EVAPORATION OF A LIQUID FROM A SURFACE IN AN AIR JET AT VARIOUS SCHMIDT NUMBERS

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The evaporation of various liquids (acetone, toluene, ethyl alcohol, etc.) from the surface of a plate was studied experimentally. The Kutateladze numbers were used to correlate the results.

Cases are encountered in drying technology requiring the removal of liquids more volatile than water. This is generally done by blast drying. Mass transfer was studied when air streams from nozzles impinge normally on the evaporation surface.

Tests were made of the validity of the equations derived for calculating mass transfer in the evaporation of water or the sublimation of naphthalene by blast drying [1, 2], and in the evaporation of other liquids.

A number of papers have appeared on the evaporation of various liquids both from a porous surface and from a free surface, but only one [3] considered the characteristics of the evaporation of different liquids in blast drying. Butyl alcohol ($C_4H_{10}O$) and acetic acid ($C_2H_4O_2$) were used to saturate the evaporation surface formed by a layer of fine sand. Measurements showed that the nature of the dependence of the Sherwood number Sh on the Reynolds number Re was independent of the kind of liquid being evaporated. On the other hand, the Schmidt number Sc clearly depended on the kind of volatile material, although it varied over a relatively narrow range. The mass-transfer rate was found to vary as $Sc^{0.34}$.

Chilton and Colburn [4] analyzed the results of an investigation of the evaporation and sublimation of various substances for characteristic cases of heat and mass transfer. They derived expressions for heat and mass transfer by using j_H and j_D. The equations involve the Prandtl number Pr and Sc to the same power $n = n' = 0.33$, although various cases of mass transfer were compared.

In [5] the equations for j were put in another form which takes account of the difference between the exponents n and n' for different cases of heat and mass transfer.

According to [5] the rate of evaporation from spherical surfaces is

$$m = \frac{\lambda_v \Delta t}{r} \pi D' \left[2 + 0.303 (\mathrm{Re}_{D'} \mathrm{Sc})^{0.6} \left(\frac{\lambda_v}{\lambda_D} \right)^{0.5} \right]. \tag{1}$$

It is clear that the physical properties of the volatile material enter in a much more complicated way through several quantities: first through Sc which appears with the same exponent as Re, through $\lambda_v \Delta t/r$, and finally through $(\lambda_v/\lambda_D)^{0.5}$, which, according to [5], takes approximate account of the simultaneous heat- and mass-transfer processes. This shows that the interaction between heat and mass transfer for a particular case may be different in the evaporation of different liquids.

The results of a study of the effect of Pr and Sc on the flow pattern of a fluid in a pipe are reported in [7]. It was established that n varies from 0.5 (for Pr and Sc close to unity) to 0.25 (for Pr and Sc larger than unity).

A further analysis of the analogy between heat and mass transfer led to a modification of the usual type of dimensionless equation

$$\mathrm{Sh} = k \, \mathrm{Re}^m \mathrm{Sc}^n \tag{2}$$

by the insertion of the dimensionless number $(p - p''_p)/p$ [8] to yield a mass-transfer equation of the form

$$\mathrm{Sh} \frac{p - p''_p}{p} = k \, \mathrm{Re}^m \mathrm{Sc}^n . \tag{3}$$

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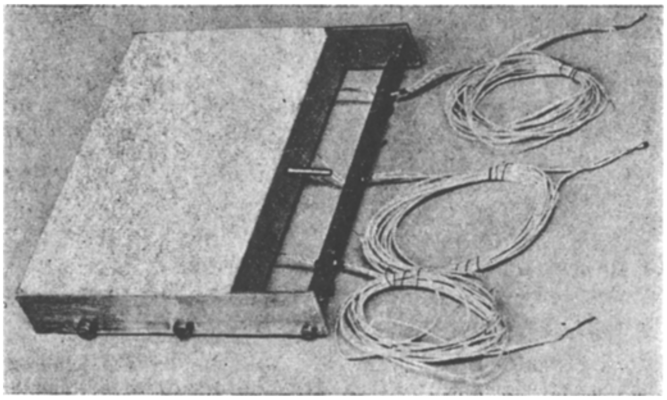

Fig. 1. Sample of frit plate.

The introduction of this dimensionless number, just as the introduction of the combination into Eq.(1), shows that the presence of further information on the flow pattern together with an improvement of the methods of measurement permitted a more accurate analysis which showed that the simultaneous processes of heat and mass transfer influence one another, and it is impossible to restrict oneself to the use of simple dimensionless relations.

