THE CHEMICAL AND PHYSICAL INVESTIGATION OF GERMICIDAL AEROSOLS

II. THE AEROSOL CENTRIFUGE

By S. R. FINN, B.Sc., A.I.C. and E. O. POWELL, B.A., B.Sc.,
From the Portslade Research Laboratories, Portslade, Sussex

(With 11 Figures in the Text)

In our work with germicidal aerosols we have used the principle of W. F. Wells's (1936, 1937) air centrifuge in the construction of several machines for various purposes. Our object here is to indicate the potentialities of the centrifuge, and no finality of design is claimed for the experimental models described; its use as an instrument for estimating the numbers of micro-organisms in an atmosphere is well established, but its sphere of application can be extended considerably beyond this.

In essence, the centrifuge consists of two coaxial cylinders, between which a gas carrying suspended particles is passed longitudinally. The outer cylinder rotates, or both do so together, and the particles then tend to collect on the outer wall of the annular space (Fig. 1). Qualitative consideration will show: (1) that particles entering the centrifugal field very close to the inner cylinder will have the best chance of escaping; (2) that when both tubes rotate together (this arrangement will be called type I) there will be a critical particle size, or 'cut-off', such that *all* particles above this size will be collected; (3) that when only the outer tube rotates (type II) there will be no such limit, even very large particles entering near the inner tube being able to escape.

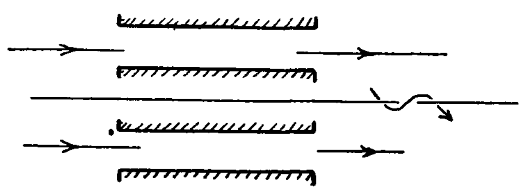


Fig. 1.

On account of end-effects and turbulence, it is hardly possible to predict exactly the performance of such a centrifuge when it is given a practical form, but a number of rather sweeping approximations enable a rough but still useful calculation to be made. It will be assumed, then, that the suspended particles are spheres of small inertia, and that the longitudinal velocity of the gas between the cylinders is small enough to make negligible its kinetic energy and compressibility. End-effects will also be left out of account. Further, it can be shown that the displacement of particles away from the axis, due to centrifuging of the gas itself, will quite definitely be negligible in practical cases.

The longitudinal velocity, dx/dt, of the gas between the cylinders, and hence of any suspended particle, at a distance c from the axis is given by

$$\frac{dx}{dt}=\frac{p}{4\eta}\{c^2+C_1\log c+C_2\}, \quad (1)$$

where η = viscosity of the gas, x = co-ordinate parallel to the axis,
t = time, p = longitudinal pressure gradient,
$C_1=(a^2-A^2)/\log(A/a)$ = constant of integration,
$C_2=(A^2\log a-a^2\log A)/\log(A/a)$ = constant of integration,
A = radius of outer wall of centrifuge, and a = radius of inner wall of centrifuge.

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

Then the total volume of gas flowing through the centrifuge per second is

$$\phi=\int_a^A 2\pi c\frac{dx}{dt}dc=\frac{\pi p\,(A^2-a^2)}{8\eta}\left\{\frac{(A^2-a^2)}{\log\,(A/a)}-(A^2+a^2)\right\}. \tag{2}$$

Type I. The radial acceleration of a particle distant c from the axis is $\omega_M^2 c$, hence by Stokes's law its rate of fall on to the outer cylinder is

$$\frac{dc}{dt}=\frac{2\omega_M^2 cr^2\rho}{9\eta},$$

where ω_M = angular velocity of centrifuge, r = radius of particle and ρ = density of particle. Combining this with (1)

$$\frac{dx}{dc}=\frac{9p}{8\omega_M^2 r^2\rho}\{c+C_1\log c/c+C_2/c\},$$

and the critical particle radius, or cut-off, r_c, will be subject to the relation

$$L=\frac{9p}{8\omega_M^2 r^2\rho}\int_a^A\{c+C_1\log c/c+C_2/c\}\,dc, \tag{3}$$

where L is the length of the centrifuge. Substituting for p from (2), this becomes

$$r_c=\sqrt{\frac{9\phi\eta\log\,(A/a)}{2\,(A^2-a^2)\,\pi\omega_M^2\rho L}}. \tag{4}$$

