MASS TRANSFER DURING EVAPORATION OF VARIOUS LIQUIDS FROM THE SURFACE OF A PIPELINE TRANSITION ELEMENT INTO A SURROUNDING GAS STREAM

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A method is proposed for the study of the mass and heat transfer during the evaporation of various liquids from the surface of a flat transition channel into a surrounding air stream, and some results are presented.

The mass transfer during the evaporation of a liquid from a surface into a gas stream, like the accompanying heat transfer, has not been sufficiently studied, because of the complexity of the process and our sketchy knowledge of its mechanism.

The principal modern approach to the study of this process is by experiment. Most experimental studies so far have been concerned with the case in which the mass-emitting surface is washed by an unbounded gas (air) stream. Several studies have been made of the mass transfer during the evaporation of a liquid from the wall surface of a rectangular channel.

At the same time, it would be of much interest to study the simultaneously occurring processes of mass and heat transfer during evaporation from the surface of transition channels and, specifically, of variously shaped converging sections, diaphragms, hydraulic grids, etc. As the basic type of transition element for a study of mass transfer we chose a flat section (diaphragm). This choice was dictated on the one hand by the wide practical use of such elements and on the other by the realization that such an element represents the limiting case of sections of other shapes. For example, in relation to a conical section serving to connect pipes of differing radii, for example, a flat element may be regarded as a cone with an apex angle approaching 180°.

A flat transition element was incorporated in our test apparatus as the mass-emitting device (Fig. 1). Air was supplied to its surface by a high-pressure fan through a mixing grid 1. This air was warmed by a sectionalized electric heater. One of the heater sections automatically maintained the air temperature at a given level (within ± 0.1°K). The temperature of the air stream was measured with a thermocouple immediately behind the mixing grid. It was varied from 305 to 388°K. With the aid of telescopic tubes 2 it was made possible to vary the length of the active segment between 10 and 300 mm. The Textolite housing for the mass emitter 5 had been turned on a lathe. Porous metal washers (1.18 mm thick stainless steel with porosity 43%) 7 were mounted in four grooves in the housing and bonded to it with epoxy resin. The width of the intermediate Textolite risers was 2 mm. In each section of the mass emitter there were two holes drilled underneath: one for feeding the liquid and one for venting the air. The thermocouples (Chromel–Copel, 0.2 mm thick) for measuring the temperature of the mass emitting surface were installed at the centers of the porous washers. The method of sealing these thermocouples has already been described in [1], and the thermal emf was measured by the bridge balancing method. Tests were performed under steady conditions. An electronic recording potentiometer controlled the operating conditions. The radiative flux impinging on the plate surface contributed not more than 6% of the heat.

This construction of the mass emitter was intended to ensure hermetic sealing between sections. The surface areas used in calculating the mass transfer between sections were: 20.1, 32.4, 46.7, and

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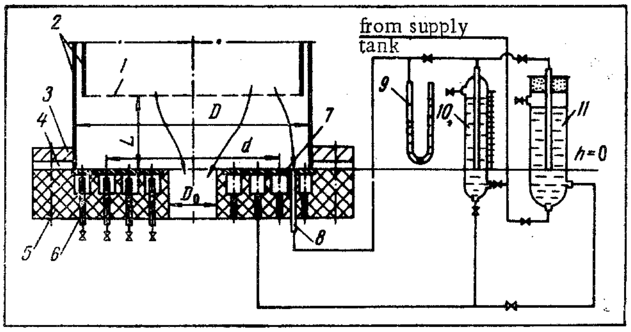

Fig.1

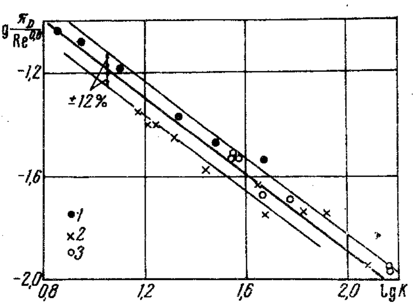

Fig.2

Fig.1. Schematic diagram of the mass emitter and the instrumentation for measuring the rate of liquid evaporation: 1) mixing grid; 2) telescopic tubes; 3) flange; 4) soft-rubber gasket; 5) housing; 6) air-venting tube; 7) porous plate; 8) velometer tube; 9) manometer; 10) burette; 11) supply tank.

