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REGULARITIES OF HYDRODYNAMICS AND MASS TRANSFER IN JET APPARATUSES

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Consideration is given to the influence of different (geometric and hydromechanical) parameters on ejection; an equation describing the ejection is proposed; a maximum possible ejection coefficient is calculated from this equation, and an attempt is made to experimentally calculate the coefficient of overall mass transfer from the evaporation of water from a jet apparatus.

Jet apparatuses are rather widely used in many branches of engineering. Granted the exceptional simplicity of their structure, their distinctive feature is the ejection of one medium by another possessing a greater potential; a highly developed surface of contact of the phases may form in the liquid phase of the apparatus.

Jet apparatuses in various branches of engineering are currently used for two purposes: to increase the pressure of the injected flow and to inject air or gas into a medium that needs to be saturated with air or gas, for instance, to ensure the course of biochemical reactions. It is possible to use jet apparatuses to pursue both purposes simultaneously.

It is necessary to note that a comparatively small number of controversial works are devoted to the creation and methods of calculation of jet apparatuses for aeration of liquid and to the problem of mass transfer in jet apparatuses. Therefore, there is still debate over the way an optimum apparatus with jet aeration of liquid can be designed.

Despite the difference of opinions, two main points of view on the determination of the ejection coefficient has been formed in the literature. The authors of the first group which includes a number of representatives of the domestic school [1, 2], base their approach on equations of the balance of momenta for liquid and gas flows and on their interaction.

The other approach is known, as a rule, from the works of a number of predominantly foreign researchers [3, 6]; it is empirical but takes into account the physical characteristics of the interacting flows.

However, due to their empirical nature, these dependences, too, do not answer the question of the mechanism and nature of the ejection coefficient and its limiting characteristics.

The following questions are considered in the paper:

1) the relationship of K_e with the hydrodynamic regime of outflow of the jet and the geometric characteristics of the nozzle;

2) the factors affecting the formation of the surface of contact of the phases in jet apparatuses;

3) the regularities that determine the coefficient of overall mass transfer in jet apparatuses.

The experiments were conducted at the laboratory stand of a jet apparatus (see Fig. 1).

The apparatus represents a cylinder 1, made of organic glass and fixed in a metal mandrel. A shaft 2 in which the ejection of air by a water flow occurs is immersed into the vessel. Side connecting pipes are attached to the shaft: one – to measure the pressure 4 and the other 5 – to feed (draw in) the gas (air). Circulating water arrives at a nozzle 9. A manometer 3 registers the pressure at the nozzle head. It is by its

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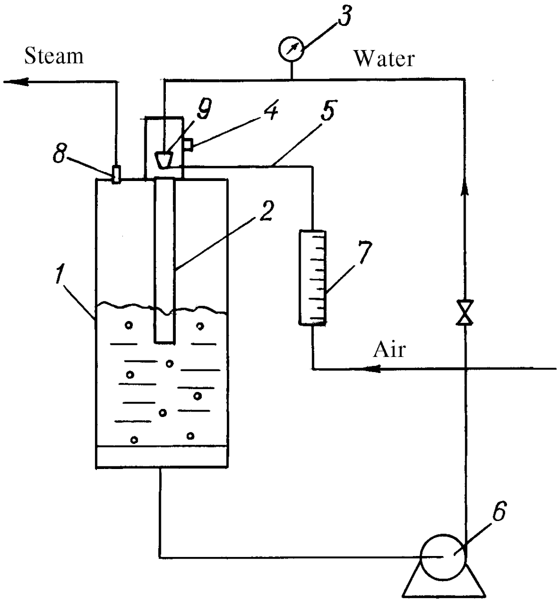

Fig. 1. Laboratory stand of a jet apparatus.

readings that the flow rate of the water fed for ejection is judged. The gas flow rate is measured by a rotameter 7. The steam-air mixture is released through a connecting pipe 8.

A liquid (water) is constantly present in the apparatus. Its continuous circulation through the system is ensured by a pump 6.

The required level of liquid in the apparatus is maintained using the pressure drop (or the metering nozzle), and its discharge is done through a drain valve.

