It is assumed that waves play the role of irregularities here, since, as in [1], the dimension of the irregularities in the equation for λ_α is replaced by half the amplitude.

In conclusion, let us indicate the boundaries within which the theoretical conclusions hold. They are determined by the requirement that the wave number k [$k \leqslant 1$, which is the basis for deriving Eq. (1.1)], the parameter ε ($\varepsilon \leqslant 1$, which is the basis for constructing the solution), and the amplitude are all small, allowing us to disregard the dependence of tangential stress on wave profile. By imposing these requirements on ε, k, and α, we find that these requirements hold when Re is less than 10^4–10^5 if $10 < \mathrm{Re} < 100$ in the case of water, for example, under downstream cocurrent conditions.

LITERATURE CITED

1. A. A. Tochigin, "Wave flow of liquid film in conjunction with gas flow," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1972).
2. L. P. Kholpanov, V. Ya. Shkadov, V. A. Malysov, and N. M. Zhavoronkov, "Acounting for tangential forces in nonlinear calculations of wave flows of a liquid film," Teor. Osn. Tekhnol., 6, No. 2 (1972).
3. H. Schlichting, Boundary Layer Theory, McGraw-Hill (1966).
4. P. L. Kapitsa, "Wave flow of thin layers of a viscous liquid," Zh. Éksp. Teor. Fiz., 19 (1949).
5. L. N. Maurin, "Ramified steady-state wave motions of a liquid film draining in a vertical plane," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1975).
6. F. P. Stainhorp, and R. S. Batt, "The effect of cocurrent and countercurrent air flow on the wave properties of falling liquid films," Trans. Inst. Chem. Eng., 45, 372 (1967).
7. A. D. Al'tshul' and P. G. Kiselev, Hydraulics and Aerodynamics [in Russian], Stroiizdat, Moscow (1965).

DROP EVAPORATION IN A TURBULENT GAS JET

V. F. Dunskii and Yu. V. Yatskov

UDC 532.517.4

Evaporation of a semidispersive drop system in a turbulent gas jet is considered. A method for calculating drop evaporation in a turbulent gas jet is proposed based on a simplified solution of the scattering problem for an evaporating admixture. Evaporation of water as it is atomized in a turbulent air jet is experimentally studied. Approximate agreement is obtained between the results of the calculations and experiments.

In contrast to evaporation processes of an individual drop, which have been widely studied and are amenable to calculation, actual evaporation processes of systems of drops have been hardly studied at all.

The concept of two evaporation regimes of drop systems in a turbulent gas jet, namely, kinetic and diffusion, has been introduced [1]. The rate of evaporation of the system is determined in the kinetic regime by the kinetic evaporation of an individual drop, and by the rate of diffusion of the external gas as a whole in the diffusion regime. The determination of the evaporation regime in a turbulent drowned jet was carried out by means of the E criterion [1].

Kinetic drop evaporation conditions are realized when $E \gg 1$ and diffusion conditions, when $E \ll 1$.

Drop evaporation in a turbulent drowned jet in the kinetic regime has been considered [2]. It was shown that irreversible ejection of drops from the jet core in the slowly moving periphery at which the evaporation process is consummated is characteristic for the scattering of an evaporating impurity in a turbulent jet. As a result, scattering of the evaporating impurity occurs more rapidly than of the nonevaporating (conservative)

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 73-79, January-February 1976. Original article submitted November 22, 1974.

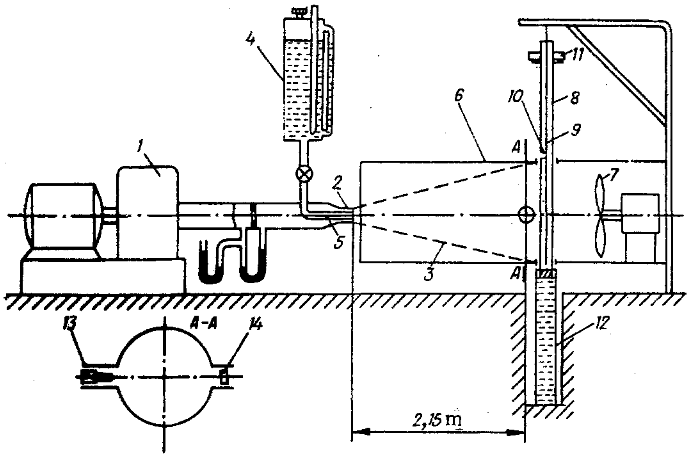

Fig. 1

impurity, and cannot be described by existing scattering theories for a conservative impurity in turbulent jets. The approximate equation [2]

