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HEAT AND MASS TRANSFER WITH LIQUID EVAPORATION

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Аннотация—В статье рассматриваются вопросы, связанные с процессами тепло-и массообмена при испарении различных жидкостей. Приводится также обоснование и вывод числа Гухмана (Gu).

NOMENCLATURE

ρ,	mixture density equal to the sum of densities of water vapour ($M_1 = 18$) and inert gas (dry air with the reduced molecular weight ($M_2 = 29$), i.e. $\rho = \rho_1 + \rho_2$;
ρ_{10},	relative vapour concentration or specific vapour mass content, $\rho_{10} = \rho_1/\rho$;
ρ_{20},	relative air concentration, $\rho_{20} = \rho_2/\rho$; $\rho_{10} + \rho_{20} = 1$;
d,	moisture content, $\rho_{10} = d/(1 + d)$;
c,	reduced specific heat of vapour–gas mixture, $c = c_1\rho_{10} + c_2\rho_{20}$;
c_1, c_2,	specific heat of vapour and dry air, respectively;
t,	temperature, degC;
τ,	time, h;
h,	specific enthalpy of system;
λ,	thermal conductivity of vapour–gas mixture;
T,	absolute temperature ($T = 273{\cdot}16 + t$);
c_f,	specific heat of liquid (water);
r,	specific heat of evaporation;
P_v,	partial vapour pressure;
P_a,	partial air pressure;
F,	evaporation surface;
w,	velocity of motion of vapour–gas mixture (air);
φ,	relative air humidity.

Dimensionless numbers

Nu,	Nusselt heat-transfer number;
Nu_m,	Nusselt mass-transfer (diffusion) number;
Pr,	Prandtl number;
Pr_m,	Prandtl diffusion number or Schmid number $Sc (Pr_m \equiv Sc)$;
Re,	Reynolds number.

Subscripts

a,	state of surrounding medium;
b,	state of adiabatic air absorption (e.g. t_b, temperature of adiabatica ir absorption or temperature of wet bulb);
v,	water vapour;
x, y, z,	directions of Cartesian co-ordinates, y is the direction of a normal to the surface of a liquid or of a solid body;
w,	surface of a liquid or of a solid body;
m,	mass-transfer characteristics.

MANY industrial processes depend on the laws of heat and mass transfer with phase conversion (liquid evaporation, vapour condensation, etc.). Heat and mass transfer is not only the theoretical basis of a large group of low-temperature production processes but is important also in solving a number of problems in agrophysics, geophysics and many other fields.

In spite of the existence of copious experimental and theoretical material on evaporation, a great deal remains yet to be done in this field. The influence of cross-flow on heat transfer, the choice of system of similarity criteria, reflecting the mutual influence of heat- and mass-transfer processes, etc., are problems which require discussion. This situation is due to the considerable complexity of the mechanism of transfer with evaporation.

Combined heat- and mass-transfer processes usually prevail when interface surfaces interact with a forced flow of vapour–gas medium. In this case thermal, hydrodynamic and diffusion boundary layers appear to be closely connected and influence each other to a considerable degree. Theoretical and experimental investigations show that rather a greater number of factors influence simultaneously proceeding heat- and mass-transfer processes than separate processes. The mechanism of transfer is very complicated close to the surface of evaporation and cannot be described by the criterial relations available for "dry" heat transfer.

Depending on the conditions of flow round an experimental body and the velocity of the approaching stream two regimes of liquid motion in a boundary layer are distinguished: laminar, and turbulent with a laminar sub-layer.

The mechanism of interaction of combined heat- and mass-transfer processes when the boundary layer is laminar may be determined by solving a suitable system of differential transfer equations. However, under real conditions liquid evaporation occurs more often when the medium flow is turbulent.

In this case the mutual influence of heat- and mass-transfer processes may be first of all determined experimentally, since rather a rigorous analytical solution of the problem considered is impossible for the present for lack of a sufficient study of the turbulent transfer mechanism. An experimental investigation on the interaction mechanism of heat- and mass-transfer processes with evaporation of various liquids in a developed turbulent flow at comparatively large Reynolds numbers is therefore the basic problem of the present work.

The paper considers:

(1) Results of investigations on heat and mass transfer with evaporation of various liquids (water, acetone, benzol and butanol) from a free surface into a turbulent air stream. Experimental data on heat transfer of a dry body are also given. Both processes were investigated simultaneously at the same thermal, hydrodynamic and other equivalent conditions. These experiments allowed an immediate comparison to be made between heat-transfer coefficients for evaporation of liquids and those for a dry body.

(2) Results of investigations on heat and mass transfer with water evaporation from a surface of a capillary-porous body and on heat transfer of a capillary-porous "dry" body. In this case both processes were again studied simultaneously under similar conditions.

