Rain Washout of Partially Wettable Insoluble Particles

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Abstract. The way in which partial wettability of airborne particles affects washout by falling rain is examined in detail, in order to extend the work of Pemberton to cover all possible contact angles ranging from 0° to 180°. The problem of shoot-through of impacting particles is considered from several new viewpoints. It is concluded that for airborne particles of commonly encountered size and density, shoot-through will be unimportant in reducing collection efficiencies. Methods are illustrated for computing percentage removal of particles of specified diameter, density, and wettability under action of rains of specified intensity and drop size. For light rains composed chiefly of small drops, rebound markedly reduces removal rates if the contact angle appreciably exceeds 90°.

Introduction. Apparently the first to consider rain scavenging of less than fully wettable airborne particles were *McCulley et al.* [1956]. They introduced the idea of minimum kinetic energy of impact for successful penetration of the raindrop by the particle, but their theoretical analysis was very limited in scope. A much more thorough and extensive analysis was subsequently given by *Pemberton* [1960], including automatic computer calculations of both the external aerodynamics of the collision process and the internal hydrodynamics accompanying the penetration process. A limitation of Pemberton's analysis results from his limiting his attention solely to *completely nonwettable* particles. It is a well-established fact of surface chemistry [*Adamson,* 1960; *Davies and Rideal,* 1961] that, of all substances, only a very few are completely wettable and still fewer (if any) attain the opposite extreme of being completely nonwettable against water, the majority of materials being *partially wettable,* with water contact angle θ greater than 0° but less than the 180° limit which implies complete nonwettability. Hence there is need to examine rain scavenging of the populous class of only partially wettable particles. The present paper will extend Pemberton's analysis to cover all possible contact angles θ.

Penetration dynamics for partially wettable particles. We may speak here of spherules to suggest that present results are closely applicable to all particles that do not depart too greatly from sphericity. If we call the spherule radius r and the raindrop radius R, we require that the inequality $R > r$ be satisfied to such an extent that the raindrop surface looks more or less flat in the immediate neighborhood of the penetration point. So long, in fact, as R is at least 4 or 5 times greater than r, this condition will be met well enough; and since even drizzle drops fulfill this requirement for the largest spherules that can become airborne, this is not a serious limitation here.

Consider Figure 1*a*, where a partially wettable spherule of radius r is shown *after* making contact with the raindrop, but *before* complete penetration has occurred. For simplicity of discussion, we assume for the present that the spherule's motion (from right to left in the figure) is radially inward relative to the raindrop. Depth of penetration is measured by the distance x; penetration is complete when $x = 2r$. The spherule radius to P, a point on the circular locus of air-water-spherule contact lying in a plane normal to the line of centers (and hence normal to the plane of Figure 1), makes some angle ϕ with the line of centers, as shown. If we designate as β the quantity $\pi - \theta$, the water surface makes angle β with the tangent PP' at P, and the surface tension force at P is acting toward the upper right, i.e., toward T in Figure 1*a*. If the spherule were *completely* nonwettable, line PT would coincide with line PP'. The illustrated case corresponds to a rather poorly wettable case of $\theta \approx 150°$.

Essential geometric details are carried over to Figure 1*b*, where the vector element of sur-

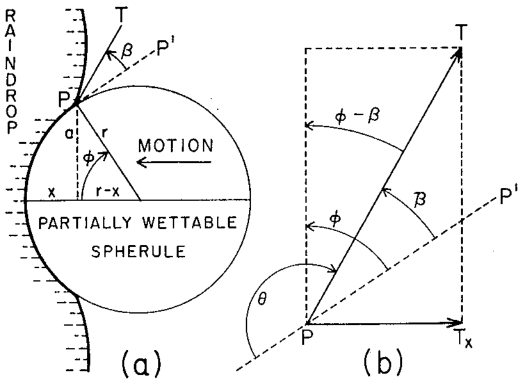

Fig. 1. Definition sketch for penetration dynamics.

face tension force acting on unit length of the circular contact locus near P is now indicated by the vector $\mathbf{T}$, whose component along the line of centers, *resisting entry of the spherule*, is shown as T_x. (The components of the surface tension forces acting normal to the line of centers cancel in pairs around the full circle of air-spherule-water contact and hence exert *no* net force on the entering spherule.) The work W done against the sum of all resisting components while the spherule penetrates to some arbitrary depth x is then given by

$$W = \int_0^x 2\pi a T_x \, dx \qquad (1)$$

where a is as shown in Figure 1*a*. This work W is done, of course, at the expense of the spherule's initial kinetic energy, so that full penetration can occur only if the latter is great enough to exceed the value assumed by the W integral when the upper limit in (1) is put equal to $2r$.