The connecting pipe for the introduction of the liquid into the apparatus ends with a threaded hole, into which the studied nozzle of the jet aerator required for the experiment is screwed in.

The inside diameter of the glass apparatus is D_{ins} = 112 mm (F = 0.00985 m^2).

In the course of the experiments, we determined the influence of the nozzle diameter, the slope of jet outflow from the nozzle, and the location of the shaft (mixing chamber) relative to the original level of liquid on the ejection.

A characteristic of the ejection is the coefficient

$$K_{\mathrm{e}} = \frac{Q_{\mathrm{g}}}{Q_{\mathrm{liq}}}, \tag{1}$$

The regularities of the formation of the phase-contact surface and the overall mass transfer were also studied at the stand.

The quantity K_{e} was used to judge the influence of respective parameters on the quality of aeration. The ejection coefficient K_{e} also depends on the hydrodynamic characteristics of the flow.

Figure 2a shows the dependence $K_{\mathrm{e}} = f(W_{\mathrm{liq}})$ in outflow of the liquid from the nozzle of d_1 = 8 mm and d_2 = 5 mm (t = 25°C). In the experiments, use was made of a shaft of diameter d_{sh} = 34 mm; d_1/d_{sh} = 0.235 and d_2/d_{sh} = 0.145. At present, experiments are being conducted to identify the dependence between the shaft's size and shape and the ejection coefficient.

The analysis of the plot shows that for both d_2 = 5 mm and d_1 = 8 mm the ejection coefficient grows as the liquid velocity increases, and for the assigned relation of the nozzle and shaft diameters it is greater for the nozzle of d_1 = 8. To obtain high values of K_{e}, it is necessary to ensure a high flow rate of the gas.

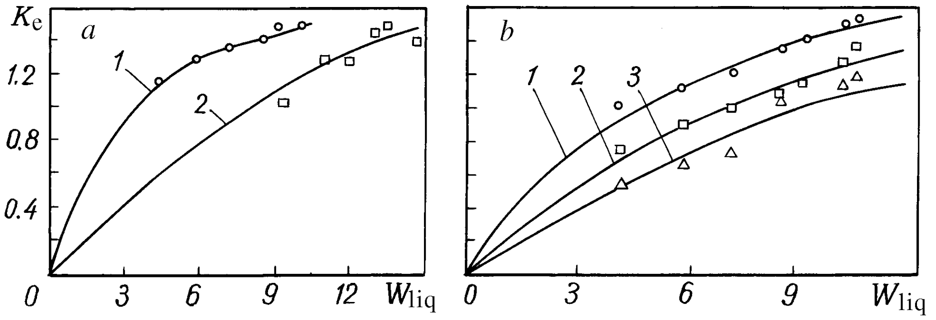

Fig. 2. Dependence of K_e on the velocity of a liquid (a) and the position of a shaft (b): a: 1) d_{nozzle} = 8 mm; 2) 5; b: 1) the shaft is submerged in water to 8 cm; 2) the shaft is at the phase interface; 3) the shaft is 8 cm above the aeration mirror.

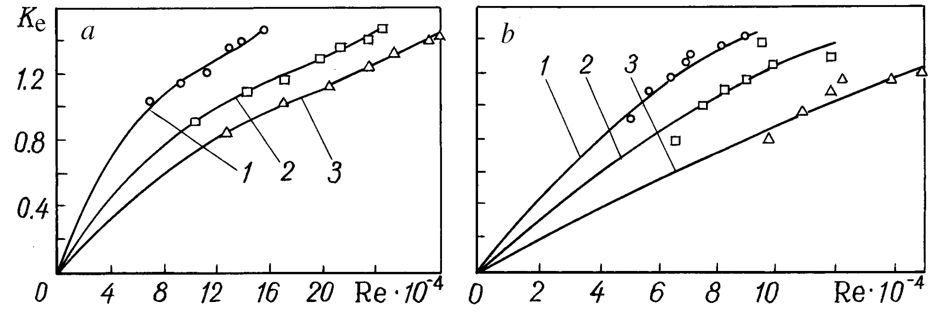

Fig. 3. Dependence of K_e on the Reynolds number for different temperatures and d_{nozzle} = 8 mm (a) and 5 mm (b): a: 1) t = 25°C; 2) 38; 3) 48; b: 1) t = 25°C; 2) 37; 3) 25.