THEORETICAL PRECONDITIONS FOR EXPERIMENTAL INVESTIGATIONS

Considerable complexity of a heat- and mass-transfer process with liquid evaporation from a free surface or from a surface of a solid capillary-porous body does not allow a purely analytical solution of the problem and necessitates the use of similarity-theory methods. The choice of similarity criteria characterizing the process considered is argued in the present paper. For subsequent analysis of liquid evaporation and determination of similarity criteria describing this process, consider the generally known equation for heat transfer in a moving liquid [1]:

$$\frac{\partial(\rho h)}{\partial\tau} = -\operatorname{div} j_h \tag{1}$$

where j_h is the specific enthalpy flow.

For a laminar boundary layer this equation may be written as follows:

$$c\rho\frac{\mathrm{d}t}{\mathrm{d}\tau} - (c_1 - c_2)\, j_1 \nabla t = \operatorname{div} \lambda \nabla t, \tag{2}$$

where j_1 is the specific flow of a diffusible vapour.

From equation (2) we have the following criteria:

$$d;\quad 1 + d;\quad d/(1 + d);\quad (c_1 - c_2)/c_2.$$

Consider their physical meaning. Substituting the specific heat for the molecular c_{1m} and c_{2m} in the relation $(c_1 - c_2)/c_2$ and performing some simple transformations, we arrive at:

$$\frac{c_1 - c_2}{c_2} = \frac{M_2}{M_1}\frac{c_{1m}}{c_{2m}} - 1. \tag{3}$$

Since

$$c_{1m}/c_{2m} \simeq 1,$$

then

$$(c_1 - c_2)/c_2 \simeq M_2/M_1 - 1.$$

As a result, from relation (3) we obtain the simplex M_2/M_1. Thus at equal degrees of freedom the simplex $(c_1 - c_2)/c_2$ represents a constant.

The physical role of parameteric criteria d, $1 + d$, $d/(1 + d)$ is reduced to calculation of change in heat capacity of a vapour–air medium depending on moisture content.

A number of authors [2–4] introduce the Gukhman number

$$Gu = \frac{T_a - T_b}{T_a} \quad (4)$$

or the temperature simplex T_a/T_b into the criterial equations describing an evaporation process. Various authors explain the physical meaning of this criterion differently. Following Gukhman [5] the criterion T_a/T_b or $(T_a - T_b)/T_a$ with adiabatic liquid evaporation coincides in its structure with the temperature factor and characterizes a thermodynamic state of the medium. Authors [2–4] consider that the Gukhman number takes into account the influence of mass transfer on heat transfer. Klyachko [6] thinks that Gu is necessary for describing non-adiabatic heat- and mass-transfer processes provided that the nature of heat transfer is convective–radiative.

The absolute value of Gu may be expressed by the following relation [7]:

$$Gu = \frac{t_a - t_b}{T_a} = \frac{(d_a - d_b)(595 - c_f t_b)}{c T_a}. \quad (5)$$

From relation (5) it follows that the absolute value of Gu is proportional to moisture content. Proceeding from the above consideration of the physical rôle of the simplex d, $1 + d$ or $d/(1 + d)$ we may conclude that Gu also takes into account the change in heat capacity of air, depending on its moisture content.

The detailed substantiation of the physical significance of Gu is presented in the works of Luikov [1, 8] who obtained this number from a differential energy-transfer equation in a boundary layer. According to Luikov's theory the smallest sub-microscopic liquid particles enter a boundary layer together with vapour when a capillary-porous plate is in a heated air stream. How such liquid particles (molar dispersing) are abstracted has not yet been studied; however, the following may be assumed: Owing to the displacement of the evaporative surface deep into a body, capillaries (macro- and micro-capillaries) are released. The presence of pressure, greater in the evaporation zone than in the external medium, favours the abstraction of the particles of liquid which enter macro- and micro-capillaries via the boundary layer.

When a gas flow interacts with a free liquid surface, then not only does evaporation occur on the surface, but separation takes place of sub-microscopic liquid particles (owing to the formation of microwaves) which enter the boundary layer and evaporate there. One would assume, however, that such evaporation would only take place in the presence of a large degree of turbulence in a vapour–gas flow, and at comparatively high stream velocities.

When evaporation occurs the heat- and mass-transfer coefficients are directly proportional to the evaporation intensity j_1. However, under the conditions considered the value of j_1 is determined not only by the surface evaporation (molecular transfer) but also by additional evaporation of sub-microscopic liquid particles which proceeds in the boundary layer itself.

Lately Mel'nikova [8] carried out thorough experiments on this problem. The presence of a refrigerator inside a porous body enabled any given temperature head to be obtained and so it was possible to directly compare heat transfer of a dry porous plate with that of a moist plate.

As a result it was determined that with moisture evaporation in a boundary layer there are sub-microscopic liquid particles the evaporation of which occurs in the boundary layer (volumetric evaporation).

The volumetric evaporation of the sub-microscopic liquid particles takes place under adiabatic conditions irrespective of the evaporation surface temperature [1]. The temperature of the liquid particles in the boundary-layer volume is equal to the adiabatic air saturation temperature t_b (wet-bulb temperature). Consequently, the energy-transfer equation should have an additional term (negative heat source) characterizing evaporation of the sub-microscopic liquid particles. Its value is equal to the product of the specific heat of evaporation r multiplied by the volumetric power I_1 of the source of sub-microscopic particles (mass of the sub-microscopic particles per unit volume abstracted in unit time from an evaporation surface).