If σ is the surface tension of water against air, we have from Figure 1*b* that $T_x = \sigma \sin (\phi - \beta)$. Changing to ϕ as a preferable variable of integration, we rewrite (1) as

$$W(\phi) = \int_0^\phi 2\pi r^2 \sigma \sin^2 \phi \sin (\phi - \beta) \, d\phi$$

$$= 2\pi r^2 \sigma \int_0^\phi (\cos \beta \sin^3 \phi$$

$$- \sin \beta \sin^2 \phi \cos \phi) \, d\phi$$

$$= (2/3)\pi r^2 \sigma [\cos \beta (2 - 2 \cos \phi$$

$$- \cos \phi \sin^2 \phi) - \sin \beta \sin^3 \phi] \qquad (2)$$

Full penetration, specified by $\phi = \pi$, is given by

$$W_\pi = (8/3)\pi r^2 \sigma \cos \beta \qquad (3)$$

and thus is seen to be controlled jointly by the surface tension of the raindrop and by the size and wettability of the impacting particle.

Equation 2 has been used to construct curves of $W(\phi)$ for four values of θ corresponding to poorly wettable particles, namely 110°, 130°, 150°, and 180°, with spherule diameter taken, for purposes of illustration, as 20 μ. The results are plotted in Figure 2. For $\theta = 180°$, complete nonwettability, the sole case treated by Pemberton, $W(\phi)$ rises monotonically with θ to the full-penetration value given by (3) for $\cos \beta = 1$; this monotonic behavior results from the circumstance that if $\theta = 180°$, T_x is, for all ϕ, a resisting component. On the other hand, for

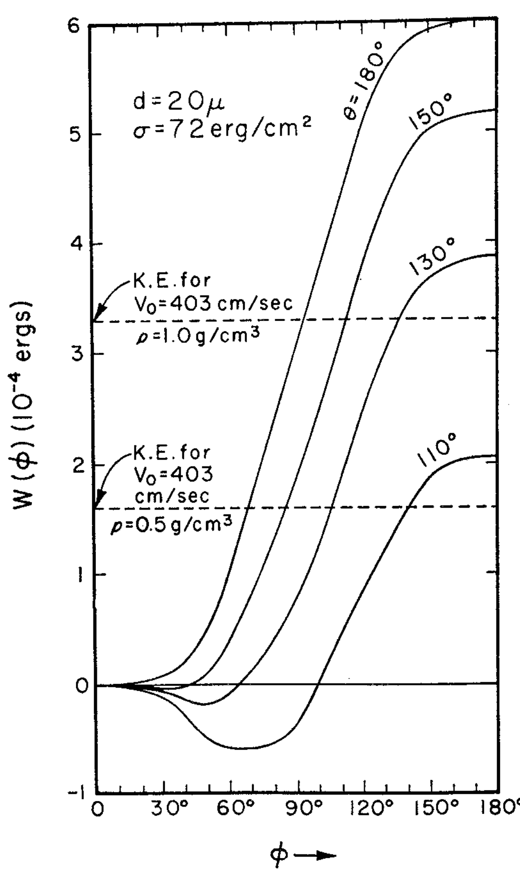

Fig. 2. Dependence of entry work on contact angle and depth of immersion.

any $\theta < 180°$, i.e., for partial wettability, T_x is initially directed into the interior of the raindrop, and it changes over to a resisting component only when the spherule has penetrated far enough so that P rides up the spherule cross section to such a point that the water surface at P is normal to the line of centers. The smaller θ, the greater x and ϕ must be for this onset of resistance to be attained. For $\theta = 110°$, for example, Figure 2 shows that $W(\phi)$ grows increasingly greater in the negative sense until onset of resistance occurs near $\phi = 65°$. Beyond that stage, T_x opposes further penetration, weakly at first but with increasing effectiveness as ϕ increases. By the time $\phi \approx 100°$, Figure 2 shows that for $\theta = 110°$ the work done against surface tension forces has just cancelled the initial work done by these forces, whence the cumulative value of $W(\phi)$ there passes through a zero value, thereafter becoming positive and rising monotonically to the full-penetration value given by (3).

To further clarify the penetration dynamics, let us consider a raindrop with $R = 0.5$ mm and hence terminal fall velocity of 403 cm/sec [*Gunn and Kinzer*, 1949; cf. Figure 6 below]. If such a raindrop overtakes our Figure 2 spherule of $r = 10$ μ, the terminal velocity of the latter is small enough to be neglected in comparison with the raindrop's velocity, so the relative velocity of approach of spherule and raindrop is $V_0 \approx 403$ cm/sec. The initial kinetic energy of the spherule, viewed in a coordinate system fixed in the raindrop, will then be proportional to V_0^2. If the spherule density ρ is 0.5 g/cm³ (a nominal lower limit for important airborne particles) for example, the impact kinetic energy is thus 1.6×10^{-4} erg; while if ρ is, for instance, 1.0 g/cm³, the kinetic energy is 3.2×10^{-4} erg. These two kinetic energies are indicated in Figure 2 by the dashed horizontal lines, whose implications we now examine.

