EFFECT OF VELOCITY OF A CONDENSING VAPOR STREAM ON DISTRIBUTION OF LOCAL HEAT EXCHANGE CHARACTERISTICS ALONG THE HEIGHT OF A VERTICAL TUBE

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Results are presented for an experimental study of the variation in the local heat exchange characteristics along the height of a vertical tube during the condensation of pure water vapor which is in motion.

In the problem of the determination of the heat exchange coefficient during film condensation of a vapor on a vertical surface there are as yet no generally accepted standard functions, which is connected with a lack of information concerning the physical model of the phenomenon especially under conditions of considerable velocities in the movement of the condensing vapor stream. Detailed experimental studies must be carried out further for the solution of this problem, which is of considerable interest in connection with the application of heat exchange devices of this type in a whole series of industries.

In the film condensation of vapor on vertical surfaces the mechanism of the heat exchange process is connected with the hydrodynamics of the condensate film, which offers considerable thermal resistance, forming at the surface.

A vapor moving concurrently with a condensate film accelerates its motion owing to the effect of frictional forces at the surface of phase separation. As a result the film thickness and the thermal resistance of heat exchange are reduced. In addition, the moving vapor exerts a turbulizing effect on the flow of the film so that the laminar mode of motion is less stable than during the condensation of a stationary vapor. Some results of an experimental study of this problem are presented in [1]. Turbulization of the film also leads to a decrease in the thermal resistance of heat exchange. In this connection one can expect a larger velocity effect during the condensation of a moving vapor on vertical surfaces than during condensation on horizontal tubes.

The results of an experimental study conducted on the determination of the local heat exchange characteristics along the height of a vertical tube during the condensation of a moving vapor are presented below.

In construction the experimental apparatus consists of the vertical copper experimental tube 1 with a diameter of 30/26 mm and a height of 3200 mm, placed coaxially in a glass tube (Fig. 1). In the annular channel which is formed the vapor moves (from top to bottom), condensing on the outer surface of the copper tube; the cooling water is fed in the opposite direction.

An auxiliary heat exchanger 2, where condensation of the emerging vapor occurs, is provided to make it possible to study the velocity effect in a wide range of variation in the velocity of the moving vapor. The flow rates of the condensate and of the cooling water are measured with the measuring tanks 3, 4, and 5 and duplicated by the readings of measuring diaphragms.

To study the local characteristics of the heat exchange the local temperatures of the surface of condensation are measured using 17 copper–constantan thermocouples distributed every 200 mm along the height of the tube. To measure the local heat fluxes similar thermocouples are fastened to a special cable

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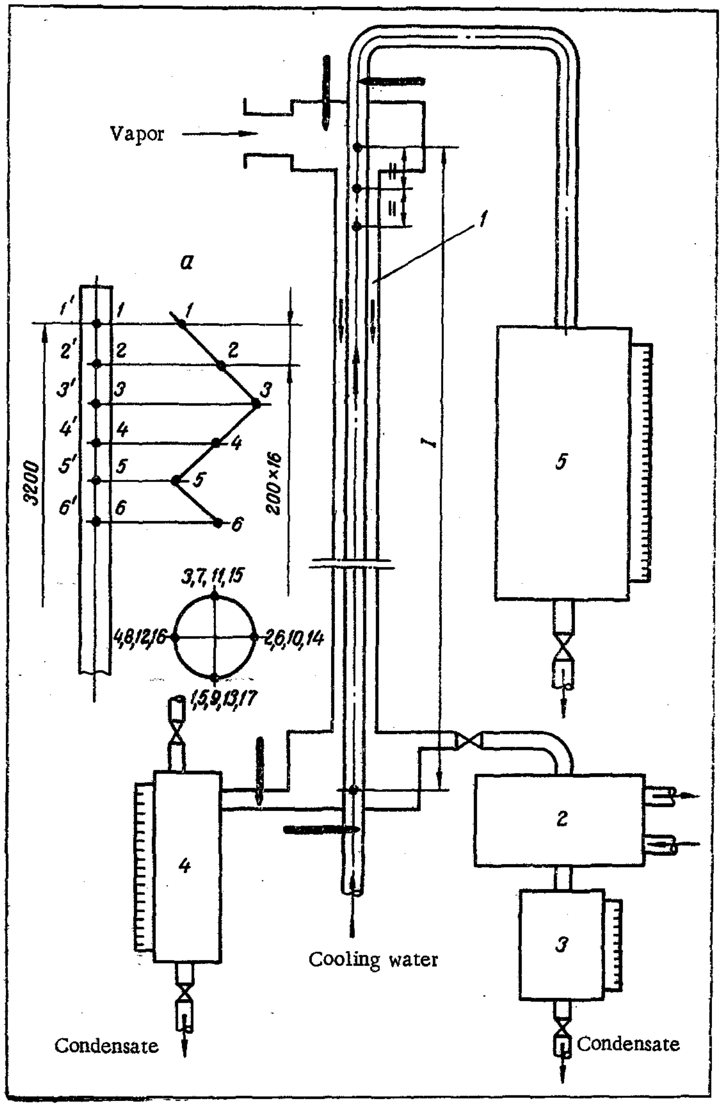

