EFFECT OF EVAPORATION ON CONVECTIVE HEAT EXCHANGE OF A POROUS PLATE IN A RAREFIED MEDIUM

P. A. Novikov, V. S. Yalovets, and Z. M. Yudovin

UDC 536.423.1:621.78.061

Two heat-exchange regimes are experimentally observed for a horizontal porous plate as liquid evaporates from the plate into a rarefied medium. In one of these regimes mass transfer of vapor completely determines the convective heat exchange.

The effect of mass exchange on heat exchange in evaporation of liquid from a free surface or from capillary-porous bodies has been studied by many authors [1-3]. These studies have all maintained that given an identical direction of heat and mass flow, mass-exchange intensifies convective heat exchange, while with heat and mass flow in opposite directions, heat exchange is decreased. However, this is not true under all possible conditions. For non-steady-state direction of the vapor flow (free-convective heat exchange in evaporation) the above principles have only been partially confirmed in experiment [4-6]. An important role is played in this case by the ratio between the linear rate of vapor escape from the evaporation surface and the rate of convective motion of the external medium. This is true, in particular, of evaporation processes in a rarefied medium, where free-convective flow of the mixture begins to degenerate with decrease in gas density, and the vapor flow is produced by convective motion of the vapor–gas mixture. The value of the evaporation rate can then have a significant effect on external heat exchange. It is thus of interest to study this effect and determine the external parameter range over which mass transfer is determined by convective heat exchange and also to establish the range of evaporation rates at which the non-steady-state convective flow regime transforms to a steady-state one. With these goals in mind, the heat exchange of a moist porous body was studied as liquid evaporated from the body into a rarefied medium.

The experiments were performed in a vacuum chamber formed by a glass dome (D = 0.4 m; H = 0.6 m), placed on a metal base. The specimen, consisting of a porous titanium plate (D = 0.13 m; δ = 0.003 m; mean pore size $(4\text{-}7)\cdot10^{-6}$ m) attached to an aluminum base, was placed in the chamber on scales. An electric heater was located in the lower part of the chamber. To decrease unwanted heat losses, the specimen was placed on needle supports. Evaporation rate and moisture content of the plate were measured by weighing. Copper–constantan thermocouples and traditional instrumentation [3, 7] were used to measure temperature. The humidity of the gaseous medium in the vacuum chamber was determined by a "wet" thermocouple, protected from heat influx by a foamed plastic covering. Thermocouple output was read by an electronic voltmeter. The rarefaction required in the chamber was produced by a forevacuum pump and measured by a mercury manometer. Total pressure under the dome was varied over the range $(0.038\text{-}10)\cdot10^4$ Pa. To eliminate significant oscillations in total pressure in the chamber an accumulation chamber and oil manometer were used, the latter serving to indicate oscillations in total pressure. The electric heater power was varied over the range 7-116 W. The liquid (distilled water) was supplied to the outer surface of the porous plate, uniformly wetting the specimen due to capillary takeup. The plate was wetted down with the same pressure in the chamber as that at which the following experiment was performed. The plate was saturated to the maximum moisture content corresponding to a given pressure of the medium.

A set of series of measurements was performed, each series corresponding to a given pressure of the medium and heat flux from the heater. Beforehand the plate was saturated several times to achieve a stationary heat-exchange regime. Readings of the scales and all thermocouples were taken synchronously from the moment of maximum plate saturation to total dryness.

It is well known [8] that in drying of a capillary-porous body there exists a constant drying rate regime, in which the mean temperature of the body and the evaporation rate do not change until some "critical" moisture content is reached. We will term this regime quasistationary (only the plate moisture content changes). In our experiments the value of the "critical" plate moisture content comprised $\sim$30%. By moisture content, we understand here the ratio of the amount of liquid contained within the plate to the maximum amount of liquid it is capable of holding.

