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# OPTICAL INVESTIGATION OF HEAT AND MASS TRANSFER IN VAPOR CONDENSATION FROM VAPOR–GAS MIXTURES

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Experimental data on the temperature and concentration fields are obtained by an interferometric procedure in vapor condensation from a vapor–gas mixture and from a vapor–vapor mixture of six working media under natural convection conditions.

The condensation of vapor–gas mixtures and vapor–vapor mixtures forming a homogeneous liquid phase is encountered frequently in practice. However, it has not been adequately studied under the conditions of natural convection. The complex mechanism of the process and experimental difficulties stand in the way.

The presence of a gas in a vapor or the intrusion of another component is known to create diffusion resistance, so that the resistances of the liquid and vapor phases must be taken into account separately. This formulation of the problem requires the determination of the temperature and concentration at the phase interface, along with the temperature and concentration distributions in the vapor phase [1]. We have therefore undertaken experimental measurements of the temperature and concentration fields in a vapor layer.

The optical method is the most practical approach to the solution of the problem. It has the important inherent advantages of quick response and freedom from any disturbance of the investigated process; it also affords the possibility of observing visually the configuration of the vapor boundary layer and the dynamics of its variation under the action of a variety of factors.

To investigate the concurrent processes of heat and mass transfer in vapor condensation from a vapor–gas mixture and from a vapor–vapor mixture on a horizontal cylinder under natural convection conditions, we designed and assembled experimental apparatus using a two-wave polarization schlieren interferometer.

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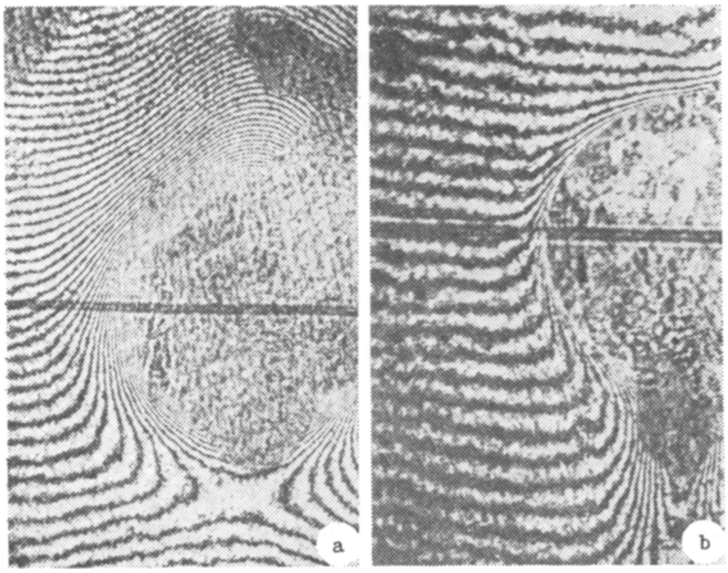

Fig. 1. Interferograms for mixtures at a wavelength $\lambda$ = 0.6328 m. a) $H_2O$–He ($P_\infty = 10^5$ Pa, $T_\infty$ = 372.9 K, $\Delta T$ = 33.6 K, $\varepsilon_{g,\infty}$ = 7.2%); b) $H_2O$–$CO_2$ ($P_\infty = 10^5$ Pa, $T_\infty$ = 375 K, $\Delta T$ = 33.2 K, $\varepsilon_{g,\infty}$ = 7.2%).

The interferometer was adjusted to horizontal fringes of finite width. The experimental tube was placed in a parallel light beam between the collimator and the receiver. The interference fringes situated around the center of the experimental tube were focused onto a screen. The number of fringes was chosen so as to obtain the optimum deflection in the vicinity of the disturbance of the object. A spindle of diameter 1 mm was placed under the experimental tube to serve as a scale. Two interferograms were recorded at the corresponding wavelengths in each experiment. The data were interpreted according to a dispersimetric method [3].