Fig.2. Dimensionless rate of mass transfer $\Pi_D/Re^{0.6}$ (averaged over the surface, $L/D = 2$) as a function of the phase-transformation number K: 1) acetone; 2) alcohol; 3) water.

53.0 cm^2. The corresponding mean diameters of the sections (porous washers) were 48.0, 79.5, 111.4, and 142.1 mm. The following substances were used in this experiment as working media: distilled water, acetone, and ethyl alcohol. The mass emitter was supplied with liquid and the evaporation rate was measured according to the schematic diagram in Fig.1. Four metering burettes 10 (one for each of the four sections, only one is shown here) ensured a constant head of liquid during a test. The quantity of evaporated liquid was determined from the change of level in the burette. The readings were accurate to within ±5 mg. Tank 11 supplied the mass emitter until steady state had been reached. The hydraulic head h was 10 mm high during water tests and 5 mm high during acetone or alcohol tests. Such values of the head were designed reliably to ensure evaporation of the respective liquids from the surface of the porous plate facing the air stream during measurements, should the evaporating surface not drop. At the same time, it was necessary also to eliminate the filtering of liquid droplets through the porous object, i.e., to eliminate any infusion of liquid droplets directly into the air stream. (In filtration-theory terms, the outer surface of the porous plate was to be a "depression" surface). For this purpose, in auxiliary tests the mass emitter was separated from the rest of the apparatus and, by the same method of measuring the liquid flow rate through the plate, the flow rate of filtered liquid j_{hydr} was measured as a function of the hydraulic heat h. The values of h here had a sufficient margin to ensure that $j_{hydr} < j_{evap}$ during measurements. Nevertheless, adjustment tests were performed under various conditions after a visual inspection of the plate surface through a Plexiglas connecting tube. These tests were essential in order to establish the required head h. The following procedure was adopted. While the state parameters were reaching their stable values, the head was increased until the liquid began to filter through. After that, the head was gradually decreased until no liquid droplets appeared any more on the surface of the porous plate. The quantity of evaporating liquid and the temperature of the plate surface were measured. Next, without a change in the test conditions, the head was again decreased several times and measured. It has been found that, within a rather wide range of head values, the evaporation rate of the liquid and the temperature of the plate surface do not depend on h; this effect, which can be fully explained by the considerable effect of capillary forces, allows a certain leeway in establishing the working head h.

The experimental data on the evaporation of liquids were evaluated with the aim of finding a relation between dimensionless groups which characterize the given process. For quasiadiabatic conditions of evaporation the general form of this relation should be

$$\Pi_D = \Phi(\mathrm{Re}, \mathrm{Ar}, \mathrm{K}, \mathrm{Pr}, \mathrm{Sc}, R_1/R_2, \varepsilon, L/D, d/D). \quad (1)$$

In order to determine the rate of mass transfer j, it is convenient to use the Π_D number rather than the Nu_D number, since it is not necessary then to know the partial vapor pressures at the surface and in the oncoming stream – provided, of course, that in the end the Π_D group is not found to depend on the parameter $(p_{1w} - p_1)/p$. According to [1, 3, 4], if the phase-transformation number K is chosen as one of the dimensionless arguments, Nu_D will be proportional to the reciprocal of the ratio $(p_{1w} - p_1)/p$ or, in other words, Π_D will in this case be independent of this ratio.

Under the stipulations of our problem, the flow parameters at the entrance to the active section (at $L = 0$) were chosen as the reference quantities and the channel diameter D as the reference dimension. Since the tests were performed under fully developed turbulent flow conditions, the Ar number could be dropped from the set of dimensionless groups in (1); the Pr number and ε were found to be almost constant.