With the well-known assumptions the differential energy-transfer equation will be as follows:

$$c\rho\left(w_x\frac{\partial t}{\partial x}+w_y\frac{\partial t}{\partial y}\right)=\lambda\frac{\partial^2 t}{\partial y^2}-rI_1. \quad (6)$$

The new generalized argument *Gu* (the Gukhman number) is obtained from the right-hand side of equation (6).

$$Gu=\frac{rI_1(l^1)^2}{\lambda T_a}=\frac{\lambda(T_a-T_b)l^1}{\lambda l^1 T_a}=\frac{T_a-T_b}{T_a} \quad (7)$$

where l^1 is some characteristic dimension.

When deriving *Gu*, the evaporation of the sub-microscopic particles was assumed to proceed at the expense of heat derived by heat conduction from the surrounding air, i.e.

$$\frac{\lambda}{l^1}(T_a-T_b)=rI_1\cdot l^1. \quad (8)$$

Consequently, *Gu* characterizes the heat loss debited to the volumetric evaporation.

The differential mass-transfer equation for an incompressible liquid will have the following form:

$$\rho w_x\frac{\partial\rho_{10}}{\partial x}+\rho w_y\frac{\partial\rho_{10}}{\partial y}=\frac{\partial}{\partial y}(j_1)_y+I_1 \quad (9)$$

where $(j_1)_y$ is the specific flow of a diffusible substance (vapour) in the direction of the axis y.

In the presence of radiative heat transfer the volumentric evaporation will be intensified owing to absorption of infra-red rays by sub-microscopic liquid particles. The additional parametric number T_{rad}/T_a should then be introduced, where T_{rad} is the temperature of the radiating surface.

The volumetric evaporation theory developed by Luikov eliminates to a considerable extent contradictions in the influence of mass transfer on heat transfer with evaporation and explains the divergence of experimental data as obtained by various investigators.

EXPERIMENTAL INSTALLATION AND METHODS OF INVESTIGATION

For an experimental investigation a wind tunnel was used, a detailed characteristic of which is given in [9]. The length of its closed air channel was 30 m and the cross-sectional area of the working section, 0·22 m². The air velocity over the range from 3 to 15 m/s was regulated by valves.

Temperature and air humidity were automatically established in the tube. The control accuracy of air parameters was reached within 0·1 deg by "dry" and "wet" bulbs. The maximum temperature of the air flow was equal to 150°C and the maximum humidity 80 per cent. The measurement of necessary parameters (temperature, humidity, flow velocity, quantity of an evaporated liquid, cooling water discharges, etc.) was made by first-grade instruments (Fig. 1).

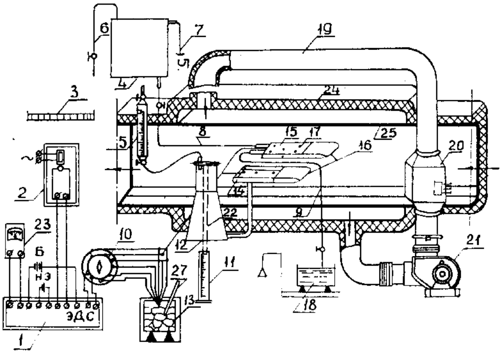

FIG. 1. Diagram of a working section of wind tunnel.

In order to create an isothermal surface round a working chamber (25) and in order to eliminate radiative heat transfer it was supplied with a jacket (24), connected with a closed air channel (19). Air, pumped by a fan (21), circulated in a space between the working chamber and jacket (24). Heating of air to a given temperature was carried out by an electric air heater (20), cooling of chamber walls, by passing cool air. Heating or cooling of walls of the working chamber (25) to a given temperature was conducted automatically.

The first series of experiments was carried out in the following way. A pan (14) with the liquid investigated and a hollow metallic body (15) (which will be referred to as a dry body) through which water was allowed to pass were placed within the working chamber of the wind tunnel.

The experimental bodies were shaped as rectangular parallelepipeds with overall dimensions 45 × 100 × 176 mm. Wedges (16) made out of heat-insulating material were attached to the frontal parts of the bodies in order to create an ordered stream above surfaces of the liquid and of the dry body. During the whole experiment the surface temperature of the latter was maintained equal to that of the evaporating liquid.

When calculating heat transfer with zero-mass transfer it was assumed that all the heat taken by the surface of a dry body is spent in heating cooling water. The coefficients of heat transfer with evaporation were determined from the value of the heat component, supplied by convection to the liquid surface.

The pan and the dry body were made out of the same material, had the same shape and surface roughness and were subject to the same conditions when testing; therefore, according to the defined value of the heat-transfer coefficient of a dry body, we determine heat supplied to the side walls and to the bottom of the pan.

