STUDY OF THE PROCESS OF FROST FORMATION IN FINNED AIR COOLERS

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The results of an experimental study of frosting in finned air coolers with a different fin spacing are presented.

When air is cooled to temperatures below the dew point, a layer of frost, which increases the thermal and aerodynamic resistance, thereby lowering the coefficient of heat transfer and causing periodicity of operation of the equipment and requiring expenditures associated with the need to defrost the equipment, forms on the surface of the air conditioning equipment. A knowledge of the laws governing frost formation is a required prerequisite for the development of efficient designs of air coolers and the selection of optimal operating conditions. The number of studies concerning the laws governing the growth of frost is inadequate [1-5]. They clarify only the characteristics of frost formation under completely definite conditions.

In this connection, we posed the problem of studying in greater detail the laws governing frost formation in finned air coolers in a wider range of variation of their operational conditions. We tested equipment with a fin spacing of 8, 11, 13.4, 17.5, and 20 mm. Sections of length 170 mm, having two longitudinal and 5 transverse rows of tubes with an outer diameter of 25 mm, were placed in an aerodynamic channel with the dimensions 400 × 400 mm. The tubes were arranged in corridors, and the longitudinal and transverse spacing between the tubes were equal to 70 and 76 mm, respectively. The flat fins, mounted on the entire bunch of tubes, were made of a steel plate 0.4 mm thick. The finning factor varied from 6 to 13. The temperature of the finned surface was held fixed by an automatic cooling machine and was maintained constant throughout the experiments. The air was injected by a centrifugal fan with a dc electrical drive, which enabled smooth regulation of the number of revolutions. The flow rate of the air was determined with the help of precalibrated nozzles, and the velocity of the air in the channels of the air cooler was monitored by dynamic-head tubes. The mass velocity of the air varied in the course of the experiments from 2 to 13 $kg/m^2 \cdot sec$, while Reynolds number varied from 3000 to 30,000. The temperatures of the walls of the tubes, fins, and even of the incoming and outgoing air were measured with the help of thermocouples. The temperature of the incoming air varied from 5 to −15°C and the average temperature head varied from 6 to 18°C. The experimental stand was equipped with a heater and a humidifier and also with a device for measuring the moisture content of the air, which varied from 0.75 to 0.96. The thickness of the layer of frost was determined with the help of special moving scales, for which purpose the sections were equipped with viewing windows. We determined the mass of the frost by weighing the condensate after defrosting the air cooler. The duration of operation in a given operational state varied from 1 to 16 h. The layout of the experimental setup and the experimental procedure are described in detail in [6].

The results of the measurements and the visual observations showed that the intensity of frosting is higher during the initial period of operation of the air coolers ($\tau < 3$ h) and decreases with time. The mass of the forming frost and its thickness do not depend on the fin spacing for constant air-flow parameters. The thickness of the frost is practically identical at different points of the fin surfaces, evidently, because of the small dimensions of the equipment. It is larger in the initial section $l_0$, whose length is equal to about 340 mm (the length of the first two sections of the equipment), and decreases along the length. The thickness and mass of the frost on the finned surfaces increase with the relative humidity and the temperature of the incoming air and they increase as the temperature of the exterior surface decreases. The latter agrees with the results obtained in [2, 3].

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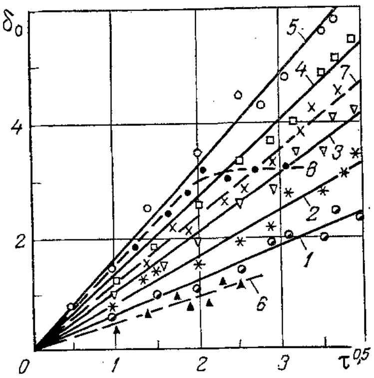


Fig. 1

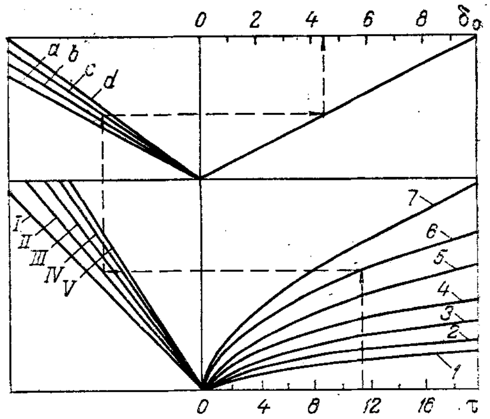


Fig. 2

Fig. 1. Values of the thickness of the layer of frost on the initial section with $\rho w$ = 6 kg/m²·sec; 1-5) based on the data obtained in this work; 6) [2]; 7) [3]; 8) [4]; 1) $\varphi=0.75$; $c_t=0.955$; 2) 0.81; 0.955; 3) 0.90; 0.955; 4) 0.96; 0.955; 5) 0.96; 0.896; 6) 0.72; 0.91; 7) 0.9; 0.896; 8) 0.9; 0.974. $\delta_0$, mm; $\tau$, h.