$$\varepsilon = \frac{\Delta N}{N_0} = 3\,(x/x_m)^2 - 2\,(x/x_m)^3 \tag{1}$$

has been proposed for the scattering of an evaporating impurity. Here ε is the degree of evaporation of the liquid of the jet at a distance x units from the nozzle, ΔN is the number of drops departing from a section of the jet core of length x, N_0 is the total number of drops passing through the initial jet cross section in 1 sec, and x_m is the length of the jet core.

It has been proved [2] that the agreement between experiments and calculations using equations determining the value of the length x_m of the jet core is satisfactory both under diffusion and under kinetic conditions in the case of the evaporation of a monodispersive water drop system in a turbulent drowned air jet.

It may be expected, in view of the nature of previous hypotheses [2] in deriving equations to determine x_m, that such computational formulas will be useful for approximating evaporation in engineering processes of atomizing liquids in turbulent cocurrent streams.

Experiments using the device schematically depicted in Fig. 1 were carried out to verify these hypotheses. Air injected by the pneumatic pump 1 flows from a cylindrical probe 2 with radius $R_0 = 15$ mm at a mean velocity $U_0 = 106$ m/sec, forming the turbulent jet 3 ($Re \approx 200{,}000$). Liquid (water) proceeds haphazardly from the tank 4 to the nozzle 5 situated coaxially with the probe and is atomized as the high-velocity airflow is ejected from the nozzle in fine drops, which are scattered in the jet and vaporize. The compartment measured $10 \times 5.7 \times 2.8$ m^3.

A bench method [3] was used to determine the drop dimension spectrum. The air–drop jet is directed into a wind tunnel 6 with radius 0.35 m and length of working section 2.4 m. The axial-flow fan 7 creates an airflow in the tunnel with a mean velocity of 6.3 m/sec. A tube 8 measuring 14 mm in diameter freely slipping on guide bushes is vertically situated relative to the exit diameter at the exit from the working section of the tunnel. An immobile bar 9 is found inside the tube. The tube contains a slit 10.2 mm in width, turned counter to the airflow. The plane working surface of a bar measuring 700 mm long and 5 mm wide is also turned counter to the flow and is preliminarily coated with a thin layer of carbon black and with a thin layer of magnesium oxide from above. Droplets suspended in the airflow that encounter the tube (due to their inertia) are deposited on it. The tube is shifted during the experiment from the extreme upper position to the extreme lower position at a constant velocity by the action of a load 11; this velocity is due to the hydraulic cylinder 12, whose plunger is connected to the lower end of the tube; here the bar is uniformly exposed and droplets that fly off through the slit are deposited on the working surface of the bar, pierce the magnesium oxide layer, and pass through the layer of carbon black. They form circular impressions against a white background which are counted and measured under a microscope and broken down into classes of dimensions, taking into account the area scanned.

