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APPLICATION OF METHODS OF THERMODYNAMICS OF IRREVERSIBLE PROCESSES TO INVESTIGATION OF HEAT AND MASS TRANSFER IN A BOUNDARY LAYER

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Abstract—This paper considers the process of heat and mass transfer in a boundary layer at evaporation of a liquid. In this case heat and mass transfer mechanism differs from the process of heat transfer without mass transfer. Experimental results obtained showed that in the boundary layer over a plate there were submicroscopic particles of liquid whose evaporation was going on in the boundary layer itself. On the basis of the theory of thermodynamics of irreversible processes methods of calculation of mass transfer with regard for the action of all the thermodynamic forces including also a new effect of separation of gas mixture components during the process of molecular transfer of kinetic energy of a regulated motion have been developed.

Résumé—Cet article considère le processus du transport de chaleur et de masse dans la couche limite au cours de l'évaporation d'un liquide. Dans ce cas, le mécanisme de transport de chaleur et de masse diffère de celui de la transmission de chaleur sans transport de masse. Les résultats expérimentaux obtenus montrent que dans la couche limite sur une plaque il y a des particules submicroscopiques du liquide, dont l'évaporation est en cours, dans la couche limite elle-même. Des méthodes de calcul du transport de masse ont été développées, elles sont basées sur la théorie de la thermodynamique des phénomènes irréversibles et tiennent compte de l'action de toutes les forces thermodynamiques, y compris d'un nouvel effet de séparation des composants du mélange gazeux au cours du processus de transport moléculaire de l'énergie cinétique d'un mouvement contrôlé.

Zusammenfassung—Die Arbeit behandelt den Wärme- und Stoffübergang in der Grenzschicht beim Verdampfen einer Flüssigkeit. Der Mechanismus des Wärme- und Stofftransports unterscheidet sich in diesem Fall von dem des Wärmeüberganges ohne Stoffübertragung. Versuche zeigten, dass in der den Platten anhaftenden Grenzschicht submikroskopische Teilchen der Flüssigkeit vorhanden sind, die dort verdampfen. Auf Grund der Theorie der Thermodynamik irreversibler Prozesse wurden Berechnungsmethoden für den Stoffübergang entwickelt, die die Wirkung aller thermodynamischen Kräfte berücksichtigen, einschliesslich eines neuen Effektes der Trennung eines Gasgemisches während des Molekularüberganges der kinetischen Energie einer geordneten Bewegung.

Аннотация—В статье рассматривается процесс тепло-и массопереноса в пограничном слое при испарении жидкости. Механизм тепло-и массопереноса в этом случае отличается от процесса теплообмена, не осложнённого массообменом. Как показали результаты проведенных опытов, в пограничном слое над пластиной имеются субмикроскопические частицы жидкости, испарение которых происходит в самом пограничном слое. На основании теории термодинамики необратимых процессов разработаны методы расчётов массопереноса с учётом действия всех термодинамических сил, в том числе нового эффекта разделения компонентов газовой смеси в процессе молекулярного переноса кинетической энергии упорядоченного движения.

NOMENCLATURE

T,	absolute temperature, °K($T = 273 + t$);
T_a and T_b,	air temperature and temperature of the adiabatic air saturation (wet bulb temperature), respectively;
T_r,	temperature of radiation surface;
u and u_c,	moisture content and critical

	moisture content of a porous body, respectively;
c_p,	specific isobar heat capacity of humid air (of vapour–gas mixture);
ρ,	density of humid air;
ν,	coefficient of kinematic viscosity ($\nu = \eta/\rho$);
a,	coefficient of thermal diffusivity ($a = \lambda/c_p\rho$);
λ,	coefficient of heat conduction of humid air;
D_{12},	coefficient of reciprocal diffusion;
p_{10},	relative partial vapour pressure equal to the ratio of partial pressure of vapour p_1 to the total pressure of vapour–gas mixture $p(p_{10} = p_1/p)$;
w,	air motion rate;
ρ_{i0},	relative concentration of the ith component in a mixture equal to the ratio of the volumetric concentration ρ_i to the density of the mixture $\rho(\rho_{i0} = \rho_i/\rho)$;
ρ_{10},	relative concentration of vapour in humid air;
ϕ,	air humidity ($\phi = p_1/p_e$);
p_e,	pressure of the saturated vapour;
μ_i,	chemical potential of the ith component;
M_i,	molecular weight of the ith component;
h_i,	specific enthalpy of the ith component;
R,	universal gas constant;
r,	specific heat of evaporation of a liquid.