Consider first the larger of these values. With an initial impact kinetic energy amounting to 3.2×10^{-4} erg, our spherule of density $\rho = 1$ g/cm³ can only continue penetrating into the raindrop until it has expended all of that energy in work done against surface tension; so from Figure 2 we find that if the spherule is completely nonwettable ($\theta = 180°$) its entry is halted well before complete immersion has occurred; in fact it is halted when $\phi \approx 90°$, i.e., when it is only half immersed. Having been brought to rest in the raindrop coordinate system, it is then *rapidly forced back out of the drop and swept away in the relative airstream;* i.e., capture has *not* occurred. Instead, we shall say here that 'rebound' has occurred. If its wettability is somewhat greater, it can achieve somewhat greater penetration. For $\theta = 150°$, its maximum penetration takes it to about $\phi = 110°$; and for $\theta = 130°$, we see that it gets to about $\phi = 130°$ before being repulsed.

On the other hand, if the wettability of this same particle is characterized by contact angle $\theta = 110°$, Figure 2 reveals that complete penetration does occur, since the work done against surface tension during the entire penetration process is now only about 2.1×10^{-4} erg, or only about two-thirds of the available impact energy. Indeed, in this last case, the spherule, after accomplishing its full penetration, is still moving toward the raindrop's interior, having a residual kinetic energy at instant of immersion of about 1.1×10^{-4} erg. Hence, we here confront the question of whether the spherule's residual energy will permit it to shoot all the way through the raindrop to the opposite surface. If so, then, as Pemberton noted, the slightest contact with that surface is sufficient to cause new surface tension effects to eject it from that opposite side and once more capture has not occurred because the particle has shot right through the raindrop. However, if the residual kinetic energy is not too great, the hydrodynamic drag of the water on the spherule will bring it to rest before it traverses the drop's interior, true capture has occurred, and the particle is destined to be rain scavenged. We return to these details in the following section; for the moment it need only be noted that it was one of the merits of Pemberton's analysis that he programmed into his calculations, as one of the several factors controlling his particular 'collection efficiency,' all of these considerations of interior hydrodynamics (including the still more complex case of 'off-center' collision which we have not yet explicitly treated here).

Next, consider the *smaller* of the two impact kinetic energies indicated in Figure 2, 1.6×10^{-4} erg, for spherule density of 0.5 g/cm³. In this less energetic impact, the spherule is not only stopped earlier than in the preceding case, but

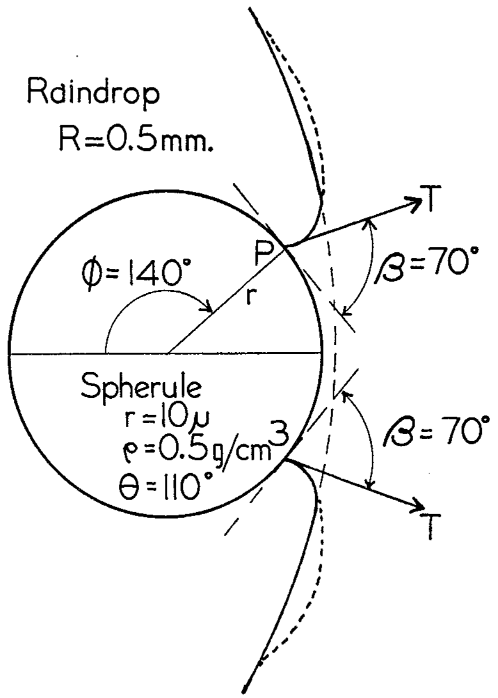

Fig. 3. Spherule at epoch of maximum immersion.

now cannot fully penetrate the specified raindrop for *any* of the four plotted contact angles. Even for θ as low as 110°, we see that it is stopped by surface tension forces by the time it has penetrated to $\phi \approx 140°$. To illustrate how nearly immersed a partially wettable particle may become, yet still be rejected by action of surface tension, this last case is shown in Figure 3, the spherule being at its epoch of deepest penetration ($\phi = 140°$). Its outermost point lies nearly flush with the local tangent to the raindrop and is actually inside the previous position (dashed arc) of the raindrop surface. (Dotted bulges will be considered later.) Despite such deep immersion, the particle is promptly forced back out of the raindrop and swept away as a case of rebound.

We may summarize the foregoing discussion of the data of Figure 2 by noting that full penetration is favored if the raindrop is large (V_0 large), if the spherule density is large, and if θ is low. Of course, if r and ρ are too great, the terminal fall velocity of the spherule grows large, diminishing the relative velocity of impact in a way that may be prejudicial to penetration. A low θ may also work in this direction, because this favors large *residual* kinetic energy, perhaps enhancing shoot-through. All such interacting factors are considered in Pemberton's model and hence in his collection-efficiency computations, which we shall use below. Detailed consideration is not necessary here, but we shall briefly reconsider some of the points below.

Present applicability of Pemberton's dimensionless parameters. Pemberton explicitly considered only a single value of θ, namely $\theta = 180°$, for theoretically nonwettable particles. We must next consider whether Pemberton's extensive computations of collection efficiency E can be used for present purposes, wherein we hope to treat θ as a parameter that may vary widely over the full range from 0° to 180°.

