STUDY OF THE PROCESS OF HEAT AND MASS TRANSFER ASSOCIATED WITH THE EVAPORATION OF A LIQUID FROM AN OPEN SURFACE IN A RAREFIED GAS MEDIUM

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The author has made an experimental study of the process of heat and mass transfer associated with the evaporation of a liquid from an open surface in a rarefied gas medium. The total gas pressure was varied from $1 \cdot 10^5$ to $1.33 \cdot 10^3$ N/m^2.

Many industrial processes take place in the presence of heat and mass transfer associated with the evaporation of various kinds of liquids in a rarefied gas medium. In particular, this relates to evaporative cooling, the evaporation of pure and multicomponent liquids, the evaporation of solutions, etc. Theoretical and experimental studies of liquid evaporation have made an important contribution to the development of ideas concerning the laws and characteristics of combined processes of heat and mass transfer; however, some of the problems, especially at reduced pressures, have not yet been sufficiently studied.

We have experimentally investigated the combined processes of heat and mass transfer associated with the evaporation of a liquid from an open surface at reduced ambient pressures. The experiments were conducted with both an external and an internal heat supply under stationary conditions. As the working liquid we employed: water (H_2O), ethanol (C_2H_5OH), and carbon tetrachloride (CCl_4).

The experiments were performed in a vacuum chamber consisting of a supporting plate and a cylindrical steel base connected with a glass hood 400 mm in diameter and 600 mm tall. Inside the chamber we installed an electric balance, to the pan of which we attached an insulated vessel containing the working liquid. In this vessel we set up an electric heater covering the entire plane cross section. The heater power was regulated by means of a laboratory autotransformer. The heater voltage and current were monitored with a voltmeter and ammeter. At fixed intervals near the evaporation surface we stretched thin nylon threads to which we attached 10 copper-constantan microthermocouples. In the vacuum chamber we installed a special micrometerscrew device by means of which a copper-constantan thermocouple could be displaced along the normal to the liquid surface. By means of this moveable microthermocouple we measured the temperature of the liquid surface and the temperature of a thin layer of vapor-air mixture at the phase interface.

The following instruments were included in the temperature measuring circuit: low-resistance potentiometer, mirror galvanometer, thermocouple switch, Dewar vessel with a thermometer for the cold junction of the thermocouples, etc.

The required working pressure in the chamber was kept at a given level by means of a vacuum pump and regulated by a needle valve. The total pressure was measured with a mercury U-manometer.

The outside of the vessel containing the liquid was well insulated, so that there were practically no heat losses.

The rate of evaporation was determined as the mass of liquid Δm evaporating from unit surface in unit time

$$j = \Delta m / F \tau. \tag{1}$$

The amount of heat released by the electric heater is given by

$$q_h = IU/F. \tag{2}$$

In the absence of an internal heat surface in the liquid the amount of heat needed for evaporation was supplied by a flow of heated noncondensing gas in which case the evaporation process was adiabatic.

The presence of a temperature difference results in the transfer of heat from the gas to the liquid surface. The amount of heat expended on evaporating the

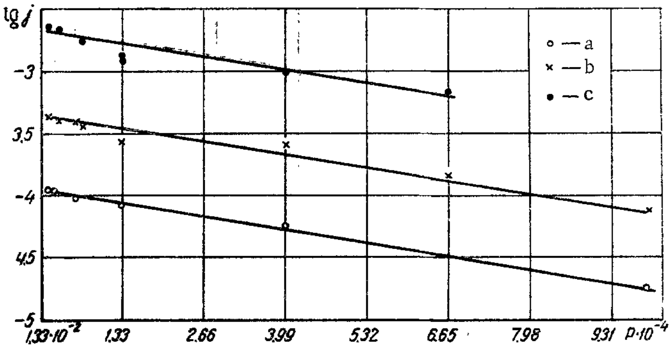

Fig. 1. Intensity of evaporation of liquid j (kg/m^2·sec) as a function of the total pressure P (N/m^2): a) for water, b) ethanol, c) carbon tetrachloride.

