

It is shown that under certain conditions the rate of evaporation of a liquid is determined not by the evaporation kinetics of the individual droplets but by the rate of diffusion of outside air into the jet as a whole.

Most published studies of droplet evaporation are concerned with the individual droplet. At the same time, in technical applications it is always necessary to deal with a system of evaporating droplets and, in particular, with a system of droplets suspended and evaporating in a turbulent stream of gas.

Under these conditions the problem reduces to the solution of Maxwell's equation [1] with allowance for the motion of the droplets relative to the gas, convective diffusion, and the variable vapor concentration. Obtaining and analyzing the solution would be difficult. This has prompted a search for simpler approximate methods.

In particular, it is possible to make use of the fact that turbulent diffusion of outside air into the stream proceeds at a certain rate described by the equations of the theory of turbulent jets. Consequently, in certain regimes of practical importance droplet evaporation may take place under conditions of "air starvation," i. e., under conditions such that the rate of evaporation is determined not by the individual-droplet evaporation kinetics (i. e., not by the rate of diffusion of air from the neighborhood of the droplet to its surface) but by the rate of diffusion of outside air into the jet as a whole.

We will estimate the conditions under which these regimes are realized.

According to [2] the admixture concentration in the main part of a submerged turbulent jet is given by

$$\alpha - \alpha_\infty = \frac{9.24 R_0 (\alpha_0 - \alpha_\infty)}{x} (1 - \xi^{1.5}). \quad (1)$$

The derivation of Eq. (1) was based on the conditions of identicalness of the excess admixture content and universality of the laws of admixture concentration and velocity distribution in different cross sections of the jet and the relation between the concentration and velocity values following from the Taylor theory of free turbulence, which has been shown to be in agreement with the experimental data; an empirical equation closely corresponding to the experimental data for incompressible fluid jets was used to describe the function determining the dimensionless velocity profiles. Consequently, Eq. (1) gives a good description of the experimentally observed distribution of excess admixture concentrations in the main part of submerged turbulent incompressible-fluid jets. Equation (1) is approximately applicable to the present case of a two-phase jet at the relatively small temperature differences characteristic of droplet evaporation in unheated or weakly heated air and at the moderate initial admixture concentrations, for which the effect of heavy admixtures on the jet structure is relatively small; in order to simplify the calculations the corresponding corrections given in [2] have been disregarded.

Following the modern theory of two-phase jets [2], we assume that the number density of the droplets in the main part of the jet is given by the expression [1]

$$n = \frac{9.24 R_0 n_0}{x} (1 - \xi^{1.5}). \quad (2)$$

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As a result of evaporation the vapor concentration at an arbitrary point of the main jet reaches a certain degree of saturation estimated by the coefficient K

$$C = KC_0.$$

From the material balance it follows that

$$KC_0 - C_\infty = n \frac{4\pi}{3} (r_0^3 - r^3) \rho_f. \quad (3)$$

Here, it has been assumed that the vapor formed as a result of droplet evaporation remains in the neighborhood of the droplet. Substituting the value of n from (2) and solving Eq. (3) for r, we obtain

$$r = r_0 \left[1 - \frac{0.026(KC_0 - C_\infty)x}{R_0 n_0 r_0^3 \rho_f (1 - \xi^{1.5})} \right]^{1/3}. \quad (4)$$

The distance from the nozzle at which droplets of initial radius r_0 are completely evaporated ($r = 0$)

$$x_t = \frac{38.7 R_0 n_0 r_0^3 \rho_f (1 - \xi^{1.5})}{KC_0 - C_\infty} = 9.24 (1 - \xi^{1.5}) BR_0, \quad (5)$$

where $B = 4\pi r_0^3 n_0 \rho_f / 3(KC_0 - C_\infty)$ is a dimensionless criterion characterizing the ratio of the initial specific rate of consumption of the liquid in the droplets to the specific "vapor capacity" of the jet.

Even if the evaporation of the droplets proceeded at an infinitely rapid rate, it could not be completed at distances from the nozzle less than x_t ; however, in this case the coefficient K would be equal to unity. Consequently, at $K = 1$ the surface $x_t = f(\xi)$, represented in the figure by a dashed line, separates the inner region of the main part of the jet, in which evaporation is incomplete owing to lack of air, from the outer region, in which evaporation goes to completion. Obviously, at a relatively high evaporation rate (relatively small droplet size) in the first approximation it is possible to neglect the deviation of K from unity and assume that evaporation is complete at the surface $x_t = f(\xi)$ with $K = 1$. In order to estimate the admissibility of this simplification it is possible to employ the dimensionless criterion

$$E = \frac{\tau_t}{\tau_d}, \quad (6)$$

where τ_t is the residence time of the droplets in the inner region of the main part of the jet (the time required to travel the distance x_t).

