

THE EVAPORATION AND REHYDRATION OF AQUEOUS SOLUTIONS

By *Walter L. Crider, SP3 Richard H. Milburn, U.S.A., and 1st Lt. Stephen D. Morton, U.S.A.R.*

Chemical Corps Biological Warfare Laboratories¹

(Manuscript received 5 March 1956)

ABSTRACT

An experiment is described in which a quartz-fiber microbalance is used to measure the course of rehydration of NaCl particles at various humidities. A comprehensive theory is presented for the rehydration and evaporation rates of droplets of aqueous solutions in terms of measurable bulk physico-chemical properties. A quantitative description of convection and various thermal effects is included. Calculations from the theory are compared with experimental rehydration data on NaCl particles of dry mass from 24 to 233 micrograms in relative humidities from 80 to 100 per cent. Agreement within expected limits of error was obtained.

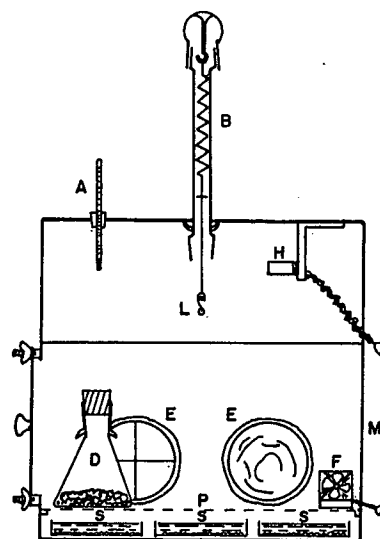
1. Introduction

The evaporation of small liquid droplets is a subject of considerable theoretical and practical interest, in the fields of spray drying and fuel dispersal, for example [1; 2; 3; 4]. The converse problem, the rehydration of hygroscopic dust particles, has applications in meteorology [5; 6]. Existing experimental work on evaporation and rehydration rates has utilized observations of drop diameters to estimate drop size and solute concentration. In this article, experiments are described in which the mass of a rehydrating NaCl particle is measured directly with a quartz-fiber microbalance (section 2). These measurements, for several dry masses of NaCl at various humidities, extend previous work (on sea salt particles) [6] to include the initial as well as the later stages of rehydration. In addition, a theory is developed for the rehydration and evaporation of spherical droplets of aqueous solutions (section 3). This theory permits the convenient calculation of evaporation and rehydration rates, once the density-concentration and vapor-pressure-concentration data for the solution are known. Temperature effects are included, and procedures are given whereby the effects of forced convection, spurious heat conduction, and heats of crystallization may be estimated readily. The theory is applied to the rehydration experiments of section 2, and is found to represent the data within the experimental uncertainties (section 4).

2. Measurement of rehydration rates

The apparatus was arranged as illustrated schematically in fig. 1. An ultramicroburet containing a solution of NaCl was inserted into the plastic chamber, *M*, containing a desiccant, CaSO₄. A drop weighing approximately 1000 μg was delivered to the wire hook, *L*. The hook was then placed on the helical quartz-

fiber microbalance, *B*, and the water from the droplet allowed to evaporate. The relative humidity was kept below 5 per cent as measured with an electric hygrometer manufactured by the American Instrument Company, and evaporation was continued until no further changes in microbalance deflection could be detected by a cathetometer, accurate to within 0.05 mm. The flask, *D*, also containing CaSO₄, was then slipped up around the salt particle, was fitted tightly to the glass housing of the quartz fiber, and was held in place with spring fasteners. The dishes, *S*, containing CaSO₄ were replaced with dishes containing a saturated solution of Na₂HPO₄, and the humidity was allowed to rise to a value slightly above 80 per cent. Small amounts of room air were drawn in at intervals,



A. THERMOMETER
B. BALANCE
D. FLASK WITH Ca SO₄
L. WIRE HOOK WITH SALT
F. FAN
P. PERFORATED FALSE BOTTOM
S. SATURATED SOLUTIONS
H. HYGROMETER SENSING ELEMENT
E. ARM PORTS
M. ALL PLASTIC CHAMBER

FIG. 1. Schematic arrangement of apparatus.

¹ Mr. Crider's present affiliation: Battelle Memorial Institute; Dr. Milburn's present affiliation: Harvard University; Mr. Morton's present address: 108 N. Spooner St., Madison, Wisc.

to control the relative humidity to within 1 per cent of the desired value. A timer was started as the flask was removed and stoppered. Microbalance deflections were measured and recorded periodically. After hydration had continued for approximately 3000 sec, the dessicant flask was placed around the hook and the salt drop again allowed to dry. The hydration procedure was repeated three times at 80-per cent relative humidity, and the data were averaged. With the same particle of salt, the procedure was repeated three times at 90-per cent relative humidity. The Na_2HPO_4 solution was then replaced with water, the relative humidity raised to 100 per cent, and the hydration repeated three more times. During the hydration process, the fan, F , was kept running except for the short periods when measurements were taken. The above procedure was repeated for four concentrations of salt solution, which gave dry NaCl weights of 24, 50, 96 and 233 μg .