We present below the results of the study of convective heat exchange during liquid evaporation from a horizontal porous plate only in the quasistationary regime. The convective heat-transfer coefficients were determined from the energy

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 3, pp. 379-384, September, 1982. Original article submitted May 4, 1981.

 0022-0841/82/4303-0966$07.50

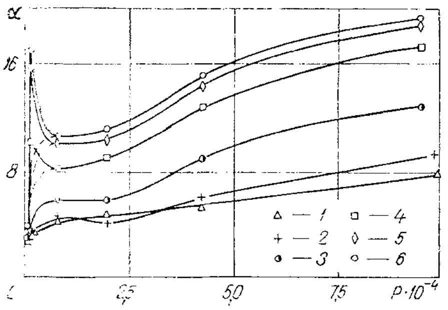

Fig. 1

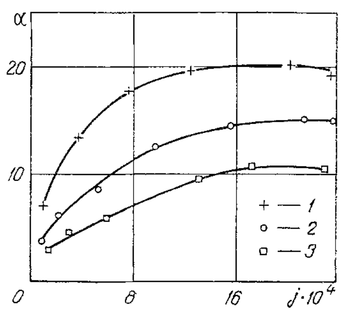

Fig. 2

Fig. 1. Convective heat-transfer coefficient α vs total medium pressure for various evaporation rates j: 1) 0; 2) $2.5 \cdot 10^{-4}$; 3) $5 \cdot 10^{-4}$; 4) $10 \cdot 10^{-4}$; 5) $15 \cdot 10^{-4}$; 6) $18 \cdot 10^{-4}$.

Fig. 2. Convective heat-transfer coefficient α vs evaporation rate j at various medium pressures P: 1) 10^5; 2) $4 \cdot 10^4$; 3) $1.9 \cdot 10^4$.

TABLE 1. Calculated Values of Coefficient $C = Nu/(Gr Pr)^{0.25}$ versus Parameters T_1/T_∞ and P_{v1}/P

T_1/T_∞	P_{v1}/P	
	$1 \cdot 10^{-4}$	$1 \cdot 10^{-1}$
0,6	0,510	0,451
1,0	0,515	0,611
1,9	0,497	0,548

balance equation for the entire specimen, all three forms of heat exchange being considered. The radiant heat flux was determined from the Stefan–Boltzmann formula for a closed space with consideration of angular coefficients and corresponding relationships for the corrected emissivity of the system [9-11].

Figure 1 shows the convective heat-transfer coefficient α as a function of total medium pressure for various evaporation rates. The uncertainty in α determination does not exceed 15%. It is evident from the curves that α decreases with decrease in pressure in the chamber and increases with increase in evaporation rate. The intensifying effect of j upon α is especially great when the directions of the heat and mass fluxes coincide ($T_1/T_\infty > 1$), which was observed in our experiments at medium pressures of $(0.267\text{-}10) \cdot 10^4$ Pa. Change in the ratio P_{v1}/P has a large effect on the heat-exchange character. Comparison with results of calculation for the case of water evaporation with data from the literature on heat exchange for free convection with a "dry" body show that the low intensity evaporation process ($P_{v1}/P < 10^{-4}$) has no significant effect on the temperature gradient and profile along the evaporation surface, and the heat exchange can be described with sufficient accuracy by using results for heat exchange uncomplicated by mass exchange. With increase in the ratio $P_{v1}/P > 1 \cdot 10^{-4}$, mass exchange gradually becomes the dominant factor, determining the intensity of convective heat exchange. Then with decrease in total medium pressure or increase in evaporation rate there is an expansion of the region of unstable free-convective flow. In this case α increases as compared to pure heat exchange.

It should be noted that in our experiments the above-noted heat-exchange principle was not confirmed at all evaporation rates. When sufficiently high rates $j > 20 \cdot 10^{-4}$ kg/m^2 sec are attained there is a reduction in convective heat exchange (Fig. 2). This can be explained by the fact that the vapor flow takes on a definite flow direction (stable flow regime) and drives the external convective flows of vapor–gas mixture away from the heat-exchange surface.

