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EXPERIMENTAL STUDY OF STEAM CONDENSATION ON A BED OF DISPERSED MATERIAL

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Results are presented from an experimental study of heat exchange in the condensation of water vapor on a bed of solid dispersed material.

The process of vapor condensation on dispersed material is used in various engineering apparatus, especially in the construction industry. Preliminary heating of concrete mixtures before forming has been empolyed in recent years in making structural elements. Analysis of the efficiency of this method shows that it is best to use steam to continuously heat the mixture at the site of formation of the element. However, it is nearly impossible to precisely design equipment for such heating due to a lack of theoretical and empirical data in the literature on heat transfer in vapor condensation on a flow of a dispersed solid material [1].

Examination of the results of studies of vapor condensation on liquid streams [2, 3] shows that the complexity and multifaceted nature of the physical phenomena realized in the mixing of vapor with a liquid phase do not allow an analytical solution or a solution, by numerical methods, of the system of differential equations which describes the course of the process in a first approximation. In connection with this, there remains only direct experiment as a recourse for determining the main factors affecting the rate of vapor condensation on a dispersed material and the relationship between these factors.

As the first step, we studied the condensation of steam during its interaction with a stationary bed of a dispersed solid. Preliminary analysis of the course of the process showed

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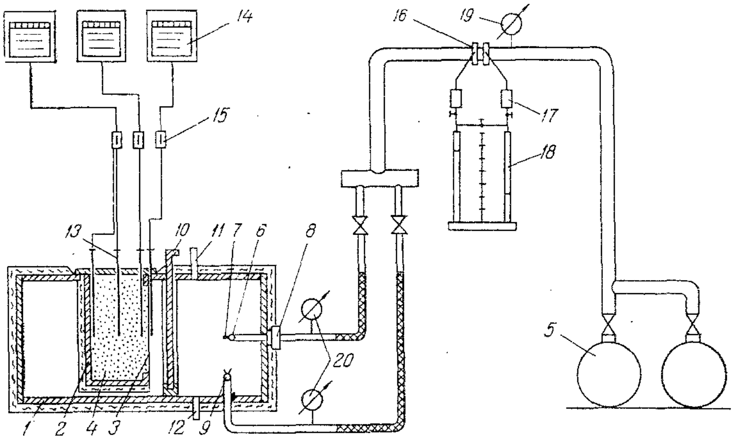

Fig. 1. Experimental unit.

that the change over time in the dimensionless excess temperature of the dispersed material in cross section δ can be represented in the form of the functional relation

$$\Theta = \varphi(\mathrm{Pe};\ \mathrm{Fo};\ W). \tag{1}$$

To validate (1) and determine the degree of the effect of each of the variables, we conducted tests on the unit illustrated in Fig. 1.

The unit consisted of an insulated body 1 containing a box 2 with a window 3 closed with a metal grid. The box contained the test material 4, which was sand from the Vol'sk quarry, with a mean particle diameter of $5 \cdot 10^{-4}$ m. The steam generated in the electric boilers 5 entered the unit through manifold 6 with cylindrical nozzles 7, the axis of which was located transversely with respect to the heat-exchange surface. The manifold inlet component 8 was in the form of a gland, which made it possible to change the distance from the nozzle edge to the heat-exchange boundary. To determine the heat transfer in the condensation of a slow-moving vapor, the unit was equipped with another manifold 9 with 16 0.002-m-diameter holes. The axis of the holes was located parallel to the heat-exchange surface. Located between the heat-exchange surface and manifolds 6 and 9 was a movable damper 10, preventing contact between the heat-exchanging media during heating of the body of the unit and its shutdown. The unit was also equipped with branch pipes 11 and 12 to drain the steam-water mixture and remove condensate.

The temperature of the steam at the heat-exchange boundary and the temperature in the thickness of the dispersed material were determined with calibrated Chromel—Copel thermocouples 13. The emf of the thermocouples was recorded with ÉPP-09 MZ single-point recording potentiometers 14 with a 0.1 precision rating. The thermocouples were connected to the potentiometers through a tumbler switch 15, making it possible to measure temperature at several points in the box. Vapor flow rate was measured with a double diaphragm 16 connected through equalizing vessels 17 to a U-shaped DT-50 differential manometer 18. The pressure of the vapor before the diaphragm and manifolds was measured with manometers 19 and 20 with a 0.5 precision rating. Time during the experiment was recorded with the aid of a stopwatch.

Before conducting the main experiments, we conducted a series of tests to: a) evaluate the kinetics of the change in vapor temperature at the heat-exchange boundary; b) compare the courses of the change in the temperature of the dispersed material with different methods of delivery of the heat-transfer agent.

It was established that the temperature of the vapor at the heat-exchange boundary reaches the saturation temperature at atmospheric pressure 1-2 sec after opening of the damper. It was also determined that the temperature of the dispersed material increases considerably more rapidly when the steam is introduced transversely with respect to the plane of the heat-exchange surface, from nozzles 7 (Fig. 1), than when it is introduced from the manifold 9, i.e., than in the case of condensation of a slow-moving vapor.