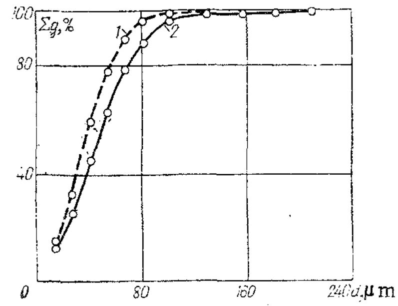

Fig. 2

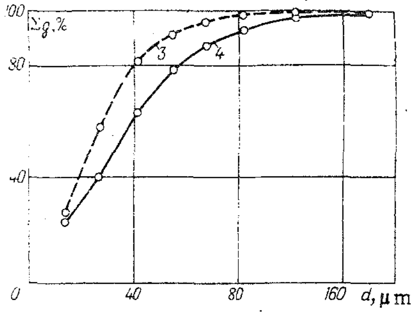

Fig. 3

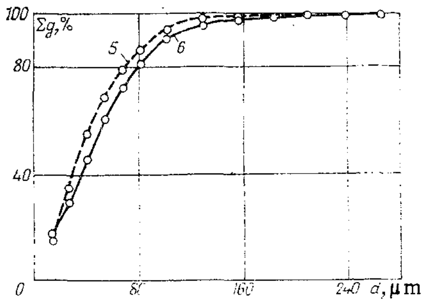

Fig. 4

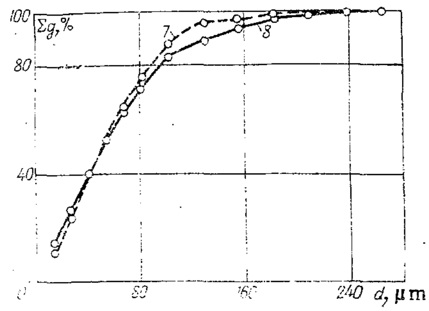

Fig. 5

TABLE 1

No. of expt.	Liquid	Q_0, cm³/sec	Q_1, m³/sec	v_0, m/sec	t, °C	W, %	c_∞	c_0	r_1	r_1^*	r_2	r_2^*	ε_1	ε
							10^6 g/cm³		μm				%	
1	Water	8,45	0,0788	111,5	24,8	16,3	3,72	11,4	24,8	—	21,3	—	32,0	18,4
2	Mixture	8,62	0,0772	109,0	21,3	23,5	—	—	—	25,4	—	21,1	—	—
3	Water	16,8	0,0824	117,0	21,4	29,0	5,43	10,7	20,7	—	18,5	—	30,0	17,6
4	Mixture	16,9	0,0779	110,3	23,0	31,0	—	—	—	21,7	—	18,6	—	—
5	Water	33,0	0,0760	107,8	20,4	19,4	3,44	9,2	24,0	—	20,3	—	18,0	16,0
6	Mixture	33,5	0,0745	105,6	17,2	17,0	—	—	—	23,9	—	19,7	—	—
7	Water	48,6	0,0744	109,9	21,9	26,9	5,19	10,5	27,3	—	22,2	—	9,0	7,45
8	Mixture	48,6	0,0775	110,0	21,7	29,4	—	—	—	25,8	—	20,6	—	—

The degree of evaporation of drops in the jet is determined at a distance of 2.15 m from the probe by measuring the attenuation of light as a light beam passes through the air–drop jet. The light intensity from the lamp 13 was measured by the photoresistor 14; the degree to which light intensity decreased, $\alpha = I/I_0$, where I is the intensity of light that passes through the aerosol jet and I_0 is the intensity of light in the absence of the jet, is determined.

The variable I is approximated by the equation [4]

$$I = kr^p n,$$

where n is the computed particle concentration, k is a coefficient, and p = 2 for particles whose radius is several multiples the wavelength of light λ (which corresponds to the experimental conditions) in the absence of multiple light scattering, i.e., for a low numerical particle concentration n).

In our experiments we thus assumed the dependence

$$\alpha_1/\alpha_2 = \bar{n}_1\bar{s}_1/\bar{n}_2\bar{s}_2, \qquad (2)$$

where $\bar{n} = Q_0/[(4\pi r_1^3/3)Q_1]$ is the mean counted drop concentration in the air–drop flow passing through the tube, $r_1 = \sqrt[3]{\frac{\sum n_i r_i^3}{\sum n_i}}$ is the mean-volume droplet radius, $\bar{s} = \pi r_2^2$ is the mean area of the droplet center section, $r_2 = \sqrt{\frac{\sum n_i r_i^2}{\sum n_i}}$ is the mean droplet radius relative to surface area, Q_0 is liquid flow rate, and Q_1 is gas flow rate through the initial jet section.

Results of experiments with a water–glycerine mixture carried out for different liquid flow rates Q_0 were used to verify the applicability of Eqs. (2); satisfactory agreement between the measured values of α_1/α_2 and values calculated using Eq. (2) was obtained. The calculated values were 10 to 15% below those measured.

