creased. For example, when $T_2 = T_0$ the maximum of the function occurs for water in the region of T = 373 K.

With the cndition $(T - T_2) = 1$ K, the function $Q = f(T)$ will differ from $G_V/\alpha F = f(T)$ only by a constant multiplier. The function is given in Fig. 3 for water with n = 1 and various values of T_0. For comparison, Eq. (2) is given on the same plot. Under the conditions of maximum pumping (T_{max}), Q_3 exceeds Q_2 by several orders of magnitude.

As the working temperature T increases the fraction of the heat transferred by the liquid decreases, while that transferred by the vapor increases. At some point the transfer of heat by the vapor begins to predominate and the device undergoes a transition to the operating conditions of a heat pipe.

The heat exchanger 4 (see Fig. 1) can be connected separately to the condenser 3 to any heat sink, by which it can be cooled even below T_0 $(T_2 < T_0)$. In this case the ratio of Q_3 to Q_2 becomes greater than 100, i.e., the main heat flux is transferred by the circulation of the liquid phase of the heat transfer medium.

NOTATION

G, volumetric flow rate; Q_1, Q_3, Q_3, heat fluxes in the evaporator, condenser, and heat exchanger; r, latent heat of vaporization; α, heat transfer coefficient of condenser; F, surface area of condenser; c, heat capacity; ρ, density; T, T_1, T_2, T_0,* temperature of the condenser walls, the surrounding medium, and the liquid at the inlet and outlet of the heat exchanger; P, pressure; M, molecular weight; R, universal gas constant; n, proportionality coefficient of the volumetric contents of vapor and liquid in the vapor-lift tube; h_1, h_2, height of the vapor-lift tube above the liquid level in the system and from the evaporation zone to the liquid level. Subscripts: V, vapor; L, liquid; K, boiling; max, maximum.

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THERMAL DIFFUSION RATIO OF SATURATED VAPOR–GAS MIXTURES

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A theoretical method of determining the temperature dependence of the thermal diffusion ratio of saturated vapor–gas mixtures is proposed.

The known experimental methods of determining the value of k_T cannot be used for saturated vapor–gas mixtures. The relationship provided by the rigorous molecular kinetics theory cannot be used reliably for calculating the value of k_T without checking its adequacy experimentally.

Our aim was to develop a theoretical method for determining the thermal diffusion ratio of saturated vapor–gas mixtures on the basis of the phenomenological linear equations of the thermodynamics of irreversible processes.

An experimental method for determining the thermal diffusion ratio of saturated vapor–gas mixtures was proposed in [2]. Its essence consists in securing a process of simultaneous evaporation of a liquid into a vapor–gas medium and condensation of its vapor in an enclosed volume under diffusion conditions. The flat evaporation and condensation surfaces are parallel to each other. A Stefanian flow is contemplated. The theoretical premise of the method involves the use of linear phenomenological equations:

$$J_{1z} = -\frac{\mu_1}{\mu}\frac{\rho D}{1-x_1}\left(\frac{dx_1}{dz} - \frac{k_T}{T}\frac{dT}{dz}\right), \qquad (1)$$

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$$q_z = -\lambda \frac{dT}{dz} + J_{1z}\left\{\left[\frac{\mu}{\mu_1\mu_2}\,\frac{RTk_T}{x_1(1-x_1)} + (H_1 - H_2)\right]\frac{\mu_2}{\mu}(1-x_1) + H\right\}, \tag{2}$$

where

$$H_1 = H_1(T);\ H_2 = H_2(T);\ \mu = \mu_2 - (\mu_2 - \mu_1)x_1;\ \rho = \mu p/RT;$$

$$D = D_0(T/273)^{1+n}\,\frac{p_0}{p};\ x_1 = \frac{p_1}{p};\quad k_T = k_T(x_1, T);\ \lambda = \lambda(x_1, T);$$

$$H = H_2 + \frac{\mu_1}{\mu}x_1(H_1 - H_2);\ \frac{dx_1}{dz} = \frac{dx_1}{dT}\,\frac{dT}{dz}.$$