Calibration of the microbalance, obtained from the Microchemical Specialties Company, showed an elongation of 1 mm for 10.5 μg , and under ideal conditions it was possible to determine mass changes of 0.5 μg . However, readings were made to the nearest microgram because of the disturbing effects of convection currents and alignment.

Another major problem of the experimental procedure was that of static charges. These static charges were finally dissipated by coating the inner surfaces of the balance housing and of the flask with a thin, transparent coating of colloidal silver, and by periodically exposing the affected areas to a polonium alpha-particle source.

It was found, through a series of preliminary experiments, that the rate of hydration was markedly dependent upon the ventilation until a wind speed around the drop of from 3 to 7 cm/sec was reached, above which the dependence on ventilation rate was much less noticeable. Consequently, ventilation of roughly 5 cm/sec was maintained during the hydrations. These experiments were all carried out at room temperature (23 to 25C). The data from these experiments will be discussed in section 4.

3. Theory of evaporation and rehydration of spherical droplets

Statement of the problem. — Extensive theoretical and experimental studies have been made of evaporation from spherical drops of pure liquids, and of the effects thereon of convection and the presence of solutes [1; 2; 3; 4]. The rehydration of droplets of salt solution has also been studied, the effects of ventilation and radiation being neglected [6]. This article gives a unified theory of the evaporation and rehydration of spherical droplets of solutions, in which ventilation, radiation, and other such processes are described quan-

titatively. The results will be expressed in formulae which lend themselves to ready calculation whenever the physico-chemical properties are known for a given solution. Aqueous solutions will be discussed as an example of prime importance.

Mass- and heat-transfer calculations. — It is assumed that the "quasi-static" approximation may be used, that is, that time derivatives may be neglected in the diffusion equations. This is a valid procedure for water at ordinary temperatures [4], for one may then neglect the movement of the drop boundary arising from evaporation or condensation. The effects of convection are estimated by conducting the heat- and mass-transfer integrations from the surface of a drop of radius a out to a finite distance, a/δ , beyond which ambient temperature and vapor-density conditions are maintained. The case $\delta = 0$ thus corresponds to the absence of convection. It is assumed that the drop remains spherical, smooth, and homogeneous in composition. Possible failure of the last three assumptions will be discussed below. Also, the vapor pressure above the drop surface is taken to be the saturation vapor-pressure over the solution at the drop temperature. Surface tension effects may be neglected for drops of radius greater than approximately 10^{-5} cm. A simplified mass-diffusion equation may be used, in which the opposing diffusing current of air is neglected. At room temperatures, the error in diffusion rates so introduced is less than 4 per cent.

Let dQ_c/dt be the total rate of heat transfer to a drop of radius a , arising from conduction and convection. Let T be the absolute temperature, and let σ be the thermal conductivity of air. Then, by the quasi-static assumption, and by noting that dQ_c/dt may be taken as a spatial constant, at room temperatures

$$dQ_c/dt = 4\pi r^2 \sigma (\partial T / \partial r), \quad (1)$$

at a variable point of radius r . Using the subscript zero to denote ambient conditions, we have

$$T_0 - T_r = [(dQ_c/dt) / 4\pi \sigma] [(1/r) - (\delta/a)]. \quad (2)$$

The mass-diffusion constant for the vapor, D , varies with temperature as

$$D(T) = D_0(T/T_0)^n, \quad (3)$$

where n is a characteristic constant. Letting dm/dt be the total rate of mass transfer to the drop, one has, similar to (1),

$$dm/dt = 4\pi r^2 M [D(T)/RT] [\partial p / \partial r], \quad (4)$$

where p is the partial pressure of the vapor at the variable point r , M is the molecular weight, and R is the gas constant. Substituting (2) and (3) in (4), and integrating, one finds, for the drop temperature T_a ,

$$p_0 - p_a = [\sigma RT_0^2 / (n - 2) MD_0] \times [(dm/dt) / (dQ_c/dt)] [(T_0/T_a)^{n-2} - 1]. \quad (5)$$

Heat may also be transferred to the drop by radiation and by conduction along mechanical supports. It is assumed that this heat is transferred at a rate, dQ_r/dt , given by Newton's law,

$$dQ_r/dt = k[T_0 - T_a], \tag{6}$$

where k is a characteristic constant. Then, if L is the latent heat of vaporization, assumed constant, one may write

$$dQ_r/dt = -L(dm/dt)(1 - \zeta), \tag{7}$$

where

$$\zeta = -[k/L(dm/dt)][T_0 - T_a]. \tag{8}$$

This factor will be discussed later. Substituting T_a from (2) into (5), one finds

$$\{1 + [L(dm/dt)/4\pi\sigma T_0][1 - \delta][1 - \zeta]\}^{n-2} = \{1 - (MLD_0/\sigma RT_0^2)(n-2)(1 - \zeta)(p_0 - p_a)\}^{-1}. \tag{9}$$

