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HEAT AND MASS TRANSFER IN DISPERSE AND POROUS MEDIA EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF NONSTATIONARY EVAPORATION OF LIQUID DROPLETS

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The results of experimental and numerical investigations of the nonstationary process of evaporation of droplets of pure liquids into a dry air at variable initial temperature of a droplet, temperature of the gas medium, and relative velocity of flow around a droplet are presented. The regions of application of the well-known laws of change in the size of an evaporating droplet in time depending on the thermal gas-dynamic conditions and thermophysical properties of the liquid and gas phases have been analyzed.

Keywords: *evaporation of droplets, binary liquids, phase transition, heat and mass transfer.*

Introduction. At present, a voluminous amount of information on heat transfer in evaporation of pure liquids from plane surfaces [1–3] as well as spheres (droplets) [4–6] has been accumulated. However, for this rather simple condition there is no uniformity of opinion on the mechanism of the interrelated process of heat and mass transfer in the presence of convective and conductive heat flows and of phase transition. Despite of the fact that the problem on evaporation of droplets of pure liquids is a classical one and a great number of monographs and reviews have been devoted to it [7–10], this problem is still in the developmental stage. At the same time, multiple applications require a more complete consideration of all thermal gas-dynamic factors that accompany the process of heating and evaporation of droplets. We note the basic features of this process. The heating (cooling) of droplets and their evaporation are usually nonstationary. Simple estimations of the Biot number in the Stokesian regime ($Nu = 2$) show that $Bi = 2\lambda_a/\lambda_{liq}$ is independent of the diameter of the droplets. For water evaporation into air at atmospheric pressure $Bi \approx 0.1$, and one must not neglect nonstationary heat transfer inside a particle. For liquids with a low thermal conductivity (alcohols, fuels, oils) the Biot number increases, and this also leads to an increase in the contribution of conductive heat transfer inside a droplet to the general heat balance. The Biot number also increases with the Reynolds number based on the relative velocity of flow around a droplet and on the droplet diameter. For droplets this increase can be rather appreciable, which also points to the necessity of solving a nonstationary conjugate problem of convective-conductive heat transfer in evaporation of droplets.

Due to evaporation, the size of a droplet decreases in time, and this makes the analytical solution of the problem difficult. Moreover, in the case of intense evaporation one must take into account the influence of the injection of evaporation products on the friction and heat- and mass-transfer laws on the surfaces of droplets. Taking account of injection requires invoking additional hypotheses or empirical correlations.

The effect of liquid circulation on the process of heat and mass transfer inside a droplet has not been studied adequately as yet. Thus, according to [10–12], the influence of circulation motion inside a droplet, especially for multicomponent liquids, can be determining.

In the literature, there is an intense discussion of the important problem on the similarity between the processes of heat and mass transfer on the surfaces with phase transitions [13–15]. There exist a great number of approaches, the main task of which is the development of simple methods of calculation of the rate of liquid evaporation and which are an integral part of a more complex process of the combustion of droplets of multicomponent fuels [8, 16, 17].

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The aim of the present work is to carry out a comparative analysis of the available models of evaporation of droplets, as well as to compare them with experimental data on evaporation of various pure liquids. The results obtained allow one to more accurately, as compared to [10, 18] and some other investigations, analyze the influence of a wide range of thermal gas-dynamic parameters on heat and mass transfer from evaporating droplets.

Models of Calculation of the Evaporation of Droplets. The first and simplest model of evaporation was suggested by Maxwell [19]. On the assumption that the process of evaporation is limited by vapor diffusion, we write the expression for a vapor flow in the form

$$j = 4\pi r^2 D_{\text{v}} \frac{d\rho}{dr} . \tag{1}$$

Integrating (1) from $r = r_0$ to $r \to \infty$, we obtain

$$j_{\text{s}} = 4\pi r_0 D_{\text{v}} (\rho_{\text{vs}} - \rho_{\text{v}\infty}) , \tag{2}$$

where j_{s} is the vapor flow from the droplet surface; D_{v}, ρ_{vs}, and $\rho_{\text{v}\infty}$ are the diffusion coefficient of vapor and its density on the surface and in the surrounding gas. With allowance for the Stefan mass flux, Eq. (2) can be transformed to give

$$j_{\text{s}} = 4\pi r_0 D_{\text{v}} \rho_{\text{vs}} (1 + b_{1\text{d}}) , \tag{3}$$

where $b_{1\text{d}} = (k_{\text{vs}} - k_{\text{v}\infty})/(1 - k_{\text{vs}})$ is the diffusion parameter of permeability (the Spalding number).