Fig. 2. Nomogram for determining the thickness of the frost on the initial section: 1) $\varphi=0.7$; 2) 0.75; 3) 0.8; 4) 0.85; 5) 0.9; 6) 0.95; 7) 1; I) $c_t$ = 0.84; II) 0.88; III) 0.92; IV) 0.96; V) 1; a) $\rho w$ = 2 kg/m²·sec; b) 4; c) 8; d) 12. $\tau$, h.

To take into account the effect of the temperatures of the air and of the exterior surface of the equipment on the process of frost growth, the following coefficient is introduced:

$$c_t = T_{\text{e.}} T_1^{-1}, \tag{1}$$

which for the conditions of the experiments varied from 0.894 to 0.98.

The nature of the change in the thickness of the frost layer as a function of time on the initial section is shown in Fig. 1. For comparison, the analogous dependences from [2-4] are also shown here by the broken lines. The effect of the relative moisture content of the air and of the temperature coefficient on the intensity of frosting, which increases with increasing $\varphi$ and decreasing $c_t$, is evident from Fig. 1. The results of the studies established that the mass velocity of the air in a narrow section of the equipment affects the intensity of frosting, which was also noted in [4] but was not observed in [3, 5]. The latter is apparently explained by the fact that in [3, 5] only the frost formation on the tubes was studied. A comparison of the results obtained here with the data in [2, 3] showed that they agree to within 6%. The data in [4] turned out to be too high for the period of operation $\tau$ < 10 h and too low for $\tau$ > 10 h. To calculate the thickness of the frost on the initial section, we obtained the formula

$$\delta_0 = 0.84 \cdot 10^{-3} (\rho w)^{0.15} \varphi^5 c_t^{-3.8} \tau^{0.5}. \tag{2}$$

Equation (2) takes into account the effect of all the basic factors on the process of frost formation. It is simpler for practical calculations than the analogous formulas presented in [3, 4], which have a more limited range of application. For convenience in determining the values of $\delta_0$ from Eq. (2), the nomogram shown in Fig. 2 was constructed.

As already noted, the thickness of the frost decreases along the apparatus. This is explained by the fact that as the frost is deposited, the moisture content of the air changes along the air conditioner. Figure 3 shows the dependences of the change in the dimensionless thickness of the layer of frost along the apparatus for different values of the relative moisture content of the air. It follows from Fig. 3 that as $\varphi$ decreases, the degree of nonuniformity of frost deposition along the air cooler increases somewhat. The instantaneous thickness of the layer of frost can be determined from the formula

$$\delta_l = \delta_0 (1 - 0.0057 \varphi^{-2.33} L^{1.75}). \tag{3}$$

For calculations of systems used to defrost the air coolers, it is necessary to know the mass of the frost formed over the period of operation. It was established that the spe-

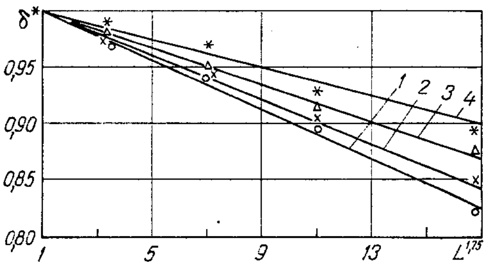

Fig. 3

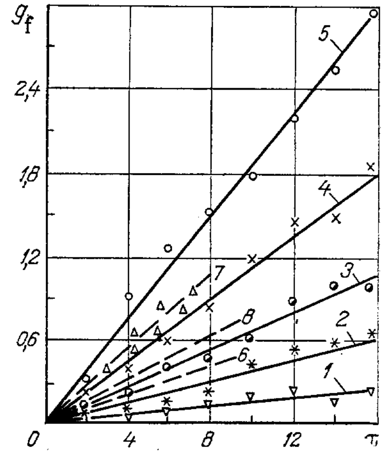

Fig. 4

Fig. 3. Change in the thickness of the frost along the air coolers: 1) $\varphi=0.75$; 2) 0.81; 3) 0.86; 4) 0.96.