Type II. Here the angular velocity ω of the gas is not constant in different layers but varies from ω_M at $c=A$, to 0 when $c=a$, according to

$$\omega=\frac{\omega_M A^2}{A^2-a^2}\left\{\frac{c^2-a^2}{c^2}\right\},$$

and instead of (3) we have

$$\frac{dx}{dc}=\frac{9p\,(A^2-a^2)^2}{8\rho r^2\omega_M^2 A^4}\left\{\frac{c^3\,(c^2+C_1\log c+C_2)}{(c^2-a^2)^2}\right\}, \tag{5}$$

the value of whose integral becomes infinite for the lower limit a, in agreement with the previous statement that there is no cut-off with centrifuges of type II. (One of the terms in (5) can only be integrated as a series, but is reducible to a form $\int_1^R\frac{\log y\,dy}{y-1}$, of which a table of values is available.) As a criterion of performance may be taken the fraction, F, of particles of radius r_F removed by the centrifuge, F being determined by

$$F=\frac{\int_{c'}^A\{c^3+C_1c\log c+C_2c\}\,dc}{\int_a^A\{c^3+C_1c\log c+C_2c\}\,dc}, \tag{6}$$

and r_F by (5) integrated between limits A and c', the parameter c' being conveniently chosen a little greater than a. F is that fraction of the total gas flow passing between the cylinder $c=c'$ and the outer wall, and r_F is the cut-off for particles entering the centrifuge at c'.

Effect of centrifuging on size distribution. Particles will obviously be removed in a proportion depending on their size, the number of very small ones being nearly unaffected, and that of the large ones much reduced. If the frequency $\mathscr{F}$ of particles having radii between r and $r+dr$ is given by $\mathscr{F}=\Psi(r)\,dr$, after centrifuging they will be present in

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

a proportion $\mathscr{F}' = (1-F)\,\Psi(r)\,dr$, F being the fraction (6) above. Thus if the original size distribution of a mist is known, the effect of centrifuging can be found by determining F and the corresponding r_F for a number of values of c' and plotting $\mathscr{F}'$ against r.

Efficiency. This is most simply regarded as the ratio of the number of particles collected to the number of particles entering the centrifuge and equal to

$$\frac{\int_0^{\infty \text{ or } r_c} F\Psi(r)\,dr}{\int_0^{\infty} \Psi(r)\,dr},$$

though this quantity will depend upon $\Psi(r)$.

Proportion by weight of mist collected by the centrifuge. With the above notation this is

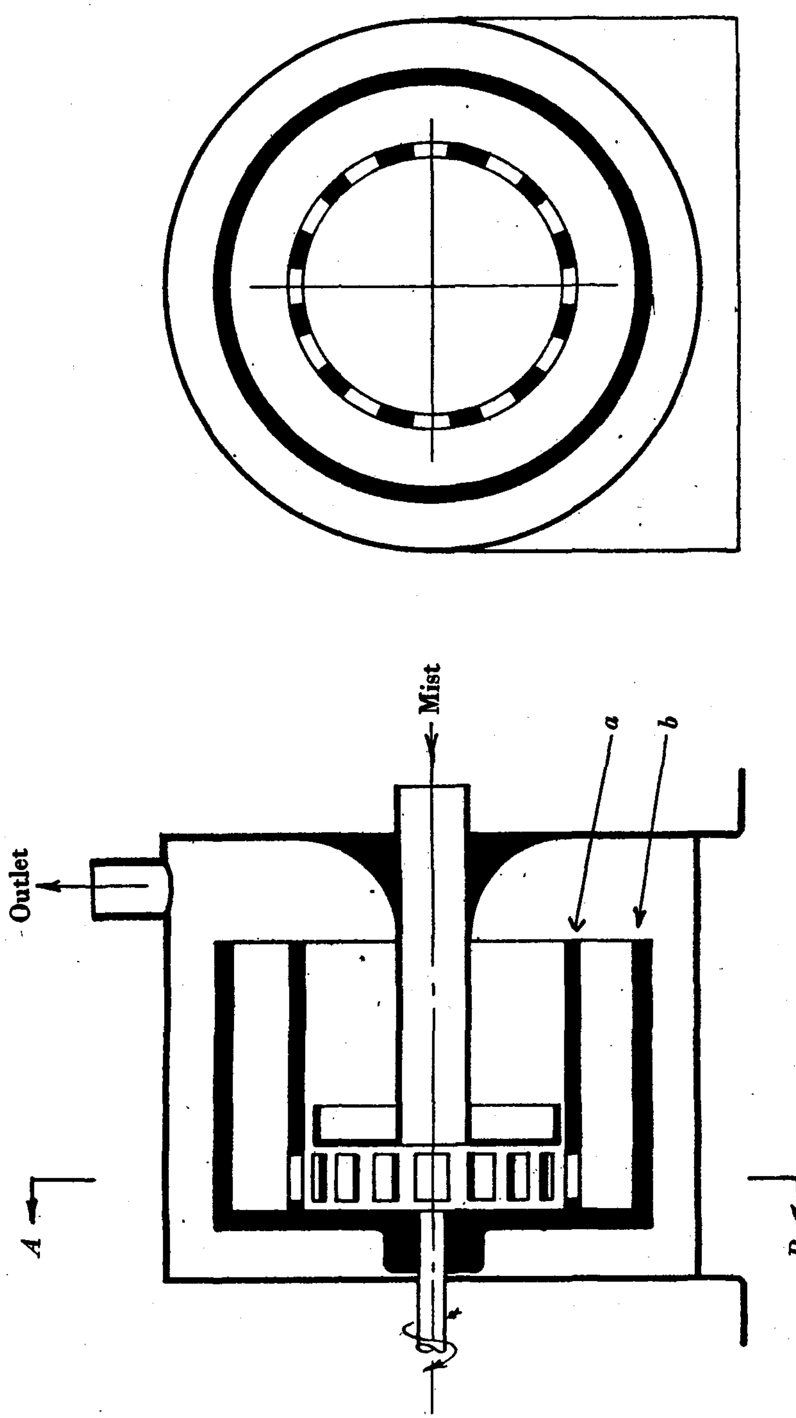
$$\frac{\int_0^{\infty \text{ or } r_c} r^3 F\Psi(r)\,dr}{\int_0^{\infty} r^3\Psi(r)\,dr}.$$