In view of the above-mentioned difficulties in determining τ_t and τ_d , it is possible to estimate τ_t from Maxwell's equation [1] (valid for the quasistationary evaporation of an individual droplet in still air with negligibly small temperature changes)

$$\tau_d = \frac{\rho_f r_0^2}{2D(C_0 - C_\infty)}. \quad (7)$$

The quantity τ_t can be approximately (without allowance for the differences between droplet and air velocities) determined by means of the empirical equation of the theory of turbulent jets [2], which gives a good description of the velocity profiles in the main part of a turbulent submerged incompressible-fluid jet*

$$u = \frac{12.4 R_0 u_0}{x} (1 - \xi^{1.5})^2, \quad (8)$$

whence we obtain

$$d\tau = \frac{dx}{u} = \frac{0.0806 x dx}{R_0 u_0 (1 - \xi^{1.5})^2},$$

and for $x = 0$ at $\tau = 0$, using (5),

$$\tau_t = \frac{0.0403 x_t^2}{R_0 u_0 (1 - \xi^{1.5})^2} = \frac{3.44 R_0 B^2}{u_0}. \quad (9)$$

*The above remarks concerning the applicability of Eq. (1) to a two-phase jet apply equally to Eq. (8).

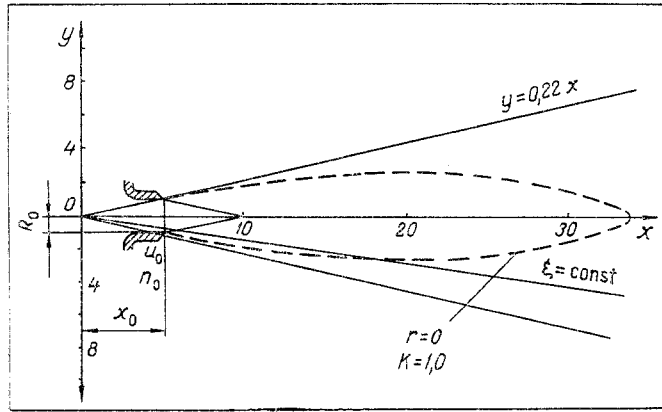


Fig. 1. Diagram of a turbulent submerged air-droplet jet; the dashed line represents the surface $x = f(\xi)$ separating the inner region of the main part of the jet, in which evaporation is incomplete owing to lack of air, from the outer region, in which evaporation goes to completion.

Substituting these values of τ_t and τ_d in (6), we find

$$E = \frac{6.88 R_0 D B^2 (C_0 - C_\infty)}{\rho_f u_0^2 r_0^2} = \frac{6.88 R_0 D \rho_f (Q_f / Q_a)^2}{(C_0 - C_\infty) u_0^2 r_0^2}. \quad (10)$$

It follows from Eq. (10) that E is the greater, the greater the initial radius of the jet and the specific liquid flow rate and the smaller the initial velocity of the jet and the droplet diameter.

Obviously, at $E \gg 1$ it is possible to employ Eqs. (4) and (5) for approximate droplet evaporation calculations. At $E \ll 1$ the degree of evaporation of the droplets in the main part of the jet is only slight, evaporation takes place chiefly outside the jet* and evaporation in the jet can be neglected. In the intermediate region it is necessary to determine the corresponding values of K experimentally.

We have considered evaporation proceeding under conditions such that temperature changes can be neglected. A similar approach is possible in the presence of nonisothermal evaporation in the jet; in this case it is necessary to take the heat balance and the temperature dependence of the vapor tension into account.

NOTATION

r	is the droplet radius;
r_0	is the initial droplet radius;
D	is the vapor diffusion coefficient in air;
ρ_f	is the liquid density;
C_0	is the saturated vapor concentration;
C_∞	is the vapor concentration in the surrounding atmosphere;
τ	is time;
u	is the air velocity in the jet in the direction of the x axis;
R_0	is the initial radius of the jet;
u_0	is the velocity in the initial section of the jet;
x	is the distance from the nozzle (from the initial section of the jet), m;
$\xi = y/0.22x$	
y	is the distance from the jet axis, m;
n	is the number density of the droplets in the jet;
n_0	is the initial number density;
κ	is the admixture concentration in the jet;
κ_0	is the initial admixture concentration;

*Theoretically the jet is of infinite extent, but in practice its limits are definite enough.

κ_{∞} is the admixture concentration in the surrounding atmosphere;
 τ_d is the droplet evaporation time;
 Q_f is the liquid flow rate;
 Q_a is the air flow rate.

LITERATURE CITED

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