Spalding's model [20] is based on the same premises as Eq. (1). The solution of the diffusion equation yields the following dependence of the change in the droplet diameter in time:

$$\left(\frac{d}{d_0}\right)^2 = 1 - \frac{8D_{\text{v}}\rho_\infty}{d_0^2 \rho_{\text{liq}}} \ln (1 + b_{1\text{d}})\, t . \tag{4}$$

Equation (4) yields a formula for determining the time of complete evaporation of a droplet:

$$t^* = \frac{d_0^2 \rho_{\text{liq}}}{8D_{\text{v}}\rho_\infty \ln (1 + b_{1\text{d}})} . \tag{5}$$

Relation (4) was called the "d^2 law," and it is widely used for computational estimations. However, Eqs. (4) and (5) provide only the functional dependence of a change in the diameter of a particle in time. In deriving (4), none conditions for heat transfer both on the droplet surface and inside it were used; therefore for this equation to be solved conditions are needed that connect the partial vapor pressure and temperature on the evaporating surface (saturation curve), as well as thermal boundary conditions.

Neglecting radiative transfer, we write the balance of heat fluxes on an evaporating surface in the form

$$\left(-\lambda \frac{\partial T}{\partial r}\right)_{\text{s}} = \alpha (T_\infty - T_{\text{s}}) - j_{\text{s}} L . \tag{6}$$

At infinitely small thermal conductivity of the liquid Eq. (6) is simplified, and it describes the relationship between the heat fluxes in adiabatic evaporation:

$$j_{\text{s}} L = \alpha (T_\infty - T_{\text{s}}) , \tag{7}$$

when the heat supplied by convection is entirely spent on evaporation.

At present, there are a great number of correlation relations for the coefficients of heat and mass transfer on the evaporating surface of a droplet of liquid. The Ranz–Marshall relations [5] below have gained wide use:

$$\mathrm{Nu} = 2 + 0.6\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}\,, \quad \mathrm{Sh} = 2 + 0.6\mathrm{Re}^{1/2}\mathrm{Sc}^{1/3}\,. \tag{8}$$

Experiments [6] refine Eqs. (8) for the case of intense injection:

$$\mathrm{Nu} = \frac{2 + 0.6\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}}{1 + b_{1\mathrm{t}}}\,, \tag{9}$$

$$b_{1\mathrm{t}} = \frac{H_\infty - H_\mathrm{s}}{L} = \frac{1}{\mathrm{Ku}}\,. \tag{10}$$

More detailed information on the laws of heat transfer for evaporating droplets can be found in reviews [8–10].

When Re → 0, the heat- and mass-transfer coefficients take the form Nu = Sc = 2, and from Eq. (7) one can find the change in the droplet diameter in the case of adiabatic evaporation:

$$\left(\frac{d}{d_0}\right)^2 = 1 - \frac{8D_\mathrm{vs}\,(T_0 - T_\mathrm{s})}{d_0^2\rho_\mathrm{liq}L}\,t\,. \tag{11}$$

As is seen, Eq. (11) corresponds to the "d^2 law," and on nondimensionalization it takes a simple form:

$$\left(\frac{d}{d_0}\right)^2 = 1 - 8\,\frac{\mathrm{Fo}}{\mathrm{Ku}}\,\frac{\rho_\infty}{\rho_\mathrm{liq}}\,, \quad \mathrm{Fo} = \frac{ta}{d_0^2}\,. \tag{12}$$

The limiting Fourier number at which the particle evaporates completely is

$$\mathrm{Fo}^* = \frac{\mathrm{Ku}}{8}\,\frac{\rho_\mathrm{liq}}{\rho_\mathrm{vs}}\,, \tag{13}$$

and the transverse vapor flow on the surface

$$j_\mathrm{s} = \frac{2\lambda_\infty\,(T_\infty - T_\mathrm{s})}{d_0L\sqrt{1 - \dfrac{8D_\mathrm{v}\,(T_\infty - T_\mathrm{s})}{d_0^2\rho_\mathrm{liq}L}\,t}} \tag{14}$$

increases proportionally to $t^{1/2}$.