Estimation of size distribution. In theory it should be possible to determine the size distribution in an aerosol by centrifuging it out, say on to a sheet of celluloid lining the outer centrifuge cylinder and afterwards determining the surface density, by number, of particles on the record for various distances from the end. This is not practicable in the cases which we have met, but it might be useful for coarser suspensions.

In these laboratories, three forms of centrifuge have been used for experimental purposes. Centrifuge no. 1 is illustrated in Fig. 2. The rotor is an aluminium casting, having $A = 5{\cdot}1$ cm., $a = 3{\cdot}8$ cm., $L = 4{\cdot}5$ cm., mounted directly on the shaft of a $\frac{1}{20}$ h.p. motor. A rheostat, tachometer and flowmeter are permanently attached. It was designed to remove particles down to $0{\cdot}05\mu$ radius at a speed of 12,000 r.p.m. and with an airflow of 2 l./min.; this expectation was very nearly realized. It was intended to be used, first, for the production of mists having a limited range of particle size; secondly, as a collector for estimating the weight concentration of mists. In the former application it was very successful and convenient; in the latter, both casual and inherent difficulties were encountered which made it unsuitable for our purpose (Twort, Baker, Finn & Powell, 1940).

Centrifuge no. 2 (Fig. 3) was intended for bacteriological purposes. It is very similar to the commercial model of Wells's centrifuge, but is lighter, more convenient, and more efficient than the latter. The motor spindle carries a rubber-lined socket which receives the bottom of a standard 6×1 in. boiling tube, and the mouth of the tube is supported by the intake of a centrifugal fan running on a ball bearing. The inner race of the latter is fixed on the stationary inner tube ($0{\cdot}76$ cm. radius), which is attached to a sliding bracket enabling the inner tube to be retracted when it is required to change the rotor. The centrifuge was expected to remove 85 % of 1μ radius particles from aerosols passed through at 20 l./min. with the motor running at 5000 r.p.m., and this figure was actually obtained.

Centrifuge no. 3 (Fig. 4) was similar to no. 2 in size but having the rotor made of copper tubing ($L = 13$ cm., $A = 1{\cdot}50$ cm., $a = 0{\cdot}76$ cm.). The rotating inner tube was supported independently on spiders; sharp changes in direction of the air stream were avoided as far as possible, and the mist issuing from the fan was collected in a volute chamber.



Section on *AB*

Sectional elevation

Fig. 2.

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

Except where the contrary is stated the aerosols used in the experiments about to be described were made by atomizing mineral oils which were shown not to be sensibly volatile in the dispersed state.

