

EVAPORATION OF A HIGHLY VOLATILE LIQUID ON A ROTARY DISK SURFACE

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A nonisothermal process of highly volatile liquid evaporation on a rotary disk surface is discussed. A suggested model describes experimental results more correctly than an isothermal model.

In some processes of chemical technology as well as in the forming of photoresist films by centrifuging [1] in the electronic industry, solutions of highly viscous fluids in highly volatile solvents are spread over rotary conic, including disks, packings. In this case, the solvent intensely evaporates from the solution, which leads to a substantial change in the physical properties of the latter. Such a process can be considered, to a first approximation, using a simple model of a pure solvent spreading over a rotary disk.

Similar work was carried out by V. F. Dunsikii et al. [2] for three highly volatile solvents, namely, ethyl alcohol, acetone, benzene, which were supplied from a syringe needle to the center of a rotary disk. The disks, which were fabricated from different materials, had radii of from 2.5 to 22.5 cm and rotated with angular speeds of from 72.8 to 314 sec⁻¹. The liquid flow rates and angular speeds of rotation were chosen so that the liquid evaporated before reaching the disc edge. Then the radius of the liquid spot R_1 was measured under stroboscopic light. The authors note that after an initial unsteady period, lasting up to 60 sec, the radius R_1 remained almost unchanged.

A theoretical model of the process suggested by the authors of [2] is based on the well known V. G. Levich equation [3]

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

The diffusion flow obtained by Eq. (1) was equated to the mass flow rate G of the liquid and the theoretical radius of film drying R_2 was determined as

$$R_2 = 0.73 \left[\frac{G}{c_0 - c_\infty} \right]^{1/2} \frac{\nu^{1/12}}{\omega^{1/4} D^{1/3}}. \quad (2)$$

Thus, the value of R_2 was found from the simple condition of mass balance.

In total, 37 experiments were carried out. Their results are presented in [2] in form of the detailed table. In all experiments the R_2/R_1 ratio was considerably less than unity and varied from 0.773 to 0.410.

In our opinion, such a considerable discrepancy between theory and experiment is explained by the fact that the concentration of the saturated vapor c_0 is calculated in [2] at the ambient temperature, while in intense evaporation the film must markedly cool off. Now we will show how the cooling effect of film evaporation on the surface of a rotary disk can be evaluated.

At the first moment, after delivery of a highly volatile liquid to the rotary disk, the liquid, evaporating, will cool off and extract an amount of heat from the disk being in contact with it. But cooling of the liquid and the disk is not a continuous process. To the extent that the temperature difference between the liquid and the disk, on the one hand, and the ambient air, on the other hand, increases, the heat flux from the ambient air toward the liquid

TABLE 1. Experimental and Calculated Data for Isothermal [2] and Nonisothermal Evaporation Processes

ω, sec^{-1}	$G \cdot 10^3$	t	$R_1 \cdot 10^2$	$R_2 \cdot 10^2$	R_2/R_1	\bar{t}	$\bar{R}_2 \cdot 10^2$	\bar{R}_2/R_1
Ethyl alcohol								
157	0.0020	18.5	2.3	1.78	0.773	3.14	2.64	1.15
157	0.0020	18.8	2.3	1.78	0.773	3.24	2.64	1.15
157	0.0020	21.8	2.3	1.78	0.773	4.74	2.51	1.09
157	0.0020	19.3	2.8	1.78	0.635	3.54	2.61	1.14
157	0.0065	19.0	6.0	3.04	0.507	3.38	4.73	0.79
157	0.0065	21.8	5.2	3.04	0.585	4.74	4.53	0.87
157	0.0047	20.0	4.4	2.60	0.590	3.87	3.96	0.90
157	0.0121	19.8	7.3	4.15	0.570	3.77	6.38	0.87
157	0.0121	19.3	7.3	4.15	0.570	3.54	6.42	0.88
157	0.0133	19.8	8.5	4.35	0.512	3.77	6.69	0.79
157	0.0163	19.9	9.8	4.85	0.494	3.82	7.38	0.75
157	0.0166	21.8	8.9	4.87	0.547	4.74	7.24	0.81
157	0.0121	19.3	7.2	4.15	0.577	3.54	6.42	0.89
314	0.0065	19.2	5.5	2.56	0.467	3.44	3.97	0.72
314	0.0121	19.8	7.2	3.51	0.487	3.77	5.36	0.75
314	0.0133	19.8	8.2	3.63	0.450	3.77	5.62	0.89
314	0.0163	19.9	9.7	4.08	0.422	3.82	6.21	0.64
314	0.0166	20.0	8.5	4.11	0.484	3.87	6.26	0.74
72.8	0.0206	21.1	10.4	7.40	0.725	4.40	9.88	0.95
72.8	0.0276	21.1	11.5	8.70	0.755	4.40	11.44	0.99
72.8	0.0368	21.1	14.8	10.1	0.682	4.40	13.21	0.89
72.8	0.0622	18.5	20.0	13.1	0.655	3.14	17.87	0.89
72.8	0.0472	16.2	16.3	11.4	0.698	1.96	16.19	0.99
Acetone								
157	0.0025	18.2	1.7	0.790	0.465	-13.37	1.60	0.94
157	0.0100	18.2	3.4	1.59	0.468	-13.37	3.20	0.94
157	0.0167	18.2	5.0	2.06	0.413	-13.37	4.13	0.83
157	0.0230	18.2	5.9	2.42	0.410	-13.37	4.85	0.82
157	0.0562	18.2	8.5	3.78	0.445	-13.37	7.58	0.89
157	0.0100	18.2	3.0	1.59	0.531	-13.37	3.20	1.07
157	0.0200	18.2	5.0	2.26	0.451	-13.37	4.52	0.90
Benzene								
157	0.0017	15.2	1.5	1.04	0.68	-1.98	1.59	1.06
157	0.0019	15.2	1.7	1.11	0.65	-1.98	1.68	0.99
157	0.0087	15.2	3.5	2.34	0.67	-1.98	3.59	1.03
157	0.0194	15.2	5.3	3.51	0.66	-1.98	5.36	1.01
157	0.0207	15.2	5.5	3.63	0.66	-1.98	5.54	1.01
157	0.0247	15.2	6.0	3.96	0.66	-1.98	6.05	1.01
157	0.1175	16.2	13.1	8.60	0.655	-1.47	13.01	0.99

