EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER DURING CONDENSATION OF WATER VAPOR FROM HUMID AIR ON A VERTICAL SURFACE UNDER NATURAL CONVECTION CONDITIONS

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Results are presented of an experimental investigation of the heat and mass transfer accompanying condensation of water vapor from vapor-air mixtures with low volumetric vapor contents ($\varepsilon_{0.v} \leq 2.1\%$). Empirical formulas are proposed for the heat transfer coefficient and the rate of condensation.

Analysis of the limited experimental data [1-4] on heat and mass transfer during vapor condensation from vapor-gas mixtures under free convection shows that all the experiments were carried out:

a) at very high vapor contents (minimum volumetric vapor content $\varepsilon_{0.v} = 40\%$);

b) on horizontal flat surfaces and horizontal pipes;

c) at a relative humidity of air $\varphi = 100\%$

d) at a temperature of the vapor-air mixture generally in excess of 50 °C.

Thus, the conditions in the experiments so far carried out differ markedly from the typical conditions of condensation of water vapor from humid air, characterized by a relative humidity of 50-90%, temperatures up to 30 °C, and a volumetric vapor content ($\varepsilon_{0.v}$) of less than 3.5%. Accordingly, we undertook an experimental investigation of the condensation of water vapor from humid air onto a flat vertical surface under natural convection with the relative humidity of the air in the range 50 to 90% and a maximum volumetric vapor content $\varepsilon_{0.v} = 2.1\%$. A vertical surface was chosen because this is the most common condition of vapor condensation from humid air.

The experimental heat exchanger (Fig. 1) consisted of a vertical metal box 1000 mm in height and 410 mm wide. The heat-receiving surface, made of copper sheet 5 mm thick, was carefully polished to minimize radiative heat transfer, and degreased and aged to ensure wettability.

Cooling water flowed through a slit-like channel, inside thickness 5 mm, divided vertically into four equal compartments by three baffles, which also acted as mixers.

After each mixer a thermocouple was placed in the flow of cooling water to measure the cooling water temperature over the height of the heat exchanger. In addition, thermocouples measured the temperature of the cooling water at the entrance to and exit from the experimental zone. The cooling water flow rate was determined by a gravimetric method, and its temperature was regulated by a thermostat. The cooling water was supplied and flowed away through an evenly distributed series of openings 1.5 mm in diameter, in order to obtain a more uniform distribution of the cooling water over the width of the heat exchanger. To the underside of the experimental condenser we soldered a sloping gutter, which served to collect condensate draining from the heat exchange surface. The mean temperature of the condensate was measured by a thermocouple, and the flow rate by a gravimetric method. The temperature of the heat-receiving surface was determined over the height and width of the plate at eight points. The experimental heat exchanger-condenser was carefully insulated. Heat losses through the insulation were determined by special calibration.

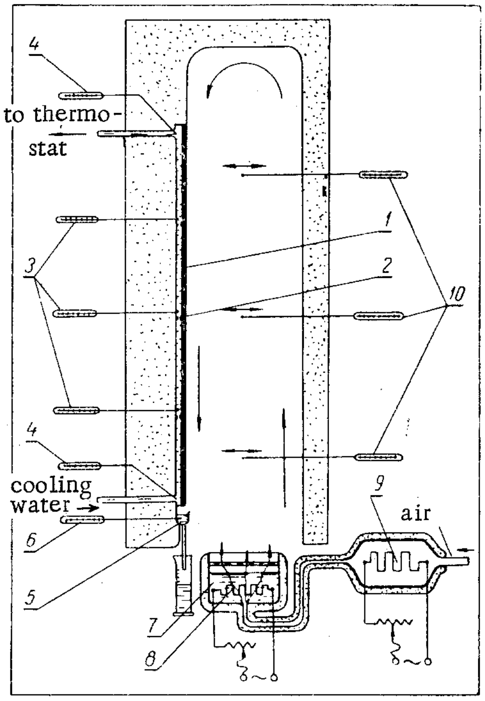

Fig. 1. Diagram of experimental apparatus: 1) heat exchanger; 2) mixer; 3,4) thermocouples for measuring cooling water temperature; 5) condensate collector; 6) thermocouple for measuring condensate temperature; 7) humidifier; 8) water heater; 9) heating element; 10) thermocouples for measuring air temperature