Dividing each term of Eq. (2) by Eq. (1), we find

$$C_0 = \frac{q_z}{J_{1z}} = \frac{\lambda\dfrac{dT}{dz}}{\dfrac{\mu_1}{\mu}\,\dfrac{\rho D}{1-x_1}\left(\dfrac{dx_1}{dz} - \dfrac{k_T}{T}\,\dfrac{dT}{dz}\right)} + \frac{RT}{\mu_1 x_1}k_T + H_1, \tag{3}$$

or, simplifying the expression obtained,

$$k_T^2 - \left[\frac{\mu_1 x_1}{RT}(C_0 - H_1) + T\frac{dx_1}{dT}\right]k_T + \left[\frac{\mu_1 x_1}{R}\,\frac{dx_1}{dT}(C_0 - H_1) - \frac{\lambda\mu x_1(1-x_1)}{\rho RD}\right] = 0. \tag{4}$$

Furthermore, assuming that

$$A = \frac{\lambda\mu(1-x_1)}{\mu_1\rho D};\ B = \frac{RT}{\mu_1 x_1};\ M = \frac{T}{2B}\left(\frac{C_0 - H_1}{T} + B\frac{dx_1}{dT}\right); \tag{5}$$

$$N = \frac{T}{B}\left[(C_0 - H_1)\frac{dx_1}{dT} - A\right],$$

we obtain

$$k_T^2 - 2Mk_T + N = 0. \tag{6}$$

Solving Eq. (6) with respect to k_T, we find

$$k_T = M \pm \sqrt{M^2 - N}. \tag{7}$$

Of the two signs in front of the square root, we use the minus sign, as k_T then vanishes for $x_1 = 0$, i.e.,

$$k_T = M - \sqrt{M^2 - N}. \tag{8}$$

After we determine experimentally the temperature and concentration fields between the evaporation and the condensation surfaces and also the heat flux and mass flux densities and substitute them in (8), we find the corresponding range of k_T values. Only those k_T values which correspond directly to the evaporation and condensation surfaces pertain to the saturated state of a vapor–gas mixture. All the other k_T values correspond to the supersaturated state of the vapor–gas mixture, since vapor condensation does not occur because of the absence of nuclei [3]. Therefore, the vapor–gas mixture is locally supersaturated in the space between the evaporation and the condensation surfaces. The degree of supersaturation passes through a maximum [3]. Under realistic conditions, the vapor–gas mixture usually contains dust particles, which constitute the nuclei of volume condensation of vapor. As a result, the state of vapor–gas mixture is close to local saturation on the side of supersaturation. Then, assuming that the mass and heat flux densities are constant in passing from the evaporation surface to the condensation surface and considering that the vapor–gas mixture is locally saturated, Eq. (8) can be transformed so that k_T is a function only of the local temperature of the vapor–gas mixture. This is possible because the pressure of the saturated liquid vapor is a function of the temperature only:

$$p_{1_s} = f(T). \tag{9}$$

Thus, since generally $x_1 = p_1/p$, we have the following for a saturated vapor–gas mixture:

$$x_{1s} = \frac{p_{1s}}{p} = \frac{f(T)}{p}, \tag{10}$$

in which case,

$$\frac{dx_{1s}}{dT} = \frac{f'(T)}{p}. \tag{11}$$

Considering (10) and (11), we write Eqs. (5) as follows:

$$\begin{aligned} A_1 &= \frac{\lambda\mu(1-x_1)}{\mu_1 \rho D}; \quad B_1 = \frac{RT}{\mu_1 x_{1s}}; \\ M_1 &= \frac{T}{2B_1}\left(\frac{C_0 - H_1}{T} + B_1 \frac{dx_{1s}}{dT}\right); \\ N_1 &= \frac{T}{B_1}\left[(C_0 - H_1)\frac{dx_{1s}}{dT} - A_1\right]. \end{aligned} \tag{12}$$

As a result, Eq. (8) becomes

$$k_T = M_1 - \sqrt{M_1^2 - N_1}. \tag{13}$$

In the approximation defined by the above assumptions, Eq. (13) determines the value of k_T at the temperature $\bar{T} = (T_e + T_c)/2$ with an accuracy to the undetermined constant $C_0 = q_z/J_{1z}$.