Fig. 1. Diagram of experimental apparatus: a) system of arrangement of thermocouples; I) 17 thermocouples spaced 200 mm apart.

within the experimental tube along its axis at the same cross sections along the height of the tube as the surface thermocouples. From their readings one can judge the local heating of the cooling water and consequently the local density of the heat flux $q_{(i)}$. In the analysis of the experiment the measured local wall temperatures were duplicated by their calculated values:

$$t_{\text{w. calc.}(i)} = \bar{t}_{2(i)} + \frac{q_{(i)}}{\alpha_{2(i)}} + q_{(i)}\frac{\delta}{\lambda},$$

$\bar{t}_{2(i)} = (t'_{2(i)} + t''_{2(i)})/2$ is the average temperature of the cooling water at the i-th section. The coefficient of heat exchange α_2 on the part of the water is determined according to [2], δ/λ is the thermal resistance of the wall of the tube.

The disagreement between the calculated and experimentally determined temperature did not exceed 6-10% in a majority of the modes. The local values of the coefficients of heat exchange on the part of the vapor were determined as:

$$\alpha_{1(i)} = \frac{q_{(i)}}{t_{\text{v}} - t_{\text{w}(i)}},$$

while the vapor velocities in cross sections of different altitude are determined as:

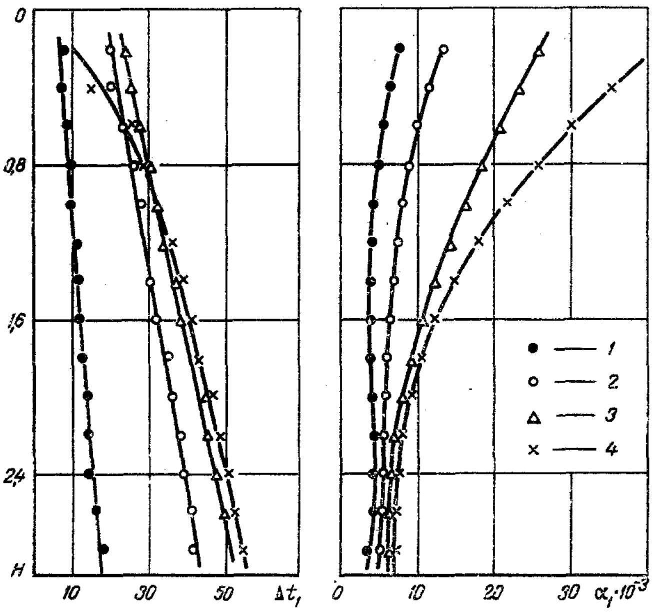

Fig. 2. Variation in thermal heads Δt_l (°C) and in heat exchange coefficients on the part of the vapor α_l (W/m^2 · deg) along height of tube H: 1) $W'_v = 13$ m/sec; 2) 27; 3) 49; 4) 75.

$$W_{v(i)} = \frac{G'_v - \dfrac{\sum_{1}^{i} q_{(i)} F_{(i)}}{r}}{S \rho_v},$$

where G'_v is the amount of vapor entering; F_i is the surface of the i-th section; S is the cross section of the annular channel.