Pemberton calculated E as a function of the usual inertial parameter K of aerodynamic collection theory, namely

$$K = (2\rho r^2 V_0)/(9\mu_a R) \qquad (4)$$

where μ_a is the absolute viscosity of air, for a series of discrete values of a second dimensionless parameter which he termed the *penetration parameter* χ, defined by

$$\chi \equiv V_{PN}/V_0 \qquad (5)$$

where V_{PN} is the velocity component *normal* to the raindrop surface required to barely permit penetration against surface tension forces (his subscript PN denoting 'normal penetration,' presumably). For his case of completely nonwettable particles, he had $V_{PN} = (4\sigma/\rho r)^{1/2}$. However, in the present context we have instead, from (3) above, on replacing W_π by $(m/2)V_{PN}^2$ and expressing the spherule mass m in terms of ρ and r,

$$V_{PN} = (4\sigma \cos \beta/\rho r)^{1/2} \qquad (6)$$

which reduces to Pemberton's V_{PN} for his case $\theta = 180°$, i.e., $\beta = 0$.

Because all Pemberton's computer calculations of E were based only on numerical magnitudes of the *dimensionless* quantities K and χ, without regard to how those quantities might be composed, it follows immediately that all his results for the integration of the nondimensionalized equations of particle motion *are* directly applicable here when we form the dimensionless parameter *using our revised definition of* V_{PN} *in place of his*. As was noted earlier, this is indeed fortunate, for it now permits us to extend the range of applicability of his results to a far broader and a far more realistic class of collection problems than that which he discussed.

We might summarize the complete set of relevant similitude criteria as follows:

1. The Reynolds number Re for the airflow relative to the raindrop is the criterion for geometric similarity of the *streamlines of the external airflow field.*
2. The inertial parameter K is the criterion for geometric similarity of the *particle trajectories* relative to the airflow field and to the raindrop in the region *exterior* to the raindrop.
3. The penetration parameter χ and K jointly form a criterion for geometric similarity of the *penetration kinematics* of the impacting particle and govern the interior hydrodynamics of movement of the particle inside the drop.

When Re, K, and χ are fixed, the particle's complete trajectory, both exterior to and interior to the raindrop, is fully determined.

A further hidden similitude condition requires that the Reynolds number of the airflow *relative* to the particle itself be small, of order less than unity, in order that the particle *drag* obey Stokes's law; and an exactly similar requirement holds for the interior hydrodynamics.

In all, we are justified in using Pemberton's results for *any* impaction problem wherein Re, K, and χ fall into the range for which he gave solutions in terms of collection efficiency E. Thus the fact that the present formulation of V_{PN} is broader than Pemberton's original formulation carries no penalty; it merely shifts our χ values, for given V_0, to other parts of the χ range he considered.

Discussion of collection efficiencies. The Pemberton curves for $E(K, \chi)$ are reproduced in Figure 4, the range of K being from about 0.4 to 30, χ varying from zero up to 0.9. It should be noted that Pemberton's assumed airflow around the raindrop was governed by the *potential-flow* solution, whence one will tend to overestimate E when dealing with very small raindrops or drizzle drops.

The uppermost curve in Figure 4 warrants special comment in two respects. It is identical with the case treated by earlier investigators who ignored the surface tension barrier, since that curve for $\chi = 0$ corresponds to the case where zero entry work must be done against surface tension. If we compare that curve with, say, Fonda and Herne's potential-flow curve [*Herne*, 1960], we find that the two curves agree as well as the sample checkpoints can be read. This constitutes a relevant check on the Pemberton formulation and calculations, but it can also tell us something more: For those of Pemberton's calculations in which $\chi = 0$, no reduction of rebound could occur as a result of surface tension effects, *yet there would be no concurrent inhibition of shoot-through losses.* Hence the fact that this uppermost curve does agree with the Fonda and Herne (and other similar) computations stands as independent evidence that shoot-through is generally unimportant. That shoot-through was probably overstressed in Pemberton's discussion can also be inferred from the following considerations: Integrating Stokes's law from an initial velocity v_0 (just inside the drop surface) to a final velocity of zero to establish the particle stopping-distance S in the water, yields $S = 2r^2\rho v_0/9\mu$, where μ is the absolute viscosity of water. Calculation then reveals that S is generally small enough compared with raindrop sizes to preclude appreciable shoot-through. For instance, the smallest particle of density 2.5 g/cm³ which could cross a drizzle drop of $R = 100$ μ would have $r = 30$ μ. Except in problems involving nuclear weapon debris, particles this large and with such high density are seldom found airborne. In addition, actual shoot-through will be a bit smaller than Pemberton's calculations predict because examination of Reynolds numbers for the particle's motion inside the drop reveals that, in just those cases most conducive to shoot-through, the particle Reynolds number inside the raindrop will be larger than unity, whence the actual drag will exceed the Stokes's magnitude. Finally, very rough considerations suggest that abstraction of particle kinetic energy as a result of wave formation (roughly suggested by the dashed bulges shown in Figure 3) and transfer of energy into drop deformation oscillations at impact may leave the particle with rather less energy after penetration than is assumed in Pemberton's model. In all, it is the present writer's conclusion that shoot-through is probably less of an inhibiting factor in washout than Pemberton indicated.