On increase in the Reynolds number (Re >> 1), the second term begins to play the determining role, and the Nusselt number in this limiting case can be written as

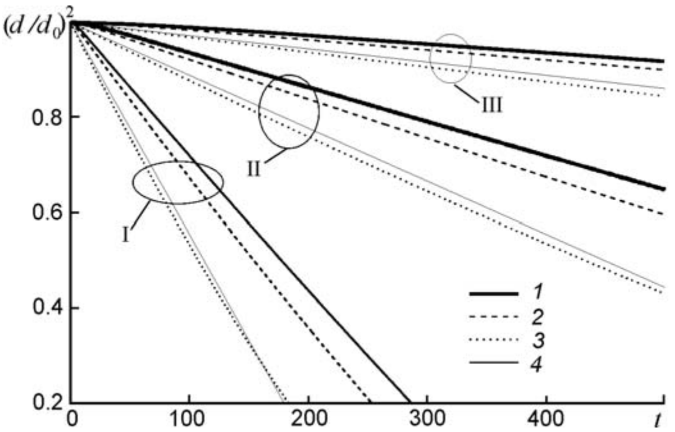
$$\mathrm{Nu} = A\,\mathrm{Re}^{1/2}\mathrm{Pr}^n\,, \tag{15}$$

where A is a constant whose value varies within the range 0.5–0.6, according to various authors. As a result, instead of the quadratic law (12) at Re >> 1 the change in the droplet diameter in time obeys the "3/2 law":

$$\left(\frac{d}{d_0}\right)^{3/2} = 1 - \frac{3A\,\mathrm{Re}^{1/2}\mathrm{Fo}}{\mathrm{Ku}}\,\frac{\rho_\infty}{\rho_\mathrm{liq}}\,. \tag{16}$$

At intermediate values of the Reynolds number the droplet diameter changes according to a more complex dependence.

To close the system of heat-transfer equations, one uses the relation of similarity between the processes of heat and mass transfer which can be written [14], 21] in its final form as



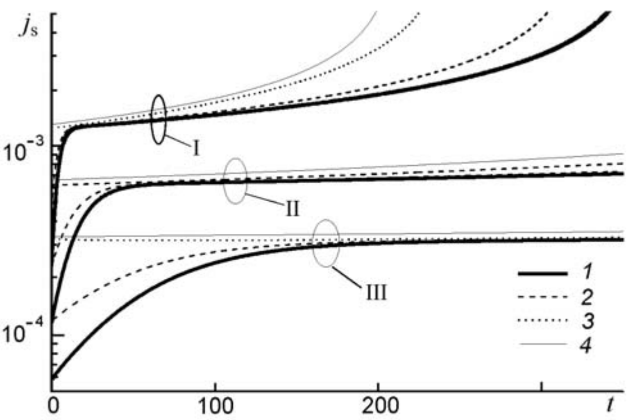


Fig. 1. The "d^2 law" for evaporation of droplets when Re → 0 [air — T_∞ = 80°C; droplet — water, initial diameter: I) d_0 = 1; II) 2; III) 4 mm] at the initial temperature of the droplet: 1) 0; 2) 10; 3) 25.5°C; 4) calculation by Spalding's formula (4). t, s.