The air velocity in these tests was intentionally held constant, since the effect of the Re number had been studied on a flat transition element of a somewhat different design. For a fully developed turbulent flow and a flat transition element with diameter in the ratio $D/D_0 = 5$, we established the following relation: Nu_D (or Π_D) $\sim \mathrm{Re}^{0.6}$; this applies also to "pure" heat transfer under identical conditions [5]. As far as we know, our tests performed with a transition element under rather complex hydrodynamic conditions, as well as tests performed by other authors [1, 3, 4, et al.] under different hydrodynamic conditions, have confirmed this general conclusion: that the hydrodynamic parameters (Re number and shape factors) of the main (gas) stream have the same effect (at least within the range of evaporation rates which has been studied, i.e., j up to 6 $\mathrm{g/m^2 \cdot sec}$) on the rate of mass transfer during evaporation, on the rate of heat transfer during evaporation, and during "pure" heat transfer unencumbered by mass transfer.

The experimental data were analyzed in terms of local values as well as of values averaged over the surface. The local rates of mass flow from the surface were calculated according to the formula:

$$j_i = \frac{m_i}{F_i \tau_i}.$$

The value of the rate of mass flow averaged over the surface was defined as

$$j = \frac{\Sigma j_i F_i}{\Sigma F_i}.$$

The mean temperature of the surface affected by mass transfer was treated in an analogous manner. The dimensionless rate of mass transfer averaged over the surface $\Pi_D/\mathrm{Re}^{0.6}$ has been plotted in Fig. 2 as a function of the phase-transformation number K. All test points fall here approximately on the same straight line of slope $n = -0.75$. The nature of the evaporating liquid is, therefore, adequately accounted for in this analysis by the phase-transformation number. An analogous result has been obtained in [4] dealing with the evaporation of acetone, benzene, and ethyl alcohol from a porous wall in a unbounded air stream.

According to Fig. 2,

$$\Pi_D = 0.41\, \mathrm{Re}^{0.6} K^{-0.75} \text{ for } L/D = 2. \tag{2}$$

A data analysis in terms of local values has shown that in this case, too, the relation between the group $\Pi_D/\mathrm{Re}^{0.6}$ and the K number is retained.

The relation between the group $\Pi_D K^{0.75}/\mathrm{Re}^{0.6}$ and the relative width of the active section L/D is shown in Fig. 3 for various zones (sections) of the mass-emitting surface in water evaporation tests. The dimensionless rate of mass transfer decreases here for all zones when $L/D < 0.3$. For the fourth zone this rate becomes slightly lower as L/D increases and it reaches a maximum at $L/D = 0.3$. Such a trend in this relation is evidently due to the specific stream pattern, which includes the changing dimension of the stagnation region. The mass transfer at the surface of a flat transition element becomes more intensive as the local radius decreases. The maximum dimensionless rate of mass transfer (group $\Pi_D K^{0.75}/\mathrm{Re}^{0.6}$) at the edge of the exit orifice is found by extrapolating the data in Fig. 3 and in three times higher than the mean-over-the-surface rate of mass transfer.

The mass transfer during evaporation is intimately tied to the simultaneous heat transfer. In essence, we are dealing here with a single process which combines mass and heat transfer. One may thus assert, in principle, that the Π_D number (mass transfer) and the Nu number (heat transfer) must depend on the same factors governing this compound process. The validity of this assertion is confirmed by the purely formal relations. Thus, for an adiabatic mode of evaporation we have

$$\mathrm{Nu} = \Pi_w K \,\mathrm{Pr} = \Pi_D (\mathrm{Sc}\, R_1/R)^{-1} K\, \mathrm{Pr}. \tag{3}$$

In our tests the quantity of heat expended on warming the liquid $c_L(t_W - t_L)$ was much smaller than the heat of evaporation (not over 3% in water and acetone tests, not over 5% in alcohol tests). The evaporation process was, therefore, quasiadiabatic. It follows then, from (3), that $\mathrm{Nu} \sim K^{0.25}$, so long as