Considering this, we gave special attention to studying the rate of heating of the bed of dispersed material when steam was introduced across the heat-exchange surface.

The ranges of the main parameters in the tests were as follows: nozzle diameters 0.0031 and 0.0040 m; number of nozzles 2 and 4; distance from nozzle edge to heat-exchange boundary

TABLE 1. Factorial Experiment Plan

Pe	Fo				
	Fo_1	Fo_2	Fo_3	Fo_4	Fo_5
Pe_1	W_4	W_2	W_3	W_1	W_5
Pe_2	W_5	W_4	W_2	W_3	W_1
Pe_3	W_1	W_5	W_4	W_2	W_3
Pe_4	W_3	W_1	W_5	W_4	W_2
Pe_5	W_2	W_3	W_1	W_5	W_4

0.11, 0.13, 0.15, 0.17 m; steam exit velocity 260-360 m/sec; test duration 120-240 sec; relative moisture content of the dispersed material 1, 3, 5, 7, 10%. We also studied the dispersed material in the dry-air condition (DC). The velocity of the steam at the heat-exchange boundary ranged from 30 to 70 m/sec. This velocity was determined from the equation [4]

$$w_z = w_0 \frac{6.2\sqrt{\beta}}{\dfrac{z}{d_n} - \bar{z}_0}. \tag{2}$$

Assuming that Θ could be determined by multiplying Pe, Fo, and W or that these arguments are exponents, we thought it would be expedient to perform the experiment in accordance with the factorial plan shown in Table 1, with a change in all of the variables at five respective levels: $Pe \cdot 10^{-6} = 0.5$; 1.2; 1.9; 2.7; 3.3; $Fo \cdot 10^2 = 3.22$; 4.51; 6.44; 11.84; 18.93; W = DC; 1; 3; 7; 10%. Since the literature does not contain any information on the dependence of the diffusivity of sand on various factors — including moisture content and temperature — we took a constant value of $0.58 \cdot 10^{-6}$ m^2/sec for this quantity when we determined Pe and Fo. The experiment plan was randomized with a random numbers table.

We studied 60 regimes. In analyzing the test data, the measurements made in each regime were averaged, and we took their arithmetic mean for the theoretical values. Analysis of the accuracy of the experiment showed that the standard deviation was no more than ±10% with a confidence level of 0.95.

Figure 2 shows the dependence of Θ on W, Pe, and Fo. These curves were plotted from the test results and analysis of the matrix. The curves are approximated by the following equations:

$$\Theta_W = 0{,}182 W^{0.37}, \tag{3}$$

$$\Theta_{Pe} = 13430\,\mathrm{Pe}^{-0.77}, \tag{4}$$

$$\Theta_{Fo} = 15 \exp[-(326\,\mathrm{Fo})^{0.44}]. \tag{5}$$

Considering that

$$\Theta = k \Theta_W \Theta_{Pe} \Theta_{Fo}, \tag{6}$$

we finally obtain

$$\Theta = 0.72 \cdot 10^6 W^{0.37}\,\mathrm{Pe}^{-0.77} \exp[-(326\,\mathrm{Fo})^{0.44}]. \tag{7}$$

Figure 3 shows the curve of the relation

$$\mathrm{Fo} = \ln \frac{\Theta}{0{,}72 \cdot 10^6 W^{0.37}\,\mathrm{Pe}^{-0.77}} \tag{8}$$

and the test data.

The standard deviation of the empirical points relative to the approximating curve is ±13%.

Thus, the completed tests confirmed that the temperature change during heating in the condensation of a steam jet on a bed of dispersed solid material depends on the initial moisture content of the material and the velocity of the vapor at the heat-exchange boundary. Heating rate increases with an increase in the vapor velocity at the boundary, while an increase in the initial moisture content of the dispersed material lowers the rate of its heating.

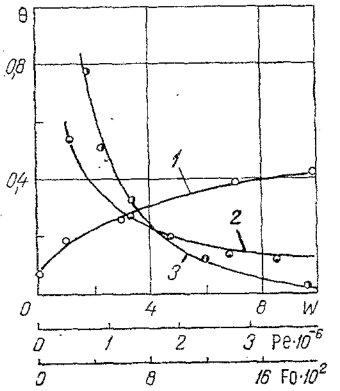

Fig. 2. Dependence of Θ on W, Pe, and Fo: 1) $\Theta_W = f_1(W)$; 2) $\Theta_{Pe} = f_2(Pe)$; 3) $\Theta_{Fo} = f_3(Fo)$.

