EFFECT OF MASS TRANSFER ON HEAT TRANSFER IN LIQUID EVAPORATION FROM A FREE SURFACE IN AN EVACUATED GASEOUS MEDIUM

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Evaporation of a liquid from a free surface is considered for pressures in the surrounding medium of $1.33 \cdot 10^3$ and $2.67 \cdot 10^3$ N/m^2. On the basis of an experimental study, a mechanism was established for the effect of mass transfer on heat transfer during evaporation under conditions of free convection.

At the present time, one can consider the effect of transverse mass flow on the intensity of heat transfer to be an experimentally established and theoretically substantiated fact.

Most investigators [1, 2] have come to the conclusion that this effect is determined by the direction of the transverse mass flow. Thus, the thickness of the boundary layer increases during evaporation into the gas flow and the heat transfer coefficient decreases with an increase in density of the transverse flow of matter.

But along with these papers there are also papers in which the intensifying effect of evaporation on heat transfer was established [3, 4]. The reason for this contradiction must be sought in the fact that heat and mass transfer during evaporation is characterized by exceptional complexity and includes a large number of diverse phenomena which are organically interrelated [5]. The creation of a new phase appears differently depending on the intensity of the basic process. If conditions are such that a process uncomplicated by mass transfer is characterized by high intensity, the formation of a new phase cannot change it significantly. On the other hand, if the fundamental process is by nature of low intensity, the role of secondary phenomena (formation of a new phase) increases. If they are of considerable intensity, conditions may become complicated in such a way that they become of controlling importance, fundamentally changing the nature of the process.

Actually, the nature of the effect of mass transfer on heat transfer depends on the ratio of the transverse flow velocity v to the basic gas flow velocity u_∞.

We consider evaporation of a liquid into an evacutated gaseous medium under free convection. In this case, the motion of the vapor–gas medium created by a temperature difference is not characterized by high intensity and, controlling the density of the transverse flow of vapor by means of a heater installed within the liquid, one can obtain a vapor velocity both less and greater than the velocity of the external vapor–gas medium.

Heat and mass transfer during evaporation under conditions of free convection are described by the fundamental conservation laws. Mathematical formulation of the laws for conservation of mass, momentum, and energy for flow under conditions of free convection leads to a complex system of equations and boundary conditions [6] which appears impossible to solve analytically at the present time.

To study this process, we completed an experimental investigation of jointly occurring processes of heat and mass transfer during evaporation of a liquid from a free surface into an evacuated gaseous medium.

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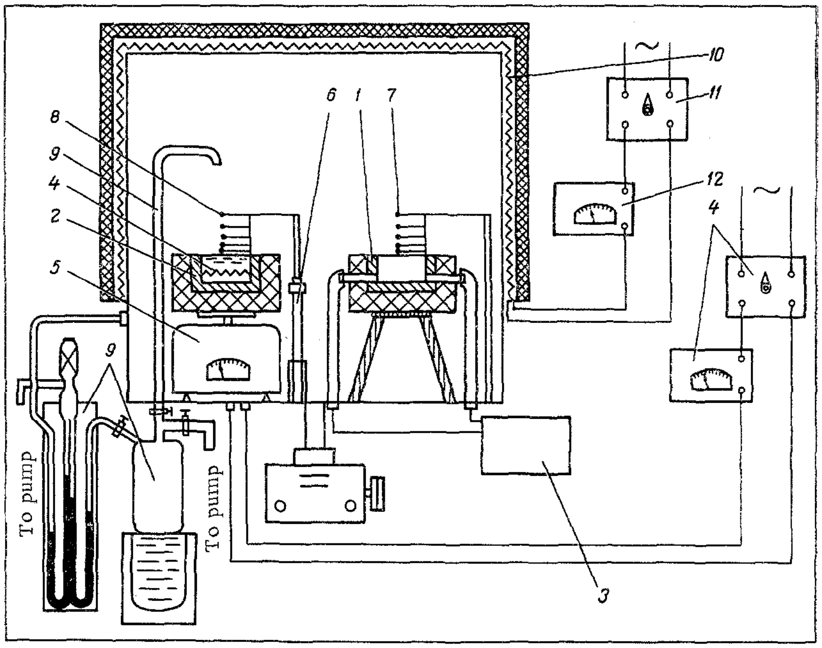

Fig. 1. Diagram of experimental apparatus.

The experiments were performed in a vacuum apparatus, for which a schematic diagram is shown in Fig. 1. A comparison method was used to evaluate the effect of mass transfer on heat transfer in the experiments. For this purpose, two model working bodies were placed in the vacuum chamber at the same time: a dry body and a liquid body located at an identical level in the horizontal plane and having identical surface heat transfer.

As the dry body, we used the thin copper plate 1, which was hermetically sealed in a cylindrical plastic cup with a thermally insulated lateral surface. Distilled water, which circulated at known velocity under the plate, acted as a heat-transfer agent in this case. The copper plate was covered with a layer of lampblack having a radiation coefficient approximately equal to the radiation coefficient of water. The temperature of the liquid surface and of the surface of the model dry body were kept the same.