The critical particle size under a given set of conditions is a fairly definite criterion of performance for centrifuges of type I. The determination was carried out on centrifuges nos. 1 and 3 by ultramicroscopic examination of the outgoing mist. A sharp cut-off was not in fact observed, owing no doubt to the paucity of droplets near the critical size, to accidents of coagulation, and to the introduction of foreign particles from the air into the ultramicroscope cell. In any one experiment the radius of the largest particle in each of a considerable number of samples was measured, and the mean of these radii taken as the cut-off. Fig. 5 gives the result for centrifuge no. 1 worked at various speeds with an air-flow constant at 10 l./min. The curves are regular, but diverge widely from those cal-

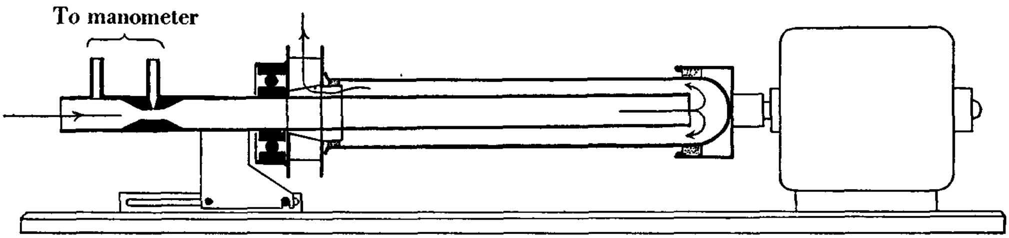


Fig. 3. Centrifuge no. 2.

Fig. 4. Centrifuge no. 3.

culated from equation (4). This is sufficiently accounted for by a large end effect (the ratio $L/(A-a)$ not being great), by turbulence at high speeds, and by the tortuous path of the air stream. With centrifuge no. 3, having stream-lined air passages and a much larger $L/(A-a)$ ratio, the agreement was satisfactory; the experimental values were within $\pm 10\%$ of the calculated values except at the lowest speeds and high rates of airflow, where particles of the critical size were rare in the original mist. Estimations were carried out over a range of both variables: airflow, 5–20 l./min.; rotation 1500–5500 r.p.m. In Fig. 6 the critical radius r_c is plotted against $\sqrt{\phi}/\omega_M$.

Experimental determinations of the effect of centrifuging on the particle size distribution in aerosols were, for centrifuges nos. 2 and 3, in fair agreement with that calculated in the manner explained above; centrifuge no. 1 showed discrepancy of the same order as that found for the cut-off. The distribution curves before and after centrifuging were obtained by a method previously described by us (Twort *et al.* 1940). Five examples are given in Figs. 7–9. It should be noted that the area under the calculated curve is to the area under the curve for the original mist as the number of particles passing the centrifuge is to the number entering; the difference in area divided by the latter area gives the efficiency in the sense defined above. To facilitate comparison, the calculated ordinates have in the figures been multiplied by a factor to make the areas the same (0·5 with 1μ as the unit of length).

The cut-off property of the centrifuge can be used in an interesting manner to determine the extent of rapid 'first phase' evaporation of a volatile component from freshly atomized mixtures. Important changes in concentration often occur during this phase

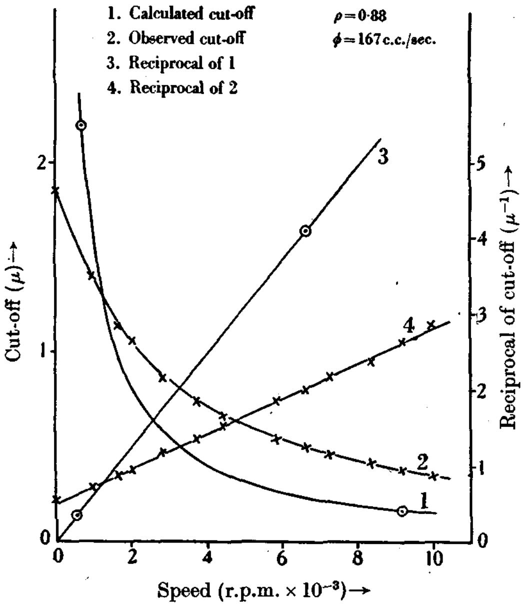


Fig. 5. Cut-off of centrifuge no. 1.

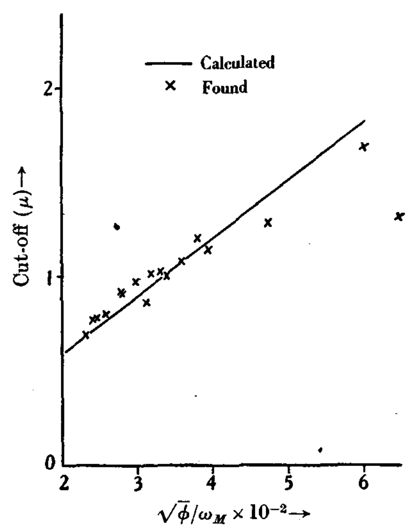


Fig. 6. Cut-off of centrifuge no. 3.

with such velocity that they are not readily accessible to measurement by any other method. If the aerosol is passed directly from the generator into a centrifuge for which the critical particle size r_c is known, no particles of radius greater than r_c will emerge; a determination of the maximum particle size in the issuing mist will, if there is appreciable evaporation, show an apparent cut-off lower than r_c, and the ratio of the cubes of these values measures the volume change which has taken place. Particles of different sizes can be dealt with by altering the conditions of centrifuging and hence the cut-off.