For water vapor, the second term in the right-hand braces is less than 0.16, so one may expand and find (to an accuracy of about 1 per cent)

$$[(1 - \delta)(dm/dt)/4\pi\sigma D_0] = (M/RT_0)(p_0 - p_a) \times \{1 + [(n-1)MLD_0/2\sigma RT_0^2][1 - \zeta][p_0 - p_a]\}, \tag{10}$$

an equation relating dm/dt to the partial vapor pressures. There is also the equation, from combining (5) and (7),

$$p_0 - p_a = [\sigma RT_0^2/(n-2)(1 - \zeta)MLD_0] \times [1 - (T_0/T_a)^{n-2}], \tag{11}$$

which determines the drop temperature. Let $P(T)$ be the saturated vapor pressure at temperature T , and let γ be the concentration by mass of the solute in the drop. Then, with H_0 and $H(\gamma)$ representing the relative humidities of the ambient air and that at the drop surface, respectively,

$$H_0 P(T_0) - H(\gamma) P(T_a) = [\sigma RT_0^2/MLD_0(n-2)(1 - \zeta)] \times [1 - (T_0/T_a)^{n-2}], \tag{12}$$

and

$$(dm/dt)/4\pi\sigma D_0 = [M/RT_0(1 - \delta)][H_0 P(T_0) - H(\gamma) P(T_a)] \times \{1 + [(n-1)MLD_0/2\sigma RT_0^2][1 - \zeta] \times [H_0 P(T_0) - H(\gamma) P(T_a)]\}. \tag{13}$$

Drop temperature and the psychrometric equation. — It is seen that (12) contains no explicit reference to the shape of the droplet, but merely assumes that the heat and mass transfer obey identical equations with identical limits. This assumption is somewhat in error for water vapor in air, as is discussed by Brunt [7]. This is a result, evidently, of different molecular mass- and heat-diffusion constants, whose experimental values are currently little known. Here an *ad hoc* experimental estimate of such effects is achieved by

requiring that (12), applied to pure water having $H(\gamma) = 1$, give an adequate representation of published psychrometric data [8]. By setting $H(\gamma) = 1$ and approximating for small temperature differences $\Delta T = T_a - T_0$, (12) becomes the standard psychrometric equation,

$$H_0 P(T_0) - P(T_a) = [\sigma RT_0/MLD_0(1 - \zeta)] \Delta T. \tag{14}$$

It will be shown in (20) that adequate ventilation, as in a sling psychrometer, insures that $\zeta = 0$. It is seen that (14), coupled with published vapor-pressure data $P(T_a)$, represents psychrometric data if the quoted value [8] of σ for air is replaced by $\sigma^* = 1.23 \sigma$. In dealing with water vapor, this replacement is made throughout the calculations. With most other vapors, the disparity between the mass and thermal coefficients is much more severe than with water, and it is doubtful whether one may utilize the present approximate approach at all.

The drop temperature may be calculated from (12). It is observed that, over a small temperature range, the saturation vapor-pressure of water is given by [7]

$$(1/T_0) - (1/T) = (1.844 \times 10^{-4})(^\circ\text{K})^{-1} \times \ln [P(T)/P(T_0)]. \tag{15}$$

Substituting (15) in (12), and expanding for small temperature differences ΔT , one obtains

$$\Delta T = T_0[H_0 - H(\gamma)]/[A(T_0)H(\gamma) + B(T_0)/(1 - \zeta)]. \tag{16}$$

The quantities $A(T_0)$ and $B(T_0)$ may be calculated for water, and depend only upon the ambient temperature T_0 . Here

$$A(T_0) = (5420^\circ\text{K}/T_0).$$

The factor

$$B(T_0) = 1.23 \sigma RT_0^2/MLD_0 P(T_0)$$

has the adjusted value of σ within it. These dimensionless coefficients are given, for water, in table 1.

It is observed that as $\zeta \rightarrow 1$, $\Delta T \rightarrow 0$, which shows that radiation and similar processes will tend to bring the drop temperature into equilibrium with that of the surroundings. It is also noted that the approximations used in obtaining (16) are only valid for $\Delta T \leq 4\text{K}$ or so, in which range the error is less than 10 per cent. Better formulae may be readily obtained

TABLE 1. Coefficients for water vapor at different temperatures.

T_0 :	283K	288K	293K	298K	303K
$A(T_0)$:	19.1	18.8	18.5	18.19	17.9
$B(T_0)$:	15.3	11.27	8.30	6.41	4.74
$C(T_0)^*$:	0.37	0.36	0.35	0.34	0.33

* Units of $C(T_0)$ are $\text{cm sec}^{-1/3} \mu\text{g}^{-2/3}$.

by a more exact solution of the system of equations (12) and (15).

