GENERALIZATION OF EXPERIMENTAL DATA ON HEAT AND MASS TRANSFER DURING THE EVAPORATION AND SUBLIMATION OF DIFFERENT SUBSTANCES IN A FORCED STREAM

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Experimental data on heat and mass transfer during evaporation (sublimation) are generalized on the basis of the usual methods of similarity theory. The results of an analysis of the author's experimental data are presented.

One of the main difficulties arising during the application of similarity theory to a specific complicated process, such as combined heat and mass transport, for example, consists in the construction of a sufficiently complete and physically correct system of criteria.

As an example of a physical system let us examine the quasistationary turbulent flow of a binary mixture at a "semipermeable" surface of evaporation (sublimation). We will assume that the sources of the physicochemical transformation are uniformly distributed over the surface and that the transformation itself takes place in thermodynamic equilibrium. We will disregard the secondary molecular processes (Dufour and Soret effects). Radiation is not important. The case of evaporation into a vacuum is not touched upon.

We will assume that the mixture and its components are close in properties to an ideal gas, $i = c_pT$. The heat capacity and gas constant of the mixture depend on the relative concentrations of the components, and the density of the mixture depends on the temperature in addition. Although there is no doubt that the transport coefficients also depend on the content of the components, in many cases this dependence is not very marked. The differential equations for the boundary layer are well known [1] for the conditions formulated.

In order for the problem in principle to admit of a unique solution the values of all the variables must be given at the boundaries of the system (or some equivalent conditions). In particular, we assume that the temperature $T_w$ and the partial pressure $p_{lw}$ at the surface of evaporation are known.

By reducing the existing relationships to dimensionless form one can use the method of scaling transformations. Here the scales of the values are their values given by the conditions of uniqueness. If there are at least two such values (such as the stream and the wall, for example), none of which is equal to zero or can be reduced to zero by a shift in the frame of reference, then a determining simplex, representing the ratio of these parametric independent values or scales, appears in the criterial relationship.

Thus, for the conditions formulated above we obtain the determining dimensionless complexes $Re$, $M$, $Pr$, and $Sc$ and the determining simplexes $(p_{lw} - p_{lf})/p$, $(p_{lf}/p)$, $(T_f - T_w)/T_f$, $R_1/R_2$, and $c_{p1}/c_{p2}$.

If the boundary conditions at the wall are written as

$$ q = jr, $$

(for "adiabatic" evaporation), where

$$ q = \alpha (T_f - T_w) = \left[ \lambda \left( \frac{\partial T}{\partial n} \right) \right]_w, \quad i = \beta (p_{lw} - p_{lf}) = \left[ -K_1 \frac{\partial p_1}{\partial n} \right] .$$

then one can obtain from (1) the criterion of phase transformation

\[ K = \frac{r}{c_p(T_f - T_m)}. \]

It is obvious that this dimensionless complex serves the same purpose as the relationship (1), i.e., it is a measure of the interdependence of the intensities of heat and mass transfer. On the basis of (2) and (3) it can also be asserted that this is a measure of the interdependence of the temperature field and the density fields at the surface of transformation. Therefore the following statement is also valid: with the assignment of the boundary condition (1) the need to assign \( P_{lw} \) falls off, and consequently \( K \) is included among the determining criteria in place of the simplex \( (P_{lw} - P_{lf})/P \). (It would not be out of place to observe that the determining criterion of mass exchange should also be taken here in such a way that knowledge of \( P_{lw} \) is not required. The criterion \( Nu_D \) does not satisfy this requirement.)

Although in principle it should be asserted that independently of how the determining complex is taken (for mass exchange or for heat exchange) the system of determining criteria for the process of combined heat and mass transfer under consideration must remain the same, the nature of the effect of the determining criteria can undoubtedly be quite different in this case. One can see from the differential equations for the boundary layer — for mass balance of the vapor and for energy — that the interdependence of their solution is manifested primarily through the density of the mixture which depends both on the concentrations and on the temperatures. Several particular cases of criterial relationships can be obtained here depending on the concrete circumstances of the process.

It is known that at low intensities of evaporation (sublimation) the criterial dependence for the diffusional Nusselt number appears analogous (down to the matching of the coefficients of the equation) to the dependence for "pure" heat exchange of incompressible liquids under the same hydrodynamic conditions (in this case the Schmidt numbers emerges as an analog of the Prandtl number). It is clear that in this case, apart from the analogous structure of the differential equations of vapor mass balance and of energy (obtained from the discarding of unimportant terms from the energy equation), the former must be solved independently from the latter (although the question is whether a solution is possible in principle).

The effect of the factor of variability of the density of the mixture increases with an increase in the intensity of evaporation, since the drops in concentrations and temperatures increased simultaneously with it. This effect should be considered as considerably greater than during "pure" heat exchange, possibly because the total density enters into the differential equation of vapor mass balance in the form of a derivative. Here additional determining criteria appear in the criterial dependence.

We conducted experiments on the porous evaporation of water, acetone, and ethyl alcohol (\( \Pi = 43\% \)) and the sublimation of a number of substances from the surface of the flat transition element of a manifold which constricts an air stream (diaphragm). The method of conducting the experiments is described in [2, 9]. The mode of flow is turbulent and subsonic. The evaporation of the liquids had a nature close to adiabatic, i.e., practically all the heat transferred from the gas went into evaporation. The sublimation had a markedly nonadiabatic nature. As a consequence of this there was no opportunity to treat the entire collection of experimental data using the phase transition criterion since in the form indicated it is a criterion only of adiabatic evaporation. However, it was possible to generalize the experimental data on evaporation and sublimation using the determining simplices

\[ \frac{P_{lw} - P_{lf}}{P}, \frac{T_f - T_m}{T_f}. \]

The simplex of pressures (Fig. 1a) plays the main role in this. The dependence represented in Fig. 1a can be described by the equation

\[ \Pi_D = 0.126 Re^{0.6} \left( \frac{P_{lw} - P_{lf}}{P} \right)^{2/3}. \]  \hspace{1cm} (4)

The scatter of the experimental points here is considerable (+30%), although it can be decreased since the stratification of the experimental points as a function of the temperature simplex is clearly revealed on the graph.