Indices

a,	medium (humid air);
ω,	surface (plate surface);
r,	surface radiation;
1,	water vapour;
2,	dry air.

Numbers of similarity of heat and mass transfer

Nu and Nu',	heat and diffusion Nusselt numbers, respectively;
Re,	Reynolds number;
Pr,	Prandtl number;
Pr',	diffusional Prandtl number (Schmidt number $Pr' \equiv Sc$);
Gu,	Gukhman number $\left(Gu = \frac{T_a - T_b}{T_a}\right)$;
Gu',	modified Gukhman number $\left(Gu' = \frac{T_b}{T_a}\right)$.

HEAT transfer between a capillary porous body and flow of a mixture of gases is not only of theoretical interest but also is of great practical importance. If heat transfer is going on in the presence of evaporation of a liquid then mechanism of heat and mass transfer in a boundary layer near the surface of a body is complicated considerably and cannot be described by the classic regularities of heat and mass transfer of a matter.

For example, with the evaporation of a liquid from a free surface under conditions of forced convection the dependence between the numbers Nu, Re and Pr, as was shown by Nesterenko [1] and Polonskaya [2, 3], is not described by ordinary empirical relations which are applied to the theory of heat transfer. Nesterenko's formulae are of the following form

$$Nu = A Pr^{1/3} Re^{n} Gu^{0{\cdot}175} \qquad (1)$$

$$Nu' = A'(Pr')^{1/3} Re^{n'} Gu^{0{\cdot}135} \qquad (2)$$

where the constants A, A', n and n' are determined from Table 1.

On the basis of experimental investigations of heat transfer between moist porous plates and a

Table 1. Value of constants in formulae by Nesterenko [1]

Range of the Reynolds number variation	A	n	A'	n'
$Re > 3{\cdot}15 \times 10^3$	1·07	0·48	0·83	0·53
$3{\cdot}15 \times 10^3 < Re < 2{\cdot}2 \times 10^4$	0·51	0·61	0·49	0·61
$2{\cdot}2 \times 10^4 < Re < 3{\cdot}15 \times 10^5$	0·027	0·90	0·0248	0·90

flow of heated air the following empirical formula was obtained by Lebedev [4]

$$Nu = ARe^{0 \cdot 5} (Gu')^{0 \cdot 4} \left(\frac{T_r}{T_a}\right)^2 \left(\frac{u}{u_c}\right)^n \tag{3}$$

where the constants A and n are given for some bodies in Table 2.

Table 2. *Value of constants in formula by Lebedev* [4]

Material	A	n
Quartz sand	0·56	0·8
Clay	0·45	0·9
Wood	0·50	0·3

Other investigators [5–7] obtained formulae analogous to the formula (3).

Till recently no detailed substantiation of the introduction of new criteria of the form Gu, (T_r/T_a), (u/u_c) into relations (1–3) has been given for the case of heat and mass transfer between a porous body containing a liquid and a heated moving gas. This fact indicates that there is a necessity for special and detailed experimental investigations on heat and mass transfer mechanism in a boundary layer flowing over a porous body containing a liquid.

Lately such investigations have been carried out by A. V. Nesterenko, N. F. Dokuchaev [8] N. S. Mikheeva [9], and P. E. Mikhailov [10].

Temperature, partial pressure and velocity of humid air motion in a boundary layer were measured in these investigations.

Recently, applying improved methods, Mel'nikova [11] has carried out analogous investigations under the leadership of the author of this paper. In particular, the presence of a cooler inside the porous body made it possible to obtain any predetermined temperature head $\Delta t (\Delta t = t_a - t_w)$ and directly compare heat transfer of a dry porous plate with that of a moist one.

These investigations show that the heat transfer coefficient is higher in the process of evaporation of a liquid from a free surface or from a capillary-porous body in comparison with the case of net heat transfer, with other conditions equal. When increase in intensity of evaporation occurs, the heat transfer coefficient increases also.