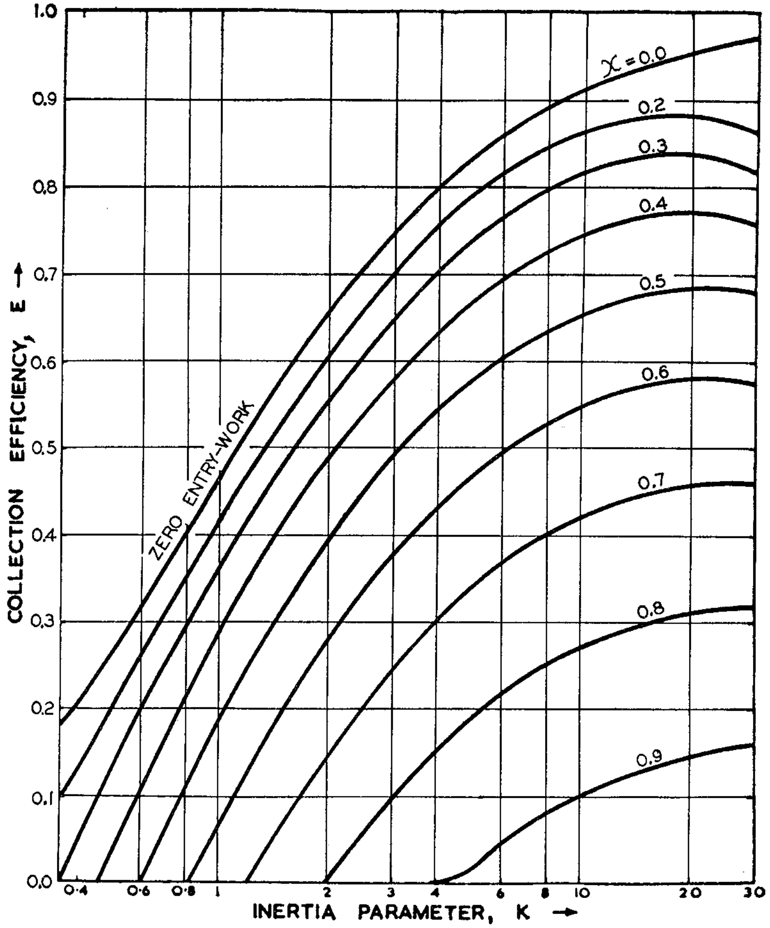

Fig. 4. Collection efficiency E as function of K and χ (after Pemberton).

Second, we must look closely at another aspect of the uppermost curve of Figure 4. Pemberton described it as the curve for 'completely wettable' particles; but this is erroneous. It is, instead, the curve for particles with $\theta = 90°$, as can be seen from (5) and (6). Now $\theta = 90°$ by no means characterizes the case of complete wettability, which calls for $\theta = 0°$. Closer scrutiny of this point raises an interesting new question: Is it possible that E will be markedly altered from its values given by the curve $\chi = 0$ in Figure 4 if $0° < \theta < 90°$? In this θ range, surface tension forces will do work on (rather than against) the particle during entry, *accelerating it and leaving it with residual energy greater than the impact kinetic energy.* This circumstance appears, per se, to enhance the possibility of shoot-through. Since Pemberton did not recognize this possibility and hence did not make any allowance for it in his model and computations, it might seem that we really cannot apply Pemberton's work to any θ's in the range $\theta < 90°$.

In fact, the latter restriction seems extremely unlikely, as will now be shown. Although particles in the range of θ from 0° to 90° will be accelerated during penetration, thereby enhancing shoot-through possibility, those same particles will face a correspondingly large barrier on trying to escape from the far side, if they do succeed in reaching it. That is, we here encounter the new factor of the *emergence work,* which we may designate as W_e. With suitable attention to signs, it is immediately apparent that W_e will be given by (3) since entry work W_π and emergence work W_e are governed by the same basic considerations and equations. For the simple case of a bottom-center impact with $\theta = 0°$, entry will be accompanied by a substantial *increase* in particle kinetic energy, by an amount equal to the absolute magnitude of W_π; but if the particle survives the Stokes's drag losses and reaches the top-center of the drop, *it must then perform emergence work W_e of exactly the same absolute magnitude of W_π in escaping through the surface tension barrier.* Thus, we sense that, broadly speaking, the inhibiting factor of emergence work will tend to just cancel the shoot-through enhancement entering by virtue of the changed sign of the entry work as we move into the range $\theta < 90°$. Hence, it becomes the present writer's conclusion that the uppermost curve of Figure 4, for $\chi = 0$, will give E quite accurately for *all* particles of $\theta \leq 90°$ so long as we do not have to consider denser and far larger particles than are usually present in the atmosphere. Nuclear debris probably warrants a special investigation on this score. Curiously, we find that scavenging of nuclear fallout from surface bursts, which may have been Pemberton's prime concern, enters repeatedly as a special case least adequately covered by Pemberton's analysis. Indeed, the values of θ likely to characterize fallout particles are actually another case in point. Some oxides have θ as low as zero (TiO_2, SnO; see *Adamson* [1960]), and no published tables of θ suggest any likelihood that fallout particles will actually have $\theta = 180°$, as Pemberton appears to have assumed in his study.