liquid was determined from the evaporation intensity, i.e.,

$$q_0 = jr. \qquad (3)$$

The resultant radiant heat flux was determined from the Stefan-Boltzmann equation on the assumption that the radiation coefficients of the materials participating in radiative heat transfer are known (glass-liquid)

$$q_{\rm rad} = C_{\rm r}\,[(T_{\rm w}/100)^4 - (T_{\rm s}/100)^4], \qquad (4)$$

where

$$C_{\rm r} = 5.673/(1/\varepsilon_1 + 1/\varepsilon_2 - 1).$$

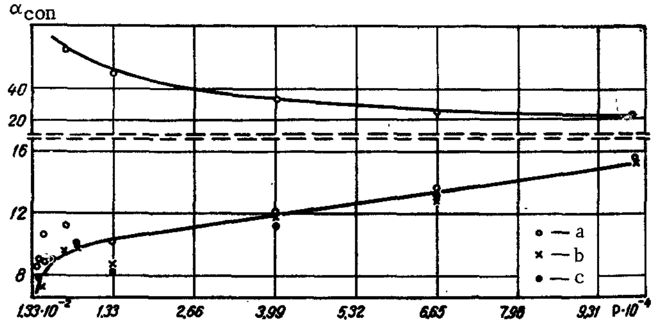

Fig. 2. Convective heat transfer coefficient α_c(W//m^2·deg) as a function of the total pressure P(N//m^2) for adiabatic (lower curve) and nonadiabatic (upper curve) evaporation (q_h = 1285 W/m^2): a) for water, b) ethanol, c) carbon tetrachloride.

The amount of heat transferred to the liquid by convection and conduction was calculated from the expression

$$q_{\rm con} = q_0 - q_{\rm rad}, \qquad (5)$$

the convective heat transfer coefficient was obtained from the equation

$$\alpha_{\rm con} = q_{\rm con}/(T_{\rm m} - T_{\rm s}), \qquad (6)$$

and the radiative heat transfer coefficient from

$$\alpha_{\rm rad} = q_{\rm rad}/(T_{\rm w} - T_{\rm s}). \qquad (7)$$

It follows from an analysis of the heat balance that the experimental conditions in fact corresponded to the adiabatic evaporation regime. In the case of nonadiabatic evaporation the liquid was heated to a certain temperature by an internal heat source, the temperature of the liquid being greater than the ambient temperature. In the general case the amount of heat q_h released by the electric heater was expended on evaporating the liquid (jr), but in part was also transferred by conduction, convection, and radiation to the ambient medium.

The amount of heat dissipated in the ambient medium by conduction and convection was determined from the heat balance

$$q_{\rm con} = q_{\rm h} - q_0 - q_{\rm rad} - q_{\rm t}, \qquad (8)$$

where $q_t = -\lambda_i(\partial T_i/\partial h)$ are the heat losses to the ambient medium through the thermal insulation.

At ambient pressures lower than $7\cdot 10^3$ N/m^2 (for the same heat flux q_h = 1660 W/m^2) the temperature of the liquid during the evaporation process was lower than the ambient temperature. In this case evaporation proceeds not only on account of the heat released by the internal source but also on account of the heat transferred by heat exchange with the ambient medium. The heat transfer between the evaporation surface and the ambient medium was calculated from the equation

$$\alpha_{\rm con} = (q_0 - q_{\rm h} - q_{\rm rad})/(T_{\rm m} - T_{\rm s}). \qquad (9)$$

We will now consider the experimental results.

It is clear from Fig. 1 that with decrease in the total pressure the evaporation intensity increases. The nature of the curves for the liquids investigated is the same, j = f(P) varying according to a power law of the type $j = aP^n + b$.

The relation between the specific convective heat flux and the total ambient pressure is governed by a similar law.

The experimental data (Fig. 2) show that for adiabatic evaporation the intensity of convective heat transfer $\alpha_{\rm con}$ decreases with decrease in total pressure. For the investigated liquids in the pressure range P = $1\cdot 10^5$ – $1\cdot 10^3$ N/m^2 the values of $\alpha_{\rm con}$ almost coincide.