The working media were $H_2O$–He, $H_2O$–air, $H_2O$–Ne, $H_2O$–$CO_2$, $H_2O$–$C_2H_5OH$ and R 113–air. The experiments were carried out in the following intervals of the parameters: $T_\infty$ = 349-382 K; $\Delta T = T_\infty - T_W$ = 3-33 K; $P_\infty$ = 0.1 MPa; $\varepsilon_{g,\infty}$ = 0.2-8.6 vol. %; for ethyl alcohol, $\varepsilon_\infty$ = 30-96.6 vol. %; $Ra_D = (2\text{-}23)\cdot 10^3$; Le = 1.2-3.8.

The interferograms clearly reveal how the configuration and thickness of the boundary layer vary around the experimental tube. Its thickness is much greater in the upper part than in the lower part in vapor condensation from a vapor–helium mixture (Fig. 1a), whereas in the case of an $H_2O$–$CO_2$ mixture (Fig. 1b) the thickness of the boundary layer is greater in the lower part than in the upper part of the experimental tube. The interpretation of the interferograms gave the distributions of the temperature and the concentration around the circumference of the experimental tube. Light diffraction prevented us from approaching the condensation surface closer than 0.2-0.3 mm, and so the temperatures and concentrations of the phase interface were determined by extrapolation.

It is important to note that the diffusion and thermal boundary layers attained very large thicknesses in the experiments with the vapor–helium mixture. In experiment 16G, e.g., they had the respective values $\delta_D$ = 12.6 mm, $\delta_T$ = 6.7 mm in the equatorial cross section, and $\delta_D$ = 21 mm, $\delta_T$ = 8.5 mm. It was also established that $\delta_D > \delta_T$. This is consistent with the Lewis number, which was equal to 3.8 for this experiment. The thicknesses of the diffusion and thermal boundary layers are observed to be equal (Le = 1.2) for vapor condensation from the $H_2O$–$CO_2$ mixture. They were equal to $\delta_D = \delta_T$ = 2.3 mm in the equatorial cross section and $\delta_D = \delta_T$ = 10.5 mm in the lower part. The thicknesses of the boundary layers for the other investigated mixtures fell within the above-indicated intervals. Thus, the boundary-layer thicknesses measured in the experiments for all the investigated mixtures were commensurate with the diameter of the experimental tube (d = 11.4 mm), making it difficult to use the boundary-layer approximation for the theoretical solution of the given problem.

We analyzed the influence of the differential temperature and the concentration of the inert component on the behavior of the temperature and concentration profiles in the boundary layer for equatorial cross sections of the experimental tube. Figures 2 and 3 show the

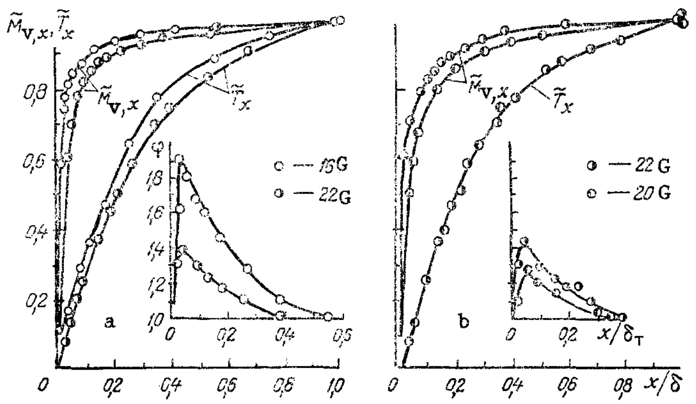

Fig. 2. Influence of the differential temperature (a) and the concentration factor (b) on the distributions of $\tilde{T}_x$, $\tilde{m}_{v,x}$, and $\varphi$ in the boundary layer for an $H_2O$–He mixture: No. 16G) $P_\infty = 10^5$ Pa, $T_\infty = 372.9$ K, $\Delta T = 33.6$ K, $\varepsilon_{g,\infty} = 7.2\%$; No. 20G) $P_\infty = 10^5$ Pa, $T_\infty = 374.0$ K, $\Delta T = 24.5$ K, $\varepsilon_{g,\infty} = 0.8\%$; No. 22G) $P_\infty = 10^5$ Pa, $T_\infty = 374.4$ K, $\Delta T = 24.4$ K, $\varepsilon_{g,\infty} = 7.4\%$.