Mass-transfer coefficients, a_m, were calculated over the whole amount of the evaporated liquid M:

$$a_m = \frac{M}{(P_v - P_a)F\tau}. \tag{10}$$

The measurements showed [10] that the absolute value of P_a is practically zero when evaporation of acetone, benzol and butanol takes place.

Cooling water was supplied under constant pressure to a dry body from a pressure tank (4) connected with an overflow pipe (7), a water-supply (6) and through a hose (8), with a pipe system of the dry body. Water, passed through the dry body, entered a balance (18) through a hose (9). Thermocouples were inserted in a measuring circuit consisting of a potentiometer I ПМС–48, a null-galvanometer (23), a switch (10), a mirror galvanometer Г3С–47 (2) with scale (3) and a thermostat (13) with melting ice.

The determination of the quantity of evaporated liquid and maintenance of the given level in the pan were carried out by means of a measuring burette (5), a pressure vessel (12) and a measuring cylinder (11). The pan (14) and vessel (12) were connected as communicating vessels. A part of a liquid entered the pan and its excess poured out through an overflow tube (22) into a measuring cylinder (11). When the liquid was tested, levels remained practically unchanged in the pressure vessel and in the pan. In the second series of experiments the heat- and mass-transfer process with water evaporation from a capillary-porous body and heat transfer of a capillary-porous dry body were investigated in the wind tunnel for the same external conditions. The dry body was, in this case, a hollow metal box made of sheet copper and covered with a thin layer of a capillary-porous material. Water passed through this box abstracting heat which entered the body surface.

Mean temperatures of surfaces of experimental bodies were maintained constant during the test. The bodies considered had the same shape (parallelepiped), dimensions, surface roughness and, during testing, were under similar thermal and hydrodynamic conditions. In this case both processes were simultaneously investigated.

In order to obtain rapidly a steady state with "rigid" drying regimes, a moist body was at first preheated to a temperature close to that of the wet bulb which corresponded to the chosen regime of drying.

Usually capillary-porous bodies are made of gypsum. Its porous structure changes considerably during moistening and drying, however.

The properties and pecularities of a capillary-porous body determine the character of the boundary layers and, consequently, influence the heat- and mass-transfer process [2, 11]. Instead of gypsum we used permeable porous ceramics, the manufacture of which is described in [12]. Porous ceramics has a number of advantages: its structure is completely retained during moistening and drying; ceramic porosity is great and uniform (of order 40 per cent) for fine pores (about 1 μ in radius); bodies out of porous ceramics are firm and easily machined.

The change in a weight of the moist body was recorded by a beam balance and, with intense moisture evaporation, by a high-precision strain-gauge balance. Experiments were conducted with evaporation velocity constant under adiabatic conditions.

Surface temperature of experimental bodies and of evaporating liquid was measured by copper–constantan thermocouples (17). The velocity of the vapour–air stream was determined by a Pitot–Prandtl tube. The latter was placed in the wind tunnel some distance upstream from the working chamber, so that the installed experimental bodies did not influence it [13].

Geometrical sizes of the experimental bodies were determined provided that their total cross-sectional area (middle section) did not exceed 5 per cent of the cross-section of the working chamber. The maintenance of this condition means that a correction for flow restriction need not be used.

Thus, the results of experimental investigation allowed comparison to be made between: (1) a heat-transfer process of a dry body and heat transfer with evaporation; and (2) between a heat-transfer process of a moist plate, made out of a capillary-porous material, and that of a dry plate.

The flow in a working tube was stabilized with the help of special meshes. Non-uniformity of the mean velocities did not exceed 1·0–1·5 per cent of the stream velocity along the axis (in the region which is occupied by 75 per cent of the whole section). The slope of velocity-vector angles was not less than ±1·5° in horizontal and vertical planes.

DISCUSSION OF RESULTS

The evaporation of liquids with different molecular weights (water, acetone, benzol, butanol) was investigated in the first set of experiments. First of all, an attempt was made to define a relation between the evaporation velocity j_m or the mass-transfer coefficient a_m and the molecular weight of the liquid M_1. The experimental results show that the rate of evaporation at a range of Reynolds number from $2{\cdot}5 \times 10^4$ to 16×10^4 is not a single-valued function of the molecular weight of an evaporating liquid, i.e. the points representing the dependence of j_m on M_1 do not lie on a smooth curve. This is explained by the fact that j_m is considerably influenced by evaporation temperature t_w, different for various liquids under the same conditions of the experiment (see Table 1). Absolute values of t_w are inversely proportional to the pressures of saturated vapours of various liquids, referred to one temperature.

In order to eliminate wave formation during liquid evaporation, an immiscible nylon mesh was placed at a small distance from the interface. It is noted that absolute values of j_m increase with the wave motion of an evaporating surface. Thus, when applying the mesh, $j_m = 13{\cdot}7$, and, also, without it, when the wave motion appears, $j_m = 14{\cdot}6$ kg/m^2 h (an experiment was carried out at $t_a = 96$°C, velocity $w = 14{\cdot}5$ m/s and the relative air humidity $\varphi = 16{\cdot}0$ per cent). The increase in j_m is explained not only by the increase in the evaporation surface, but also by the change in character of the boundary layer. Moreover, the value j_m with water evaporation is inversely proportional to the humidity of the air stream.