The curves of Figure 4, other than the topmost curve, whose meaning has now been clarified and extended, display the increasingly greater importance of rebound suppression of E as we raise the relative magnitude of the surface tension barrier (i.e., as we raise V_{PN} relative to V_0). Whereas the cutoff point of ($E = 0$) in potential flow as deduced by previous investigators who have ignored wettability considerations (and as indicated roughly by the trend of the $\chi = 0$ curve in Figure 4) lies at $K \approx 0.08$, we see that as χ increases from 0, the cutoff value of K marches to the right, so that when we reach $\chi = 0.9$, rebound holds E to zero until the inertia parameter K exceeds about 4.

To permit ready use of Pemberton's E curves of Figure 4, the writer has computed from (6) and plotted in Figure 5 curves for V_{PN} as a function of spherule diameter d for three commonly encountered densities and for four different values of θ in the range to which Pemberton's results apply unequivocably, namely the range $\theta \geq 90°$. On the same figure is plotted the variation of raindrop terminal velocity V_0 as a function of raindrop diameter D as found by *Gunn and Kinzer* [1949]. The use of Figure 5 may be illustrated with reference to the dotted lines shown in the figure. Suppose $d = 30\ \mu$, $\rho = 0.5$ g/cm^3, and $\theta = 150°$. From the point $d = 30\ \mu$ on the lower abscissa of Figure 5 we find that $V_{PN} \approx 570$ cm/sec for $\rho = 0.5$ g/cm^3, $\theta = 150°$. If we wish to know the smallest raindrops whose fall velocity V_0 is great enough to permit capture of these particles in the most favored case of bottom-center impact, we move to the left along the dashed horizontal line to the V_0 curve, then vertically to the upper abscissa scale, where we read $D \approx 1.6$ mm. In general, Figure 5 displays the important point that, aside from aerodynamic collision-theory considerations, small particles will tend to be poorly scavenged because they can be captured only by rare, large raindrops (upper left-hand portion of the field of V_{PN} curves), though the chance of capture will be enhanced if the density is high and θ low (area of interest then shifted to lower right-hand corner of Figure 5).

Scavenging rates. In this section, the effects of partial wettability on the efficiency of rain washout of particles will be illustrated by computation for some representative cases, using Figures 4 and 5. Because the writer's immediate interest in undertaking the present analyses lay in checking whether earlier analyses of pollen and spore washout [*McDonald,* 1962] could have been seriously in error for reasons of partial wettability of pollen grains, only densities of the sort found in such particles have been considered, $\rho = 0.5$ g/cm^3 and $\rho = 1$ g/cm^3 being chosen as illustrative. Values of 90°, 110°, 130°, 150°, and 180° were used for θ.

Values of V_{PN} were obtained from Figure 5 for four different raindrop diameters, namely 0.5, 1, 2, and 4 mm, and for three spherule diameters, namely 10, 20, and 50 μ, spanning the likely range of pollen grain diameters and also covering the larger sizes of common airborne particles of any sort. Values of the collection efficiency E (expressed as percentages)

