HEAT AND MASS TRANSFER DURING CONDENSATION OF WATER VAPOR FROM MOIST AIR IN NARROW CHANNELS

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The results of an experimental investigation of heat and mass transfer during condensation of water vapor in narrow channels at pressures $P = (0.133\text{-}1.0) \cdot 10^5$ N/m^2 and velocities of the moist gas $v_{mix} = (0.5\text{-}10)$ m/sec are presented.

During cooling of a moving vapor–gas mixture in channels the total heat flux to the wall is composed of the heat flux due to convective heat transfer and the heat flux due to condensation of vapor. This separation of the total heat flux into individual components is purely arbitrary and permits a considerable simplification of the analysis of heat and mass transfer processes. In reality heat and mass transfer processes occur siumltaneously and have a mutual effect on each other.

The rate of condensation during cooling of a vapor–air mixture is determined in the general case by diffusion of vapor to the condensation surface, by heat transfer between the vapor–gas mixture and condensate film, and the hydrodynamic conditions of the flow of the vapor–gas mixture and condensate. The presence of air in the vapor–gas mixture strongly affects the process of vapor condensation. The layer formed at the condensation surface with a high concentration of air in comparison with the flow core is the main resistance for diffusion of water vapor.

So far heat and mass transfer processes during condensation of vapor from moving vapor–gas mixtures have been studied little. Relations of calculating the average heat- and mass-transfer coefficients over the length of the channels in a narrow range of variation of the principal parameters are presented mainly [1-5]. As the result of our investigation show, the intensity of heat and mass transfer over the length of channels varies considerably.

The purpose of the present investigations was to obtain reliable experimental data for calculating heat and mass transfer during cooling of a vapor–air mixture in narrow channels for a wide range of variation of velocities, pressures, and moisture contents. The data obtained are especially important for planning compact heat-exchange apparatus.

The experiments were conducted on an experimental device whose basic scheme is given in [6]. We additionally connected to this device a steam delivery system at the inlet to the experimental heat exchanger and at its outlet we installed a moisture separator with a measuring vessel for collecting the condensate. The required quantity of vapor was delivered to the heat exchanger from an electric steam tank with an adjustable steam output. The steam tank was installed on a VTK-500 balance with a 0.1 g scale value and connected by a flexible rubber tube with the air delivery line to the heat exchanger. The vapor flow rate was determined by the change of weight of water in the steam tank during steady vaporization. The moisture content of the mixture was constant while measuring the vapor flow rate. By calibration we introduced the appropriate correction taking into account the effect of the flexible connection on the readings of the balance.

The error of measuring the per-second vapor flow rate with consideration of the error of measuring the humidity of the air entering from the atmosphere was not more than 7%.

The experiments were conducted on heat exchangers made up from identical copper tubes with inside diameters of 3, 4, and 6 mm. To determine the change of the average values of the heat- and mass-transfer

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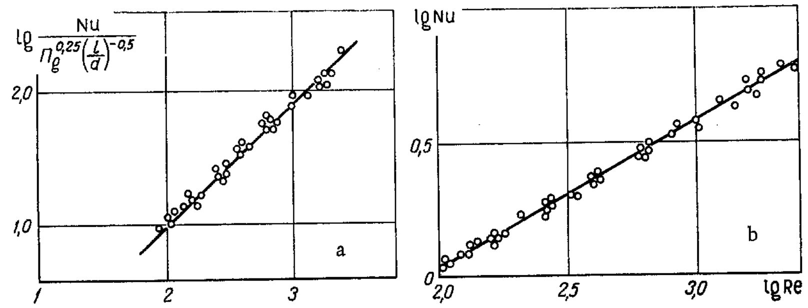

Fig. 1. Generalized relation $Nu/(l/d)^{-0.5}\Pi_g^{0.25} = f(Re)$ for mass transfer (a) and relation $Nu = f(Re)$ for convective heat transfer (without consideration of mass transfer) (b).

coefficients over the length of the channels, we used heat exchangers with a different length of the channels ($l/d = 40$, 75, 95, 145, and 200).

In conducting the experiments the regime parameters of the mixture were varied with the following range: temperature of moist air $t_{mix} = 20\text{-}60°C$; air–wall mean temperature difference $\Delta t = 11\text{-}50°C$; volume content of vapor in moist air

$$\varepsilon = \frac{P_v}{P_{mix}} = 0.05 \text{ to } 0.5;$$

Reynolds number

$$Re = \frac{(v_{mix}\rho_{mix})\,d}{\eta_{mix}} = 100 \text{ to } 2400.$$

The total heat-transfer coefficient during cooling of the vapor–air mixture can be calculated from the equation

$$\alpha_\Sigma = \alpha_c + \beta_d\, r\, \frac{P_v - P_w}{t_{mix} - t_w}.$$

The convective component of the total heat-transfer coefficient α_c, just as for heat transfer of "dry" gas, was calculated from the difference of enthalpies of the air between the inlet and outlet of the heat exchanger. As a result of treating and analyzing the experimental data the process of heat and mass transfer during cooling of a vapor–air mixture in narrow channels can be described by the equations:

for convective heat transfer

$$Nu = 0.12\, Re^{0.56};$$

for mass transfer

$$Nu_D = 0.107\, Re^{0.9}\,\Pi_g^{0.25}\left(\frac{l}{d}\right)^{-0.5}.$$

All physical quantities figuring in the Nusselt and Reynolds numbers were determined from the parameters of the vapor–air mixture at the inlet of the experimental heat exchanger.

