EVAPORATION OF LIQUID DURING ITS ATOMIZATION ON A ROTATING DISK

V. F. Dunskii, N. V. Nikitin,
and G. A. Shul'ginova

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The article suggests an approximate method of determining the evaporation rate of a liquid film moving diametrically over the surface of a rotating disk. The results of experiments and of calculations by the suggested method were similar.

In technology and in scientific research, liquids atomized by rotating atomizers, e.g., a rotating disk, are used. During the process, the liquid, moving as a thin film over the surface of the rotating disk from its axis to the circumference, evaporates. It is often essential to take this evaporation into account.

For instance, in laboratory practice, generators of monodisperse aerosols of the type of rotating disk are used [1]. With the aid of these generators, a liquid can be divided into drops of approximately the same radius that is controllable within wide limits (e.g., with the aid of the generator "Volchok" with pneumatically driven rotor, within the limits 3-30 μm). If smaller drops have to be obtained, the investigated liquid with low volatility, mixed with a volatile diluent, is atomized; the diluent quickly evaporates, and in the air there remain drops with a radius $r < 3$ μm containing hardly any diluent. However, the diluent may evaporate chiefly while the liquid film still moves over the surface of the rotating disk, i.e., prematurely, before drops are formed; in that case, in the evaporation of the mixture, the radius of the drops r would be the same as in atomization of the investigated liquid (without diluting it with a volatile diluent), i.e., the method of obtaining drops with $r < 3$ μm would be unsuitable. Obviously, this is one of the cases when it is necessary to take the evaporation of the liquid over the surface of a rotating disk in the form of a thin film into account. Below we examine in particular this case, but the results are naturally of wider significance.

To reduce r substantially by the evaporation of the volatile diluent, two conditions must be fulfilled: the rate of evaporation of the film I has to be low compared with the flow rate G of the liquid

$$K_1 = IG^{-1} \ll 1, \tag{1}$$

and the rate of evaporation of the mixture has to be sufficiently high for the bulk of the diluent to evaporate at the time the drops are in a state of suspension

$$K_2 = \tau V H^{-1} \ll 1. \tag{2}$$

In the evaporation of the bulk of the volatile diluent, a drop of the diluted solution behaves approximately in the same way as a drop of pure diluent [2], i.e., in the case of small drops slowly settling in air, the evaporation time of the bulk of the diluent can be approximately determined by the formula [3]*

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*When this formula is used for τ, we assume that the initial concentration of diluent in the drop is high, and that the accelerated evaporation at the time of braking of the drop, thrust from the circumference of the disk at high initial speed relative to the air, need not be taken into account. The first assumption is due to the fact that for substantial reduction in size of the drop by evaporation of the volatile diluent it is necessary that its initial concentration in the drop be high; e.g., to reduce the drop size in this way by one half, the concentration of the diluent has to be 87.5%. The second assumption is based on the fact that though the high initial speed of the drop relative to the air substantially accelerates evaporation, the period of braking of the small drops that are here under consideration is extremely short, therefore the degree of evaporation of the drop at the time of its accelerated evaporation is negligible; this was proved by the numerical solution of the system of equations of motion and evaporation of a drop under analogous conditions obtained in the "kinematic" regime of evaporation of a drop in a turbulent air stream [4].

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TABLE 1. Characteristics of Disks Used in the Experiments

Disk No.	Radius, cm	Material	Weight, g	Heat capacity, cal/deg	Thermal conductivity of material, cal/cm·sec·deg
1	2,5	Organic glass	8,6	3,1	0,0056
2	5,0	»	24,5	8,8	»
3	10,0	»	102,0	36,7	»
4	5,15	Glass	57,6	5,8	0,0020
5	7,8	»	216,0	21,6	»
6	15,0	Duralumin	235,0	49,2	0,48
7	22,5	»	650,0	136,5	»