Thus radiant heat flow was identical to both bodies. Temperature of the surface of the copper plate was kept constant by means of thermostat 3. The difference in temperatures at the inlet and outlet was measured with a differential thermocouple. The flow rate of the heat-transfer agent was determined by the volume method. Knowing the flow rate of the heat-transfer agent and the temperature difference at the cup inlet and outlet, one can determine the heat flow to the surface of the dry body. Excluding the radiant component and heat loss, we determine from the equation of heat balance the density of convective heat flow and the corresponding value of the heat-transfer coefficient.

In the cup 2 containing liquid, an electrical heater 4 was mounted by means of which the density of vapor flow could be changed over large limits without changing the external conditions for the process. Decrease in mass during evaporation was measured with the VTK-500 scales 5 with a scale division of 0.1 g. Temperature of the liquid surface was measured by two copper–constantan thermocouples which were moved by means of the micrometer screw 6. The temperature field in the neighborhood of the surface of the dry body 7 and that in the neighborhood of the surface of the liquid 8 were also measured. Partial pressure of the vapor in the chamber was measured by pumping off a portion of the vapor–air medium with subsequent freezing, 9.

The experiments were performed at medium pressures of $1.33 \cdot 10^3$ N/m^2 and $2.67 \cdot 10^3$ N/m^2. In order that the external conditions in the chamber not change, the difference in temperature between the medium and the surface of the working body was kept approximately constant. The vacuum chamber was covered by a thermal shell containing the electric heater 10. The required temperature of the chamber walls was obtained by means of this heater, which was regulated by the autotransformer 11 and the control ammeter 12.

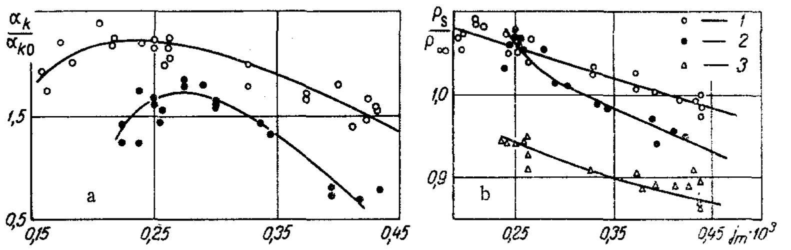

Fig. 2. Relative coefficient of heat transfer (a) and relative density of vapor–air medium (b) as function of density of transverse vapor flow: 1) $P = 2.67 \cdot 10^3$ N/m^2; 2) $P = 1.33 \cdot 10^3$ N/m^2; 3) ratio between density of vapor–air medium near liquid and density near dry surface.

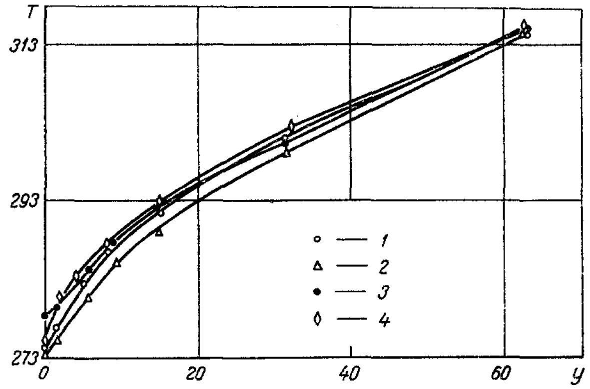

Fig. 3. Temperature distribution near the surface of evaporation, $P = 1.33 \cdot 10^3$ N/m^2, y in mm: 1) $j_m \cdot 10^3 = 0.240$; 2) 0.275; 3) 0.418; 4) temperature distribution near dry surface.

In all the experiments, the temperature of the liquid during evaporation was held below the temperature of the surrounding medium; thus the convective heat flow and the vapor flow from the surface were in opposite directions.

From an analysis of the experimental results, we see (Fig. 2a) that for small densities of transverse vapor flow, the coefficient of heat transfer which is accompanied by mass transfer is greater than the coefficient of heat transfer for the dry body and with an increase in density of vapor flow, the ratio α_k/α_{k0} increases to some maximum value typical of the particular pressure. With subsequent increase in the density of vapor flow, the ratio α_k/α_{k0} decreases and may become less than one.

During the evaporation of distilled water, the molecular weight of which is one and one-half times less than the molecular weight of air, the density of the vapor–gas mixture alongside the surface of evaporation is lower in comparison to the density of the gaseous medium alongside the dry surface (Fig. 2b, curve 3). But since the intensity of evaporation is insignificant, the condition $\rho_s/\rho_\infty > 1$ is still satisfied near the surface. Thus a picture of very complex motion is observed; on the one hand, convective motion, which is directed downwards from the surface of evaporation (drainage flow) and on the other hand, transverse motion of the vapor, which is created by the drop in partial pressures near the surface of evaporation and in the medium, are imposed on the motion resulting from free convection. All this leads to an intensification of heat transfer in comparison with a dry body. With subsequent increase in the density of transverse vapor flow, ρ_s/ρ_∞ approaches one, but becomes less than one at small distances from the surface, i.e., free convection at a few millimeters from the surface is directed upwards because of the effects of buoyant forces. One obtains a picture of extremely unstable convective motion upon which is superimposed diffusion motion of the vapor produced by differences in partial pressures. Motion along the surface is intensified. One can suppose that some production of turbulence occurs in the medium, which also gives rise to an increase in the intensity of heat transfer.