Fig. 2. Cross flow of vapor at different initial temperatures of the droplet. The initial conditions and designations of the curves are the same as in Fig. 1. j_s, kg/(m^2·s); t, s.

$$\frac{c_{p\infty}(T_\infty - T_s)}{L} = \frac{k_{vs} - k_{v\infty}}{1 - k_{vs}} \mathrm{Le}^n \, . \tag{17}$$

According to the estimations made in the introduction, in the majority of practical cases an essential role in droplet evaporation can be played by the conductive component of a heat flux; it is spent on heating or cooling to the temperature of adiabatic evaporation. In this case, the solution of the problem consisted of the use of the nonstationary equation of heat conduction in spherical coordinates:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right)$$

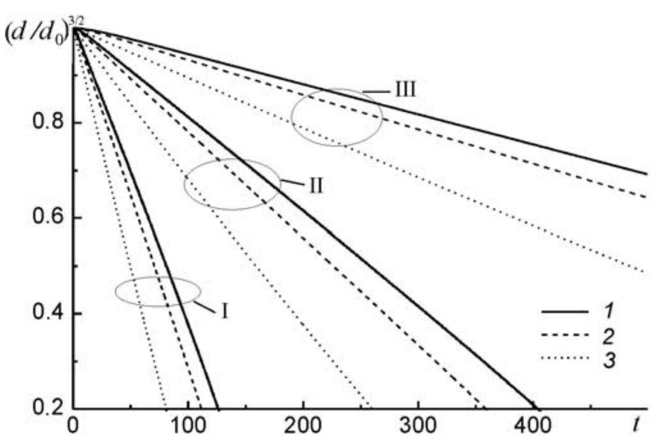
with boundary-value conditions $r = 0$, $\frac{\partial T}{\partial r} = 0$ and $r = r(t)$, $T_s = f(k_s)$ and initial conditions $t = 0$ and $T = T_0$.

The system of equations obtained was solved according to the implicit scheme by the method of finite differences. The thermophysical properties of substances were determined as functions of temperature.

Results of Computational Investigation. Comparison of Various Methods. Calculations were carried out for evaporation of droplets of various liquids: water, ethanol, methanol, and acetone. The main series of calculations was carried out for evaporation of water into a dry air having the temperature T_∞ = 80°C in the Stokesian regime (Nu = 2) and during flow of air around a droplet at the velocity V_∞ = 1 m/s. The initial temperature of droplets T_0 was equal to 0, 10, and 25.5°C. The latter temperature corresponded to the temperature of adiabatic evaporation which imitated the case of an infinitely large thermal conductivity of a liquid. The initial diameter of the droplet was 1, 2, and 4 mm. The main aim of the calculation was to analyze the influence of subcooling of liquid (nonstationary thermal conductivity) on the character of the change in the droplet diameter and on the magnitude of the transverse flow of a substance.

The calculated data for Nu = 2 correspond to the "d^2 law." Indicative of this are the results of calculation presented in Fig. 1. With the exception of the short starting length, a decrease in d^2 occurs linearly in time, with the value of the initial temperature of a droplet exerting a strong influence on the speed of change of its diameter.

The necessity of taking into account the phase of nonstationary heating of droplets is especially clear from Fig. 2, which shows the change in the velocity of the transverse vapor flow on an evaporating surface in time for droplets of different initial sizes and initial temperatures. Droplets of small size display a more powerful transverse flow of the evaporating substance and a small period of nonstationary heating. As was expected, calculations by Spald-



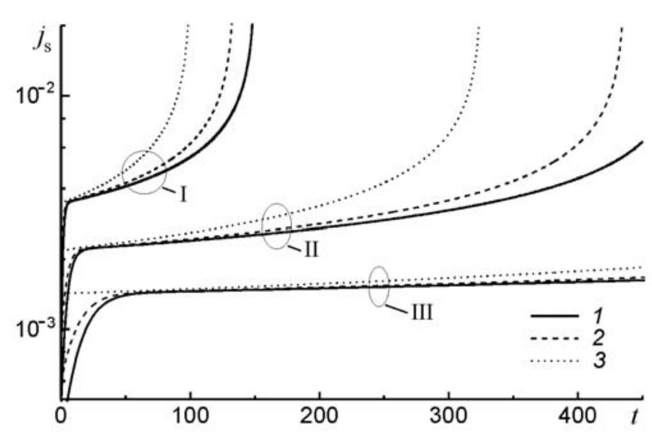


Fig. 3. Law of evaporation during convective flow around droplets [$V_\infty = 1$ m/s, air — $T_\infty = 80^{\circ}$C; droplet — water, initial diameter: I) $d_0 = 1$; II) 2; III) 4 mm] at the initial droplet temperature: 1) 0; 2) 10; 3) 25.5°C. t, s.