As we have previously pointed out, the break in the evaporation curves for mixtures which are not too complex is fairly sharp, so that the quantity thus estimated is more definite than might at first sight appear. To exemplify the method, measurements of apparent cut-off were made on two solutions for which the disparity of volatilities of the two components was very great, (*a*) 9·1 % W/W benzilic acid in benzyl alcohol, $\rho = 1{\cdot}062^{20^\circ}_{4^\circ}$, (*b*) 20 % W/W retene in diphenylmethane, $\rho = 1{\cdot}014^{20^\circ}_{4^\circ}$, and the results compared with those obtained by working with a non-volatile oil in the atomizer, the centrifuging conditions remaining the same (Table 1).

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

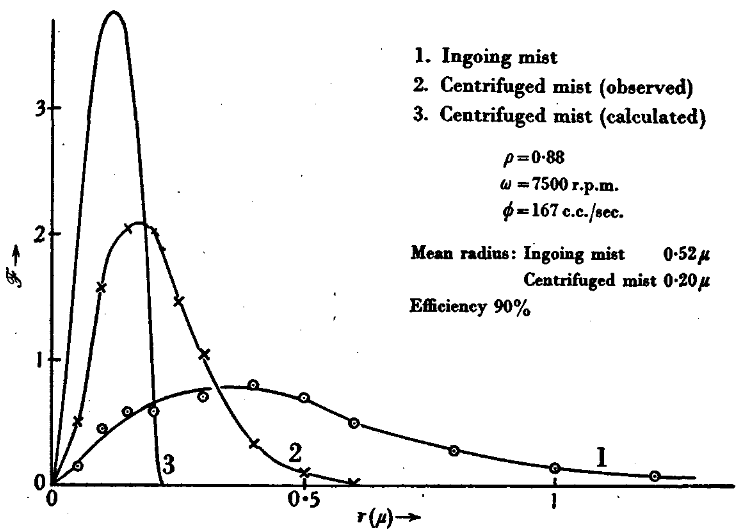


Fig. 7. Centrifuge no. 1. Effect on size distribution.

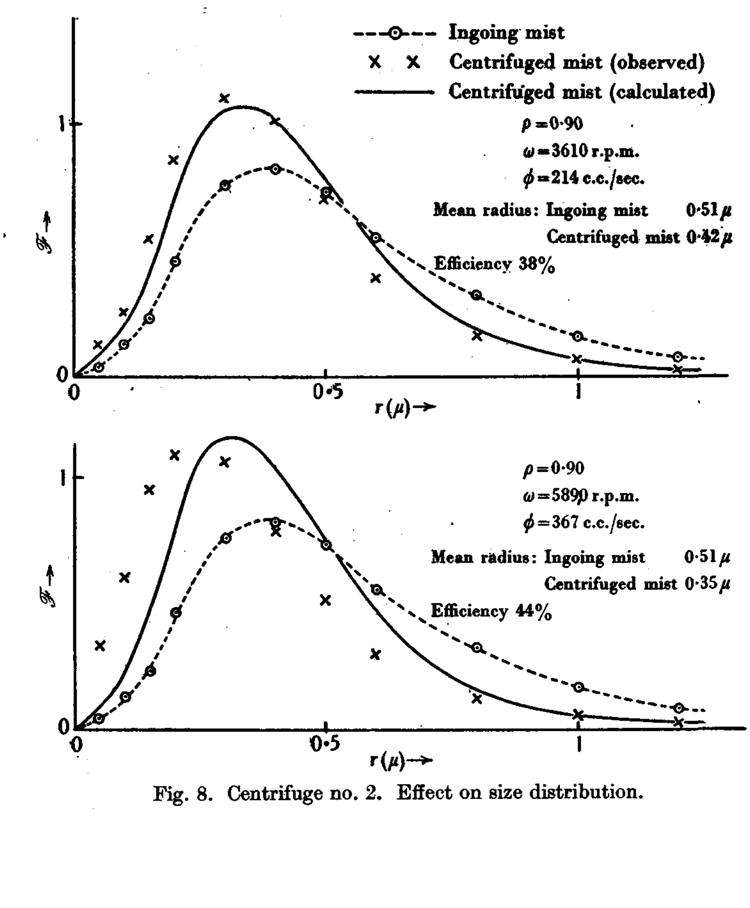


Fig. 8. Centrifuge no. 2. Effect on size distribution.