film-disk system will increase. And some time later, equilibrium between these two heat fluxes must be reached. Thus, in the steady state, the heat balance condition must be also fulfilled in addition to the mass balance. If we assume that the liquid film-disk system has a mean temperature corresponding to the heat equilibrium condition, then it can be readily determined. For this, we use an equation describing heat transfer from a rapidly rotating flat disk to a gas [4]:

$$Q = \pi R^2 \lambda \omega^{1/2} \nu^{-1/2} t_1'(0) (T_\infty - T_w), \quad (3)$$

in which for the case of heat transfer to air it should be assumed that $t_1'(0) = 0.329$.

Since heat is transferred from the both surfaces of the disk, the heat flux calculated by Eq. (3), must be doubled, i.e., written as

$$Jr = 2Q. \quad (4)$$

The concentration of the saturated vapor is a single-valued function of temperature. It can be related to temperature by known expressions, e.g., the Antuan, Harlaher [5] and other equations. Then relation (4) becomes the equation for the unknown temperature T_w . Having determined the latter, we calculate the function $c_0(T_w)$ and, substituting it into Eq. (2), find the refined value of the drying radius \bar{R}_2 .

In Table 1, along with the results of [2], the last three columns give our calculated quantities corrected with allowance for liquid cooling. As is seen from the table, the mean temperatures for all three used liquids differ markedly from the ambient temperature. For acetone this difference reached almost 31.6 K and evaporation occurred at -13.37°C , while the air temperature was 18.2°C . For all 37 experiments our results were closer to the experimental values than the calculated values in [2], where the mean value of the R_2/R_1 ratio was 0.58. In our work, it was equal to 0.914. The scatter of 8.6% is comparable with the error of the experiment itself.

While in [2] the largest difference between theory and experiment pertains to acetone evaporation (the mean value of the \bar{R}_2/R_1 ratio is 0.455), our analysis describes the evaporation process more exactly ($\bar{R}_2/R_1 = 0.913$). In our experiment, the \bar{R}_2/R_1 ratio differs most from unity for the evaporation of ethyl alcohol at $\omega = 314 \text{ sec}^{-1}$. This is probably explained by the fact that at high circumferential speeds the mass transfer process manifests turbulent effects, which are not taken into account in Eq. (1) and decrease the mean temperature of the evaporating liquid film even more. If we exclude five experiments conducted at $\omega = 314 \text{ sec}^{-1}$ from the table, then the mean \bar{R}_2/R_1 ratio makes 0.946.

It should be noted that owing to the clarity of the experimental procedure of drying radius determination for a film on a rotary disk as well as the simplicity of its proposed theoretical interpretation, this procedure can be adopted for approximate estimation of such parameters entering Eqs. (2) and (3) as the liquid flow rate, the angular speed of rotation, the diffusion coefficient, etc.

The results given in the table can be also considered as a clear experimental confirmation of relations (1) and (3).

Moreover, it is possible to take into account inconstancy of the liquid-film temperature in the radial and transverse directions as well as turbulization effects of the boundary layer in a gas, which allows experimental results to be described even more exactly.

NOTATION

c_0, c_∞ , concentrations of saturated vapor near the liquid film surface and in the ambient air, respectively, kg/m^3 ; D , diffusion coefficient of vapors in air, m^2/sec ; J , diffusional flow, kg/sec ; G , liquid flow rate, kg/sec ; Q , heat flux, W ; R , disc radius, m ; R_1 , radius of the liquid spot measured in [2], m ; R_2, \bar{R}_2 , theoretical drying radii in [2] and in our work, respectively, m ; r , specific heat of evaporation, J/kg ; T_w, T_∞ , vapor temperatures at the liquid film surface and in the ambient air, respectively, K ; t, \bar{t} , temperatures according to [2] and to our model, respectively, $^\circ\text{C}$; λ , thermal conductivity of air, $\text{W}/(\text{m}\cdot\text{K})$; ν , kinematic viscosity of the gas, m^2/sec ; ω , angular speed of disc rotation, sec^{-1} .

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