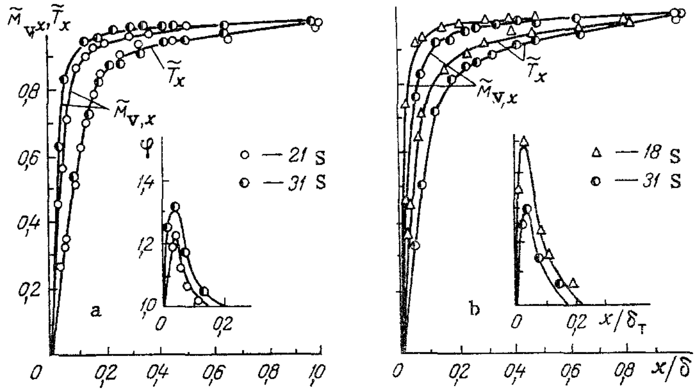

Fig. 3. Influence of the concentration factor (a) and the differential temprature (b) on the distributions of $\tilde{T}_x$, $\tilde{m}_{u,x}$, and $\varphi$ in the boundary layer for an $H_2O$–$CO_2$ mixture: No. 18S) $P_\infty = 10^5$ Pa, $T_\infty = 375$ K, $\Delta T = 33.2$ K, $\varepsilon_{g,\infty} = 7.2\%$; No. 21S) $P_\infty = 10^5$ Pa, $T_\infty = 374$ K, $\Delta T = 19$ K, $\varepsilon_{g,\infty} = 0.9\%$; No. 31S) $P_\infty = 10^5$ Pa, $T_\infty = 375$ K, $\Delta T = 21.5$ K, $\varepsilon_{g,\infty} = 7.2\%$.

influence of a difference in the temperatures and concentrations of the inert component on the temperature and concentration profiles in the boundary layer for $H_2O$–He and $H_2O$–$CO_2$ mixtures. An increase in the differential temperature causes the temperature and concentration profiles to bulge upward, whereas an increase in the concentration merely changes the concentration profile and leaves the temperature profile virtually unchanged. Also, an increase in the differential temperature auses the boundary thickness to increase in vapor condensation from mixtures with a lighter inert component relative to the condensed vapor. This result is attributable to the fact that the convection currents produced by the temperature and concentration nonuniformities are in different directions. The opposite pattern is observed for mixtures with an inert component of the same or larger molecular mass, i.e., the thickness of the boundary layer decreases, because the thermal and concentration convection components are in the same direction.

An analysis of the temperature and concentration profiles indicates that vapor supersaturation is observed in the boundary layer (Figs. 2 and 3). Here $\varphi$ increases with the differential temperatue and the thermal conductivity. The possibility of the formation of supersaturated vapor in the boundary layer has been suggested in several papers [4-6].

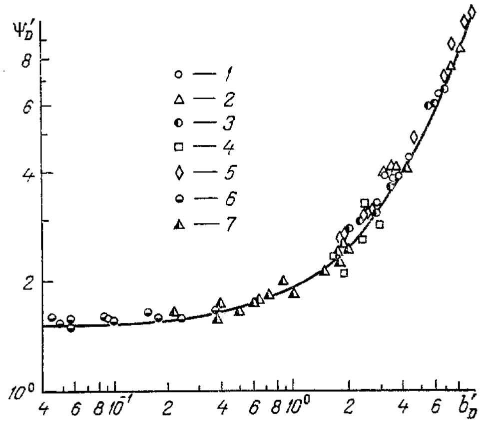

Fig. 4. Generalization of experimental data on the mean mass transfer. 1) $H_2O$–He; 2) $H_2O$–$CO_2$; 3) $H_2O$–air; 4) R 113–air; 5) $H_2O$–Ne; 6) $H_2O$–$C_2H_5OH$; 7) $H_2O$–air [9].