Considering the variation of $\alpha_{\rm con} = f$(P) (P > $6.6\cdot 10^3$ H/m^2) for nonadiabatic evaporation of a liquid with an internal heat source (upper curve), we see that with

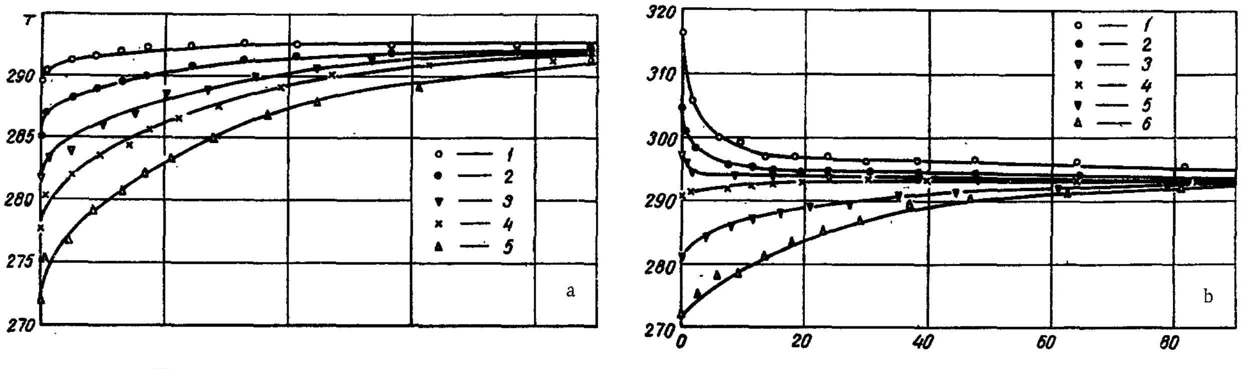

Fig. 3. Temperature distribution near the surface of water for adiabatic (1—for $1\cdot 10^5$ N/m^2, 2—$2.66\cdot 10^4$; 3—$1.33\cdot 10^4$; 4—$5.32\cdot 10^3$; 5—$1.33\cdot 10^3$) and nonadiabatic (1—$1\cdot 10^5$ N/m^2, 2—$3.99\cdot 10^4$; 4—$6.65\cdot 10^3$; 5—$2.66\cdot 10^3$; 6—$1.33\cdot 10^3$) b) evaporation in a rarefied gas medium. Abscissas—y in mm.

decrease in total pressure α_{con} increases. In nonadiabatic evaporation of a liquid with an internal heat source part of the heat released by the source is expended on phase transformation, while part is dissipated in the ambient medium. In this case with fall in total ambient pressure the fraction of the heat expended on the phase transition increases. Then the vapor flow, acting in the same direction as the heat flow, intensifies the convective heat flux component. Other things being equal, with decrease in pressure the temperature head decreases, which leads to an increase in α_{con} in accordance with Newton's law.

Thus, the convective heat transfer coefficient of the liquid depends on the total pressure, liquid temperature, direction of heat flow, temperature head, etc.

Figure 3 shows the temperature distribution near the evaporation surface. The origin is located on that surface. Along the axis of abscissas we have plotted the distance from the evaporation surface into the ambient medium y (in mm), along the ordinate axis the absolute temperature. The curves in Fig. 3a correspond to adiabatic evaporation, those in Fig. 3b to nonadiabatic evaporation of water with an internal heat source of constant power (q_h = 1285 W/m^2).

As follows from these measurements, the lowest temperature is established at the evaporation surface, while the temperature field near that surface (along the normal to it) gradually approaches the temperature of the ambient medium, except for a thin layer immediately adjacent to the evaporation surface. In this layer the temperature of the vapor-air medium changes abruptly (with a jump) as may be seen from the graph. The thickness of the layer and the magnitude of the jump depend on the ambient pressure. For example, at $P = 2.66 \cdot 10^4$ N/m^2 the change in temperature at a distance of 1 mm from the evaporation surface is equal to 1.8° K; subsequently the temperature curve rapidly adjusts to the temperature of the medium. With decrease in pressure the thickness of the layer in which a sharp temperature change is observed and the temperature jump increase: at $P = 1.33 \cdot 10^3$ N/m^2 the temperature change at a distance of 1 mm from the evaporation surface is already 3.5° K, and the adjustment of the temperature to the temperature of the medium is very smooth. For comparison, the figure also shows the temperature distribution near the evaporation surface at atmospheric pressure (curve 1, Fig. 3a).