The degree of evaporation of water drops in a jet section x units from the nozzle has the form

$$\varepsilon = 1 - \frac{Q_0'}{Q_0}$$

or, when the initial water and water–glycerine mixture flow rates are equal ($Q_0 = Q^*_0$),

$$\varepsilon = 1 - \frac{Q_0'}{Q_0^*}.$$

The degree of light attenuation by water drops is given by

$$\alpha = \overline{n}\overline{s} = \frac{Q_0' \pi r_2^2}{\frac{4\pi r_1^3}{3} Q_1'},$$

where Q_0 and Q^*_0 are the initial water and water–glycerine mixture flow rates and Q_0' and Q_1' are water and air flow rates through a section x units from the nozzle.

For the water–glycerine mixture drops we have

$$\alpha' = \overline{n'}\overline{s'} = \frac{Q_0^* \pi r_2^{*2}}{\frac{4\pi r_1^{*3}}{3} Q_1'},$$

and the ratio

$$\frac{\alpha}{\alpha'} = \frac{Q_0' r_2^2 r_1^{*3}}{Q_0^* r_2^{*2} r_1^3},$$

so that

$$\frac{Q_0'}{Q_0^*} = \frac{\alpha r_2^{*2} r_1^3}{\alpha' r_2^2 r_1^{*3}}$$

and, consequently, the degree of evaporation is given by

$$\varepsilon = 1 - \frac{\alpha r_2^{*2} r_1^3}{\alpha' r_2^2 r_1^{*3}}. \tag{3}$$

Here an asterisk denotes the mean drop radius of the water–glycerine mixture.

The values of α, α', r_1, r_2, r^*_1, and r^*_2 were determined experimentally and the value of the degree of evaporation for x = 2.15 m was found using Eq. (3).

In all, four pairs of experiments were carried out (four with water and four with the water–glycerine mixture), differing only by the liquid flow rate, namely, 0.5 liter/min, 1.0 liter/min, 2.0 liter/min, and 3.0 liters/min. Each experiment was repeated 6 to 10 times. The resulting drop dimension distribution, averaged for each experiment, are presented in Figs. 2-5. Integral drop dimension curves relative to liquid weight for water are depicted by a broken line, while the solid lines depict these curves for the water–glycerine mixture; the digits on the curves denote the number of the experiment. A variation of liquid flow rate within a given range does not influence the distribution curves to any great extent in accordance with the Nukiyami–Tanasov equation [4]. The drops were somewhat larger in all cases for the water–glycerine mixture than for water. Averaged conditions under which the experiments were carried out and the experimental and theoretical values of the degree of evaporation of water ε_1 and ε are presented in Table 1, in which t and w represent the temperature and relative humidity of the surrounding air.

It was necessary to vary previous [2] calculated degrees of evaporation ε_1 in order to compute them from the data of our experiments. As a result, jet lengths x_m were determined in Eq. (1), since the experiments were carried out in a wind tunnel, i.e., under conditions corresponding to the propagation of a turbulent jet in a gas slipstream, while previous [2] equations refer to a turbulent drowned jet.

Propagation of a turbulent jet in a gas slipstream [5] is characterized by a number $m = u_1/u_0$, where u_1 is slipstream velocity. In our case, this number is low ($m \approx 0.06$), so that we may use previous approximation theory [5].

Gas velocity on the jet axis is given by

$$u_m - u_1 = \frac{12.4 R_0 (u_0 - u_1)}{x}, \qquad (4)$$

where R_0 is the radius of the initial jet section.

The impurity concentration (counted drop concentration) on the jet axis is given by

$$\frac{n_m}{n_0} = \frac{\Delta\bar{u}_m 0.134 (1-m) + 0.258m}{\Delta\bar{u}_m 0.180 (1-m) + 0.428m},$$

where

$$\Delta\bar{u}_m = \frac{u_m - u_1}{u_0 - u_1} = \frac{12.4\, R_0}{x}.$$

The equation for determining jet length for the diffusion regime is transformed, taking into account these equations, into the form

$$x_m = \frac{-b + \sqrt{b^2 - 4qc}}{2q}, \qquad (5)$$

where

$$q = \frac{0.428m\,(c_0 - c_\infty)\,Q_1}{\rho Q_0};$$

$$b = \left[\frac{2.23 R_0 (1-m)(c_0 - c_\infty)\,Q_1}{\rho Q_0} - 3.2 m R_0\right];$$

$$c = -20.6 (1-m) R_0^2;$$

c_0 is the concentration of vapor saturated at the temperature of the drop surface and c_∞ is vapor concentration in the surrounding gas.