We have plotted profiles of the relative enthalpies on the basis of the distributions of $\tilde{T}_x$ and $\tilde{m}_{v,x}$. Their agreement with the relative concentration curves for the $H_2O$–$CO_2$ and $H_2O$–Ne mixtures indicates a similarity between the concurrent heat- and mass-transfer processes, and their disagreement for the other investigated mixtures indicates the absence of such a similarity.

We give special attention to vapor condensation from a vapor–vapor mixture. We measured the temperature and concentration fields in the condensation of an $H_2O$–$C_2H_5OH$ mixture. In the main experiments, the temperature on the condensation surface was maintained slightly higher than the condensation temperature of ethyl alcohol, which created a diffusion boundary layer whose thickness in the equatorial cross section varied from 2.1 to 3.2 mm. The ethyl alcohol condensed along with the water vapor, and so we used a somewhat different equation to calculate the local mass-transfer coefficient. It is important to mention that supersaturation was not observed in the $H_2O$–$C_2H_5OH$ mixture in the range of the investigated parameters. In several experiments, where the temperature was below the condensation point of $C_2H_5OH$, the diffusion boundary layer vanished, and the concentration of ethyl alcohol in the vapor layer approached its concentration in the condensate film, consistent with previous work [7].

The local mass-transfer coefficients were calculated from the concentration fields with allowance for Stefan flow and were then integrated around the circumference of the experimental tube in order to obtain their mean values.

The mean values of the mass-transfer coefficients for all the investigated mixtures were generalized according to the procedure of Kutateladze et al. [8, 9]. The results are shown in Fig. 4 in the form of a graph, which is described by the following equations within ±20% error limits:

$$\Psi_D' = (1 + 0{,}25 b_D')^2 \quad \text{for} \quad 0{,}045 \leqslant b_D' \leqslant 2{,}8, \tag{1}$$

$$\Psi_D' = 1{,}08\,(b_D')^{0,972} \quad \text{for} \quad 2{,}8 \leqslant b_D' \leqslant 10. \tag{2}$$

An analysis of the graph in Fig. 4 indicates a lack of similarity for the vapor–gas mixtures $H_2O$–$CO_2$, $H_2O$–He, $H_2O$–Ne, $H_2O$–air, and R 113–air in the investigated range of the separate heat- and mass-transfer processes and the occurrence of similarity for the vapor–vapor mixture $H_2O$–$C_2H_5OH$.

We note in conclusion that these equations can be used in engineering calculations for the design of heat-exchanging equipment in which vapor condensation takes place from vapor–gas and vapor–vapor mixtures under natural convection conditions.

## NOTATION

$\varepsilon$, volume concentration, v/v; m, mass concentration, m/m; P, pressure of mixture, Pa; $\varphi = P_{v,x}/P_{vs,x}$, degree of vapor supersaturation; T, temperature of mixture, K; h, enthalpy, kJ/kg; Nu, Nusselt number; St, Stanton number; $\rho$, density of mixture, kg/m$^3$; w, velocity of mixture, m/sec; $\delta$, thickness of boundary layer, mm; $\tilde{m}_{v,x} = (m_{v,if} - m_{v,x})/(m_{v,if} - m_{v,\infty})$, relative concentration; $\tilde{T}_x = (T_{if} - T_x)/(T_{if} - T_\infty)$, relative temperature; $\tilde{h}_{mx,x} = (h_{mx,if} - h_{mx,x})/(h_{mx,if} - h_{mx,\infty})$, relative enthalpy; $\Psi'_D = Nu_D(1 - m_{v,if})/Nu_{D_0}$; $b'_D = j/p_\infty w_\infty St_{D_0}$; j, mass flux density of active component. Indices: D, diffusion; T, thermal; x, instantaneous coordinate along thickness of boundary layer; $\infty$, parameters in undisturbed region; if, parameters at liquid–vapor phase interface; o, parameters in the absence of transverse mass flow; s, parameters in saturated state; mx, parameters of mixture; v, condensing vapor; g, inert or low-boiing component.

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