While the calculations of heat transfer process between the surface of a porous wall and the flow of a gas, with blowing of an inert gas (hydrogen, helium), involve the theory of a boundary layer and produce the contrary phenomenon: i.e. with increase of intensity of gas supply into the boundary layer the coefficient of heat transfer decreases.

To reveal the mechanism of heat and mass transfer in the boundary layer special experiments were carried out. Temperature, partial pressure and velocity of air motion in a boundary layer flowing over a porous (gypsum) plate were measured by special devices. The plate was continuously moistened, i.e. the amount of evaporation of the liquid was calculated according to water flow rate and was controlled by weighing the whole plate.

A special cooler was mounted inside the plate so that the temperature of the plate surface t_w was maintained constant and at any predetermined value.

The heat flow was directed from the moving gas mixture to the plate (heat required for evaporation of the liquid) and supplied by forced convection from the air, moving with the velocity W_x.

The flow of mass (vapour) was directed from the surface of the plate into the surrounding air.

Distribution of temperature, partial pressure and motion velocity were thoroughly measured along the Y-axis and X-axis every 0·1 mm.

As a result it was determined that:

(1) At the evaporation of a liquid from the capillary porous body there are submicroscopical particles of liquid in the boundary layer whose evaporation is going on in the boundary layer itself (volumetric evaporation). The Gukhman number Gu or its modification Gu' as well as the parametric criterion T_r/T_a characterizes the volumetric evaporation of particles of the liquid in the boundary layer. The criterion u/u_c reflects the decrease in intensity of liquid particle emergence out of the porous body to the boundary layer as moisture content of the body decreases.

For well-known assumptions, differential equations of heat and mass transfer in a laminar boundary layer for the incompressible liquid flowing over a flat capillary porous plate will be as follows:

$$\rho w_x \frac{\partial \rho_{10}}{\partial x} + \rho w_y \frac{\partial \rho_{10}}{\partial y} = \frac{\partial}{\partial y}(j_{m1})_y + I_1, \quad (4)$$

$$c_p \rho w_x \frac{\partial t}{\partial x} + c_p \rho w_y \frac{\partial t}{\partial y} = \lambda \frac{\partial^2 t}{\partial y^2} + r I_1, \quad (5)$$

where I_1 is the specific capacity of a vapour source stipulated by evaporation of submicroscopic particles of the liquid in the boundary layer.

(2) In the range of variation of *Re* from 8000 to 100 000 for fine porous bodies, mass transfer constrained with the evaporation of a liquid has no influence upon the curves of air motion velocities distribution in a boundary layer (see Fig. 1). These results corroborate the detailed analysis of heat and mass transfer mechanism at evaporation of liquid from a free surface. This analysis is given in a review-article by Polushkin [12].

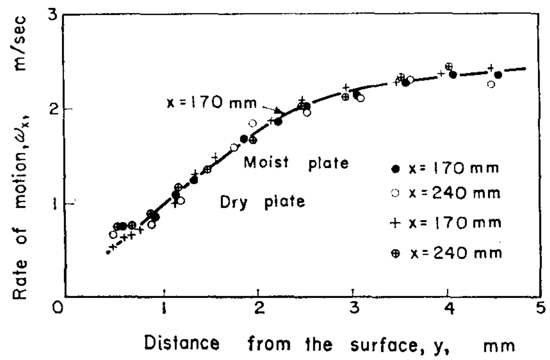

FIG. 1. Heated air flowing over a gypsum plate 350 mm in length ($l = 350$ mm) at $t_a = 35$°C with the rate of $w_a = 2{\cdot}5$ m/s, temperature of the plate surface is $t_w = 22{\cdot}5$°C.

(3) Water vapour partial pressure cannot be considered as a potential of mass transfer in a boundary layer. This may be confirmed by direct experiments. For example, from distribution curves $t^*(y)$ and $p_1^*(y)$ in Fig. 2 it follows that vapour transfer is going on from the lower partial pressure to the higher one.†

We shall dwell now on mass transfer potential without going into a detailed substantiation of introduction of the substance source I_1 into the differential equation of heat and mass transfer as is given in [11].