The rate of mass transfer.—Equation (13) for fixed T_0 gives dm/dt as a function of the drop radius a , and of the varying vapor pressure over the solution, $H(\gamma)$. If the droplet contains a dry mass m_0 of solute,

$$dm/dt = (d/dt)(m_0/\gamma) = - (m_0/\gamma^2)(d\gamma/dt).$$

Also, if the mass density of the solution is $d(\gamma)$,

$$1/a = (4\pi/3)^{1/3}[d(\gamma)]^{1/3}/m_0^{1/3}.$$

One may now integrate (13) to find the time t for the droplet to change from a concentration γ_1 to a concentration γ_2 . To do this conveniently requires the recognition that the coefficient of $1 - \zeta$ in (13) is small relative to unity, which permits one to make a simple expansion of the inverse of the factor in the braces. One finds, using (14) and (16),

$$t = C(T_0) m_0^{2/3} \int_{\gamma_2}^{\gamma_1} [1 - \delta(\gamma)]\gamma^{-5/3}[d(\gamma)]^{1/3} \times \left\{ \frac{B(T_0) + A(T_0)(1 - \zeta)H_0}{H_0 - H(\gamma)} - [A(T_0) + \frac{1}{2}(n - 1)][1 - \zeta] \right\} d\gamma. \quad (17)$$

It is assumed that δ , a known function of a , has been written in terms of γ . For water vapor, $n = 1.75$. For m_0 measured in micrograms, and $d(\gamma)$ in grams per cubic centimeter, the coefficient $C(T_0)$ is also given in table 1. In general,

$$C(T_0) = [(4\pi)^{-2/3}(3)^{-1/3}L/1.23 \sigma T_0]. \quad (18)$$

When $H(\gamma)$ and $d(\gamma)$ are known for a particular solution, t may be readily calculated from (17) by numerical integration between the two limits.

Correction for radiation and similar effects.—It is desirable to estimate ζ . From (10) and (11) it may be seen that, to a first approximation,

$$dm/dt = - [4\pi\sigma a/L(1 - \delta)][T_0 - T_a]. \quad (19)$$

Thus, approximately,

$$\zeta = (1 - \delta)k/4\pi a\sigma. \quad (20)$$

From the Stefan-Boltzmann law, for a spherical black body, it may be calculated that $\zeta \approx 2.6(1 - \delta)a$, with a in centimeters. Hence, radiation will be unimportant if $a \leq 0.05$ cm or so. Other, conductive, effects may make a much larger contribution, however. It is seen that good ventilation ($\delta \rightarrow 1$) will minimize the effects of radiation and of similar forms of heat transfer.

Effects of convection.—Convective heat and mass transfer from a body to a surrounding medium are usually described in terms of dimensionless "Nusselt numbers" [3], N_{nu} . For heat transfer from spheres, in

the present notation,

$$N_{nu} = 2aq/\sigma, \quad (21)$$

where q is the heat transferred per unit time, area, and temperature difference between the body and its surroundings. Comparing with (2), one finds that

$$1 - \delta = 2/N_{nu}. \quad (22)$$

A similar Nusselt number involving mass transfer may be defined and, by means of (4), a relation identical to (22) may be established. Empirically [3] the mass and heat Nusselt numbers of water are almost identical, and this is the basis of the use of a common δ for (2) and (4). This is not true of most other solvents. Indeed, the extent to which it is true for water is questionable. It is assumed that the earlier adjustment of σ to fit psychrometric data will approximately remedy any deficiency.

Ranz and Marshall [3] have measured the dependence of N_{nu} upon the size, temperature, and velocity of forced convection. For a drop of radius a cm, having a temperature difference ΔT (degrees absolute) from ambient, one has, for *free convection*,

$$1 - \delta = \{1 + 1.52 [a^3 \Delta T]^{1/4}\}^{-1}; \quad (23)$$

for *forced convection*, with wind velocity v cm/sec,

$$1 - \delta = \{1 + 0.95 [va]^{1/2}\}^{-1}. \quad (24)$$

Forced convection will obtain when

$$v \gg 2.56 [a \Delta T]^{1/2}. \quad (25)$$

Heats of crystallization.—If the solute possesses an appreciable heat of crystallization, this will affect the process rate during the time the solution is saturated. If γ_s is the saturation concentration of the solution, and Q_0 is the heat released upon the solution of a unit mass of solute, this may be allowed for by making the replacement $L \rightarrow L + [\gamma_s/(1 - \gamma_s)]Q_0$, when $\gamma > \gamma_s$. For NaCl, this results in a reduction in L by 1.3 per cent; for Na_2HPO_4 , by 7.7 per cent. The effect of this substitution will be to decrease $C(T_0)$ and increase $B(T_0)$ by 1.3 per cent for the NaCl, or 7.7 per cent for the phosphate. For $\zeta = 0$, this will decrease t by comparable amounts. For $\zeta = 1$, temperature effects are negated altogether [because $C(T_0)B(T_0)$ is independent of L] and t will not be altered. For most salts, evidently, the energy of crystallization may be neglected.