The dependence of K_e on the shaft's position relative to the level of the liquid in the apparatus is shown in Fig. 2b. It is obvious from the plot that:

1. The lowest K_e are obtained in the case where the shaft is higher than the level of the liquid in the apparatus. This is due to the fact that in this case the suction of the gas occurs not only from the atmosphere through the rotameter that shows the gas flow rate but also from the apparatus itself. This additional suction of air is not taken into account by the rotameter; therefore, the calculations of K_e register only the portion of air that is drawn in from the atmosphere. This position of the shaft leads to lower values of K_e.

2. The best values of K_e are obtained in the cases where the shaft is submerged in the liquid (to a depth of 80 mm).

It is known that the interrelationship of the forces of friction and forces of inertia is expressed by the Reynolds criterion. In heating of water, K_e decreased but the value of Re grew since with increase in temperature the water viscosity (molecular) decreases. One could assume that the value of Re must determine the ejection in the jet apparatus. For intense ejection which is characterized by a greater K_e it would be natural to expect high Re numbers; however, the results of the experiment do not show this (see Fig. 3).

This discrepancy can probably be explained by the fact that in the course of the experiment to achieve good ejection, Re numbers must exceed 10^5, i.e., the regime of outflow from the nozzle is a developed turbulence. In this case, the character of the flow can already be influenced not by molecular but by turbulent viscosity. The effective viscosity will result from their sum. In the regime of developed turbulence, much significance is acquired not by the properties of the medium determined by molecular viscosity but by the hydrodynamic conditions influencing turbulent viscosity, i.e.,

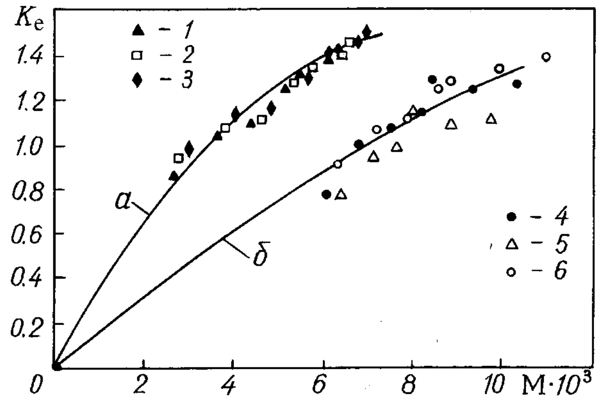

Fig. 4. Dependence of K_e on the Mach number: a) $d_{nozzle} = 8$ mm; 1) $t = 25^oC$; 2) 38; 3) 48; b) $d_{nozzle} = 5$ mm; 4) $t = 28^oC$; 5) 40; 6) 52.

$$\mathrm{Re} = \frac{W_{liq}}{\frac{\nu}{\rho d}} = \frac{W_{liq}}{\frac{\nu_t + \nu_m}{\rho d}} = \frac{W_{liq}}{\frac{\nu_t\left(1 + \frac{\nu_m}{\nu_t}\right)}{\rho d}} . \tag{2}$$

The classical Re number degenerates into the Mach number (M), which represents the ratio of the flow velocity W_{liq} to the velocity of sound in a given medium.

In aerohydrodynamics, for large values of Re the Reynolds number is replaced by the Mach number to characterize the aerohydrodynamic situation (Re > 10^5–10^6).

For the velocity of sound it is known [7] that

$$W_{sound} = (W_{sound})_0 \sqrt{\frac{T}{273}} , \tag{3a}$$

where $(W_{sound})_0$ is the velocity of sound at $T = 273$ K, or

$$W_{sound} = \sqrt{\frac{1}{k\rho}} . \tag{3b}$$

It follows from the analysis of expression (3a) that W_{sound} increases as the temperature grows. If the velocity of sound is a characteristic of turbulence, then the combination $\nu_t/(\rho d)$ characterizes turbulence for high Re numbers (as is common in aeromechanics) and it is readily understood why this combination grows as the temperature increases. This fundamentally distinguishes the behavior of molecular viscosity that substantially decreases as the temperature increases.