Fig. 4. Intensity of evaporation of water droplets in an air flow. The initial conditions and designations of curves are the same as in Fig. 3. j_s, kg/(m^2·s); t, s.

ing's quadratic model (12), (14) plotted in Figs. 1 and 2 coincide with the results of calculation for the conditions of adiabatic evaporation. It is important that Figs. 1 and 2 point to the necessity of taking into account the period of droplet heating, despite the small differences in its initial temperature.

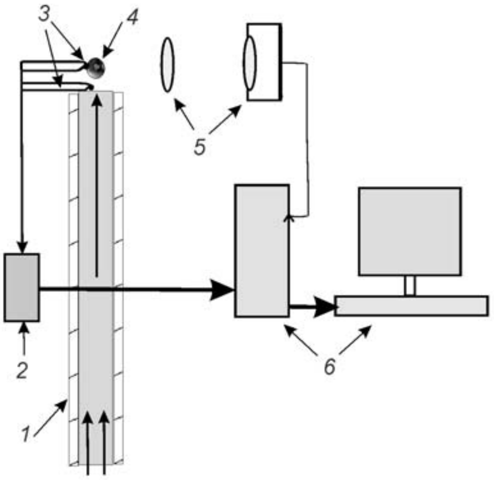
The process of evaporation in the presence of forced flow around a droplet has similar tendencies (Figs. 3 and 4). In contrast to the previous data, the law of change in the diameter obeys the dependence $(d/d_0)^{3/2}$. As before, the heating of droplets to the temperature of adiabatic evaporation exerts a strong influence on the size of a droplet not only in the period of heating but also further, when adiabatic conditions have already been achieved. This is explained by the fact that large droplets with subcooling attain these conditions in a large interval of time, which further leads to a decrease in the rate of evaporation. Moreover, from Figs. 3 and 4 one can easily estimate the possible influence of internal circulation of liquid on intensification of heat transfer. A droplet with the initial temperature $T_0 = T_{\text{ad}}$ corresponds to the regime of maximum mixing. Paradoxical as it may seem, for large droplets the internal circulation may exert a substantially slighter influence than for small ones.

It is natural that liquid circulation may intensify heat transfer inside a droplet only during the heating of droplets. In the thermal stationary regime, when the temperature gradient along the droplet radius is absent, mixing will not exert an influence on the regime of evaporation of droplets.

Such tendencies of the influence of the subcooling of droplets and of regimes of flow around them are observed also for other liquids. However, a detailed analysis of the results of calculations and a comparison require special consideration.

Experimental Investigations. Discussion of Results and Comparison with Calculation. The experimental setup was described in detail in [22]. It is shown schematically in Fig. 5. Experiments were conducted on an aerodynamic rig with air heating up to 300°C and practically zero humidity ($\varphi < 3\%$). At the exit from the channel of 52 mm in diameter the investigated droplet of liquid of about 2 mm in diameter was suspended on a metal ring made from a thermocouple wire of diameter $d = 0.1$ mm so that the junction of thermocouples could be at the center of the droplet. The aerodynamic channel was positioned vertically, and air flowed from below upward so that the levitation effects could suspend the droplet. The air velocity varied within the limits $V_\infty = 0$–6 m/s, and the initial diameter of the droplet did not exceed 3 mm. The maximum Reynolds number in the experiments was equal to $\text{Re} = 1.2 \cdot 10^3$. Usually experiments continued until the size of the droplet constituted 0.3–0.5 of the initial one.

The linear scale of the droplet and the temperature of its surface were measured by a Thermo Tracer TH7102IR infrared camera with microscope objectives. A series of calibrations showed a good correspondence between the results of measurements of the temperature of an evaporating droplet obtained by the infrared camera and the thermocouple located on the surface of the droplet (Fig. 6). Thermographic microsurvey also recorded a change in the external view of the droplet, as shown in Fig. 7. There data were processed by special computer programs as a result of