Other corrections.—Conduction of heat into the droplet through supporting members [see (6) and (8)] may, under suitable conditions, make $1 - \zeta \rightarrow 0$ and reduce t by as much as a factor of three. Although radiation may be neglected for small drops, such drops become all the more subject to heat conducted along supports. Of course, free droplets are not so affected.

A rough-surfaced or non-spherical drop, such as

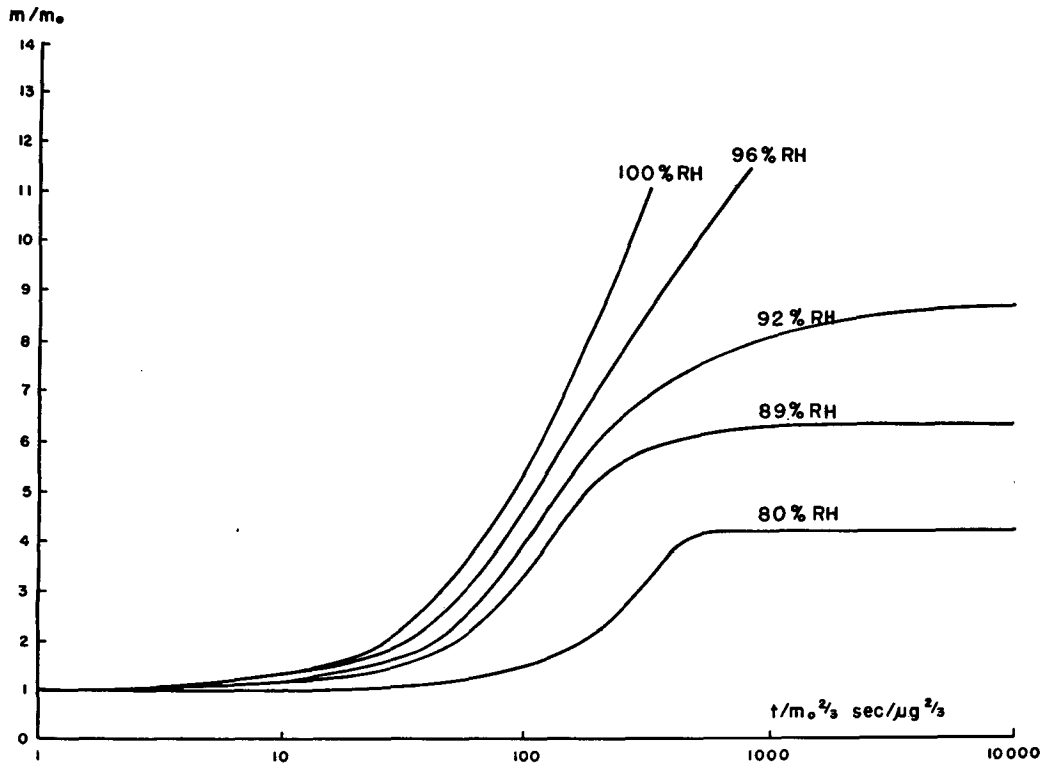


FIG. 2. Rehydration of NaCl vs. time, at various humidities. No convection, radiation or spurious conduction effects are included.

might be formed when the particle is nearly dry, would have a larger surface-volume ratio than a sphere and would evaporate or rehydrate proportionately faster.

It may be that a drop on evaporating will not remain homogeneous in composition and will become saturated, or even form a skin, at the surface. This will be reflected in a spurious value of the $H(\gamma)$ used