The values of the mass-transfer coefficients a_m increase with liquid molecular weight (see Table 2).

For butanol and acetone, having similar values of molecular weights, the values of the mass-transfer coefficients are almost the same. The

Table 1

	Evaporation conditions				Evaporation conditions			
Liquid investigated	t_a (degC)	φ (%)	w (m/s)	t_w (degC)	t_a (degC)	φ (%)	w (m/s)	t_w (degC)
Water	45	15	6	26·9	126	9	6	65·3
Acetone	45	15	6	10·8	126	9	6	33·1
Benzol	45	15	6	21·1	126	9	6	50·1
Butanol	45	15	6	37·7	126	9	6	72·0

Table 2

Liquid investigated	Molecular weight M_1	Range of values obtained		
		$w = 5$ m/s	$w = 9$ m/s	$w = 14$ m/s
Water	18	0·125–0·185	0·181–0·232	0·269–0·377
Acetone	58	0·243–0·271	0·343–0·351	0·489–0·505
Butanol	74	0·329–0·366	0·439–0·472	0·570–0·710
Benzol	78	0·330–0·370	0·410–0·470	0·729–0·788

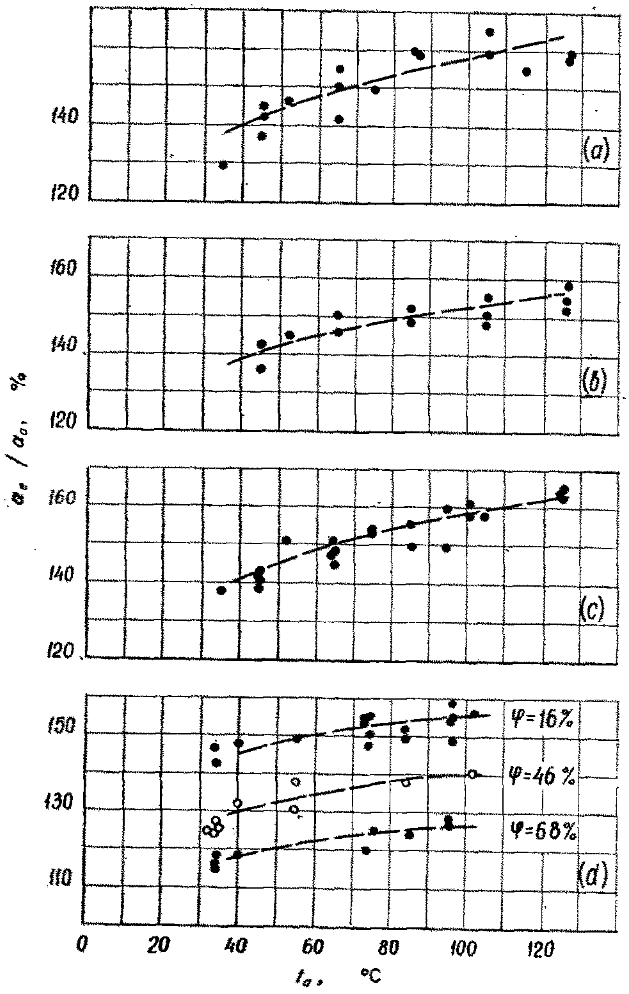

FIG. 2. Relation between α_e/α_a and temperature (degC) and air humidity. (a) Benzol, (b) acetone, (c) butanol, (d) water.

comparison of values of heat and diffusion Nusselt numbers shows that, for all the liquids investigated, $Nu_m > Nu$.

It is seen from Fig. 2, in all cases, the coefficients of heat transfer with evaporation, α_e, are greater than those of a dry body, α_a, and the relation α_e/α_a increases with air temperature. Air humidity (Fig. 2) influences the value of the relation α_e/α_a as well when water evaporates from an open surface. With increase in air humidity the absolute value of α_e/α_a approaches unity. Any noticeable change in the quantity α_a depending on medium temperature is not observed. The scattering of experimental points (Fig. 2) is explained by the absence of a single-valued relation between α_e/α_a and t_a.

Experimental data on water evaporation from a free surface are presented in Fig. 3 as the dependence of $Nu/Pr^{0\cdot33}$ and $Nu_m/Pr_m^{0\cdot33}$ upon Re. The experimental points did not lie on one curve and the influence of air humidity on the coefficient of heat and mass transfer with evaporation was distinctly confirmed.

The results of experimental investigation on an evaporation process show that the simplex $(T_a - T_b)/T_a$ should be introduced into the known relations between $Nu = f(Re, Pr)$ and $Nu_m = f(Re, Pr_m)$.