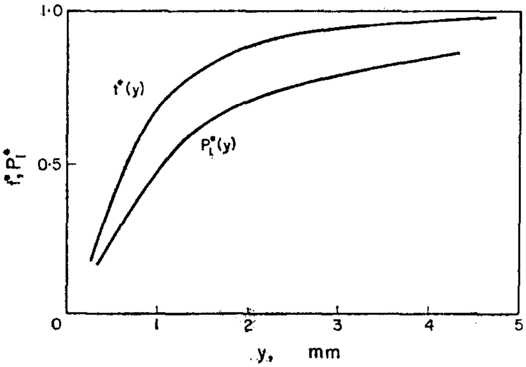

FIG. 2. Curves of distribution of temperature and partial pressure at the distance $x = 170$ mm from the plate edge ($t_a = 36{\cdot}5$°C, $t_w = 27$°C, $w_a = 5{\cdot}8$ m/s).

Usually the partial pressure p_1 or concentration ρ_1 is taken as the transfer potential of a condensing gas (vapour). Then the law of vapour transfer by diffusion in a binary mixture may be expressed in the following form:

$$j_{m1} = -D_{12}\rho \frac{M_1}{M} \nabla p_{10}. \quad (6)$$

Moreover, the value of thermal diffusion flow is assumed to be neglected.

However, the analysis by the methods of thermodynamics of irreversible processes shows that formula (6) is valid for non-condensing

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† This somewhat unlooked-for result has been already displayed in earlier works. For example, it follows from Fig. 4, given in the paper "Investigation of drying mechanism of moist materials" [9] that at the distance equal to $y \geqslant 2$ mm from the surface of the gypsum plate humidity of air has practically no change, i.e. $\phi =$ const. At the same time it is evident from Fig. 2 of the same paper that the humid air temperature continuously increases as it moves away from the surface up to the distance equal to $y = 10$ mm. Consequently, the vapour partial pressure $p_1(p_1 = \phi p_e)$ will increase in the range of $2 < y < 10$.

gas mixtures and is not valid for condensing gases as well as for water vapour.

According to the Onsager theory the molecular transfer of heat and matter is interdependent and described by a system of linear equations. For a gas mixture we have:

$$j_{m1} = \sum_{j=1}^{n-1} L_{ij}(X_j - X_n) + L_{iT}X_T, \tag{7}$$

$$j_q = L_{TT}\, X_T + \sum_{j=1}^{n-1} L_{Tj}(X_j - X_n), \tag{8}$$

where the thermodynamic motive forces X_T and X_j are correspondingly equal to

$$X_T = -\frac{1}{T}\nabla T; \quad X_j = -\nabla T\left(\frac{\mu_j}{T}\right), \tag{9}$$

j_q and j_{mi} are energy (heat) and mass flow of matter of the ith component conformably, L_{ij} are the Onsager kinetic coefficients.

The chemical potential μ_i of the ith component is the function of the temperature T, the pressure p and $(n - 1)$ of the relative concentrations ρ_{i0}. In the absence of external forces and at the constant pressure (p = const) it is possible to write equation (7) as [13]:

$$j_{mi} = \sum_{j=1}^{n-1} L_{ij}\left\{\sum_{k=1}^{n-1}\left[\frac{\partial(\mu_j - \mu_n)}{\partial\rho_{k0}}\nabla\rho_{k0}\right]_T - (Q_j^* - h_j + h_n)\frac{\nabla T}{T}\right\} \tag{10}$$

where Q_j^* is the heat of transfer equal to the amount of heat transferred per unit of mass of the component j at the constant temperature ($X_T = 0$). The value Q_j^* depends on coefficients L_{iT} and L_{ij} and enters the following relation:

$$L_{iT} = \sum_{j=1}^{n-1} L_{ij}Q_j^*. \tag{11}$$

As an approximation we shall take humid air for a binary mixture consisting of water vapour ($M_1 = 18$) and dry air ($M_2 = 29$). In this case we may write equation (10) as:

$$j_{m1} = -j_{m2} = -L_{11}\left[\frac{1}{\rho_{20}}\left(\frac{\partial\mu_1}{\partial\rho_{10}}\right)_T \nabla\rho_{10} + (Q_1^* - h_1 + h_2)\frac{\nabla T}{T}\right]. \tag{12}$$

Approximate evaluation of terms, which are in square brackets of formula (12), applying to the conditions of the experiment (see Fig. 2), shows that the first term is approximately equal to 34 cal/g cm and the second term is about equal to 80 cal/g cm, i.e. 2 or 3 times more. Moreover, the specific enthalpy of superheated vapour was taken equal to $h_1 = 595 + 0{\cdot}47t$ and the value $Q_1^* = L_{iT}/L_{11}$. Since the value $(Q_1^* - h_1 + h_2)$ is negative, then the molecular transfer of vapour is going on in the direction of the temperature gradient, i.e. from the surface of the plate into the surrounding medium.