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

The discrepancy between the mass ratios found and those expected may mean that some of the solvent is retained, but may in part be due to slight evaporation within the centrifuge. With solution (*a*) the first phase was not quite over when the sample came under observation in the ultramicroscope; with (*b*) no evaporation was detectable, and therefore the change was complete within 1 sec. of the particles emerging into free air.

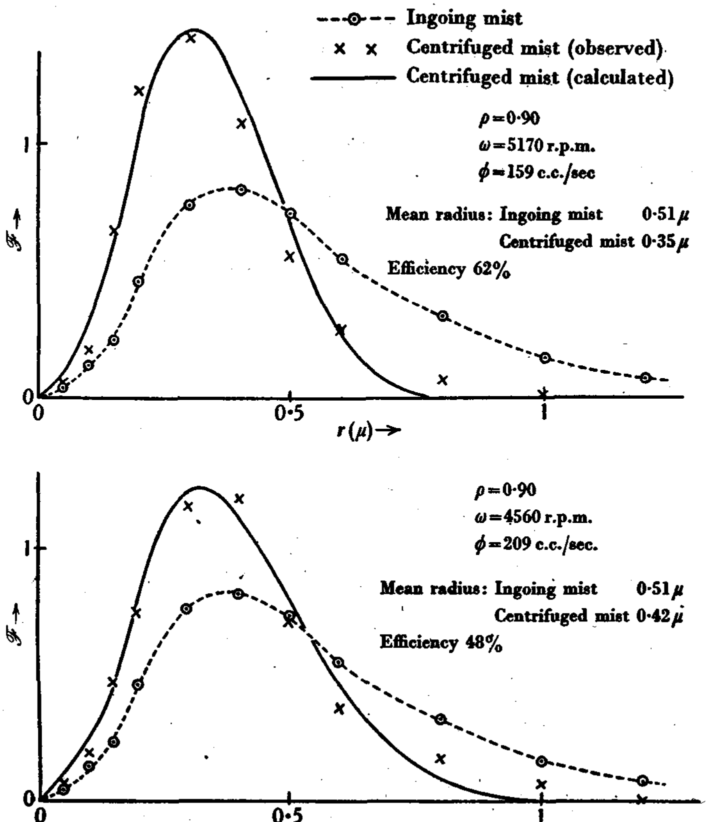


Fig. 9. Centrifuge no. 3. Effect on size distribution.

Table 1. *Estimation of first-phase evaporation*

Centrifuge no. 3, $\phi = 142{\cdot}5$ c.c./sec.

Solution	r_c found μ	Corresponding r_c for involatile aerosol μ	Volume ratio	Mass ratio	Mass ratio expected
(*a*)	0·40	0·86	0·10	0·12	0·091
(*a*)	0·37	0·75	0·12	0·13	0·091
(*b*)	0·49	0·82	0·21	0·22	0·20
(*b*)	0·46	0·74	0·24	0·25	0·20

In a practical problem, this method was used to determine the initial loss of solvent from particles of a 10 % solution of hexyl resorcinol in propylene glycol. Centrifuge no. 1 was used with a wide range of speeds. It was found that during the first phase the largest particles dealt with (1·8μ radius) lost about 65 %, the smallest (0·2μ) about 90 % of their propylene glycol.

As a selector for producing mists of a regulated average particle size, the air centrifuge is inefficient in that a particle's chance of escaping the centrifugal action depends on its distance from the axis when it enters, and many particles of a size below the critical are thus removed. For experimental work this defect is not a great disadvantage, but when the centrifuge is used in connexion with an atomizer for practical air disinfection, it results in a serious loss of germicide in useful form. The modification shown in Fig. 10 overcomes