At the same time, it is expedient to discuss the values of the Mach numbers themselves, which correspond to Re > 10^5–10^6. If the M number, just as the Re number, expresses a measure of the ratio of the inertial forces to the frictional forces in the developed-turbulence regime, the M numbers themselves for gases and liquids must differ in order of magnitude due to the difference of the densities of the gas and the liquid that affect the evaluation of the inertial forces. Hence it follows that for one and the same Re number the M numbers for the liquid must be 2–3 orders of magnitude lower than for the gas.

It was also established that the dependence of the ejection coefficient on the M number is satisfactorily described by the equation

TABLE 1. Dependence of the Coefficient of Overall Mass Transfer on Ejection Conditions

P, at	τ, min	T_{med}, $^{\circ}$C	Q_g, m^3/h	$dG/d\tau \cdot 10^2$, m^3/h	$P^* \cdot 10^2$, at	$P_{\text{real}} \cdot 10^2$, at	$\Delta P \cdot 10^2$, at	S, m^2	K, m^3/(m^2·h·at)
0.3	25	28	1.158	2.15	3.9	1.76	2.14	2.36	0.446
		43	1.22	7.46	8.65	5.57	3.08	2.25	1
		53	1.258	19.3	14.35	13.3	1.49	2.16	5.2
0.4	25	30	1.45	2.86	4.3	1.93	2.37	3.15	0.39
		43	1.51	9.39	8.65	5.85	2.8	3.13	1.01
		53	1.56	23.1	14.35	12.5	1.88	2.45	3.5
0.5	25	28	1.49	3.1	3.9	1.97	1.92	3.53	0.49
		43	1.54	11.2	8.65	6.6	2.05	3.35	1.5
		53	1.61	27	14.35	13.9	0.5	2.94	–
0.6	25	27	1.67	3.6	3.65	2.1	1.55	4.51	0.55
		44	1.764	13.4	9	6.83	2.17	4.12	1.3
		53	1.81	31.2	14.35	14.2	0.1	3.73	–

$$K = K_{\max} - K_{\max} \exp(-B\text{M}) . \tag{4}$$

For the nozzle with a diameter of 8 μm the coefficient $1/B$ is equal to 0.00417 under optimum ejection conditions, while the maximum ejection coefficient $K_{\max}$ calculated from this equation is 1.8084.

Thus:

1) the ejection coefficient is determined by the measure of the ratio of inertial forces and frictional forces. For high values of Re ($\text{Re} > 10^5$–10^6), this measure is expressed by the M number;

2) the values of M corresponding to $\text{Re} > 10^5$–10^6 are 2–3 orders of magnitude lower for a liquid than the values of M corresponding to the regime of developed turbulence for gases.

Figure 3 presents the plots showing the influence of Re on ejection, where Re as a function of temperature is calculated in terms of the change in the molecular viscosity of water. Figure 4 gives the plots showing the dependence of the ejection coefficient on the Mach number for nozzles of different diameters, where W_s was determined in the M number according to [5].

As is seen from the plots, it is expedient to use the Mach number for the generalization of the ejection coefficients for different temperatures, whereas it is impossible to use the Reynolds numbers to achieve the same.

In investigating mass exchange in jet apparatuses, it was necessary to determine the coefficient of overall mass transfer for apparatuses of this type per unit surface of phase contact.

The experiment was conducted at a laboratory stand described earlier for optimum conditions of ejection at different temperatures.

The coefficient of overall mass transfer is determined from the basic equation of overall mass transfer from the formula

$$K = \frac{dG/d\tau}{\Delta P\, S} , \tag{5}$$

$$\Delta P = P^* - P_{\text{real}} , \tag{6}$$

$$P_{\text{real}} = \frac{G_{\text{steam}}}{Q_{\text{air}} + G_{\text{steam}}} P_s , \tag{7}$$

$$G_{\text{steam}} = \frac{\Delta G_{\text{water}}}{\rho_{\text{steam}}}. \quad (8)$$

In analyzing the experimental data (see Table 1) we see that:

a) as the temperature increases, the amount of evaporated moisture increases; this occurs, also, with growth in the gas flow rate and the liquid flow rate;

b) as the temperature increases, the partial pressure of the steam in the steam-air system increases.