Therefore, under certain conditions the molecular transfer of vapour is determined not by the drop of the vapour partial pressure but by the temperature drop, i.e. by the potential component μ_1/T the value of which depends on temperature change.

This type of transfer cannot be considered as thermal diffusion of a vapour, since the Soret thermo-diffusion effect in accordance with the system of the Onsager linear equations (7–8) is determined by the value $Q_1^*\nabla T/T$ which, in our case, is small in comparison with the value $(h_1 - h_2)\nabla T/T$.

Under certain conditions it is possible to take the difference between the chemical potentials in a state of saturation μ_{1e} and in a given state μ_1 at one and the same temperature [14] for the potential of vapour molecular transfer in order to obtain approximate calculations:

$$\tilde{\mu}_1 = \mu_{1e} - \mu_1. \tag{13}$$

For the mixture of ideal gases we have:

$$\mu_1 = \mu_1^0(T) + \frac{RT}{M_1}\ln p_1. \tag{14}$$

Then we shall get:

$$\frac{\tilde{\mu}_1}{T} = -\frac{R}{M_1}\ln\phi. \tag{15}$$

Therefore, we may take air humidity for the potential of vapour molecular transfer. For the first time relation (15) based on some other assumptions was proposed in [9]. Here the curves of temperature distribution and of air humidity built in relative values are close to each other (Fig. 3).

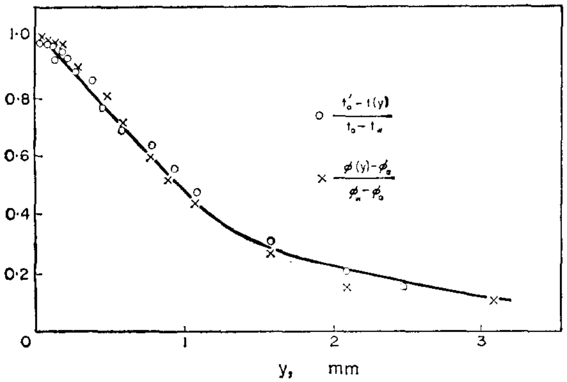

FIG. 3. Curves of distribution of temperature and air humidity in a boundary layer flowing over the moist gypsum plate ($t_a = 36{\cdot}5$°C, $t_w = 27$°C, $w_a = 5{\cdot}8$ m/s).

At the isothermal conditions (T = const) we can take the concentration ρ_{10} or the partial pressure p_{10} for the potential of vapour mass transfer. The calculations obtained with these assumptions for the uniform temperature process at small temperature drop in a boundary layer give a satisfactory result.

A new effect based on such a phenomenon as internal friction or viscosity influences vapour molecular transfer in a boundary layer.

Consider a general case of molecular transfer of heat, mass and impulse in the presence of chemical reactions, whose rate we shall designate through Γ_i. Now we write the system of the Onsager linear equations as follows

$$j_q = L_{TT}X_T + \sum_j L_{Tj}X_j, \tag{16}$$

$$j_{mi} = \sum_j L_{ij}X_j + L_{iT}X_T, \tag{17}$$

$$(\mathbf{P} - p\,\mathbf{1})_{ij} = \sum_{kl} L_{ij}^{kl}\,(X_w)_{kl}, \tag{18}$$

$$\Gamma_i = \sum_j L'_{ij}X_{ci} \tag{19}$$

where

$$X_w = -\nabla\,\mathbf{w}\ ; \quad X_{ci} = A_i,$$

A_i is the chemical affinity, p is the statistic pressure which differs from the tensor of pressure $\mathbf{P}$, $\mathbf{1}$ is the single vector.

According to the principal relation of thermodynamics of irreversible processes the components of total flows are the combinations of generalized thermodynamic motive forces.

Motive forces are the tensors of various classes. It is possible to show by virtue of tensor transformations that some combinations cannot take place. If the system is an isotropic one then the combination may occur only between such tensors that have an even difference in classes.