The local values of the velocity coefficient $\beta_{(i)} = \alpha_{l(i)}/\alpha_{v(i)}$ were determined, i.e., the ratios of the actual heat exchange coefficient to the heat exchange coefficient determined from the theoretical Nusselt equation

$$\alpha_{v(i)} = \sqrt[4]{\frac{\rho_k^2 g r \lambda_k^3}{4 \mu_k (t_v - t_{w(i)}) X_i}}$$

for the case of condensation of a stationary vapor on a vertical surface with a laminar mode of motion of the condensate film [2].

The experiments were conducted in a range of variation in the initial vapor pressure of 1-5 bar, and in this case no significant effect of the initial pressure was detected in the range of its variation studied when the intensity of heat exchange is considered as a function of the initial kinetic energy of the vapor stream.

The range of specific heat loads averaged over the surface was $(0.5\text{-}5) \cdot 10^5$ W/m^2.

The local heat exchange characteristics obtained for the range of variation in the initial vapor velocity of 10-75 m/sec with the stream at atmospheric pressure are presented in Figs. 2 and 3.

An analysis of the data obtained shows that with a low initial velocity of the vapor stream (the kinetic energy very rapidly approaches zero already in the initial section) and low heat loads the values obtained in the experiment for the heat exchange coefficients α_l in the upper half of the tube hardly differ from α_v (the coefficient β is close to unity over almost half the height of the tube), which indicates a laminar mode of film runoff and the absence of a clearly-expressed velocity effect. The later increase in β is a result of the draining film. After the turbulent mode is established the ratio α_l/α_v stabilizes somewhat. Figure 2 serves as an illustration of the variation in the modes of flow of the film (the variation in α_l with height at the entrance velocity $W'_v = 13$ m/sec). At first α_l decreases smoothly because of the increase in thickness

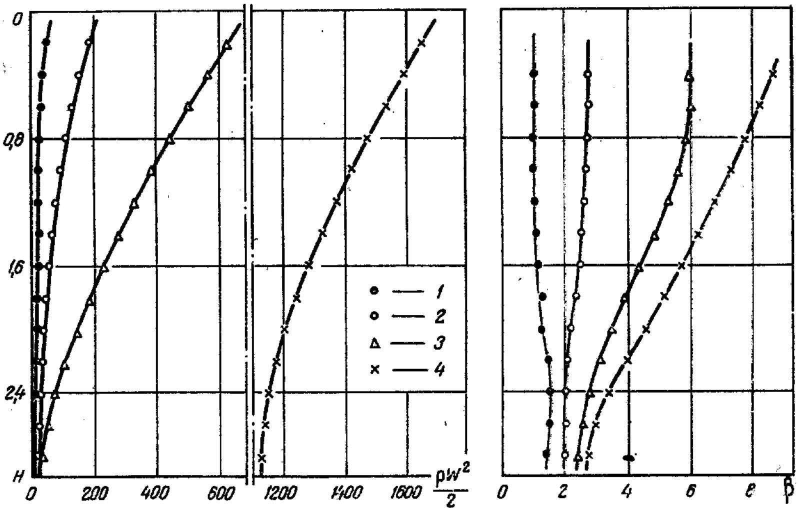

Fig. 3. Variation in kinetic energy complex $\rho W^2/2$ (J/m^3) and velocity coefficient β along height of tube H: 1) $W_V' = 13$ m/sec; 2) 27; 3) 49; 4) 75.

of the laminar runoff film and then at a certain section α_1 is unchanged. Since a further increase in film thickness occurs here the constancy of α_1 can be explained by a change in the mechanism of heat transport through the film, namely, by the appearance and subsequent development of a laminar-wave mode of motion [3] with its later conversion to a turbulent mode, which is indicated by the increase in α_1.

The velocity effect is already clearly observed in mode 2 (at the initial velocity $W_V' = 27$ m/sec). It is characteristic that at the middle of the tube, where the value of the kinetic energy is small (such a value of the kinetic energy in the initial section in mode 1 produced hardly any velocity effect), the ratio β reaches 2.5, which indicates the considerable turbulizing effect on the film of the initial kinetic energy. In this mode the variation of β with height is slight despite the fact that the kinetic energy decreases more strongly. Clearly, the decrease in the kinetic energy of the vapor stream with height is accompanied by the simultaneous development of a turbulent mode in the runoff film. The effect is intensified by the greater film thickness in the initial section.