In [4] results were presented of a study of heat-exchange intensity about horizontally oriented water evaporation surfaces and a "dry" plate, located under identical conditions, in the region of non-steady-state free-convective flow, and for opposite directions of heat and mass flows ($T_1/T_\infty < 1$). This study revealed that with increase in evaporation rate the ratio $\alpha/\alpha_0 > 1$ also increases, reaching a maximum. With further increase $j > 2.5 \cdot 10^{-4}$ kg/m^2 sec, the ratio α/α_0 falls and may become less than unity. In this case the non-steady-state vapor flow regime transforms to steady state.

It follows from analysis of the numerical solution of the problem of convective heat exchange of a vertical subliming plate in boundary-layer theory approximation that two parameters have a significant effect on the stability and intensity of convective heat exchange: T_1/T_∞ and P_{v1}/P. Table 1 shows this effect on the coefficient C of the criterial

TABLE 2. Outer and Inner Plate Surface Temperatures for Various P and q

$P \cdot 10^{-3}$		q: 570	1090	2160	3725	5537	T_{sat}
0,67	T_1	274,04	273,92	274,12	274,24	274,75	274,2
	T_2	274,28	274,22	274,94	275,22	276,26	
1,33	T_1	282,2	282,5	282,3	282,25	282,76	283,3
	T_2	282,7	282,88	283,1	283,62	284,58	
2,67	T_1	293,4	293,48	294,0	294,14	293,72	290,5
	T_2	293,66	294,22	295,7	296,16	295,48	
8,0	T_1	299,1	303,5	308,9	312,06	313,42	315,1
	T_2	299,87	305,0	310,24	316,74	318,2	

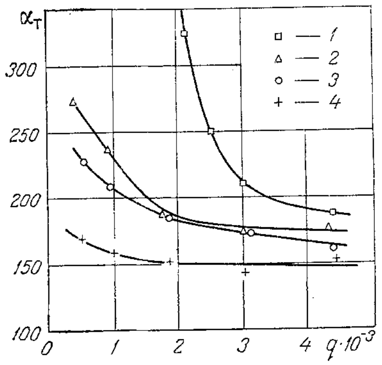

Fig. 3

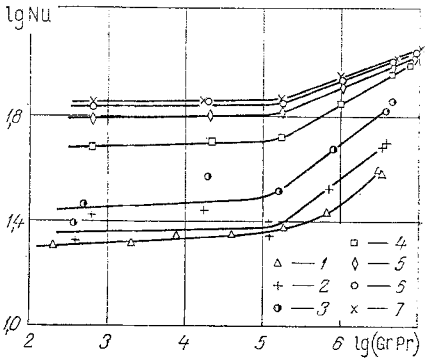

Fig. 4

Fig. 3. Heat liberation coefficient α_T vs thermal flux density q for various surrounding medium pressures: 1) $8 \cdot 10^3$; 2) $2.67 \cdot 10^3$; 3) $1.33 \cdot 10^3$; 4) $0.67 \cdot 10^3$.

Fig. 4. Number Nu vs GrPr for various evaporation rates j: 1) 0; 2) $2.5 \cdot 10^{-4}$; 3) $5 \cdot 10^{-4}$; 4) $10 \cdot 10^{-4}$; 5) $15 \cdot 10^{-4}$; 6) $18 \cdot 10^{-4}$; 7) $20 \cdot 10^{-4}$.

relationship $Nu = C(GrPr)^{0.25}$. Thus, development of a vapor phase manifests itself in a differing manner depending on the ratio of the velocities v_v/u, while the quantities T_1/T_∞ and P_{v1}/P prove to have a significant effect on the stability of free-convective flow and the intensity of convective heat exchange. Analysis of the above permits the conclusion that the results presented in Fig. 1 refer to the region of unstable vapor flow regime (at large j the increase in α is retarded). Apparently, under conditions of evaporation from porous bodies the unstable convective vapor flow regime shifts in the direction of larger j values in comparison to evaporation from an open surface [4].