The thermodynamic forces X_T and X_j are the vectors (tensors of the same class), therefore the combination may occur between them. This combination is observed as the Soret effect (thermal diffusion) and the Dufour effect (diffusional thermal conductivity).

The value X_w is the second class tensor and the chemical affinity X_{ci} is the zero class tensor. Consequently, there is no place in isotropic systems for the combination of effects from the action of these forces with diffusion and heat conduction. Therefore, the chemical reaction rate does not involve the emergence of concentration or temperature gradient. However, due to the fact that the difference in classes of X_{ci} and X_w is equal to 2 (an even number), generally speaking, the combination between these two processes is possible in essence. It should not take place in the case when the tensor difference ($\mathbf{P} - p\,\mathbf{1}$) is equal to zero.

For an incompressible liquid when dealing with one-dimensional problems (flat parallel laminar flow of a liquid over a body) internal friction phenomenon may be considered as molecular transfer of kinetic energy of translational movement of the liquid ($\epsilon = \frac{1}{2}\rho\omega_x^2$) along the normal, y, towards the body surface [15]. For one-component system one can write:

$$j_\epsilon = -\ \nu\nabla(\tfrac{1}{2}\rho w_x^2), \tag{20}$$

where

$$\nabla(\tfrac{1}{2}\rho w_x^2) \equiv \frac{\partial}{\partial y}\,(\tfrac{1}{2}\rho w_x^2).$$

Therefore, the molecular flow of energy of the regulated motion is directly proportional to the gradient of kinetic energy of translational motion of the liquid, i.e. the motive force of X_ϵ of such transfer is a vector (gradient from scalar).

It follows that in gas mixtures the motive force X_ϵ may have a combination with forces X_T and X_j, since they all are the tensors of the same class.

Then equation (17) will be of the following form:

$$j_{mi} = \Sigma L_{ij}X_j + L_{iT}X_T + \sum_j L_{\epsilon ij}X_{\epsilon j}. \qquad (21)$$

From equation (21) it follows that in the process of molecular transfer by kinetic energy of motion at isothermal conditions ($X_T = 0$) the effect of moisture separation must take place; which is analogous to the Soret effect.

We have recognized the separation effect experimentally on a rotating separation column of the Clausius–Dickel type in the absence of temperature gradient (T = const) on molar solutions and binary gas mixtures (solution NaCl and binary mixture H_2 and N_2). This experiment was carried out on a column which was 1550 mm in height and had a clearance of 0·25 mm. We have obtained 70 per cent separation of NaCl at 20 rev/min for 1·5 h.

The separation process was going on at a constant temperature of 25·5°C. We are inclined to explain the separation coefficient increase on a rotating thermal diffusion separation column by this effect. This increase of separation coefficient was observed in [17] on separation of binary mixture n—$CH_3(CH_2)_{14}CH_3$—$C_{10}H_{18}$ (see Fig. 4). The kinetic curves of separation of binary mixture H_2–N_2 under the isothermal conditions on the rotating column at 20, 60 and 100 rev/min are given in Fig. 5.

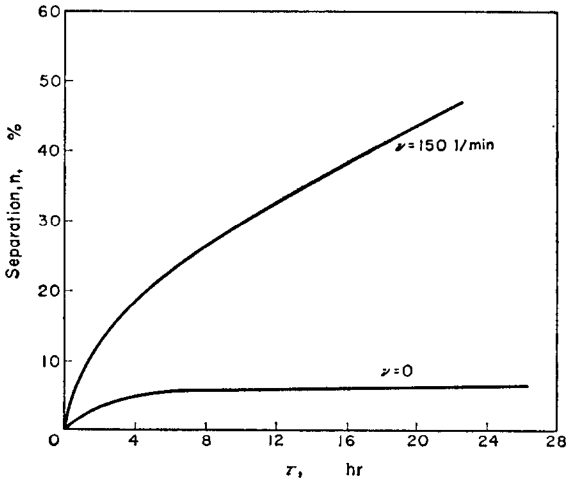

FIG. 4. Kinetic curves of separation of mixture n—$CH_3(CH_2)_{14}CH_3$—$C_{10}H_{18}$ on the rotating thermodiffusional column [17].