In mode 3 (Fig. 3) the ratio β reaches a high value in the initial section and retains its value over some distance, despite the strong decrease in kinetic energy. In all probability, such a nature of the variation in β is connected with the very rapid loss in stability of the laminar film under the effect of the high initial vapor velocity and the establishment of a turbulent mode already in the initial section of the condensation surface ($X = 0.15$ H). The subsequent considerable change in β with height is the result of the effect of the decreasing kinetic energy on the turbulent runoff film.

In the three modes examined above almost complete condensation of the entering vapor occurs in the experimental section, so that the kinetic energy of the stream approaches zero in the lower sections of the tube.

In mode 4 only a fifth of the amount of vapor entering condenses in the experimental section, the rest going into the emerging vapor (which condenses in the heat exchanger 2), thanks to which the vapor velocities are high not only at the entrance but also at the exit ($W_V' = 75$ m/sec; $W_V'' = 61$ m/sec). The high values of the heat exchange coefficient in the upper section of the tube and the sharp decrease here in the thermal head Δt_1 (Fig. 2) indicate the instability of the film condensation in the initial section under conditions of high vapor stream velocities (foci of dropwise condensation are observed). The subsequent strong decrease in α_1 indicates the stabilization of the film condensation. The section of laminar motion of the film is clearly absent under such conditions (high heat loads and the strong turbulizing effect of the kinetic energy of the entering vapor stream), which is also indirectly indicated by the monotonic decrease in β in proportion to the decrease in kinetic energy of the vapor. It should be noted in particular that the high values of the complex $\rho W^2/2$ (kinetic energy) in the lower sections of the tube do not produce the velocity effect which is observed in the upper sections even at lower vapor velocities. Despite the sharp difference in the velocities of the vapor stream in the lower sections of the tube the heat exchange coefficients are almost the same in modes 3 and 4; the same applies to the values of β (the thermal heads in these sections are practically equal in these modes). The effect of the velocity of the vapor stream is reduced in proportion to the increase in the thickness of the runoff film, since the momentum incorporated in it increases approximately in proportion to the fifth power of the film thickness (the theoretical Nusselt equations). Moreover, a turbulently moving film because of the properties of the turbulent motion is less subject to the effect of the kinetic energy of the accompanying stream compared with a film moving laminarly.

The curves of the variation in α_1 with height in the lower sections of the tube, despite the difference in modes, almost coincide on the graph shown, since the amount of condensate formed, the thickness of the film in the lower sections of the tube, and its degree of turbulization increase with an increase in the heat loads. In the entire series of experiments conducted the values of β in the lower sections of the tube were in the range of 1.5-2.5 with a variation in the output kinetic energy of 0-1400 J/m^3.

Consequently, the principal effect of the velocity of the vapor stream, as the experiments conducted show, appears in the upper half of the tube, i.e., for $H/d_1 < 50$, and therefore an increase in the height of the tube reduces the value of the velocity effect averaged over the surface, and consequently the average over the surface of the heat exchange coefficient, to a considerably greater extent than under the conditions of the condensation of a stationary vapor.

Thus, the results obtained reveal a number of properties connected with the condensation of a moving vapor. The calculation of heat exchange from the Nusselt equation with the introduction of a correction for the wave motion gives good agreement with experiment for an initial kinetic energy of the vapor stream of $\rho W_V'^2/2 \leq 60$ J/m^3.

The results of the experiment show that the heat exchange of a vertical tubular surface can be considerably intensified with the organization of concurrent flow of a vapor stream with high velocities.

The nature of the variation over the height of the surface of the indicators of the intensity of heat exchange obtained experimentally, like the data of visual observations, indicates that with high initial vapor velocities ($\rho W_V'^2/2 > 600$ J/m^3) the laminar section of film motion is practically absent, which must be kept in mind when analyzing the theoretical means of calculation of this process.

NOTATION

q_i	is the heat flux density at a section of the surface;
$t'_{2(i)}$ and $t''_{2(i)}$	are the temperatures of cooling water at the entrance and exit of the section under consideration;
t_W	is the temperature of the condensation surface;
t_V	is the temperature of the vapor;
ρ_V	is the density of the vapor;
r	is the heat of vaporization;
W'_V and W''_V	are the velocities of vapor at the entrance to the experimental section and at the exit from it;
Δt_1	is the thermal head from the side of the vapor;
α_1 and α_2	are the heat exchange coefficients for vapor and water, respectively.

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