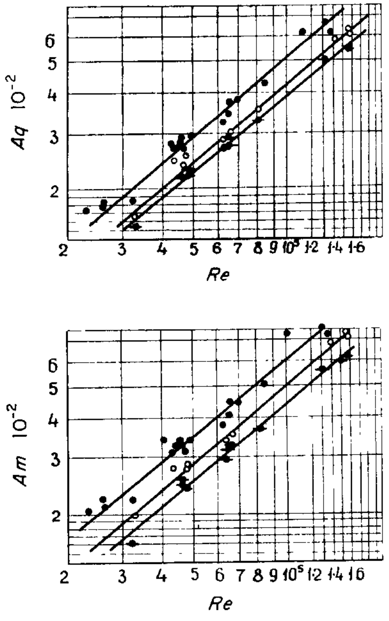

FIG. 3. Relations between $Nu/Pr^{0\cdot33} = Aq$ and $Nu_m/Pr_m{}^{0\cdot33} = Am$ and Re at various values of relative humidity (water evaporation).

When treating experimental data, the following relations were adopted in the power criterial equations:

$$Nu = f(Re, Pr, Gu) \tag{11}$$

$$Nu_m = f(Re, Pr_m, Gu). \tag{12}$$

The values of diffusion coefficients for water, benzol and butanol are listed in [14, 15] and for acetone were calculated by the empirical Gilliland formula [16].

Values of the diffusion Prandtl numbers $Pr_m = \nu/D$ with evaporation of acetone, benzol and butanol were calculated by kinetic viscosity coefficients of a "pure" carrying gas (air) and by diffusion coefficients of vapour of evaporating liquids (3).

The treatment of experimental data on liquid evaporation from the surface leads to the following criterial equations:

for heat transfer

$$Nu = 0\cdot086\ Re^{0\cdot8}\ Pr^{0\cdot33}\ Gu^{0\cdot2} \tag{13}$$

for mass transfer

$$Nu_m = 0\cdot094\ Re^{0\cdot8}\ Pr_m^{0\cdot33}\ Gu^{0\cdot2}. \tag{14}$$

From Fig. 4 it is seen that the experimental points are grouped quite satisfactorily close to a straight line (±15 per cent scatter). Our experiments confirm the relations obtained by Nesterenko [17] and extend the range of their application up to $1\cdot6 \times 10^5$. From Fig. 4 it follows that the absolute values of Nu and Nu_m increase with the evaporation intensity, other conditions being equal. This conclusion is confirmed by direct experiment.

An experimental investigation (the second series of experiments) of the interaction mechanism between simultaneous heat- and mass-transfer processes and water evaporation from the surface of a capillary-porous body confirms the conclusions mentioned above which were obtained as a result of the first series of experiments.

On the basis of the experimental data the average temperature of the surface of a dry and moist body, average heat- and mass-transfer

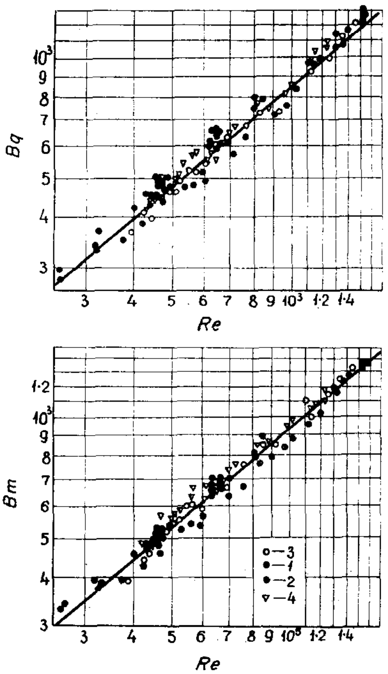

FIG. 4. Relations between $NuPr^{-0\cdot33}\,Gu^{-0\cdot2} \equiv Bq$ and $Nu_mPr_m^{-0\cdot33}Gu^{-0\cdot2} \equiv Bm$ and *Re*. (1) Water, (2) acetone, (3) benzol, (4) butanol.

coefficients were calculated and curves of the dependence of specimen mass content on the time of drying were plotted.

From the analysis of experimental data it follows that heat- and mass-transfer intensity is directly proportional to temperature, to velocity of motion, and inversely proportional to the vapour–air medium humidity (other conditions equal). The heat flow to the surface of the moist body was determined by the amount of moisture evaporated.

In this case the coefficients of heat transfer with evaporation are also greater than those of a dry body (up to 15 per cent). At small values of air humidity the difference between the coefficients was maximum. With increase in absolute values of φ (per cent) the coefficients of heat transfer with evaporation decrease. However, it should be noted that in the case under consideration the effect of mass transfer on heat transfer is small and in the majority of practical cases may be neglected.

From the analysis of relations $Nu = f(Re)$ and $Nu_m = f(Re)$ given in Fig. 5 it follows that the distribution of experimental points in a chart depends on the humidity of the vapour–air medium (with moisture evaporation by a capillary-porous body).