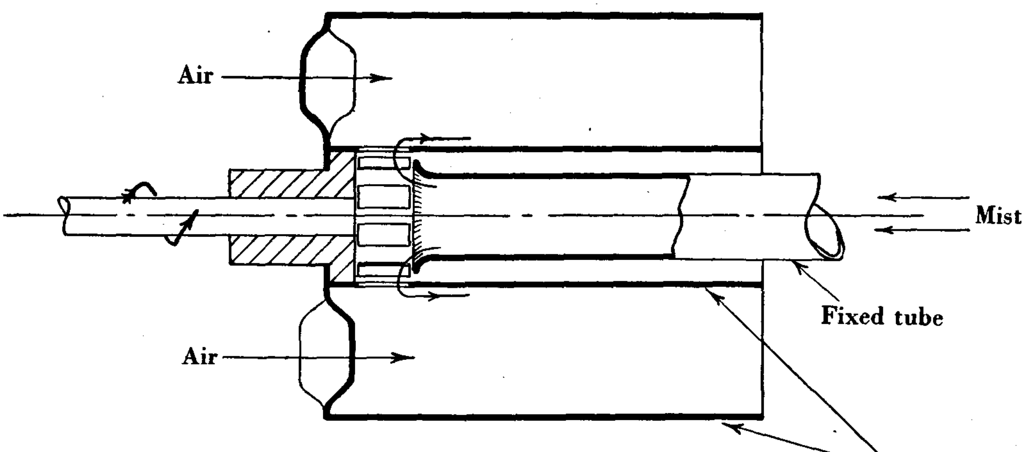


Fig. 10. Improved centrifuge.

it to a considerable extent (Finn, Powell & Shepherd's Industries Ltd., 1939). The blind end of the centrifuge is pierced with radial slots, and it is then formed into a fan which drives a current of air between the cylinders when they rotate. The stream of mist enters through holes in the inner cylinder, and is bent sharply round by the air from the fan to follow a path of limited cross-section near the axis. The suspended particles are thus subjected to a much more nearly equal centrifugal force, and their fate is more closely dependent on their radii. In this application the very considerable dilution of the mist not only does not matter, but assists in rapid distribution.

Discussion

The following results, taken together with the proportionality relations indicated by equations (4) and (5), will indicate the directions in which changes have to be made in order to meet an assigned requirement.

Table 2. *Performance of centrifuges running at* 5000 *r.p.m. and* 10 *l./min. airflow*

Taking $\rho = 1$ and $\eta = 1{\cdot}8 \times 10^{-4}$.

Centrifuge	Cut-off μ	Fraction of particles removed: $0{\cdot}5\mu$ radius	$1{\cdot}0\mu$ radius
No. 1	0·62	0·72	1·0
No. 2	—	0·62	0·95
No. 3	0·74	0·64	1·0

The rate of rotation and airflow are readily variable; apart from this it is to be noted that the efficiency also depends largely on the ratio A/a, being greater the nearer this approaches 1. A rather short, wide rotor makes for mechanical strength and stability, and is capable of being driven at high speeds with a reasonable airflow, but its performance

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

departs very considerably from the simple ideal. While the mathematical formulae given here are invaluable in working out a design, obviating the construction of trial models, it is evident that calibration will in general be desirable.

For bacteriological work, Wells's ingenious method of construction is especially convenient, and involves a minimum danger of contamination to sterile surfaces. The ordinary stout boiling tubes of our no. 2 centrifuge have the advantage over the specially formed Pyrex vessels of Wells that they are much less expensive and more easily replaced. While our rotor is smaller, its efficiency is increased by the lower A/a ratio, so that shorter sampling times can be used. We have had no breakages due to lack of balance up to speeds of 6000 r.p.m. using tubes selected for symmetry.

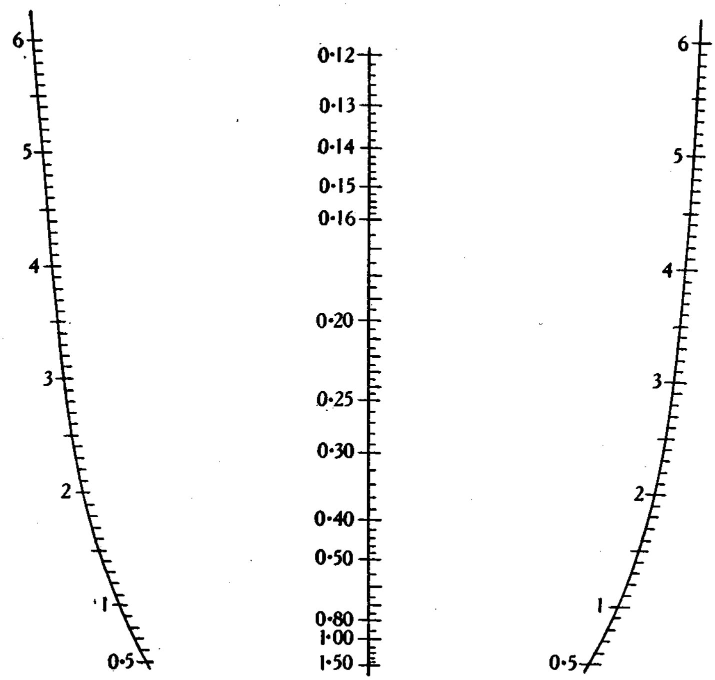


Fig. 11. Nomogram for $\sqrt{\frac{\log_e (A/a)}{A^2-a^2}}$ (centimetre units).