To obtain the prescribed temperature and humidity in in the bulk of the mixture, the experimental heat exchanger was arranged in a closed space. The distance between the working surface of the condenser and the opposite wall was chosen so that the boundary layers near the surface of the condenser and near the wall did not exert any influence on each other or on the progress of free convection between them. The surface of the walls facing the working surface of the experimental condenser had aluminum foil stuck to them to minimize radiative heat exchange between these walls and the surface of the condenser. A humidifier, filled with water, was placed beneath the experimental chamber. Air was humidified partly by passage over the water and partly by being bubbled through it. The water was heated by means of an electric heater mounted in the humidifier. The air was heated by means of a heating element and bubbled through the water by means of a blower. The quantity of air supplied was regulated in accordance with the required humidity in the working space. The temperature and partial pressure fields in the boundary layer and in the working space were measured by means of movable, connected thermocouples, diameter 0.1 mm, located at three equidistant points over the height of the plate. The connected thermocouples were constructed as follows. To the end of a coordinate-regulating tube we soldered three holders, spaced 40 mm apart, on which were mounted two copper-constantan thermocouples all in a line and parallel to the plate. One thermocouple served as a wet bulb thermometer and was wrapped in thin filter paper, to which distilled water was fed. The thermocouples were moved by a micrometer screw.

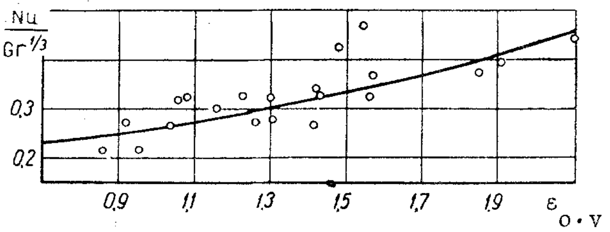

Fig. 2. Experimental data on heat transfer

The average heat transfer coefficient over the plate was calculated from the formula:

$$\alpha = Q/(t_h - t_w^{av})F.$$

The quantity of heat Q includes the heat that went into the cooling of the air in the boundary layer and the heat given out on condensation of the vapor. It is determined from the flow of cooling water and the difference in its enthalpy on entering and leaving the experimental condenser.

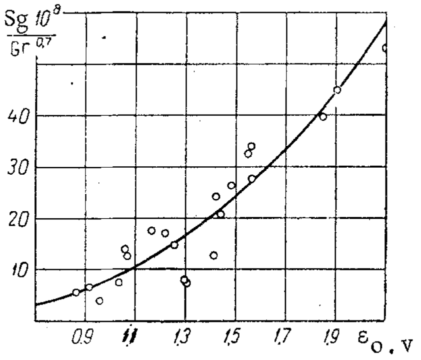

Fig. 3. Experimental data on rate of condensation

In determining Q a correction was introduced for the inflow (or loss) of heat through the insulation, for which a preliminary calibration was specially made, and for radiation, which, because of the precautions taken, did not exceed 1% of the total quantity of heat.

The temperature of the humid air outside the limits of the boundary layer was taken as the mean of the thermocouple readings. The maximum difference between these readings was 0.5°C.

The mean temperature of the heat-receiving surface t_w^{av} was already averaged by the thermocouples applied to the surface of the condenser.

In the experiments the basic parameters that determine heat and mass transfer during condensation of water vapor from humid air under free convection conditions were varied over the ranges: temperature of humid air t_h = 8-30°C; relative humidity of air φ = 50-90%; temperature difference air-wall Δt = 7-25°C; volumetric vapor content of humid air $\varepsilon_{o \cdot v} = \varphi P_s / P_h$ = 0.8-2.1%; Grashof number Gr = $(0.8\text{-}3.5) \times 10^9$.

From an analysis of the experimental data empirical relations were obtained. In specific cases, these permit the calculation of the heat transfer coefficient to the surface (1) and the rate of condensation (2)

$$\mathrm{Nu} = 0.16\,\mathrm{Gr}^{0.33} \exp(0.45\,\varepsilon_{o \cdot v}), \qquad (1)$$

$$S_g = 8.5 \cdot 10^{-8}\,\mathrm{Gr}^{0.7} \varepsilon_{o \cdot v}^{2.6}, \qquad (2)$$

where $S_g = g_k l / D_p P_h$ characterizes the rate of condensation;

$$D_p = 7.92 \times 10^{-2} \left(\frac{t_h + 273}{273} \right)^{1.75} \frac{1}{R_v (t_h + 273)}$$

and is the molecular diffusion coefficient of water vapor in air (m/hr).

The characteristic dimension l appearing in equations (1) and (2) is assumed to be the height of the working surface. The physical parameters of the humid air were taken as $t_T = 0.5(t_h + t_w^{av})$.

In Fig. 2 the experimental heat transfer data and the empirical relation (1) are compared. The mean square deviation of the experimental points from the average curve is ±20%.

The experimental mass transfer data (rate of condensation) are compared with the empirical relation (2) in Fig. 3. The mean square deviation of the experimental data from the mean curve is ±25%.

NOTATION

P_s – saturation vapor pressure of water at temperature of humid air; P_h – pressure of humid air (atmospheric pressure); g_k – rate of condensation ($kg \cdot m^{-2} \cdot hr^{-1}$); R_v – gas constant for water vapor; t_T – mean temperature of boundary layer.

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