The data obtained show that the mass flow directed perpendicular to the main direction of motion intensifies considerably convective heat and mass transfer. For the transverse vapor flows that occurred in the experiments ($g < 2.0 \cdot 10^{-2}$ kg/m^2 · sec) the heat-transfer coefficient, as we see from Fig. 1, is considerably higher (by about 50%) than the heat-transfer coefficient during cooling of "dry" air [6].

We also see from the experimental data that the intensity of mass transfer depends on the velocity of forced motion to a greater degree than the intensity of heat transfer, i.e., in our case a complete analogy is not observed between the processes of heat and mass transfer.

The intensity of mass transfer increases considerably with a decrease of the total pressure of the vapor–air mixture.

Experiments conducted at different relative lengths of the channels enabled us to establish the dependence of heat and mass transfer on the length of the channels. With a decrease of the length of the channels an intense increase of heat and mass transfer is observed. This marked increase of heat and mass transfer can be explained by the considerable drop of the partial pressure at the initial section of the channels. As the vapor–air mixture advances over the channel length the resistance increases, preventing condensation of the vapor both due to an increase of air concentration near the condensation surface and due to a decrease of the partial pressure gradient between the flow core and the condensation surface.

The character of condensation of the vapor from the moving vapor–air mixture also has a considerable effect on heat and mass transfer. A visual observation of condensation in small-diameter glass tubes showed that for all regimes that occurred in the experiments dropwise condensation was observed, which is confirmed also in [4, 5, 7]. During condensation of vapor from the vapor–air mixture in channels individual drops form on the walls, which on reaching a certain size are removed as individual streams under the effect of the dynamic head of the flow. With an increase of the flow velocity the size of the condensate drops, which remain stationary on the surface for a certain time, decreases. At flow velocities at the inlet greater than 5 m/sec their partial separation from the condensation surface and removal into the flow core, as well as fractionation into smaller parts along the course of the flow, are observed.

The aforesaid permits the assumption that in the general case during cooling of a vapor–air mixture the intensity of the process is affected also by interphase heat and mass transfer between the condensate drops and vapor–air mixture.

Comparing our data with the data in [7] obtained in an investigation of cooling of a vapor–air mixture at atmospheric pressure in slit channels for the laminar flow region, we see that the heat- and mass-transfer coefficients obtained from our experimental data are considerably lower than in [7]. The lower results in this case can be explained by the absence of developed free convection in narrow channels, which under the experimental conditions of the author of [7] had a considerable effect on heat and mass transfer.

NOTATION

P_v, P_{mix}	are the partial pressures of vapor and mixture, respectively;
P_w	is the partial pressure of vapor at wall temperature;
r	is the specific heat of condensation;
β_p	is the mass-transfer coefficient referred to difference of partial pressure;
$\Pi_g = (P_v - P_w)/P_{mix}$	is a complex taking into account the molar flux of material;
U_{mix}, ρ_{mix}, η_{mix}	are the velocity, density, and dynamic viscosity coefficient of the vapor–air mixture, respectively;
$Nu_D = \beta_d d/D_d$	is the diffusion Nusselt number;
$D_d = 2.11\ [(t_{mix} + 273)/273^{1.82}]\,[1/(P_{mix} R_v (t_{mix} + 273)]$	is the coefficient of molecular diffusion of water vapor into the air;
t_{mix}	is the temperature of the mixture at the inlet of the heat exchanger;
R_v	is the vapor constant of vapor;
l, d	is the length and diameter of the channel, respectively.

LITERATURE CITED

1. V. A. Baum and P. M. Brdlik, Teploénergetika, No. 1 (1957).
2. V. G. Fastovskii and A. E. Rovinskii, Izv. VTI, No. 4 (1950).
3. L. D. Berman and S. N. Fuks, Izv. VTI, No. 11 (1952).
4. A. M. Baklastov and Zh. F. Sergazin, Izv. VUZ, Énergetika, No. 2 (1965).
5. Yu. N. Pchelkin, Teploénergetika, No. 6 (1961).
6. P. A. Novikov and L. A. Shcherbakov, Inzh.-Fiz. Zh., No. 5 (1971).
7. V. M. Semein, Teploénergetika, No. 4 (1956).