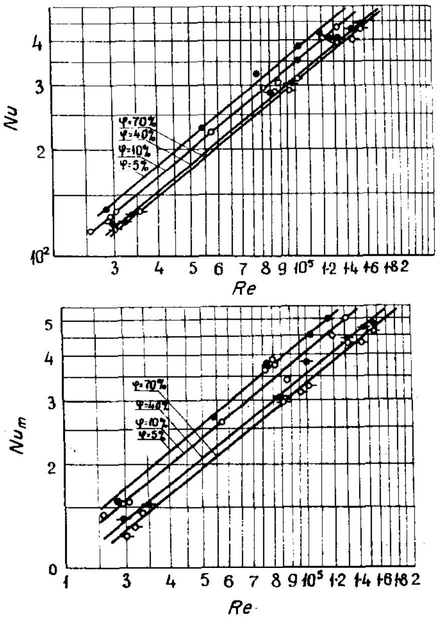

FIG. 5. Relations between *Nu*, Nu_m and *Re* (moisture evaporation from capillary-porous body).

Having introduced *Gu* into the empirical equations, the correlation of experimental points became satisfactory. Experimental curves may be approximated by the following formulae:

for heat transfer

$$Nu = 0{\cdot}083\ Re^{2/3}\ Pr^{1/3}\ Gu^{0\cdot1} \tag{15}$$

for mass transfer

$$Nu_m = 0{\cdot}11\ Re^{2/3}\ Pr_m^{1/3}\ Gu^{0\cdot14}. \tag{16}$$

The results of treatment are given in Fig. 6. Experimental points are grouped close to straight lines, the scatter not exceeding $\pm 7{\cdot}0$ per cent.

In equations (15) and (16), parameters are related to the medium temperature. The heat conduction equation was calculated by the following formula [17]:

$$\lambda = \lambda_0 + 0{\cdot}0041\varphi \tag{17}$$

where λ_0 is the thermal conductivity of dry air.

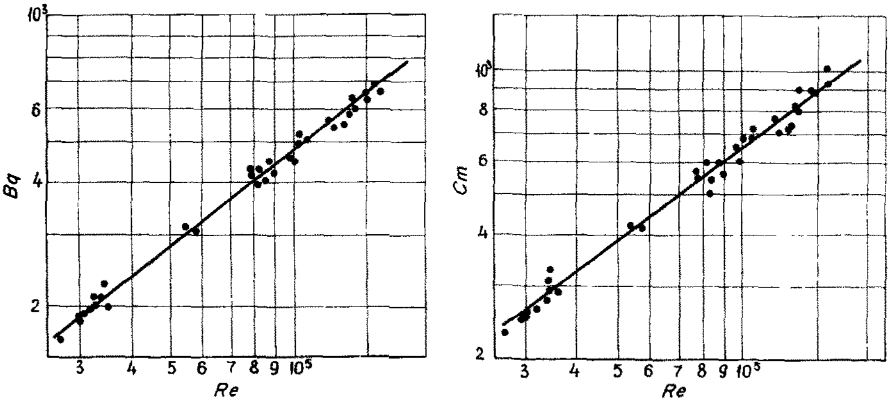

FIG. 6. Relations between $NuPr^{-0\cdot33}\,Gu^{-0\cdot1} \equiv Bq$ and $Nu_mPr_m{}^{-0\cdot33}\,Gu^{-0\cdot14} \equiv Cm$ and Re (moisture evaporation from capillary-porous body).

Experimental points characterizing heat transfer of dry bodies (metallic and capillary porous) lie on a straight line of the known criterial relation (with a scatter of ±5 per cent):

$$Nu_a = 0\cdot037\ Re^{0\cdot8}\ Pr^{0\cdot33}. \qquad (18)$$

In equations (13), (14) and (18) all the parameters are related to the medium temperature.

From the analysis and treatment of experimental data it follows that if heat transfer takes place in the presence of liquid evaporation, the heat- and mass-transfer process in a boundary layer close to a body becomes very complicated and may not always be described by the classical regularities of heat and mass transfer [1].

In some works the mechanism of mass transfer in gas filtration through a porous body is identified with vapour diffusion or effusion in body capillaries. However, in the first case mass (vapour) transfer in a cross direction proceeds mainly by diffusion (molecular transfer taking place for instance in the drying of capillary porous bodies) and, in the second place, according to hydrodynamic flow (molar transfer) occurring with gas injection through the porous wall. In the cases considered, the mass-transfer laws are distinct and the effect of a mass cross-flow on heat transfer will, therefore, be different [18]. Even more distinct are the transfer mechanisms with liquid evaporation from a free surface, and transfer with gas supply through a porous wall.

It was determined from numerous theoretical and experimental investigations dealing with porous cooling that, with injection of an inert gas into a boundary layer through a porous wall and with increase in the intensity of injection, the values of heat-transfer coefficients decrease as compared with pure heat transfer.