The results of an investigation of the evaporation of various liquids reported in [9] showed that an increase in the evaporation rate is accompanied by an increase in the heat-transfer rate. By introducing the Gukhman number $\mathrm{Gu} = (t - t_m)/T$ the results could be described by a single equation. It was noted in [9] that the mass-transfer coefficient β increases with an increase in the molecular weight of the liquid. The results of experiments with a longitudinally streamlined plate are presented in [10] for parameters which ensure a high evaporation rate. This results from a higher transverse mass flux, which is one of the factors affecting the flow pattern. The transverse flux is expressed by the ratio of the velocity of the liquid vapor from the evaporation surface to the velocity of air flowing past this surface. The effect of the flow pattern, and consequently also of the transverse flux, was taken into account by Gu or the Kutateladze number K defined as

$$\mathrm{K} = \frac{r}{c_k (t - t_p)} . \qquad (4)$$

The Sc and Pr numbers were generally not used in [9-11] to correlate the results.

It is clear from this analysis of papers on the evaporation of various liquids that the method of correlating results and obtaining working equations is based on supplementary data on the flow pattern and the use of more accurate methods of measurement.

We present the results of a study of the evaporation of various liquids (butyl alcohol $C_4H_{10}O$, ethyl alcohol C_2H_6O, methyl alcohol CH_4O, carbon tetrachloride CCl_4, acetone C_3H_6O, toluene C_7H_8, ethyl acetate $C_4H_8O_2$) from the surface of a plate in a stream of air from a single-slit nozzle. The data cited in the papers mentioned above were taken into account in analyzing our experiments.

A solid frit plate 100 × 170 mm was used to study mass transfer during the evaporation of the various liquids. With this arrangement it is possible to limit oneself to the measurement of average mass-transfer coefficients. The frit plate was placed on a supporting Dural plate. The liquid was fed into the space under the frit plate through a pipe connected to a container mounted on a Sartorius electronic balance. The amount of liquid evaporated was determined by weighing the container.

The frit plate method and the associated equipment for measuring mass-transfer coefficients were invented in Czechoslovakia [12]. Holes for thermocouples were bored in three places directly under the active surface of the frit plate.

The general form of the plate is shown in Fig. 1.

During the experiment the plate was placed under the slit nozzle mounted on the experimental equipment for studying blast drying described in [1]. The plate was positioned relative to the nozzle in such a way that there was a uniform flow of air past it.

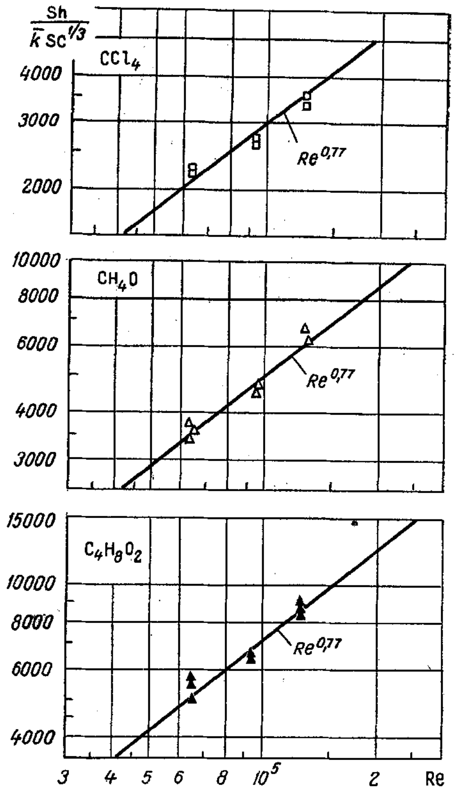

Fig. 2. $Sh/\bar{k}\,Sc^{1/3}$ versus Re for CCl_4, CH_4O, and $C_4H_8O_2$.

With some liquids it was found that after evaporation had gone on for about 20 min the surface temperature of the plate changed as a result of the condensation of water vapor from the air circulating past it. This effect was more pronounced the lower the surface temperature of the plate. The condensation of water vapor also affects the evaporation rate to a certain extent. To limit this effect the experimental plate was carefully wiped with a tissue wetted in the liquid being evaporated before each experiment.

The following working equations were used:

$$\bar{m} = \Delta G / F\tau, \tag{5}$$

$$\bar{m} = \frac{\beta}{R} \cdot \frac{p''_p}{\bar{T}}, \tag{6}$$

$$\beta = \frac{\Delta G R \bar{T}}{F \tau p''_p}, \tag{7}$$

$$\mathrm{Sh} = \beta L / D, \tag{8}$$

$$\mathrm{Re} = w_0 L / \sqrt{s/p}\,\nu. \tag{9}$$

The vapor pressure p''_p on the saturation line in (6) and (7) was determined from the average surface temperature of the plate t_p measured with a thermocouple. The value of ν in Eq. (9) was determined at the temperature of the air at the nozzle outlet. The average boundary-layer temperature

$$\bar{t} = \frac{t_0 + t_p}{2}. \tag{10}$$

was used to find $\bar{T}$ and D. To estimate the results it is necessary to know the vapor pressure p''_p, the diffusion coefficient D for the air–volatile liquid system, and the gas constant R. Further dimensionless correlation of the results requires a knowledge of certain physical properties of the liquids used in the experiments. The