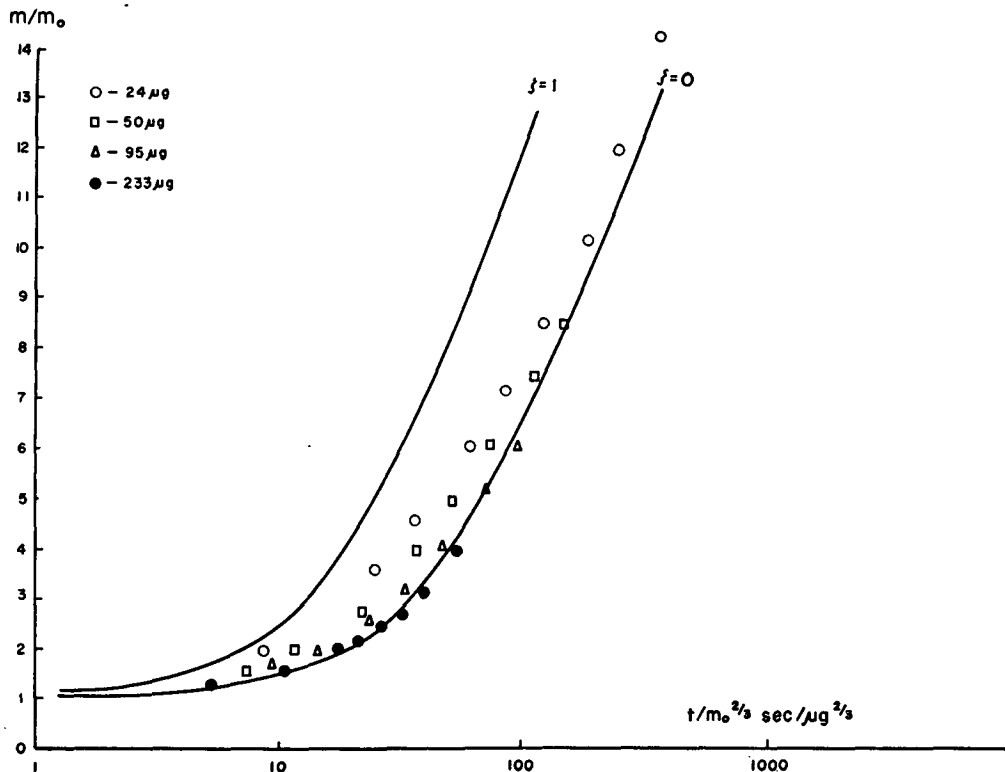


FIG. 3. Experimental rehydration at 99- to 100-per cent relative humidity. Theoretical curves (solid) for 100-per cent relative humidity include convection effects and represent extreme cases of heat conduction along supporting wire with no conduction ($f = 0$) and infinite conduction ($f = 1$).

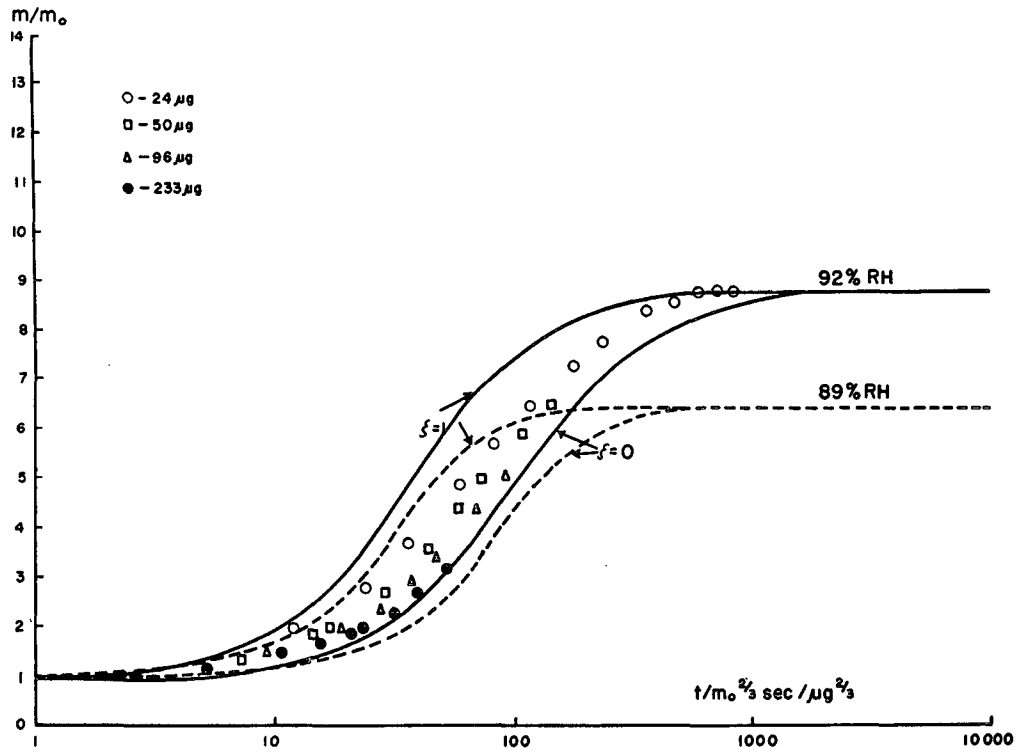


FIG. 4. Experimental rehydration at 89- to 91-per cent relative humidity. Theoretical curves are as described in fig. 3 and are drawn for 89- and 92-per cent relative humidity.

in (17). These corrections can be estimated conveniently only for given experimental situations.

Equation (17) also assumes that $\Delta T \leq 4C$. A more

exact formula of less tractable character is readily obtainable by use, instead of (16), of a more precise form for the temperature difference ΔT .