Fig. 4. Values of the specific mass of the frost: 1-5) based on the experiment described here (same notation as in Fig. 1); 6) [4], $\varphi=0.82$; $c_t$ = 0.94; 7) [5], 0.95; 0.84; 8) [7], 0.75; 0.9. $g_f$, kg/m$^3$; $\tau$, h.

cific mass of the frost, forming on 1 m$^2$ of the finned surface, is proportional to the length of time the apparatus operated and depends on the parameters of the air flow. It increases with the mass velocity, relative humidity, and temperature of the incoming air. The nature of the change in the specific mass of the frost as a function of time is shown in Fig. 4. The dependences shown in this figure qualitatively agree with all known results. The effect of the mass velocity of the air is manifested in $g_f$ to the same degree as in the heat flux density, which agrees with [5]. Based on the analysis of the experimental data, the following relation was obtained for calculating $g_f$:

$$g_f = 0.03\,(\rho w)^{0.7}\,\varphi^{6.5}\,c_t^{-5.5}\,\tau. \tag{4}$$

The analogous dependences from [4, 5, 7] are shown in Fig. 4 by the dashed lines. A comparison of the results of a calculation based on (4) with the data presented showed that they agree to within ±20%, which permits judging the validity of the coefficient $c_t$ introduced in order to generalize the data obtained under different thermal conditions of operation of the air coolers.

To calculate the intensity of heat exchange under conditions of frost formation, in addition to the thickness of the layer of frost it is necessary to have data on its thermal conductivity, which, as follows from [1, 7], is uniquely related to the density of the frost. The density of the frost is easily determined based on (2)-(4):

$$\rho_f = g_f\,\delta_{cp}^{-1} = 35.7\,(\rho w)^{0.55}\,\varphi^{1.5}\,c_t^{-1.7}\,\tau^{0.5}. \tag{5}$$

It should be noted that there are essentially no other formulas for determining the instantaneous density of the frost during the operation of the air coolers. An analysis of expressions (2), (4), and (5) confirms the assumption [5] that the density and thickness of the layer of frost increase proportionally to the square root of the time; in addition, the increases in density and thickness of the layer each absorb approximately one-half of the condensing moisture.

## NOTATION

$T_e$, average absolute temperature of the exterior surface of the air cooler, determined during the initial period of operation; $T_1$, absolute temperature of the air entering the air cooler; $\rho$, density of the air at the average temperature; w, velocity of the air in the channels of the air cooler; $\varphi$, relative moisture content of the air at the inlet to the equipment in fractions of unity; $\tau$, duration of operation, h; $g_f$, mass of the frost settling on 1 m$^2$ of finned surface; $\rho_f$, density of the frost; $l_0$ and $l$, respectively, the length of the initial section and the running length of the equipment; $\delta_0$, $\delta_l$, $\delta_{cp}$, respectively, the thickness of the frost on the initial section, at a distance $l$, and the average thickness of the layer; $\delta^* = \delta_l \delta_0^{-1}$; $L = l l_0^{-1}$.

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# FILTRATION OF A MAGNETIC FLUID IN A DEFORMABLE POROUS MEDIUM


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The equations of motion of a magnetizing fluid are obtained in a deformable nonmagnetic porous medium.


Filtration of a magnetic fluid in nondeformable porous media was examined in [1, 2]. Derivation of the equations of magnetic fluid filtration in a deformable porous matrix consisting of deformable grains that are displaceable relative to each other is of interest.

It is assumed that an inhomogeneous magnetizing fluid fills the pore space entirely, i.e., the medium is saturated; there are no phase transitions associated with absorption (desorption) of the solid ferromagnet particles on the pore surface. The equations of fluid motion in a porous medium are obtained by local volume averaging [3] of the microequations of fluid motion in the pores, the Maxwell equation for the magnetic field in the pores and the matrix, as well as the equations of porous matrix deformation, with thermal expansion of the grains, from which the matrix consists, and the relative grain displacement taken into account. The magnetic properties of the medium as a whole (matrix + fluid) are characterized by the effective magnetic permittivity of the medium. The interphasal heat transfer between the liquid and solid phases is taken into account in the averaged heat conduction equations for the fluid and porous matrix.

The following relationships [3]

$$\langle \nabla_i f_\alpha \rangle = \nabla_i \langle f_\alpha \rangle + \sigma_{12} \langle n_{\alpha i} f_\alpha \rangle_{12}, \qquad \langle \partial_t f_\alpha \rangle = \partial_t \langle f_\alpha \rangle - \sigma_{12} \langle n_{\alpha i} u^i f_\alpha \rangle_{12}. \tag{1}$$

are used to average the microequations.


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