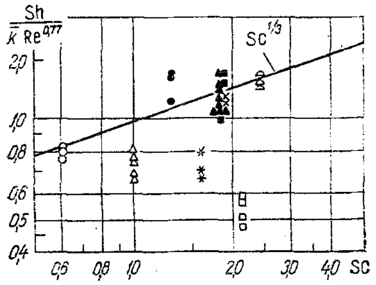

Fig. 3. $Sh/\bar{k}\,Re^{0.77}$ versus Sc.

values of these quantities reported in the literature differ somewhat from one another. The different values were compared and a critical estimate was made of them. We then chose relations and data which we judged to be reliable. A more detailed discussion of this problem is beyond the scope of the present paper.

The investigations were performed with a slit width b = 10 mm, a distance between the nozzle outlet and the plate s = 100 mm, and air speeds w_0 = 20, 30, and 40 m/sec at the nozzle outlet. The parameters were chosen to lie in the range of applicability of the equation

$$Sh = 0.2\,b^{-0.155}\,Re^{0.77}\,Sc^{1/3} = \bar{k}\,Re^{0.77}\,Sc^{1/3}, \tag{11}$$

cited in [1].

Values of Sh for various Re were obtained by varying the velocity w_0 in order to verify the exponent of Re. The effect of different values of s/b and b was not determined because when Eq. (11) is applicable for s/b = 10 and b = 10 mm and various values of Re for the evaporation of various liquids there is no reason to doubt that it can be used for s/b and b which differ from the values cited above.

About 60 experiments were performed altogether. The evaporation rate was determined by averaging the results of two or three experiments.

The values of Sh and Re were determined experimentally. They were used first to verify the choice of the exponent of Re in Eq. (11). To do this the values of $Sh/\bar{k}Sc^{1/3}$ with $\bar{k}$ = 0.1399 were determined. This quantity depends on Re only. The results for CCl_4, CH_4O, and $C_4H_8O_2$ are plotted in Fig. 2 and show that the condition

$$Sh/\bar{k}\,Sc^{1/3} \sim Re^{0.77}.$$

is fairly well satisfied.

If the results are written in the form

$$Sh/\bar{k}\,Re^{0.77} = Sc^{1/3},$$

corresponding to (11), it follows that the effect of the physical properties of volatile liquids is not adequately described by $Sc^{1/3}$ as indicated by (11). The deviations of individual liquids from the proposed relation are shown in Fig. 3. It is clear that the deviations are considerable in some cases (CH_4O, CCl_4, C_3H_6O). The figure also shows why this deviation was not found in experiments on the evaporation of water and the sublimation of naphthalene. For them Eq. (11) is applicable.

In a further analysis of the results the possibility of introducing the dimensionless number $(p - p''_p)/p$ ($p = 10^4$ kN/m^2) was tested. The results plotted in Fig. 4 show that the spread of experimental values is increased. Subsequent consideration was given to the correlation of the results by means of K.

First an attempt was made to correlate the results by a method similar to that used in [10] by replacing Sc by K in the dimensionless equation. The values of K for the individual experiments were determined from Eq. (4) and used to calculate $Sc/\bar{k}\,Re^{0.77}$. The results are shown graphically in Fig. 5. The distribution of points obtained did not show any clear dependence on K.

Only the introduction of the ratio of the total atmospheric pressure p and the vapor pressure p''_p mentioned in [11] led to a satisfactory correlation of the experimental results. The numerical values of $Sh/\bar{k}\,Re^{0.77}$ were divided by the value of this ratio and plotted as a function of K in Fig. 6. This graph shows a unique dependence on K. The dependence of $(Sh/\bar{k}\,Re^{0.77})\,(p/p''_p)$ on K was analyzed by the method of linear regression, and the equation:

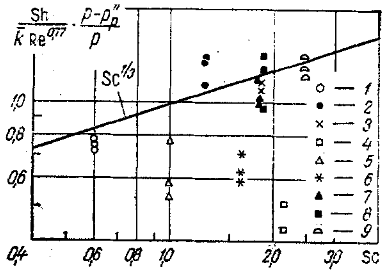

Fig. 4

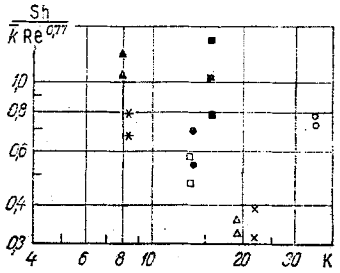

Fig. 5

Fig. 4. $(Sh/\bar{k}\ Re^{0.77})\ (p - p''_p)/p$ versus Sc, 1) H_2O; 2) C_2H_6O; 3) $C_4H_{10}O$; 4) CCl_4; 5) CH_4; 6) C_3H_6O; 7) $C_4H_8O_2$; 8) C_7H_8; 9) $C_{10}H_8$.