For a jet in a slipstream we have for low m, as in the case of a drowned jet,

$$\frac{n}{n_m} = \left[1 - \left(\frac{y}{R}\right)^{1.5}\right]; \quad \frac{u}{u_m} = \left[1 - \left(\frac{y}{R}\right)^{1.5}\right]^2,$$

where R is jet radius.

It can be proven that Eq. (1) remains true for a jet in a slipstream by using these equations and reproducing the conclusions presented in [2].

The transit time τ_2 for a path x_m units of inertialess particles, i.e., moving at air velocity along the jet axis in the slipstream, can be determined by integrating Eq. (4), setting $u = dx/d\tau$,

$$\tau_2 = \frac{x}{u_1} - \frac{12.4\, R_0 (u_0 - u_1)}{u_1^2} \ln\left[1 + \frac{u_1 x}{12.4 R_0 (u_0 - u_1)}\right].$$

If drop occupation time in the jet core is set equal to Maxwell total drop evaporation time [6],

$$\tau_1 = \frac{r_0^2\, \rho}{2D\,(c_0 - c_\infty)},$$

we obtain an equation for numerically determining x_m under the kinetic regime for a jet in the slipstream,

$$x_m - \frac{28.6R_0(u_0-u_1)}{u_1}\lg\left[1+\frac{u_1x_m}{12.4R_0(u_0-u_1)}\right]=\frac{r_0^2\rho u_1}{2D(c_0-c_\infty)}. \tag{6}$$

We may establish, using the E criterion [1], that experiments 1, 2 and 3, 4 (Figs. 2 and 3) were carried out in the kinetic regime, while experiments 5, 6 and 7, 8 (Figs. 4 and 5) were carried out in the diffusion regime. Jet core length x_m was calculated using Eq. (5) accordingly from data of experiments 5 and 6, 7 and 8, and the degree of evaporation ε at a distance $x=2.15$ m was then calculated using Eq. (1); the corresponding values of 7.45% and 16% are presented in Table 1.

The value of x_m was numerically (graphically) determined using Eq. (6) for each drop fraction in calculating ε for the kinetic regime (experiments 1 and 2, 3 and 4), and the value of ε_i for $x=2.15$ m was calculated using Eq. (6); the relative amount of evaporated water $\Delta\varepsilon=\varepsilon_i g_i$ was calculated for a relative weight g_i of the given fraction. The degree of evaporation for the entire set of drops was determined by the sum $\varepsilon=\Sigma\Delta\varepsilon=\Sigma\varepsilon_i g_i$; the corresponding values of 17.6% and 18.4% are presented in Table 1.

It is evident from Table 1 that values of ε_1 obtained experimentally and values of ε calculated using our equations are sufficiently close (if we take into account the approximate nature of both the experimental and computational methods for determining ε). This indicates that our method can be used to approximate the evaporation of a liquid as it atomizes in turbulent gas jets.

LITERATURE CITED

1. V. F. Dunskii and Yu. V. Yatskov, "Evaporation in a turbulence-free air-drop jet," Inzh.-Fiz. Zh., 20, No. 3, 423 (1971).
2. V. F. Dunskii and Yu. V. Yatskov, "Evaporation of drops in a turbulent air jet in the kinetic regime," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 112 (1974).
3. V. F. Dunskii and N. V. Nikitin, "Method of determining droplet dimension spectra in liquid atomization," Inzh.-Fiz. Zh., 12, No. 2, 254 (1967).
4. H. L. Green and W. R. Lane, Particulate Clouds: Dusts, Smokes, and Mists, Barnes and Noble (1964).
5. G. N. Abramovich, Turbulent Jet Theory [in Russian], Fizmatgiz, Moscow (1960).
6. N. A. Fuks, Evaporation and Growth of Drops in a Gaseous Medium [in Russian], Izd. Akad. Nauk SSSR, Moscow (1958).