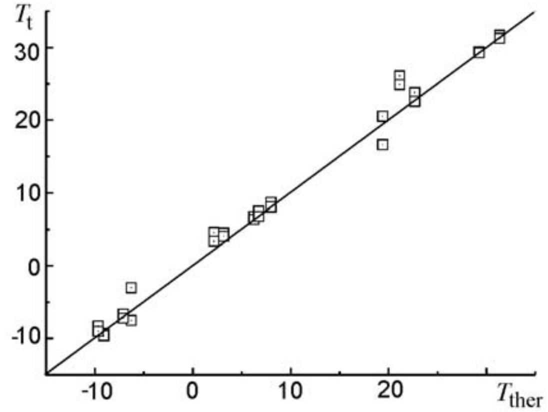
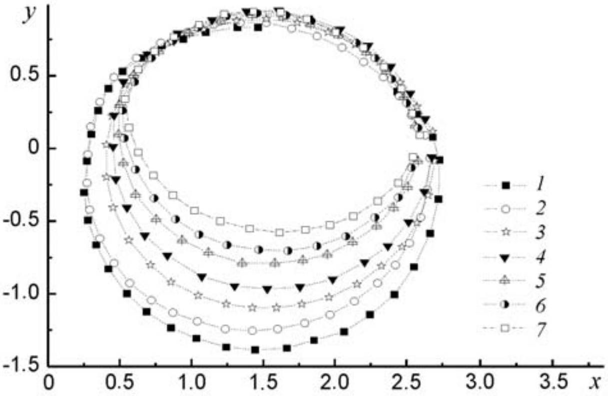


Fig. 5. Schematic of the experimental setup: 1) aerodynamic channel; 2) A/D converter for thermocouple measurements; 3) thermocouples; 4) evaporating droplet of a liquid; 5) infrared imaging setup with microscope objectives; 6) block of processing the results of measurements and a PC.

Fig. 6. Comparison of results of measurements of the temperature of the droplet surface by an infrared imager (vertically) and by a thermocouple (horizontally) T, $^\mathrm{o}$C.



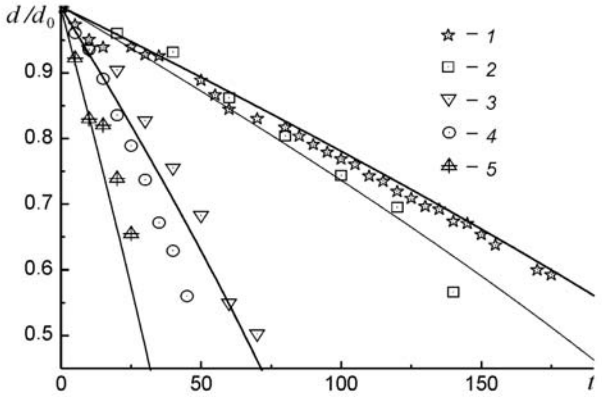


Fig. 7. Change in the shape of a water droplet evaporating in a flow of dry air in time (V_∞ = 3.5 m/s, temperature — T_∞ = 80$^\mathrm{o}$C): 1) t = 0; 2) 40; 3) 80; 4) 120; 5) 160; 6) 200; 7) 240 s. Along the axes — size of a droplet in the x and y directions in millimeters.

Fig. 8. Comparison of experimental and calculated data on change in the diameter of droplets of various liquids in time (points — experiment, curves — calculation): 1) water, T_∞ = 78$^\mathrm{o}$C, V_∞ = 5.1 m/s; 2) water, 80.5 and 5.14; 3) ethanol, 71.5 and 5.1; 4) methanol, 70.2 and 4.3; 5) acetone, 78 and 5.1. t, s.

which it was possible to determine a change in time of the droplet volume, its surface area, and its effective diameter. The error of the change in the linear dimension of the droplet did not exceed 0.1 mm and in the temperature — 0.2 deg. For pure liquids this technique made it possible to determine the value of the mass vapor flow on the droplet surface.

As is seen from Fig. 7, for a long time the droplet preserved its sphericity and then, as its mass decreased, acquired the form of an ellipsoid due to the forces of surface tension. Such configurations were further excluded from processing.