The error of Eq. (13) decreases with the interval

$$T_c \leqslant T \leqslant T_e. \tag{14}$$

It is obvious that, for a sufficiently small difference $T_e - T_c$, the vapor-gas mixture in the space between the evaporation and the condensation surfaces can be considered to be locally saturated with a high degree of accuracy. In this case, Eq. (13) becomes exact within the limits of the temperature range in question. It should be mentioned that, with changes in the limits of the temperature range (14), C_0 in Eq. (13) assumes different values, i.e., C_0 is a function of the local temperature value. If we establish in some fashion the specific form of this function for the assigned temperature range

$$T_h \leqslant T \leqslant T_e, \tag{15}$$

Eq. (13) will reflect the temperature dependence of k_T for the saturated vapor-gas mixture under consideration.

In order to determine the temperature dependence of C_0 in the temperature interval (15), this interval must be subdivided into n equal parts so that, in every obtained subinterval that is used as interval (14), the condition of local saturation of the vapor-gas mixture is satisfied with a sufficient degree of accuracy in this temperature subinterval. The value of C_0 changes with passage from one subinterval to another. It should be borne in mind that the temperatures corresponding to the ends of a subinterval are the temperatures of the evaporation and the condensation surfaces, respectively.

For convenience in subsequent considerations, we introduce the notation (T_{ei}, T_{ci}), the temperature subinterval, where i = 1,...,n, while

$$\sum_{i=1}^{n} (T_{ei} - T_{ci}) = T_0 - T_c. \tag{16}$$

Here, $T_{e1} = T_0$ for i = 1 and $T_{cn} = T_h$ and also $T_{e(i+1)} = T_{ci}$ for i = n.

If we know the value of k_T corresponding to $T_{e1} = T_0$, then, using it in accordance with Eq. (13), we can determine the value of C_0 corresponding to the temperature $T_{e1} = T_0$. This value can be reduced to the subintegral (T_{e1}, T_{c1}).

Thus, we use the found value of C_0 for calculating the value of k_T corresponding to the temperature T_{c1} and reduce it to the subinterval (T_{e2}, T_{c2}), considering that $T_{c1} = T_{e2}$ in this case. Furthermore, with an allowance for the found value of $k_T(T_{e2})$, we determine the value of C_0 at the temperature $T_{c2} = T_{e3}$ and reduce it to the subinterval (T_{c1}, T_{e3}), which yields the value of k_T (T_{e4}). We then calculate successively the values of C_0 and k_T until we obtain $C_0 = C_0(T_{en})$, and $k_T = k_T[T_{e(n+1)}]$. As a result, we obtain the following series of C_0 values:

TABLE 1. Values of C_0 and k_T at Different Temperatures

T	C_0	k_T	T	C_0	k_T
372,74	2675545	0	333,51	2695130	—0,03403
372,73	2675550	0,000006437	328,61	2703680	—0,04374
371,73	2675250	0,001749	323,70	2714070	—0,05310
370,73	2674980	0,003261	318,80	2726400	—0,06182
369,73	2674750	0,004518	313,89	2740670	—0,06965
368,73	2674550	0,005550	308,99	2756650	—0,07639
367,85	2674400	0,006287	304,08	2773760	—0,08186
362,94	2674080	0,007765	299,18	2790740	—0,08592
358,04	2674670	0,005542	294,27	2805250	—0,08849
353,13	2676280	0,0005298	289,37	2813130	—0,08953
348,23	2678990	—0,006529	284,46	2807430	—0,08905
343,32	2682940	—0,01500	279,56	2776980	—0,08713
338,42	2688270	—0,02432	274,65	2704340	—0,08390