Consequently, independent of the relative direction of the heat and mass flows in the region of unstable convective flow an intensification of heat exchange occurs, while in the stable flow regime region, there is either no effect or even an attenuation of heat exchange due to mass exchange.

In the medium pressure range $(1\text{-}5) \cdot 10^3$ Pa and for $j > 5 \cdot 10^{-4}$ kg/m²·sec (Fig. 1) the value of α changes discontinuously. From analysis of the energy balance equation for these conditions the discontinuity can be explained by expulsion of liquid from the porous material as the boiling regime is achieved. Establishment of such a regime is confirmed by the fact that the plate temperature is practically independent of the value of the thermal flux and corresponds to the saturation temperature (Table 2). The curves of $\alpha_T = f(q)$ presented in Fig. 3 for various medium pressures are similar to analogous curves for boiling in a large volume [12], which indirectly confirms the existence of liquid boiling in the plate pores. Meanwhile, with decrease in medium pressure the heat-liberation coefficient α_T decreases. From Fig. 3 it is also evident that the heat-liberation coefficient α_T also decreases with increase in thermal flux density and for $q > 3 \cdot 10^3$ W/m² is practically independent of thermal loading, which indicates a change in the boiling regime in the pores. In our experiments, in accordance with [12], this regime at $q > 3 \cdot 10^3$ W/m² is similar to the regime of film boiling in a large volume. Thus, the abrupt change obtained in α is fictitious, which requires us to interpolate α values for the case of boiling (Fig. 1).

The experimental results were generalized in criterial form. In calculating the similarity criteria, the characteristic geometric dimension used was the plate diameter, while $T = (T_1 + T_\infty)/2$ was used as the characteristic temperature. The kinetic coefficients entering into the similarity criteria were calculated with formulas obtained on the basis of the molecular-kinetic theory of gases [13].

Figure 4 shows the function Nu = f(GrPr) for various evaporation rates. Also shown here are data on "dry" heat exchange of a plate with natural convection (curve 1), which differ from the results of [14] by 5%, which does not exceed the experimental uncertainty. The limits of GrPr variation are expanded because of change in total medium pressure.

It is evident from Fig. 4 that depending on the value of GrPr, one of two convective heat-exchange regimes is realized. The first regime ($10^5 \leqslant \mathrm{GrPr} \leqslant 10^7$) is characterized by increase in Nu with increase in GrPr. In this case, with increase in j the slope of the curve Nu = f(GrPr) decreases, tending to zero in the limit. This indicates that with increase in j, natural convection of the surrounding medium has an ever smaller effect on convective heat exchange between plate and medium. The second regime ($10^3 \leqslant \mathrm{GrPr} < 10^5$) is characterized by a very weak dependence of Nu on GrPr, while with growth in j this dependence degenerates, and convective heat exchange is essentially determined by mass transfer of vapor into the surrounding medium.

Thus, the traditional processing of experimental data in the form Nu = f(GrPr) for natural convection in evaporation of liquid from porous bodies into a rarefied medium (especially for the second heat-exchange regime) becomes incorrect. To generalize the experimental results into a functional dependence Nu = f(GrPr) a Reynolds number for the transverse vapor flow $\mathrm{Re_v} = jl_0/\mu_v$ was introduced. For the first regime, $\mathrm{Re_v}$ considers the effect of mass transfer on heat exchange, while for the second, it totally determines convective heat exchange. Below we present empirical relationships Nu = f(GrPr, $\mathrm{Re_v}$), describing both heat-exchange regimes $2 \leqslant \mathrm{Re_v} \leqslant 25$ (for $\mathrm{Re_v} \leqslant 2$ convective heat exchange in evaporation shows practically no difference from "dry" heat exchange):

first regime

$$\mathrm{Nu} = 0{,}33\,\mathrm{Re_v^{1,17}}(\mathrm{Gr\,Pr})^{0.257-0.006\mathrm{Re_v}}, \tag{1}$$