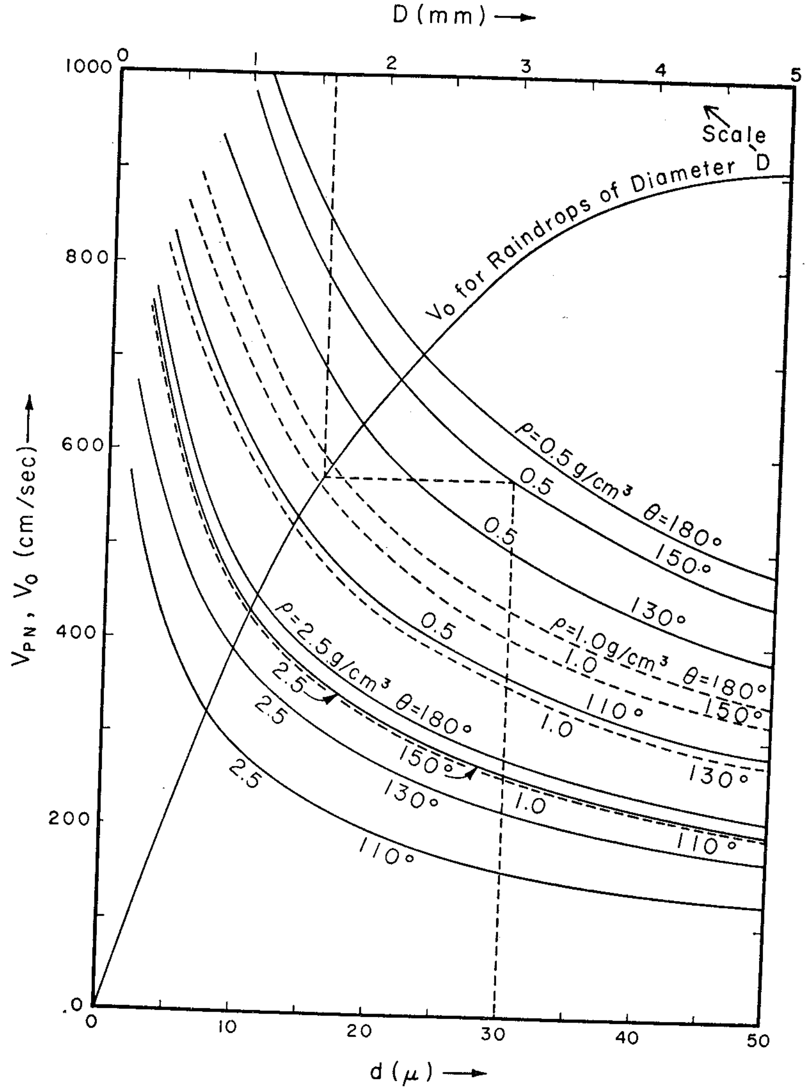

Fig. 5. Penetration velocity and terminal velocity curves.

are given in Table 1, since these E values are of direct physical interest in their own right. The values entered in parentheses were estimated from the curves of Figure 5 by plausible extrapolations extended somewhat outside the range of K for which Pemberton calculated E. The values for $\theta = 90°$ correspond to values obtained by previous investigators who have ignored surface tension effects. Table 1 shows that as θ rises above the neutral value, $\theta = 90°$, E falls off to smaller values, especially with the smaller raindrop sizes, for which rebound is critically important. With larger drops the θ effect is less marked, but even for $D = 4$ mm, we see that E falls from 97 to 77 per cent as θ increases from 90° to 180° if $\rho = 1$ g/cm³. For the lower particle density considered in the table, rebound suppression of E is noticeably greater owing to the lesser inertia of less dense particles of a given size overtaken by a raindrop of given V_0.

To show how these E values lead to corresponding estimates of rain washout, it will be adequate here to consider only a simple model, one in which the raindrops are all of some single diameter D in each rain considered. Let E be

TABLE 1. Values of Collection Efficiency E (per cent)
See text for explanation.

		ρ = 0.5 g/cm³ θ (deg)					ρ = 1.0 g/cm³ θ (deg)				
D, mm	d, μ	90	110	130	150	180	90	110	130	150	180
0.5	10	48	0	0	0	0	71	0	0	0	0
	20	84	0	0	0	0	91				
	50	97	0	0	0	0	(99)	(1)	0	0	0
1.0	10	51	0	0	0	0	72	0	0	0	0
	20	82	0	0	0	0	91	28	0	0	0
	50	97	45	9	0	0	(99)	(65)	(45)	(30)	(25)
2.0	10	46	0	0	0	0	66	16	0	0	0
	20	81	32	0	0	0	89	64	44	30	20
	50	97	74	58	46	39	(99)	(80)	(75)	(70)	(65)
4.0	10	36	0	0	0	0	55	28	5	0	0
	20	73	47	25	8	0	85	72	61	53	47
	50	95	82	73	67	63	97	84	81	78	77

regarded as already determined for the specified particles of diameter d to be washed out by drops of diameter D, whose effective capture cross section is $E\pi D^2/4$. Consider a vertical cylindrical portion of the atmosphere of horizontal cross section A (let it be thought of as small, of order 1 cm², to fix ideas) containing spherules at randomly located positions. Designating the dimensionless ratio $E\pi D^2/4A$ as q, we find that the probability that any one grain will be *missed* by descent of one raindrop falling somewhere within our cylinder is $1 - q$. The probability that the given grain will be missed by *all* of n successive drops is $P_n = (1 - q)^n \approx e^{-nq}$, since $q \ll 1$. If a given rain deposits precipitation in total depth p, our cylinder is swept by a rain volume Ap, whence in that rain, we have, as the total number of drops of uniform diameter D falling, the number $n = (6Ap)/\pi D^3$. Finally, the probable fraction of *all* the randomly located spherules *removed* is

$$P_p = 1 - \exp(-3pE/2D) \qquad (7)$$

after fall of p cm of rain of drop diameter D cm and collection efficiency E for the given particles.

Using (7), plus E values from Table 1, we compute the values of P_p shown in Table 2, assuming first a very light rain, $p = 0.1$ cm, and second an amount typical of a moderate shower $p = 1$ cm. It is seen that for rains composed (hypothetically) of very large thunderstorm-type drops, a very high washout percentage occurs regardless of the degree of wettability in a shower of $p = 1$ cm. But for a very small amount of rain, wettability exerts a dominant influence, suppressing P_p markedly if the rain is characterized by near-drizzle drops of $D = 0.5$ mm. The effects of particle diameter and density are obvious from what has already been said of the E variations of Table 1, and a number of other relevant features of the process evident in Table 2 need no comment.