The results of experimental investigations [2–4, 8, 9, 17] of a heat- and mass-transfer process with liquid evaporation cogently show that the difference between the values of the coefficients of heat transfer with evaporation and of pure heat transfer increases with intensity of evaporation. Under certain conditions the coefficient of heat transfer with evaporation is greater than that of a dry body.

REFERENCES

1. A. V. LUIKOV, *Theoretical Fundamentals of Building Thermophysics* (Teoreticheskiye osnovy stroitel'noi teplofiziki). Izd. Akad. Nauk B.S.S.R., Minsk (1961).
2. B. M. SMOLSKY, *External Heat and Mass Transfer in Convective Drying Process* (Vneshnii teplo-i massoobmen v protsesse konvektivnoi sushki). Izd. Gosuniversiteta, Minsk (1957).
3. P. D. LEBEDEV, *Drying by Infra-red Rays* (Sushka infrakrasnymi luchami). Gosenergoizdat, Moscow (1955).
4. F. M. POLONSKAYA, Heat and mass transfer at constant rate of drying (Teplo-i massoobmen v period postoyannoi skorosti sushki). *Zh. Tekh. Fiz.* **23**, 802–807 (1953).
5. A. A. GUKHMAN, One of the arguments for criterial equations of heat and mass transfer in evaporation and drying processes (Ob odnom iz argumentov

kriterial'nykh uravnenii teplo-i massoobmena v protsessakh ispareniya i sushki). *Teploenergetika*, No. 5, 32–41 (1954).

6. L. S. Klyachko, Theory and calculation of evaporation processes from liquid surface (Teoriya i raschet protsessov ispareniya s poverkhnosti zhidkosti). *Zh. Tekh. Fiz.* No. 6, 4–11 (1936).
7. A. V. Luikov, *Heat and Mass Transfer in Drying Processes* (Teplo-i massoobmen v protsessakh sushki). Gosenergoizdat, Moscow (1956).
8. A. V. Luikov and I. R. Mel'nikova, Heat and mass transfer in evaporation processes (Teplo-i massoobmen v protsessakh ispareniya). *Izd. Akad. Stroitel'stva i Arkhitektury SSSR* (1959).
9. G. T. Sergeev, Investigation of external heat and mass transfer with liquid evaporation from a capillary porous body (Issledovaniye vneshnego teplo-i massoperenosa pri isparenii zhidkosti kapillyarnoporistym telom). *Inzh. Fiz. Zh.* No. 5, 33–37 (1961).
10. M. V. Alekseeva, *Determination of Air Pollution in Industrial Establishments.* (Opredeleniye vrednykh veschestv v vozdukhe proizvodstvennykh pomeshchenii). Goskhimizdat, Moscow–Leningrad (1949).
11. A. V. Luikov, *Transfer Phenomena in Capillary Porous Bodies* (Yavleniya perenosa v kapillyarnoporistykh telakh). Moscow (1954).
12. B. I. Fedorov and Z. P. Shulman, Application of permeable porous ceramics to the experimental study of mass-transfer phenomena (Primeneniye pronitsaemoi poristoi keramiki dlya eksperimental'nogo izucheniya yavlenii massoobmena). *Inzh. Fiz. Zh.* No. 2, 99–102 (1961).
13. R. C. Pankhurst and D. W. Holder, *Wind-tunnel Technique* (Tekhnika eksperimenta v aerodinamicheskikh trubakh). Izd. Inostrannoi Literatury (1955).
14. I. I. Chernobylsky, *Machines and Apparatus in the Chemical Industry* (Mashiny i apparaty khimicheskikh proizvodstv). Mashgiz, Moscow (1959).
15. V. M. Ramm, *Absorption Processes in the Chemical Industry* (Absorbtsionnyie protsessy v khimicheskoi promyshlennosti). Goskhimizdat, Moscow (1954).
16. E. R. Gilliland and T. K. Sherwood, *Ind. Eng. Chem.* **26**, 516–525 (1934).
17. A. V. Nesterenko, Heat and mass transfer with liquid evaporation from a free surface (Teplo-i massoobmen pri isparenii zhidkosti so svobodnoi poverkhnosti). *Zh. Tekh. Fiz.* **24**, 729–737 (1957).
18. A. A. Polushkin, Similarity criteria in heat and mass transfer in liquid evaporation processes (O kriteriyakh podobiya teplo-i massoobmena v protsessakh ispareniya zhidkosti). *Inzh. Fiz. Zh.* No. 2, 129–143 (1959).

Abstract—The present paper deals with heat- and mass-transfer problems in connexion with evaporation of various liquids. The basis and derivation of the Gukhman number (*Gu*) is also given.

Résumé—Cet article concerne les problèmes d'échange de chaleur et de masse au cours de l'évaporation de différents liquides. Il donne également la définition et la façon d'établir le nombre de Gukhman (*Gu*).

Zusammenfassung—Es werden Wärme- und Stoffübergangsprobleme in Verbindung mit Verdunstungsvorgängen behandlt. Die Grundlage und Ableitung der Gukhman-Zahl ist angegeben.