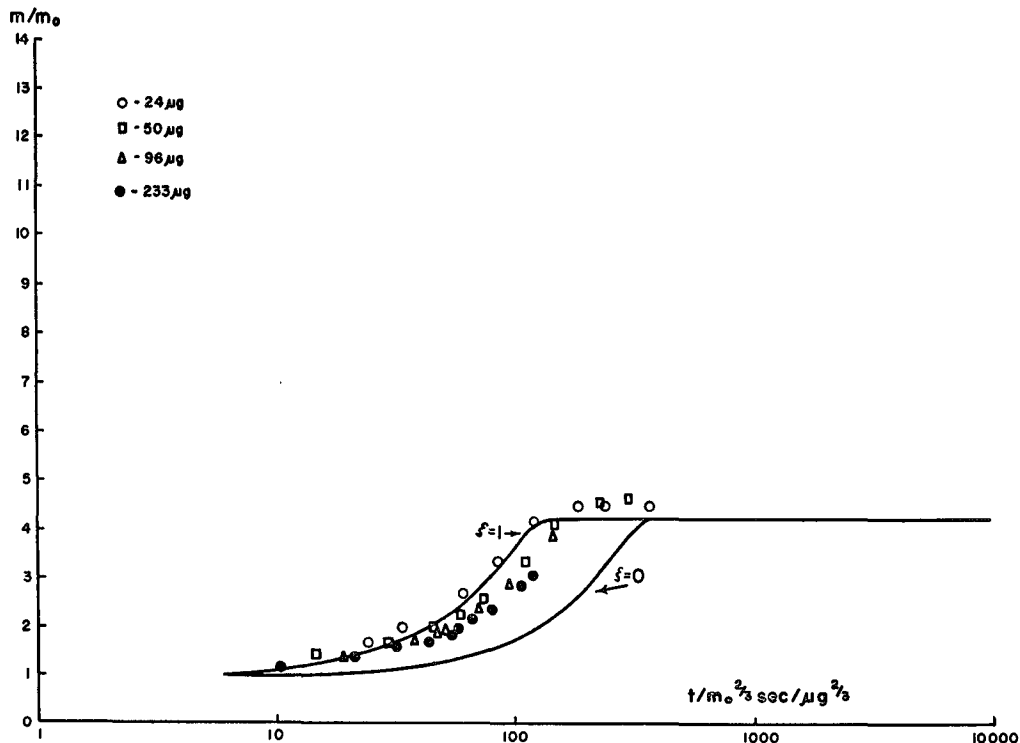


FIG. 5. Experimental rehydration at 80-per cent relative humidity. Theoretical curve is as described in fig. 3 and is drawn for 80-per cent relative humidity.

4. Results for rehydration of NaCl particles at 25°C

Formula for rehydration time.— The formula (17) holds for both rehydration and dehydration processes. This article specializes to the case $\gamma_1 = 1$ (an initially dry particle). It is also assumed that $\zeta = 0$, and that $1 - \delta$ is substantially independent of γ , which will be true as long as a does not vary too much or $\delta \ll 1$ [see (23) and (24)]. With use of tabulated data on $\bar{d}(\gamma)$ and $H(\gamma)$ for NaCl solutions [9], the ratio $[t/m_0^{2/3}(1 - \delta)]$ as a function of $m/m_0 = 1/\gamma$ has been plotted in fig. 2 for values of ambient relative humidity $H_0 = 1.00, 0.96, 0.92, 0.89$ and 0.80 . With m_0 in micrograms, t is in seconds.

These graphs, as they stand, are for the idealized case of droplets suffering no convective, radiative, or similar spurious heat-transfer processes. The minute, unsupported droplets in an aerosol cloud would be expected to satisfy these conditions.

Comparison with experiment.— To compare the theory with the experimental rehydration data obtained with a quartz microbalance (section 2), it is necessary to estimate the magnitudes of the corrections δ and ζ .

The mean convective velocity in these experiments was estimated, with use of smoke, to be about 5 cm/sec. The hanging droplets ranged in dry mass from 24 to 233 μg , or from radius 0.014 to 0.056 cm. Using (24), one finds that $1 - \delta$ varies from 0.80 to 0.67. Within the large experimental fluctuations, one may consider $1 - \delta$ to be about constant at 0.75, a value also relatively insensitive to velocity fluctuations.