As is known, the coefficient of overall mass transfer is calculated from the formula

$$K_y = \frac{1}{\dfrac{1}{\beta_y} + \dfrac{m}{\beta_x}}. \quad (9)$$

If $\beta_x >> \beta_y$ and $1/\beta_y >> 1/\beta_x$, the term m/β_x can be disregarded since in this case the limiting phase is a liquid phase. If an inverse picture is observed, the limiting phase is a gas phase and then the coefficient of overall mass transfer also depends on the equilibrium, i.e., $1/K_y \approx m/\beta_y$.

In this case (see Table 1), the coefficient of overall mass transfer increases many times as the temperature increases from 28 to 53°C.

CONCLUSIONS

1. We identified factors affecting ejection: the geometric dimensions of the nozzle, the position of the nozzle in relation to the connecting pipe introducing air, and the position of the mixing chamber relative to the aeration mirror.

2. It has been established that high values of the ejection coefficient ($K_e > 1$) are achieved in the regime of developed turbulence ($\text{Re} > 10^5$); the ejection coefficient K_e exponentially depends on the Mach number.

3. As a result of jet aeration, the surface of contact of the phases (which exceeds by 2–3 orders of magnitude the surface of the aeration mirror) is formed from rather uniform gas bubbles whose size depends on the size of the nozzle and seems to be determined by the scale of turbulence.

4. It has been established that the limiting phase of the process of overall mass transfer in the air-water system during jet aeration is a gas phase.

NOTATION

K_e, ejection coefficient; D_{ins}, inside diameter of the jet apparatus, m; F, surface area of the aeration mirror, m^2; Q_g, flow rate of the gas, m^3/h; Q_{liq}, flow rate of the liquid circulating through the apparatus, m^3/L; W_{liq}, velocity of outflow of the liquid from the nozzle, m/sec; d_1 and d_2, diameters of the nozzle used, m; t, temperature of the medium, °C; d_{sh}, diameter of the mixing chamber (shaft), m; Re, Reynolds criterion; K_{max}, maximum ejection coefficient; M, Mach number; W_s, velocity of sound in a given medium, m/sec; K, reduced coefficient of overall mass transfer, m^3/(m^2·h·atm); ν, kinematic viscosity, m^2/sec; ν_m, molecular viscosity, m^2/sec; ν_t, turbulent viscosity; ρ, density of the medium, kg/m^3; d_{nozzle}, diameter of the nozzle, m; k, coefficient of adiabatic compressibility; T, temperature of the medium, K; S, surface of contact of the phases formed by gas bubbles, m^2; ΔP, driving force of the process (difference of the equilibrium and real pressures), atm; $\Delta G_{\text{water}} = dG/d\tau$, amount of evaporated water, kg/h (m^2/h) (it was determined from the evaporation (decrease) of the water in the steady-state regime of aeration); P^*, equilibrium partial pressure of saturated steam (reference data), atm; P, actual pressure of saturated steam in the system, atm; G_{steam}, amount of steam produced per unit time, m^3/h; $Q_{air} = Q_g$, amount of air entrained by the liquid flow, m^3/h; P_s, pressure of the system, atm; $1/B$, segment cutoff on the axis of ordinates by the tangent drawn to the curve at point M = 0; ρ_{steam}, density of the steam (according to the Mendeleev–Clapeyron equation), kg/m^3; ρ_{water}, density of the water, kg/m^3); K_y, coefficient of overall mass transfer expressed for the gas phase, m^3/(m$\cdot^2$sec); β_y and β_x, mass-transfer coefficients in the gas and liquid phases respectively, W/(m$^2\cdot$deg.); m, slope of the equilibrium line (separation factor). Subscripts: e, ejection; ins, inside; g, gas; liq, liquid; sh, shaft; max, maximum; sound, sound; real, real; steam, steam; air, air; nozzle, nozzle; s, system; water, water; t, turbulent; m, molecular; y, gas (phase); x, liquid (phase).

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