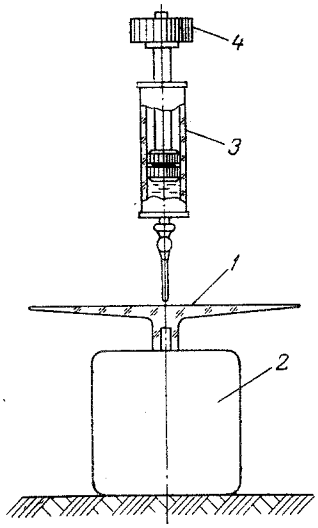

Fig. 1. Diagram of the experimental device.

$$\tau \approx \frac{\rho r_0^2}{2D(c_0 - c_\infty)}.$$

The initial radius of the drops in the first monodisperse regime of evaporation of liquid by a rotating disk is determined by the formula [1]

$$r_0 = \frac{C}{\omega}\sqrt{\frac{\sigma}{\rho R}}.$$

For water and mineral oils, C ≈ 2.9.

The settling rate of drops after Stokes at the beginning of evaporation is

$$V = \frac{2}{9}\frac{\rho g r_0^2}{\eta}.$$

As evaporation proceeds ($r < r_0$), V decreases.

We substitute τ, r_0, and V into the inequality (2) and write it as follows:

$$K_2 = \frac{1}{9}\frac{C^4\sigma^2 g}{DH(c_0 - c_\infty)R^2\omega^4} \ll 1. \tag{2a}$$

All the magnitudes on the left-hand side of this inequality are known, and it can be used for approximately determining K_2.

TABLE 2. Physical Characteristics of Liquids [6-8]

Liquid	ρ, g/cm^3	D, cm^2/sec	$c_0 \cdot 10^4$, g/cm^3 at 20°C	λ, cal/g
Ethyl alcohol	0,815	0,102	1,107	204,2
Acetone	0,790	0,122	5,87	124,5
Benzene	0,880	0,082	3,19	94,2

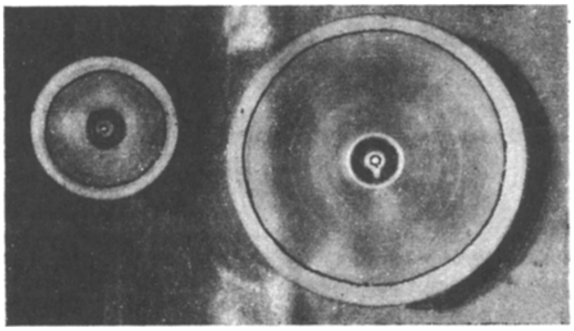

Fig. 2. Photograph of a liquid film on a rotating disk.

Evaluating K_l with the aid of inequality (1) is more complicated because evaporation of a liquid film moving over the surface of a rotating disk has not yet been sufficiently studied, and the correlation between the evaporation rate I of the film and the parameters of the process is still unknown.

The process of evaporation of the film is determined by the nature of its motion over the surface of the disk and the nature of the motion of the air, near the surface of the film by the diffusion of the vapor of the liquid from the surface of the film through the adjacent layer of moving air, by the heat transfer from the disk to the film, from the air to the film and the disk, from the drive shaft to the disk, from other parts of the drive to the shaft. An accurate solution of the problem would be very complicated.

To obtain an approximate solution, we assume that in view of the intense heat transfer to the disk and the film from the surrounding air and from the drive shaft at a low flow rate of the evaporated liquid (i.e., at small expenditure of heat on evaporation), the processes of heat transfer need not be taken into account, and specifically, that we may neglect the lowering of the temperature of the disk and the film upon evaporation, i.e., take it in this case that the temperature is equal to the ambient temperature.

Under steady-state conditions, the amount of liquid evaporating in unit time from a surface element of the disk with area $ds = 2\pi R dR$ is equal to

$$dI = D\left(\frac{\partial c}{\partial z}\right)_{z=\delta_l} dS = 2\pi DR\left(\frac{\partial c}{\partial z}\right)_{z=\delta_l} dR \tag{3}$$

With low rates of the liquid, typical of monodisperse atomization regimes, the motion of the film is laminar, the thickness of the film δ_l and its speed relative to the disk are small [1], and this speed may be neglected in comparison with the air speed relative to the disk.