Objections to the use of the Wells centrifuge for determining bacterial populations have been raised on the score of its poor efficiency (Bourdillon, Lidwell & Thomas, 1941). These are only partly justified. It is true that for a bacterial aerosol of quite unknown constitution the discrepancy between the number of organisms collected and the number actually present cannot be assessed readily, but often only a single species or a restricted class will be dealt with, their sizes will be known, and the true number can then be estimated from the calculated efficiency. In any case a centrifuge of type I can be constructed which will remove most common organisms completely.

Summary

The principle of the aerosol centrifuge is described, and an elementary mathematical treatment is given.

The relations between the behaviour of the centrifuge and its dimensions, speed and

https://doi.org/10.1017/S0022172400035567 Published online by Cambridge University Press

airflow have been tested experimentally on three machines. It is shown that the mathematical formulae given are an adequate basis for design.

Various applications are mentioned.

Note 1. *Size-frequency curves*

The method used here for the determination of particle size distribution curves of aerosols was that used by us previously (Twort *et al.* 1940). In each case at least twenty samples of mist were counted for 10 min. each. Although fully aware of its probably high inaccuracy at the ends of the size range, we have continued to use the method because others appear to be hardly less doubtful when applied to liquid droplets of 0·5μ average radius, and because our experience has shown it to be satisfactorily self-consistent.

Note 2. *Integrations*

The integration of equations (3), (5) and (6) is conveniently carried out graphically, but with the last the error may be large. In equation (6) there is a term $c^3 \log c/(c^2-a^2)^2$:

$$\int \frac{c^3 \log c\,dc}{(c^2-a^2)^2} = \frac{1}{4}\left[\log a^2 \int \frac{x\,dx}{(x-1)^2} + \int \frac{\log x\,dx}{(x-1)^2} + \int \frac{\log x\,dx}{(x-1)}\right],$$

where $x = c^2/a^2$, and the value of the last term can be obtained from

$$\int_1^R \frac{\log x\,dx}{x-1} = \sum_1^\infty (-)^{n+1} \frac{(R-1)^n}{n^2} \quad (0 \leqslant R \leqslant 2)$$

$$= \frac{\pi^2}{6} + \log R\,\{\log (R-1) - \tfrac{1}{2} \log R\} - \sum_1^\infty R^{-n} n^{-2} \quad (1 \leqslant R).$$

Note 3

The nomogram of Fig. 11 will be found convenient for rapid calculation with equation (4). A line passed through the value of A on either curved scale and through a on the other gives the value of $\sqrt{\frac{\log (A/a)}{A^2-a^2}}$ by its intercept on the central scale. If the other variables in equation (4) are already determined, any line passed through the corresponding value of $\sqrt{\frac{\log (A/a)}{A^2-a^2}}$ on the central scale will intercept the other two in appropriate values of A and a, which can thus be conveniently chosen by tilting the line; this operation is very tedious when carried out arithmetically as it must be by trial and error. It has to be remembered that as A and a approach each other, the pressure required to produce a given airflow increases.

REFERENCES

Bourdillon, R. B., Lidwell, O. M. & Thomas, J. C. (1941). A slit sampler for collecting and counting air-borne bacteria. *J. Hyg., Camb.*, **41**, 198.

Finn, S. R., Powell, E. O. & Shepherd's Industries Ltd. (1939). An improved centrifuge for forming aerosols. British Patent 534,849 (1941).

Twort, C. C., Baker, A. H., Finn, S. R. & Powell, E. O. (1940). The disinfection of closed atmospheres with germicidal aerosols. *J. Hyg., Camb.*, **40**, 253–344.

Wells, W. F. (1936). Centrifuging apparatus. U.S.A. Patent 2,043,313.

Wells, W. F., Phelps, E. B. & Winslow, C. E. A. (1937). A bacteriological method of sanitary air analysis. Report of sub-committee, *Amer. J. Publ. Hlth* (*Yearbook*), **27**, 97–101.