It may be briefly noted here that the laboratory estimates of the degree of wettability of a number of representative types of pollen grains, cited earlier, gave the result that all tested cases behaved as if their contact angles against water lay well under 90°; so for this particular class of airborne particles, wettability does *not* appear capable of suppressing scavenging rates. In general, it will be particles with an oily or paraffin-type coating that might be found in some industrial effluents and perhaps in a few organic products whose contact angles will be most likely to exceed appreciably the 90° neutral value. If those latter were characterized by microscopically rough surfaces, wettability suppression of E and hence of P_p could be particularly marked in view of Wenzel's rule [*Adamson,* 1960], whereby micro-roughness

TABLE 2. Scavenging Percentages P_p
See text for explanation.

p, cm	D, mm	d, μ	$\rho = 0.5$ g/cm³ θ (deg) 90	110	130	150	180	$\rho = 1.0$ g/cm³ θ (deg) 90	110	130	150	180
0.1	0.5	10	76	0	0	0	0	88	0	0	0	0
		20	92	0	0	0	0	93	0	0	0	0
		50	94	0	0	0	0	95	3	0	0	0
	1.0	10	52	0	0	0	0	66	0	0	0	0
		20	71	0	0	0	0	74	34	0	0	0
		50	77	49	12	0	0	78	62	51	37	30
	2.0	10	26	0	0	0	0	39	11	0	0	0
		20	46	21	0	0	0	49	38	28	20	15
		50	95	43	35	29	25	52	44	42	40	38
	4.0	10	12	0	0	0	0	18	10	2	0	0
		20	24	16	9	3	0	27	24	20	18	16
		50	30	27	24	22	21	31	27	26	25	24
1.0	0.5	10	99	0	0	0	0	99	0	0	0	0
		20	99	0	0	0	0	99	0	0	0	0
		50	99	0	0	0	0	99	26	0	0	0
	1.0	10	99	0	0	0	0	99	0	0	0	0
		20	99	0	0	0	0	99	98	0	0	0
		50	99	99	73	0	0	99	99	99	99	97
	2.0	10	97	0	0	0	0	99	70	0	0	0
		20	99	99	0	0	0	99	99	96	89	78
		50	99	99	99	97	95	99	99	99	99	99
	4.0	10	74	0	0	0	0	87	65	17	0	0
		20	94	83	61	26	0	96	93	90	86	83
		50	97	95	94	92	91	97	96	95	95	94

tends to make the *effective* contact angle shift farther away from 90°, regardless of which side of 90° it lies on, for ideally smooth surfaces of the same material. The bulk of the materials that would commonly be encountered in the atmosphere will have $\theta < 90°$, and, in view of the arguments given above concerning the role of the emergence work in the shoot-through phenomenon, these should not be subject to removal at rates differing appreciably from those for fully wettable particles.

Summary and suggestions for future research. A theory of rain scavenging of atmospheric particles composed of materials for which the surface contact angle θ attains the upper limiting value $\theta = 180°$ has been given by Pemberton. In the present paper that theory has been extended to cover all possible contact angles, an extension needed because few known substances have water contact angles as high as 180°. Several considerations have suggested that shoot-through will be rare for all but particles of such large size and density that they can probably be found in significant concentrations only in local fallout from surface-burst nuclear weapons. It has been shown that all of Pemberton's computer results for collection efficiency E as a function of the penetration parameter χ and of the familiar inertial parameter K can be carried over to application to the present case of only partially wettable spherules. A number of illustrative results, including estimates of scavenging efficiency for a simple rain model, have been presented to show how the general problem of rain scavenging of partially wettable particles can be handled in particular cases.

Because certain physical features of the scavenging processes here considered will be conclusively examined only when someone repeats in extended form Pemberton's computer studies, the writer adds the following suggestions for such future research: The range $\theta < 90°$ was shown to be not rigorously covered by Pemberton (though the writer has offered what he regards as good reasons for believing that E will not vary appreciably over that θ range). In covering that slightly uncertain range, a comprehensive computing model would take into account acceleration during entry and its inverse process, i.e., what has here been related to the concept of the emergence work; so it is urged that the dynamics of the emergence process be programmed into any future computations patterned after Pemberton's. Second, because Pemberton made calculations only for the limiting case of *potential* flow around the raindrop, there is evident need for corresponding calculations at the other limit of *viscous* flow. Third, there is a need to drop the assumption of Stokes's drag within the raindrop and to take into account, as outlined above, gross drop deformations and capillary wave generation as factors of importance. Finally, in any computer studies of this phenomenon, physical insight into the underlying mechanisms would be increased by arranging for a readout of illustrative data bearing on the shoot-through process. Efforts to read out representative values of the trajectory details inside the raindrop would surely be repaid in improved understanding of the quantitative effects of shoot-through in rain scavenging of partially wettable particles.

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