It is a characteristic feature of the temperature field for nonadiabatic evaporation (Fig. 3b) that with decrease in total pressure the temperature jump close to the evaporation surface decreases. At a heat flux q_h = 1285 W/m^2 and a total pressure of $6.5 \cdot 10^3$ N/m^2, there is no temperature jump at the phase interface.

At lower ambient pressures it is necessary to increase the power of the internal heat source in order to keep the surface temperature of the liquid above the temperature of the ambient medium. For the above-mentioned heat flux the surface temperature lies below the ambient temperature and heat is supplied to the evaporation surface both from the internal heat source and from the vapor-gas medium. Accordingly, the nature of the temperature field differs from the case of adiabatic evaporation.

In our case, for adiabatic evaporation, when thermal energy is supplied to the evaporation surface from the ambient medium which is at constant temperature, with decrease in total pressure the external resistance to vapor mass transfer decreases, and the rate of evaporation increases sharply. In this case the temperature of the liquid falls, and consequently the temperature head increases, which, in its turn, causes an increase in the conductive component of the heat flux. The direction and intensity of the heat fluxes in the liquid and gas phases depend on the relation between the temperatures of the liquid, the phase interface, and the vapor-gas medium. Depending on the change in the temperature of the liquid surface and the vapor-gas mixture the heat flow due to convective heat transfer is directed either from the vapor-gas medium to the liquid ($T_m > T_s$) or from the liquid to the vapor-gas medium ($T_s > T_m$). When $T_s = T_m$ there is no convective heat transfer, but some thermal energy is transported by convective mass transfer; in this case the rate of evaporation is maintained by the internal heat source and radiative heat transfer.

The rate of evaporation depends on the ratio of the number of liquid molecules escaping from the surface to the number of vapor molecules condensed on it. The vapor molecules penetrate into the gaseous medium as a result of diffusion and convection. With decrease in the pressure of the uncondensed gas above the liquid surface the resistance of the external medium falls and molecules of liquid vapor penetrate more rapidly into the rarefied space. Consequently, the lower the pressure of the vapor-air mixture, the more intense will be the flow of vapor through the layer of noncondensing gas. Since at pressures of the vapor-air mixture corresponding to the viscous regime of gas flow the removal of vapor molecules from the vapor of the liquid lags behind their rate of formation, the vapor concentration in a thin layer near the evaporation surface increases. In accordance with the kinetic theory the disturbance of thermodynamic equilibrium between a liquid and its vapor is associated with the formation at the phase interface of a partial pressure and temperature jump. The latter is clearly visible in Fig. 3.

Thus, the presence of a considerable temperature gradient and pressure gradient, together with the transverse flow of vapor near the surface of a liquid evaporating into a rarefied medium, causes molecular motion of the vapor-air mixture near the liquid surface. Stefan has obtained a correction for the influence of molecular motion on evaporation intensity which is proportional to the ratio of the barometric pressure to the partial pressure of air. Since during the evaporation of liquids under conditions of free convection, convective currents due to the vapor flow are also formed, these convective currents, as it were, assist the movement of molecules escaping from the liquid surface into the ambient medium. Therefore

Stefan's formula gives considerable discrepancies as compared with our experiment.

NOTATION

j is the evaporation rate, kg/m$^2\cdot$sec; r is the specific heat of phase transition; ε_1 and ε_2 are the radiative power of liquid and glass, respectively; T_m, T_s, and T_w are the absolute temperature of medium, liquid surface, and wall of vacuum chamber, respectively; λ_i is the heat conductivity of insulating material, C_r is the reduced emissivity of system, W/m$^2\cdot$deg^4.

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