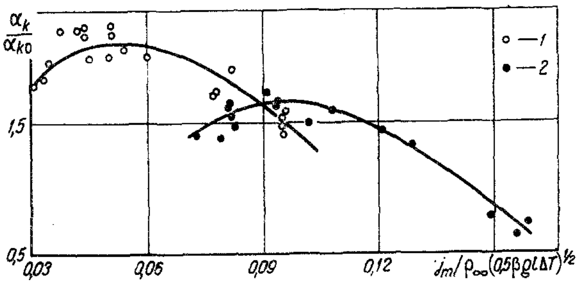

Fig. 4. Relative heat transfer coefficient as a function of the velocity ratio v_s/u: 1) $P = 1.33 \cdot 10^3$ N/m^2; 2) $P = 2.67 \cdot 10^3$ N/m^2.

With further increase in the density of transverse vapor flow, $\rho_s/\rho_\infty < 1$, the motion becomes directed strictly upwards; near the surface of evaporation, the vapor concentration rises, which begins to have an effect on the temperature distribution around the surface of evaporation. In this case (curve 3, Fig. 3), there is no sharp rise in the temperature of the medium near the surface, i.e., a dense vapor layer of considerable thickness is formed alongside the surface of evaporation preventing the penetration of "hot" molecules to the surface of evaporation and leading to a reduction in heat transfer. Also, for considerable densities of vapor flow, heat transfer complicated by mass transfer can become less than the heat transfer of a dry body.

For other ratios T_s/T_∞, for example where $P = 2.67 \cdot 10^3$, the zone of intensification of heat transfer because of mass transfer is shifted although the mechanism remains the same. One can therefore conclude that the effect of mass transfer on heat transfer is determined not only by the density of transverse vapor flow but also by the temperature ratio T_s/T_∞. It is possible there is still a reason for intensification of heat transfer which we have not considered but which exhibits considerable influence on the process. We compared our results with the results of theoretical [7] and experimental [8] work which describe transpiration cooling under conditions of free convection. In them, a detailed analysis was made of the heat transfer mechanism in the presence of material injection through a porous surface (cylinder) with consideration of thermal diffusion and diffusion thermo. Of course, the process of heat and mass transfer during evaporation of a liquid under conditions of free convection cannot be made completely similar to the process of heat and mass transfer with injection of material. We therefore made only a qualitative comparison of our results with the results of the papers mentioned above.

The fundamental result of these papers is that the injection of gas into the boundary layer first leads to an increase in the heat transfer coefficient for small flow rates of the injected gas, and then the heat transfer coefficient begins to fall with a rise in the gas flow rate. The initial rise results from an increase in the buoyant forces produced by the injection of a lighter gas at the surface. With higher flow rates, the increase in the boundary layer counteracts the buoyant force, and the heat transfer coefficient decreases.

As the injection parameter, we take the quantity

$$\frac{\rho_s v_s}{\rho_\infty (gr)^{1/2}} \sqrt{\frac{r(gr)^{1/2}\rho_\infty}{\mu_\infty}},$$

where r is the radius of the cylinder.

If we arbitrarily make evaporation similar to gas injection and look for the range of injection parameter values obtained in our experiments, we see that the injection parameter under our conditions varies from 0.01 to 0.1, which corresponds to that range of the injection parameter in [7] for which there was observed intensification of heat transfer because of mass transfer, i.e., we obtained qualitatively similar results.

Thus the creation of a new phase actually appears differently depending on the velocity ratio v_s/u. We took the quantity $v_s = j_m/\rho$ for the velocity of transverse vapor flow and the free convection velocity was characterized by the quantity $u = \sqrt{0.5\beta g l \Delta T}$, which O. Krisher introduced as a characteristic of free motion [9].

Figure 4 shows the dependence of the intensity of heat transfer accompanied by mass transfer on the velocity ratio v_s/u, from which the behavior obtained is clearly seen.

NOTATION

P	is the medium pressure, N/m^2;
ρ	is the density, kg/m^3;
μ	is the dynamic viscosity, $kg/m \cdot sec$;
g	is the gravitational acceleration, m/sec^2;
β	is the thermal expansion coefficient;
l	is the characteristic dimension, m;
j_m	is the density of transverse vapor flow, $kg/m^2 \cdot sec$;
α_k, α_{k0}	are the heat-transfer coefficients of moist and dry bodies, respectively, $W/m^2 \cdot deg$.

Subscripts

s	denotes the surface;
∞	denotes the medium.

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