Fig. 5. $Sh/\bar{k}\,Re^{0.77}$ versus K.

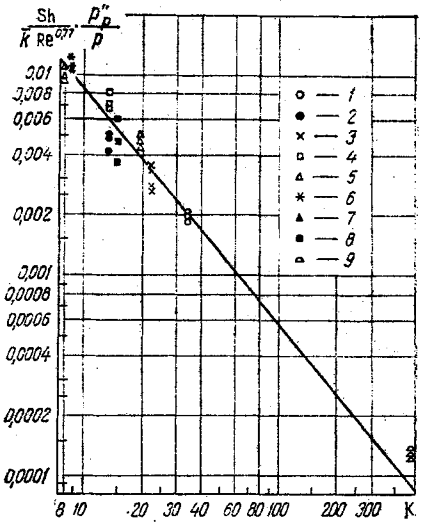

Fig. 6. $(Sh/\bar{k}\ Re^{0.77})\ (p''_p/p)$ versus K. Notation is the same as in Fig. 4.

$$\frac{Sh}{\bar{k}Re^{0.77}} \cdot \frac{p''_p}{p} = 1.002K^{-1.184} \tag{12}$$

or

$$Sh = 1.002\bar{k}\ Re^{0.77}\ K^{-1.184}\ \frac{p}{p''_p}. \tag{13}$$

was determined from the straight line drawn through the experimental points.

This implies that the mass-transfer rate decreases with increasing K, in accord with the results in [11] where a similar conclusion was drawn for longitudinal flow past a plate, the only difference being that the exponent of K was 0.6. Figure 6 also shows the experimental points for the sublimation of naphthalene for which K is an order of magnitude larger (r was taken as the heat of sublimation). In spite of this if the straight line given by Eq. (12) is extrapolated into this region it passes very close to the experimental points.

Analysis of the experimental data showed that the physical properties of the volatile liquid and the interaction of heat and mass transfer cannot be satisfactorily taken into account solely by Sc and the ratio $(p - p''_p)/p$. The use of K and the ratio p/p''_p, on the other hand, helped to correlate the results and to obtain Eq. (13) which can be used to determine mass-transfer coefficients in blast drying using a slit nozzle or a system of slit nozzles for Sc = 0.6-2.5 or K = 7-500. The ranges of the remaining parameters (w_0 = 10-40 m/sec, b = 5-40 mm, L/b = 1.25-20, s/b = 8.5-80) remain the same as for Eq. (11).

The question of the exponent of K in Eq. (13) remains open. The appreciable difference between the appropriate values of this exponent for longitudinal flow past a plate and blast drying with a slit nozzle shows its dependence on mass transfer. Tests must be performed to find whether the exponent of K for blast drying with a circular nozzle, for example, is the same as in Eq. (13).

NOTATION

D	is the diffusion coefficient, m^2/h;
F	is the area, m^2;
G	is the weight, kg, g;
L	is the characteristic dimension, m;
R	is the gas constant, J/kg · deg;
T	is the absolute temperature, °K;
a	is the thermal diffusivity, m^2/h;
b	is the nozzle width, mm, m;
c_k	is the specific heat of liquid, J/kg·deg;
p''_p	is the vapor pressure at saturation point, N/m^2, kN/m^2;
p	is the total atmospheric pressure, N/m^2, kN/m^2;
r	is the heat of evaporation, J/kg, kcal/kg;
s	is the distance between plate and nozzle outlet, mm;
$\underline{t}$	is the temperature, °C;
t	is the temperature according to Eq. (10), °C;
w	is the efflux velocity, m/sec;
w_0	is the efflux velocity at nozzle outlet, m/sec;
α	is the heat-transfer coefficient, $W/m^2 \cdot deg$, $kcal/m^2h$ °C;
β	is the mass-transfer coefficient, m/h;
λ	is the thermal conductivity, W/m · deg;
ν	is the kinematic viscosity, m^2/sec;
$Nu = \alpha L/\lambda$	is the Nusselt number;
$Sh = \beta L/D$	is the Sherwood number;
$Re = wL/\nu$	is the Reynolds number;
$Sc = \nu/D$	is the Schmidt number;
$Pr = \nu/a$	is the Prandtl number;
$K = r/c_k\,(t - t_p)$	is the Kutateladze number.

Indices

k	is the liquid;
v	is the air;
D	is the vapor;
p	is the surface.

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