$$C_0(T_{e1}),\ C_0(T_{e3}),\ C_0(T_{e5}),\ \ldots,\ C_0(T_{en}), \tag{17}$$

where n is chosen so that, for analogous temperatures, the calculated values of k_T differ from each other by an amount smaller than the allowable error. By approximating series (17) by a function of T and substituting it in (13), we obtain a specific expression for determining the temperature dependence of the thermal diffusion ratio of the saturated vapor–gas mixture in question within the assigned temperature range (15).

As an example, we provide the results of calculation of the C_0 and k_T values according to the above method for a saturated vapor–gas mixture in the temperature range

$$273 < T < 373\,°K \tag{18}$$

under normal atmospheric pressure.

According to [4], the temperature dependence of saturated water vapor is given by the expression

$$p_{1s} = 10^{10{,}004 - \frac{1625}{T-48}}. \tag{19}$$

Considering (19), we find the following for the saturated vapor–gas mixture:

$$x_{1s} = \frac{p_{1s}}{p} = \frac{1}{p}\cdot 10^{10{,}004 - \frac{1625}{T-48}},\ \text{where } p = 10^5\ \text{Pa};$$

$$\frac{dx_{1s}}{dT} = x_{1s}\frac{3742}{(T-48)^2},\quad \mu_1 = 18,\ \mu_2 = 29,$$

$$\rho = \frac{\mu p}{RT},\quad R = 8314,\ \mu = 29 - 11x_{1s}.$$

Furthermore, according to [5], we have

$$D = D_0\,(T/273)^{1{,}8},\quad D_0 = 0{,}0000216,$$

$$\lambda = \left\{\frac{0{,}0084\,(T-81)}{1 + 0{,}278\left(\frac{1}{x_{1s}} - 1\right)\left[1 + \sqrt{\frac{T-40}{T+85}}\right]^2} + \frac{0{,}0077\,(T+44)}{1 + 0{,}219\,\frac{x_{1s}}{1-x_{1c}}\left[1 + \sqrt{\frac{T+85}{T-40}}\right]^2}\right\}\cdot 10^{-2}.$$

For a saturated vapor–gas mixture at T = 372.74°K and p = 10^5 Pa, we find p_{1s} = 10^5 Pa in accordance with (19), i.e., we have the case of pure vapor. Since k_T = 0 for pure vapor, then, assuming that k_T = 0 at T = 372.74 in Eq. (13), we find C_0 = 2,675,545.

Table 1 provides the calculation data for the temperature range (18), based on the above-described scheme and the step $\Delta T = 0.01°K$ as well as some intermediate values of C_0 and k_T.

Analysis of the data in Table 1 reveals a very complex temperature dependence of the thermal diffusion ratio of the saturated vapor–gas mixture in the temperature range (18). The value of k_T first increases, remaining positive up to the maximum. Then, decreasing to a minimum, it passes through zero. The temperature corresponding to the zero value of k_T is referred to as the inversion temperature [6]. The k_T value subsequently increases, remaining negative.

The values of C_0 given in the table were approximated to fit suitable functions for different subintervals of range (19):

$$273 \leqslant T \leqslant 290\ K, \quad C_0 = -619{,}545(-T^2 + 576{,}085T - 78424); \tag{20}$$

$$290 \leqslant T \leqslant 330\ K, \quad C_0 = 2800(1295 - T); \tag{21}$$

$$330 \leqslant T \leqslant 363\ K,$$

$$C_0 = 818{,}64(3630 - T); \tag{22}$$

$$363 \leqslant T \leqslant 372{,}74\ K, \quad C_0 = 148{,}87(17600 + T). \tag{23}$$

Calculation of k_T values based on Eq. (13) with an allowance for the C_0 values from (20)-(23) yields results which are in satisfactory agreement with those given in Table 1. The maximum relative error does not exceed 5%. The maximum relative error of expression (21) does not exceed 0.5%.