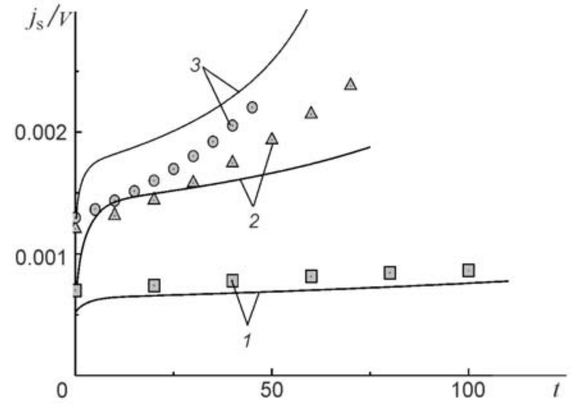


Fig. 9. Change in the transverse flow of vapor on the surface of droplets of various liquids (points — experiment, curves — calculation): 1) water, T_∞ = 72; 2) ethanol, T_∞ = 71.5; 3) methanol, T_∞ = 80.5°C. t, s.

Experiments on evaporation of droplets were carried out for a wide range of pure liquids: water, ethanol, methanol, and acetone, with the temperature of the main flow being varied, T_∞ = 20–80°C. Figure 8 demonstrates the change in the effective diameter of droplets of various liquids in time. As was expected, water droplets evaporate the most slowly; acetone droplets evaporate more rapidly. The rates of evaporation of droplets of methanol and ethanol are close and lie between those of water and acetone. The calculated lines in Fig. 8 on the whole correctly describe the experiment, especially for water droplets. For the remaining droplets the coincidence is somewhat worse, pointing to the necessity of perfecting both experimental investigations and the theory.

A comparison between experimental and calculated data on a change in the intensity of a cross flow in time for droplets of various liquids is presented in Fig. 9. For water droplets, the value of $j_s/(\rho_\infty V_\infty)$ is preserved practically constant for a long time. At the same time, for ethanol, and especially for methanol, the flow of evaporating mass is severalfold higher than for water and increases noticeably with time. The calculated data, which qualitatively correctly describe the experiment, exhibit the same tendency.

CONCLUSIONS

1. An analysis of the available methods of calculation of evaporation of droplets under different thermal and dynamic conditions has been carried out. A nonstationary model of calculation in the presence of the stage of heating of a droplet is given.

2. The results of calculations of the rate of evaporation of droplets in a quiescent medium (Re → 0) and in the regime of forced convection confirm the "d^2 law" and "$d^{3/2}$ law," respectively.

3. The initial subcooling of droplets relative to the equilibrium one exerts a strong influence on the rate of their evaporation at both small and large Reynolds numbers based on the relative velocity of flow around droplets.

4. Experimental data obtained for various liquids with the aid of a microthermographic camera agree on the whole with predicted data.

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NOTATION

a, thermal diffusivity, m^2/s; b_{1d}, b_{1t}, diffusional and thermal parameters of vapor injection; Bi = $\alpha d/\lambda_{\rm liq}$, Biot number; $c_{p\infty}$, specific heat at constant pressure in an air flow, J/(kg·°C); d, diameter of a droplet, m; D, diffusion coefficient, m^2/s; Fo, Fourier number; H, enthalpy, J/kg; j, mass velocity of vapor on the droplet surface, kg/(m^2·s); k, mass concentration of a component; Ku = $(H_\infty - H_s)/L$, Kutateladze number; L, heat of vapor generation, J/kg; Le = D/a, Lewis number; Nu = $\alpha d/\lambda$, Nusselt number; Pr = ν/a, Prandtl number; r, current radius, m; Re = $V_\infty d/\nu$, Reynolds number of a droplet; Sc = ν/D, Schmidt number; Sh = $\beta d/D$, Sherwood number; t, time, s; t^*, time of complete evaporation of a droplet, s; T, temperature; x, y, directions of axes, mm; V, air flow velocity, m/s; α, heat-transfer coefficient, W/(m$^2\cdot^o$C); β, mass-transfer coefficient, m/s; λ, thermal conductivity, W/(m$\cdot^o$C); ν, gas viscosity, m^2/s; ρ, density, kg/m^3; φ, relative humidity of air, %. Subscripts: a, air; ad, adiabatic conditions; d, diffusion; im, measurement by an infrared imager; liq, liquid phase; t, thermal; ther, thermocouples; v, vapor; ∞, flow core; 0, initial conditions.

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