The relative concentration of nitrogen at the bottom of the column is counted off along the ordinate axis and time in minutes is counted off along the abscissa axis. Fig. 5 shows that in 1 h at n = 100 rev/min 26 per cent of nitrogen separation was obtained.

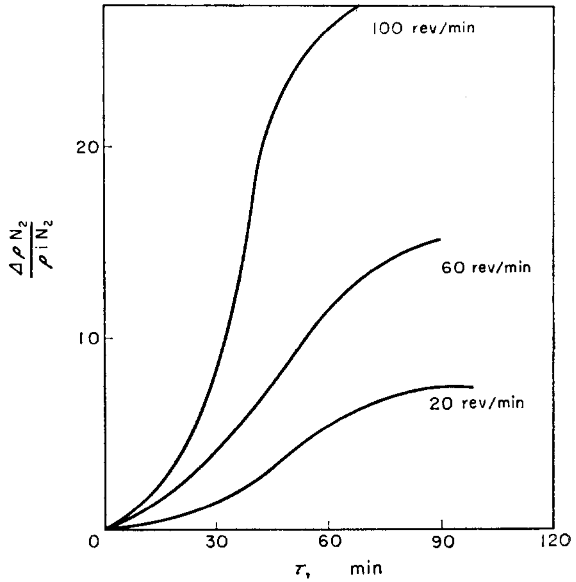

FIG. 5. Curves of kinetics of separation of the binary mixture (N_2–H_2).

From the analysis of experimental data as well as in accordance with equation (20) it follows that mass transfer under the action of the thermodynamic force X_ϵ is directly proportional to the gradient of the square velocity of the flow. The gradient of the square velocity in the separating column at 20 rev/min is approximately equal to 30 m/s^2 when the radius of the rotating cylinder is equal to 42·3 mm and the clearance is equal to 0·25 mm.

The value of ∇w_x^2 is much greater in a boundary layer. For example, from the curve $w_x(y)$ given in Fig. 1 we obtain ∇w_x^2 which is equal to 750 m/s^2, i.e. it is 25 times as much. If the rate of air motion is w_a = 5 m/s then the gradient of square velocity in a boundary layer according to the experimental data is equal to 1200 m/s^2.

i.e. it is 400 times as much in comparison with the value of Δw^2 in the separating column. Consequently, the value of Δw_x^2 in the boundary layer is greater by 2–3 orders, therefore, the influence of the thermodynamic force $X_{\epsilon i}$ on molecular transfer of matter may be of importance. It is necessary to have the experimental data for the transfer coefficients $L_{\epsilon ij}$ to obtain a final conclusion, then we can calculate in detail the molecular transfer of matter in a boundary layer taking into account all the thermodynamic forces.

Therefore, in the boundary layer flowing over a moist porous plate the water vapour ($M = 18$) will strive (under the action of the force X_ϵ) to move in the direction y, while the air (the reduced molecular weight of which is $M = 29$) will strive to move in the opposite direction, i.e. to the surface of the plate, under certain conditions the motive force X_ϵ may be greater than the force X_j, therefore water vapour will move from the lower partial pressure to the higher, as happened in our experiments.

An analogous phenomenon will occur when air flows over a porous plate with hydrogen supply into the boundary layer. The moving force X_ϵ will intensify the transfer of molecules of hydrogen from the wall to the flow of gas. The contrary phenomenon may be observed with a heavy gas, for example, CO_2 supplied to the boundary layer, through the pores of the plate.

In this case the molecules of CO_2, under the action of the force X_ϵ, will move into the region of low velocities of the regulated air motion, i.e. to the wall surface. Consequently, the force X_ϵ will prevent mass transfer of the cooled gas.

In the general case we shall introduce the corresponding expression from relation (21) instead of the flow j_{m1} into the differential equation of mass transfer (4). In this case differential equation (4) will be interconnected with that of heat transfer.

Interconnection between the phenomena of molecular transfer directly follows from the physical nature of these phenomena. The analytical description of transfer phenomena in their interconnection is possible on the basis of thermodynamics of irreversible processes, the theory of which was founded by Dutch and Belgian physicists (Onsager, de Groot, Prigogine [13, 18]).

The application of thermodynamics of irreversible processes to the transfer phenomena makes it possible not only to define more exactly the existing methods of heat and mass transfer calculation but also to obtain quite new solutions for a number of problems which are of importance in modern engineering.

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