As the solution of Eq. (3) we may take the formula obtained in studying convective diffusion to the surface of a rotating disk [5, p. 78]:

$$I = 1.9D^{2/3}\nu^{-1/6}\omega^{1/2}R^2(c_0 - c_\infty). \tag{4}$$

Equation (4) is approximately correct for the rotation of a disk, not only in a liquid, but also in a gaseous medium [5, p. 80].

As noted before, in this equation the concentration of saturated vapor c_0 was taken as corresponding to the ambient temperature.

TABLE 3. Conditions of Experiments and Their Results

Working liquid	w, sec^{-1}	G, g/sec	t, °C	$c_0 \cdot 10^4$, g/cm^3	R, cm	R_1, cm	R_2, cm	R_2/R_1
Ethylalcohol	157	0,0020	18,5	1,025	7,8	2,3	1,78	0,773
	157	0,0020	18,8	1,04	2,5	2,3	1,78	0,773
	157	0,0020	21,8	1,22	2,5	2,3	1,78	0,773
	157	0,0020	19,3	1,07	10,0	2,8	1,78	0,635
	157	0,0065	19,0	1,05	10,0	6,0	3,04	0,507
	157	0,0065	21,8	1,22	10,0	5,2	3,04	0,585
	157	0,0047	20,0	1,10	5,0	4,4	2,60	0,590
	157	0,0121	19,8	1,10	10,0	7,3	4,15	0,570
	157	0,0121	19,3	1,07	10,0	7,3	4,15	0,570
	157	0,0133	19,8	1,10	10,0	8,5	4,35	0,512
	157	0,0163	19,9	1,10	10,0	9,8	4,85	0,494
	157	0,0166	21,8	1,22	10,0	8,9	4,87	0,547
	157	0,0121	19,3	1,07	10,0	7,2	4,15	0,577
	314	0,0065	19,2	1,07	10,0	5,5	2,56	0,467
	314	0,0121	19,8	1,10	10,0	7,2	3,51	0,487
	314	0,0133	19,8	1,10	10,0	8,2	3,63	0,450
	314	0,0163	19,9	1,10	10,0	9,7	4,08	0,422
	314	0,0166	20,0	1,10	10,0	8,5	4,11	0,484
	72,8	0,0206	21,1	1,17	15,0	10,4	7,40	0,725
	72,8	0,0276	21,1	1,17	15,0	11,5	8,70	0,755
	72,8	0,0368	21,1	1,17	15,0	14,8	10,1	0,682
	72,8	0,0622	18,5	1,03	22,5	20,0	13,1	0,655
	72,8	0,0472	16,2	0,89	22,5	16,3	11,4	0,698
Acetone	157	0,0025	18,2	5,11	2,5	1,7	0,790	0,465
	157	0,0100	18,2	5,11	10,0	3,4	1,59	0,468
	157	0,0167	18,2	5,11	10,0	5,0	2,06	0,413
	157	0,0230	18,2	5,11	10,0	5,9	2,42	0,410
	157	0,0562	18,2	5,11	10,0	8,5	3,78	0,445
	157	0,0100	18,2	5,11	7,8	3,0	1,59	0,531
	157	0,0200	18,2	5,11	7,8	5,0	2,26	0,451
Benzene	157	0,0017	15,2	2,62	5,15	1,5	1,04	0,680
	157	0,0019	15,2	2,62	5,15	1,7	1,11	0,650
	157	0,0087	15,2	2,62	7,8	3,5	2,34	0,670
	157	0,0194	15,2	2,62	7,8	5,3	3,51	0,660
	157	0,0207	15,2	2,62	7,8	5,5	3,63	0,660
	157	0,0247	15,2	2,62	7,8	6,0	3,96	0,660
	157	0,1175	16,2	2,67	15,0	13,1	8,60	0,655