Experimental data on the temperature field and the densities of the mass and energy fluxes between the evaporation and the condensation surfaces are given in [7] for the case where the temperature of the evaporation surface is equal to 330°K, while the temperature of the condensation surface is equal to 291°K. The experiments were performed in such a manner as to eliminate completely the effect of free convection on the diffusive heat and mass transfer. The results of experimental investigations of simultaneous evaporation and vapor condensation in the diffusion chamber indicates that the vapor–gas mixture in the space between the evaporation and the condensation surfaces is at least locally saturated (the humidity data unit does not make it possible to measure supersaturation); according to the results obtained in [8], it is even supersaturated. Since the degree of supersaturation is insignificant, we shall consider in the first approximation that the vapor–gas mixture in the chamber is locally saturated and that the densities of the mass and energy fluxes are constant in the direction from the evaporation surface to the condensation surface. The results of measurements of the heat and mass flux densities are also given there. For the above temperatures of the evaporation and the condensation surfaces, they are respectively equal to $q_z = 234\ W/m^2$ and $J_{1z} = 85.2 \cdot 10^{-6}\ kg/m^2 \cdot sec$.

Therefore,

$$C_0 = \frac{q_z}{J_{1z}} = 2746479. \tag{24}$$

The value of C_0 should, appropriately, be reduced to the arithmetical mean of 291 and 330°K.

By substituting C_0 in Eq. (13) at $T = (291 + 330)/2 = 310.5°K$, we find $k_T = -0.07857$. We obtained earlier the local value of C_0 in the temperature range

$$291 \leqslant T \leqslant 330\ K \tag{25}$$

on the basis of theoretical considerations. It is given in expression (21). By means of this expression, we find the integral-mean value of C_0 for the temperature range (25):

$$C_0 = \frac{1}{330-291} \int_{291}^{330} 2800(1295-T)\,dT = 2756489. \qquad (26)$$

Comparing Eqs. (24) and (26), we reach the conclusion that the value of C_0 determined theoretically is in fairly good agreement with the experimental value. The discrepancy amounts to only 0.37%. The values of k_T corresponding to the above theoretical and experimental values of C_0 are equal to −0.07504 and −0.07857, respectively, i.e., the difference between them amounts to 4.5%. Our earlier determination based on another approximate theoretical method [9] yielded −0.088 as the value of k_T for T = 310.5°K, i.e., this result also is in satisfactory agreement with our data given here. Further experimental investigations must be carried out in order to confirm the validity of the proposed theoretical method of determining the thermal diffusion ratio of saturated vapor–gas mixtures in the wide temperature range (18).

NOTATION

J_{1z}, density of the diffusion mass flow; q_z, energy flux density; μ_1, μ_2, and μ, molecular masses of the components and of the vapor–gas mixture, respectively; ρ, density of the mixture; D, mutual diffusion coefficient; x_1, mole fraction of vapor in the mixture; z, coordinate; T, temperature of the mixture; k_T, thermal diffusion ratio of the vapor–gas mixture; λ, thermal conductivity coefficient of the mixture; R, universal gas constant; H_1 and H_2, specific mass enthalpy values of the mixture components; H, specific mass enthalpy of the mixture; p, total pressure of the mixture; D_0, diffusion coefficient of the mixture at $p = 10^5$ Pa and T = 273°K; n, exponent of the temperature dependence of the coefficient of mutual diffusion in the mixture; p_1, partial pressure of vapor in the mixture; C_0, ratio of the thermal flux to the mass flux; p_{1s}, saturated vapor pressure in the mixture; x_{1s}, mole fraction of saturated vapor in the mixture; T_e, temperature of the evaporation surface; T_c, temperature of the condensation surface; the subscript 1 pertains to the light component of the vapor–gas mixture.

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