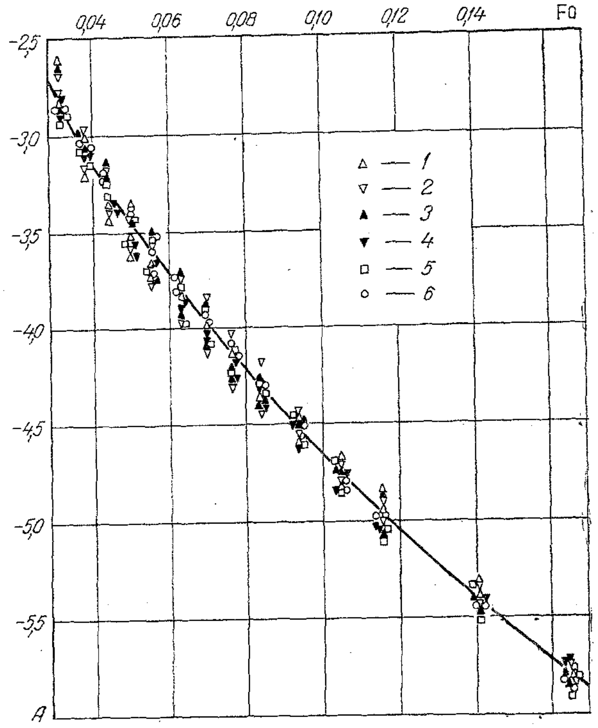

Fig. 3. Comparison of theoretical formula with test results: 1) W = DC; 2) 1%; 3) 3%; 4) 5%; 5) 7%; 6) 10%. $A \equiv \ln(\Theta/0.72 \cdot 10^6 W^{0.37} Pe^{-0.77})$.

Within the ranges of the parameters used in the present study, the dimensionless temperature of the dispersed solid material Θ can be calculated from Eq. (7) with an accuracy sufficient for engineering purposes (±15%).

NOTATION

T_0, initial temperature of the dispersed material, K; w_0, vapor exit velocity, m/sec; w_z, velocity of vapor at heat-exchange boundary, m/sec; δ, thickness of bed, m; d_n, nozzle diameter, m; z, distance from nozzle edge to heat-exchange boundary, m; τ, time, sec; B, initial absolute moisture content of the dispersed material, kg; G, weight of the dry dispersed material, kg; a, diffusion coefficient of the dispersed material, m^2/sec; $\Theta = (T_S - T_T)/(T_S - T_0)$, dimensionless excess temperature of the dispersed material in cross section δ; W, initial relative moisture content of the dispersed material, %; $\beta = 1, 2$, correction factor for momentum for the initial section of the jet; $z_0 = -2.54$, relative polar distance of the jet; k = 19.63, arithmetic mean of the constant coefficient found in the matrix analysis.

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TRANSITIONAL REGIME IN THE RAPID EVAPORATION OF LIQUIDS FROM CAPILLARY TUBES

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The region in which excess pressure exists in capillary tubes is determined. A table of values of excess pressure in the case of water evaporation is presented. The results of calculations are compared with experimental data. A new method is proposed for determining the radii of capillary tubes.

The use of Stefan's equation is generally accepted as an approach to theoretically describing the evaporation of liquids from a cylindrical capillary tube. This equation is valid when the atmospheric pressure is greater than the saturation pressure at the given temperature. The discrepancy between experimental results and the Stefan theory at room temperature is attributable to the contribution of liquid boundary films to the mass flow, a contribution which the theory ignores. However, this contribution can be ignored above 70°C [1] and, as numerous experiments have shown, Stefan's equation is satisfied with a high degree of accuracy. As the evaporation temperature of the liquid increases above the boiling point, the saturation pressure becomes greater than the atmospheric pressure and the Stefan regime of vapor flow in the capillary tube is replaced by viscous flow. However, viscous flow of the gas cannot explain the empirical fact of the generation of excess pressure inside a porous body at drying temperatures above the boiling point [2]. The excess-pressure generation has to do with a radius-independent counterdirected diffusional flow of air. As the dimensions of the capillary tube are reduced, this air flow is compensated for by an increase in the total pressure above the meniscus. Obviously, there should be a region which is intermediate between the Stefan and viscous regimes of vapor flow in capillary tubes. Let us turn our attention to this region, characterized by the presence of a pressure of the vapor—gas mixture above the meniscus which is higher than the saturation pressure at the given temperature.

The authors of [3] developed a theory of isothermal evaporation of liquids from capillary tubes at temperatures above the boiling point. They obtained an equation making it possible, with known boundary conditions, to calculate the excess pressure. After refining of the numerical multiplier and assuming that the slip diffusion coefficient is negligibly small, this equation is written in the form

$$\ln\frac{P_X}{P_X-P_s}=\frac{r^2(P_X^2-P_\infty^2)}{16\eta P_\infty D}. \tag{1}$$

To solve Eq. (1), a computing program was devised which makes it possible to determine P_X as a function of temperature and the tube radius with an accuracy limited only by the accuracy of the parameters introduced. The temperature dependences of the viscosities of the vapor and surrounding gas, the diffusion coefficient of the vapor—gas mixture, the pressure of the saturated vapor, and the heat of vaporization — all needed for the calculations — were taken from handbooks [4, 5].

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