This equation was experimentally verified with the aid of a device diagrammatically illustrated in Fig. 1. To the center of the smooth disk 1 driven by electric motor 2 (n = 695, 1500, or 3000 rpm), liquid is supplied from the needle of syringe 3 whose plunger is loaded by weight 4. For very low flow rates corresponding to monodisperse atomization regime [1], the needle of the syringe was placed near the center of the surface of the disk in such a way that the gap between them amounted to ~0.2 mm. Then the liquid flowing from the needle was not fed to the disk in the form of large drops but dispersed continuously over the disk surface, which is indispensable for monodisperse atomization. The disks used in the experiments were made of Duralumin, organic glass, or glass; their radii, weights, heat capacities, and specific thermal conductivities are presented in Table 1.

The experimental method consisted in the following. The flow rate of the liquid was gradually reduced until the film evaporated completely on the surface of the rotating disk before it could reach its edge and form drops. This regime, corresponding to the equality $I = G(K_1 = 1)$, was determined by visual observation of the liquid film on the rotating disk with the aid of a strobotachometer ST-5. The "stopped" film was of approximately circular shape with serrated circumference (Fig. 2). After an initial non-steady-state period lasting up to 1 min, the radius R_1 of the film remained approximately constant; it was measured with a ruler while the disk rotated, and at the same time the flow rate G of the liquid was measured.

The radius R_1 of the film measured in the experiment was compared with the radius calculated by Eq. (4), solved with respect to $R = R_2$ for $I = G$:

$$R_2 = 0,73 \left[\frac{G}{c_0 - c_\infty} \right]^{1/2} \frac{\nu^{1/12}}{\omega^{1/4} D^{1/3}} . \tag{5}$$

The degree of agreement between the experimental data and the results of calculation by Eq. (5) was judged by the magnitude of the ratio R_2/R_1.

The experiments were conducted with three liquids: ethyl aclohol, acetone, and benzene. Some physical characteristics of these liquids are presented in Table 2.

Altogether 37 experiments were made. The disk radius was varied from 2.5 to 22.5 cm, the rotary speed of the disk from 695 to 3000 rpm, the volumetric flow rate of the liquid from 0.00187 to 0.1335 cm^3/sec, the diffusion coefficient of the vapor of the liquid in air D from 0.082 to 0.122 cm^2/sec, the concentration of saturated vapor of the liquid from $0.89 \cdot 10^{-4}$ to $5.11 \cdot 10^{-4}$ g/cm^3, the heat of vaporization from 94 to 204 cal/g, the thermal conductivity of the material of the disk from 0.002 to 0.48 cal/cm·sec·deg, the heat capacity of the disk from 3.1 to 136.5 cal/deg.

The experiments were carried out with values $Re = (\omega R^2)/\nu$ varying from $2.33 \cdot 10^3$ to $1.96 \cdot 10^5$. However, Eq. (4) applies to laminar movement of the medium, which corresponds to values of Re not exceeding 10^4 or 10^5 [5].

Nevertheless, Eq. (4) remains approximately correct even for turbulent flow [5, p. 80].

The experimental conditions and results are presented in Table 3. The obtained values of R_2/R_1 varied from 0.41 to 0.77; their mean value was 0.58.

Analysis of the data in Table 3 shows that there are some weak tendencies of the rotary speed of the disk, its radius, the flow rate of the liquid and its properties affecting the magnitude of the deviations of R_2/R_1 from the mean value; however, these tendencies are not sufficiently distinct. Taking this circumstance into account, and also the low accuracy of visual determination of the film radius R_1, it is an advantage to consider the deviations of R_2/R_1 from the mean value as random deviations. The standard deviation of this value from the mean is equal to 0.186.