second regime

$$\mathrm{Nu} = 11.2\,\mathrm{Re_v^{0,57}}. \tag{2}$$

NOTATION

D, diameter, m; H, height, m; δ, thickness, m; α, convective heat-exchange coefficient for evaporation, $\mathrm{W/m^2 \cdot deg\ K}$; α_0, convective heat-exchange coefficient for "dry" body, $\mathrm{W/m^2 \cdot deg\ K}$; α_T, heat-liberation coefficient from heated surface to porous plate, $\mathrm{W/m^2 \cdot deg\ K}$; q, thermal flux density, $\mathrm{W/m^2 \cdot deg\ K}$, P, total pressure of medium in chamber, Pa; P_{P1}, partial vapor pressure over the porous plate surface, Pa; T_1, temperature of outer surface of plate, °K; T_2, temperature of the inner surface of the plate, °K; T_∞, medium temperature far from the plate surface, °K; T_{sat}, saturation temperature, °K; j, evaporation rate, $\mathrm{kg/m^2 \cdot sec}$; v_v, linear vapor escape velocity from evaporation surface, m/sec; u, velocity of free-convective motion of external medium, m/sec; Nu, Nusselt number; Gr, Grashof number; Pr, Prandtl number; $\mathrm{Re_v}$, Reynolds number for transverse vapor flow; l_0, characteristic length, m; μ_v, dynamic viscosity coefficient of vapor, Pa·sec.

LITERATURE CITED

1. A. V. Lykov, "Heat and mass transfer in evaporation processes," Inzh.-Fiz. Zh., 5, No. 11, 12-24 (1962).
2. A. V. Lykov and L. L. Vasil'ev, "Heat and mass transfer of capillary-porous bodies with rarefied gas draft," in: Heat and Mass Transfer at Low Temperatures [in Russian], ITMO Akad. Nauk SSR, Minsk (1970), pp. 3-24.
3. V. I. Balakhonova, "Study of the heat- and mass-transfer process in liquid evaporation from an open surface in a rarefied gas atmosphere," Inzh.-Fiz. Zh., 12, No. 1, 3-9 (1967).
4. V. I. Balakhonova, P. A. Novikov, and V. M. Subach, "Effect of mass transfer on heat transfer in liquid evaporation from an open surface in a rarefied gas medium," Inzh.-Fiz. Zh., 20, No. 3, 405-510 (1971).
5. E. M. Sparrow, W. S. Minkovicz, and E. R. G. Eckert, "Transpiration-induced buoyancy and thermal diffusion-diffusion thermo in a helium–air free convection boundary layer," J. Heat Transfer, 86, No. 4, 48-56 (1964).
6. E. M. Sparrow, C. S. Scott, R. J. Fostrom, and W. A. Ebert, "Experiments on the diffusion thermoeffect in a binary boundary layer with injection of various gases," Trans. ASME, No. 3, 1-9 (1965).
7. V. I. Balakhonova, P. A. Novikov, B. M. Smol'skii, et al., "Study of the process of liquid evaporation from a porous metal under vacuum conditions," Inzh.-Fiz. Zh., 14, No. 1, 48-54 (1968).
8. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
9. A. G. Blokh, Fundamentals of Radiant Heat Exchange [in Russian], Gosénergoizdat, Moscow (1962).
10. N. B. Vargaftik, Tables on the Thermophysical Properties of Liquids and Gases, Halsted Press (1975).
11. N. B. Vargaftik, Thermophysical Properties of Materials (Handbook) [in Russian], Gosénergoizdat, Moscow (1956).
12. S. S. Kutateladze, Fundamentals of Heat Exchange Theory [in Russian], Nauka, Novosibirsk (1970).
13. J. Hirshfelder, C. Curtiss, and R. Bird, Molecular Theory of Gases and Liquids, Wiley (1964).
14. W. H. McAdams, Heat Transmission, McGraw-Hill (1954).