom of the exhaust was so unstable, that no reliable measurements of the gas velocity could be made. However, it was found, by using small wind vanes, that the general direction of the radial gas flow was directed towards the centre, and not outwards as Mr. Foster had indicated in Fig. 41.

The influence of the gas temperature on the efficiency of a cyclone was an interesting question. The rate of settlement of a dust particle decreased with an increased gas temperature, and hence a lower collection efficiency might be expected at high temperatures, but his experiments with large cyclones of a refuse-burning plant had shown no decrease in efficiency even at temperatures of 1,400 deg. F. The increased viscosity of the gases at higher temperatures probably produced a less turbulent gas flow, which would be more favourable for the dust separation.

He had investigated the problem of using a cyclone as a wind sieve, as there was a great demand for a good wind sieve, but the results, as yet, had been unsatisfactory: a quantity of the

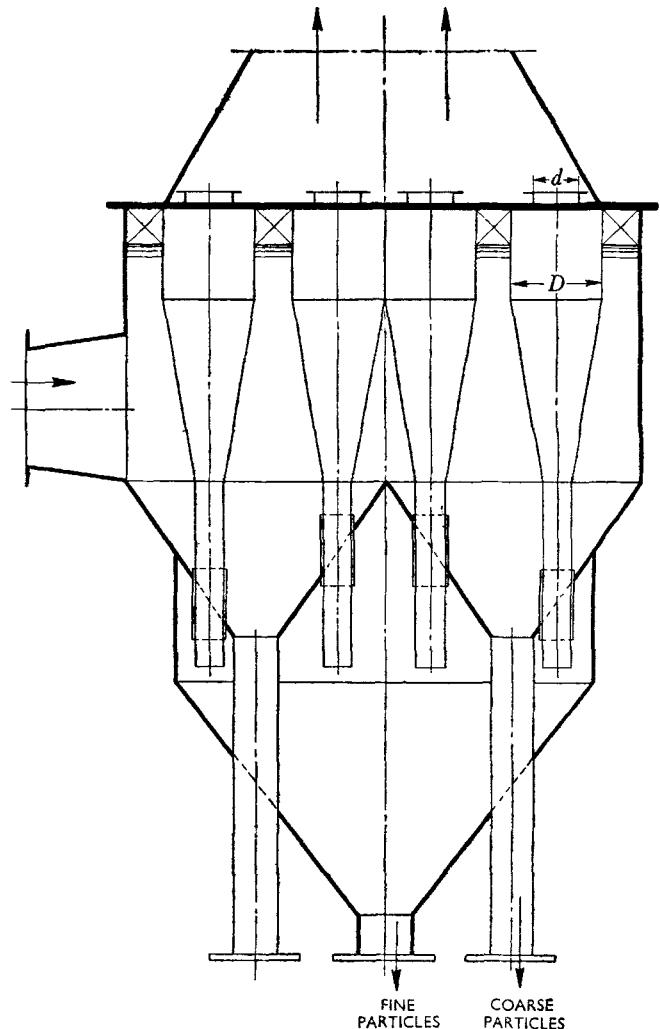


Fig. 45. Multi-cyclone Construction

fine particles were always dragged away by the coarse particles, so that no clean cut could be attained. Modern cyclone wind sieves of Swedish and German design tested in their laboratory had not come up to expectation.

He considered that it was advisable to keep the dust particles entering the cyclone as far as possible from the centre of the cyclone, and in that case a broad inlet ($A > B$ in Fig. 9) was preferable for cyclones where the inlet surface was outside the cylindrical part (see P in Fig. 44). A small and high inlet was required for cyclones where the inlet surface was inside the cylindrical part (see Q in Fig. 44).

He agreed that there were many practical difficulties in cyclone testing: a complete cyclone test should include not only the measurement of the dust quantities but also a determination of the particle size at the inlet, outlet, and in the dust bunker. In practice it was almost impossible to carry out these measurements, but it was less difficult in a laboratory where a good standard dust was available. He had obtained good results with a special pulverized-clay dust, that had a practically constant size distribution, did not stick to the walls of the separator, and was not hygroscopic. For that dust, the grinding effect in a cyclone was negligible, so that it was only necessary to measure the weights of dust fed to the cyclone and collected in the bunker.

Fig. 21 had been derived from results of several cyclones with exhaust pipes varying from 1 inch to 12 inches in diameter and of some larger industrial installations. It was not intended to give exact values of efficiency for all cyclones, but it did indicate the efficiency of a cyclone of the type described in his paper for dust with a given size distribution.

Fig. 21 could also be used to determine the effect of connecting cyclones in series: if the size distribution of the dust particles and the diameter of the exhaust pipe were known, the efficiency of the first cyclone and the size distribution of the leaving dust could be calculated, and hence the efficiency of the second cyclone. Usually it was advantageous to replace a large cyclone by smaller units in parallel than to connect two large cyclones in series.

He had observed the phenomenon of coarse particles, initially separated, bouncing from the walls to reach the "danger zone" near the exhaust in small cyclones; that tendency was especially noticeable with dusts having "elastic" qualities such as sand particles, but he did not consider that difficulty to be very serious. In medium-sized cyclones an inner cone, as shown in Fig. 44, could be fitted: the coarse particles would pass through the

annular space between the inner and the outer cones, and thus would be unable to bounce into the "danger zone". For small cyclones, the arrangement shown in Fig. 45 offered a solution: the small units were fitted in a large casing where the gas velocity was relatively small so that the coarse particles would settle and be unable to enter the small cyclones. An even gas distribution over the cyclones was automatically attained by that construction, and the wear of the cyclones was diminished. In very small cyclones, however, the small passages might get blocked, especially when the dust tended to adhere to the walls.

The straight-through type of cyclone illustrated in Fig. 31 was interesting, especially as the small dimensions compared favourably with the orthodox cyclone. He had never tested that type of cyclone, so he could not express any opinion on its efficiency.

His objections to Professor Ramsin's cyclone theory had already been published*. He did not consider that it was essential for a dust particle on its way through a cyclone to touch the outer wall of the cylindrical part, but he did think it was essential for the particle to avoid the "danger zone" in the centre. Many of the finer particles were separated without touching the cylindrical wall at all: they passed through the inner cone, whereas the coarser particles passed through the annular space between inner and outer cones (see Fig. 44).

Fig. 9 showed clearly that for a given exhaust diameter, d , the efficiency increased with an increase in cyclone diameter, D . He did not deny that good results could be obtained with small diameter cyclones, but he was convinced, that even better efficiencies would be obtained by increasing the diameter D .

He agreed that a low pressure drop was an important factor for a dust separator, but he was not convinced that Mr. Poulston's non-dimensional performance factor would give a good standard. A high dust content of the gases influenced both the pressure loss and the efficiency of a cyclone favourably, so that the performance factor would depend mainly on the dust content of the gases and not on the construction of the separator. Moreover, it would be easy to improve the performance factor by replacing a single cyclone by two similar cyclones in parallel: the pressure drop would then diminish to about a quarter of the original value, whereas the efficiency would only alter slightly. The space required by the separator, however, would be doubled and so would the cost of the installation.

* TER LINDEN, A. J. 1933 *Engineering*, vol. 136, p. 353.