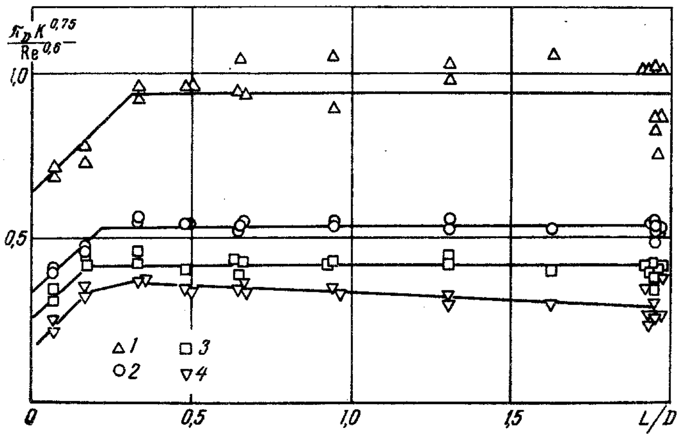

Fig. 3. Local rate of mass transfer, as a function of the relative length of the active chamber: 1) first zone (d = 48.0 mm); 2) second zone (d = 79.5 mm); 3) third zone (d = 111.4 mm); 4) fourth zone (d = 142.1 mm).

$\Pi_D \sim K^{-0.75}$. A graphical analysis indicates that, more precisely, Nu $\sim K^{0.3}$ for all three liquids. Some deviation of the K exponent is in this case due to the slight nonadiabaticity of the real process, since Nu is defined by the equation:

$$\mathrm{Nu} = \frac{j\,[r + c_L\,(t_w - t_L)]\,D}{\lambda\,(T - T_w)}. \tag{4}$$

According to Eq. (3), however, the dependence of Nu on K is not the only way the nature of the liquid affects the heat transfer. An analysis of test data on the mean-over-the-surface rate of heat transfer yields the following criterial relation (for L/D = 2):

$$\mathrm{Nu} = 0.24\,\mathrm{Re}^{0.6}\,K^{0.3}\,(\mathrm{Sc}\,R_1/R_2)^{-1}. \tag{5}$$

Comparing Eqs. (2), (3), and (5), the essential difference between the values of the constants in Eqs. (2) and (5) is seen to be that, in our case, Pr remained almost constant and equal to 0.7, together with a slight correction of the K exponent. Because of the low vapor and mixture contents (which was also related to our choice of the parameters at the entrance to the active section as the reference quantities), $R \cong R_2$.

The variation in the rate of heat transfer (local and mean) depending on the L/D ratio and on the radius (local) is analogous to the respective variation in the rate of mass transfer. For calculating the Nu number for local heat transfer as well as the numbers which characterize local mass transfer, moreover, the quantity j was replaced by the local values j_i.

NOTATION

$\mathrm{Nu}_D = jD/K_{p1}(p_{1w} - p_1)$;	
$\Pi_D = jD/K_{p1}p = \mathrm{Nu}_D(p_{1w} - p_1)/p$;	
$\Pi_w = jD/\mu$	are numbers characterizing the rate of mass transfer;
j	is the mass flow-intensity of the active component (vapor);
$K_{12} = K_{p1}R_1T$	is the vapor–air interdiffusivity;
p	is the pressure;
μ	is the dynamic viscosity;
R	is the gas constant;
T	is the temperature;
L	is the length of the active section;
d	is the diameter corresponding to local rates of mass and heat transfer;
$D = 154$ mm	is the channel diameter;
$D_0 = 30$ mm	is the orifice diameter;
$K = r/c_p(T - T_w)$	is the number characterizing the phase transformation;
r	is the heat of phase transformation;
c	is the specific heat;

$Sc = \nu/K_{12}$ is the Schmidt number;
$\varepsilon = p_2/p$ is a number characterizing the content of inert substance in the mixture;
Nu is the Nusselt number characterizing heat transfer;
λ is the thermal conductivity;
F is the area;
τ is the time.

Subscripts

1 denotes vapor;
2 denotes air;
w denotes wall;
L denotes liquid.

Symbols without subscripts refer to the vapor–air mixture.

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