Heat conducted away by the supporting wire contributes a much more profound effect. The wire of diameter $2a_w = 1.3$ mil, and length $l = 1$ cm, was an alloy of silver and copper, having a conductivity σ_w of the order of $1 \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$. Assuming convective heat transfer along its length to the surrounding air, one may estimate k by standard methods [10], and thence ζ . Since radiation may be neglected for the drop sizes used, one finds

$$1 - \zeta = 1 - [N_{\text{nu}}'/4a][(\tanh \beta l)/\beta], \quad (26)$$

where N_{nu}' is a Nusselt number for cylinders having a minimum value of about 0.5. Also, a is the drop radius, and

$$\beta = (\sigma N_{\text{nu}}')^{1/2}/a_w \sigma_w^{1/2}.$$

Here σ is the thermal conductivity of the air. For the wire used, $1 - \zeta = [1 - (0.04 \text{ cm}/a)]$. Hence, for most of the range of drop sizes used, 0.014 to 0.056 cm, the factor $1 - \zeta$ would be expected to vanish (negative values being meaningless). Thus, the wire should conduct away enough heat to eliminate any appreciable temperature difference between the drop and its surroundings. This estimate neglects, however, the finite conductivity of the drops themselves, which is

about 0.1 per cent of that of the wire, and which will impede the flow of heat between the wire and the drop surface. This will reduce the radius below which $1 - \zeta$ vanishes to about 0.03 cm, and will yield non-vanishing values of $1 - \zeta$ for drops of radius greater than this figure. Unfortunately, the drop sizes and wires used lie in a critical range for the computation of $1 - \zeta$. One can only predict that the empirical curve for small particles (less than 230 μg of dry mass of NaCl, or about 150 μg of solution) should lie along the theoretical values for $1 - \zeta = 0$. The curve for larger droplets should approach the theoretical values for $1 - \zeta = 1$. Beyond this semi-quantitative statement, it would be unwise to make any more definite assertions, in view of the many approximations in the derivation.

In figs. 3, 4 and 5 are shown plots of experimental data for three different ambient humidities and for various dry masses m_0 . The solid curves are the theoretical predictions, for $\zeta = 0$ and 1, with $\delta = 0.75$ in both cases. It is seen that the experimental values are consistent with the theoretical predictions. The experimental data at 90-percent relative humidity suggest that the actual humidity was nearer 92 per cent for the 24- μg particle.

5. Conclusion

The agreement between theory and experiment of the preceding sections indicates that (17) represents an adequate description of the evaporation and rehydration of droplets of aqueous solutions. It is unfortunate that the artifact of forced convection used to maintain a constant ambient humidity, and that of mechanical support, should introduce some uncertainties into the measurements. However, it has been shown that reasonable estimates of these artifacts can be made, even in a complicated experimental situation.

Fortunately, in an extrapolation of the theory to the aerosol particles which make up meteorological clouds, most of the corrections assume a very simple form. Indeed, the droplets are unsupported and, moreover, are sufficiently small for one to take $\zeta = 0$ in all cases. The effects of convection, if not actually negligible, at least may be estimated readily for small, freely falling droplets. Thus, the curves in fig. 2 may be expected to give an accurate representation of the rehydration of NaCl particles of radii down to a small fraction of a micron. As noted in section 3, extrapolation of the theory as it stands to radii less than about 0.1 μ would be expected to lead to progressively erroneous results, arising from the increase of vapor pressure over curved surfaces of liquids with surface tension. Within this limitation, and those of the final paragraphs of section 3, (17) provides a simple connection between the dynamics of cloud-droplet growth and the gross

physico-chemical properties of the solution of which the droplets are composed. Such a connection should prove convenient and useful in analyzing the effects of various hygroscopic nuclei upon cloud development.

REFERENCES

1. Fuchs, N., 1934: Über die Verdampfungsgeschwindigkeit kleiner Tröpfchen in einer Gasatmosphäre. *Phys. Z. Sowjetunion*, **6**, 224–243.
2. Langstroth, G. O., C. H. H. Diehl, and E. J. Winhold, 1950: The evaporation of droplets in still air. *Canad. J. Res.*, A, **28**, 580–595.
3. Ranz, W. E., and W. R. Marshall, Jr., 1952: Evaporation from drops. *Chem. Engin. Prog.*, **48**, 141–180.
4. Luchak, G., and G. O. Langstroth, 1950: Applications of diffusion theory to evaporation from droplets and flat surfaces. *Canad. J. Res.*, A, **28**, 574–579.
5. Howell, W. E., 1949: The growth of cloud drops in uniformly cooled air. *J. Meteor.*, **6**, 134–149.
6. Keith, C. H., and A. B. Arons, Jr., 1954: The growth of sea-salt particles by condensation of atmospheric water vapor. *J. Meteor.*, **11**, 173–184.
7. Brunt, D., 1944: *Physical and dynamical meteorology*, London, Cambridge Univ. Press, 428 pp.
8. Hodgman, C. D., (ed.) 1951: *Handbook of chemistry and physics* (33rd ed.) Cleveland, Chemical Rubber Publ. Co., 2950 pp.
9. Washburn, E. W., (ed.) 1928: *International critical tables* (Vol. 3), New York, McGraw-Hill Book Co., 444 pp.
10. McAdams, W. H., 1942: *Heat transmission*. New York, McGraw-Hill Book Co., 459 pp.