These relatively narrow limits of variation of R_2/R_1 and the closeness of the mean value of R_2/R_1 to unity with the large range of changes in parameters that may affect heat transfer (heat capacity of the disk, thermal conductivity of the material of the disk, heat of vaporization of the liquid) indicate that the adopted assumption that it is possible not to take the processes of heat transfer into account, making it possible to simplify greatly the solution of the problem, is close to the truth in the given range of changes of the parameters.

As applied to the concrete problem under examination (obtaining drops with a radius $r < 3$ μm with the aid of a rotating atomizer), the degree of accuracy ensured by Eq. (5), and consequently also by Eq. (4), is completely sufficient, and Eq. (4) (with the coefficient 1.1 on the right-hand side instead of 1.9) may be recommended for practical calculations (with some "safety factor," e.g., adopting as permissible values $K_1 < 0.03$).

NOTATION

I	is the rate of evaporation of liquid film;
G	is the liquid flow rate;
δ_l	is the thickness of liquid film;
σ, ρ	are the surface tension and density of liquid, respectively;
R_1, R_2	are the measured and calculated radius of liquid film, respectively;
c_0, c_∞	are the concentration of saturated vapor at the surface of the liquid film and in the surrounding air, respectively;
D	is the diffusion coefficient of the vapors in air;
ν, η	are the kinematic and dynamic viscosity of air, respectively;
$\bar{K}$, ω	are the radius and angular velocity of rotation of the disk, respectively;
r, r_0, V	are the radius of drop, initial radius of drop, and its settling rate after Stokes, respectively;
τ	is the time of evaporation of diluent contained in the drop;
H	is the height of the atomizer above the ground;
C	is the constant;
g	is the acceleration of gravity;
S	is the disk surface area;
z	is the distance from the disk surface;
n	is the revolutions per minute of the disk;
λ	is the heat of vaporization.

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THERMAL CONDUCTIVITY OF CD_3OH, CH_3OH, C_2D_6, C_2H_6 IN THE GASEOUS PHASE

L. V. Yakush, N. A. Vanicheva,
and L. S. Zaitseva

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Results of measurements of the thermal conductivity of CD_3OH, CH_3OH, C_2D_6, and C_2H_6 in the gaseous phase are presented.

The present study is a continuation of a series of experiments on the thermal conductivity of deuterium- and hydrogen-containing isotopic compounds [1-3].

Experimental data are available for the thermal conductivity of methanol CH_3OH and ethane C_2H_6 [4]. It was thus of interest to study the thermal conductivity of CD_3OH and C_2D_6 in the gaseous phase using the same apparatus. The measurements were performed by the heated filament method. The major part of the experimental apparatus consisted of a quartz measurement tube. Tube parameters were: internal diameter D_{in} = 4.07 mm, external diameter D_{ex} = 5.69 mm, platinum wire diameter d = 0.10 mm.

In determining the thermal conductivity coefficient, corrections were considered for radiation from the measurement wire, for temperature drop in the measurement tube wall, and for heat loss from the ends of the apparatus.

TABLE 1. Experimental Data on CH_3OH Thermal Conductivity

T, °K	Q, W	$T_f - T_w$, °K	δT_q, °K	ΔT_g, °K	$\lambda \cdot 10^4$, W/(m•°K)
308,28	0,1464	26,37	0,04	26,33	177
318,89	0,2255	39,56	0,07	39,49	182
342,52	0,3782	58,75	0,11	58,64	206
367,45	0,0707	9,89	0,02	9,87	229
382,99	0,2340	31,03	0,06	30,97	241
436,51	0,3784	39,90	0,10	39,80	300
490,94	0,1365	11,80	0,04	11,76	364
503,25	0,3894	31,83	0,10	31,73	385
516,81	0,6743	52,70	0,17	52,53	402
529,59	0,2634	19,70	0,07	19,63	421
547,79	0,3922	27,52	0,10	27,42	448
558,65	0,3936	27,12	0,10	27,02	454
589,75	0,4108	26,07	0,10	25,74	499

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