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PRESSURE LOSSES IN FINNED AIR COOLERS DURING FROST FORMATION

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UDC 536.24:621.945

The article presents the results of experimental investigations of the relative pressure losses in finned air coolers with different pitch of the finning.

When the operation of finned air coolers is accompanied by frost formation, the cross section for the passage of air continuously decreases, and in consequence the aerodynamic resistance increases and the performance of the fan and the air cooler decreases. Beginning at some instance after the onset of the deposition of frost, the heat-exchange surface of the apparatus operates with decreasing efficiency, and the expenditures on the transport of air continuously increase. When the regularities of the change of loss of pressure head during frost formation are known, a fan with the required characteristic can be chosen, and in addition it is possible to determine the optical regimes of operating the air coolers involved.

In the literature there are a limited number of investigations [1-4] shedding light on the change of the aerodynamic characteristics of air coolers upon frosting. The suggested methods of calculating pressure losses are not of a universal nature and cannot be extended to apparatus with a different geometry of the finning and different operating conditions. Ivanova [1] recommended that pressure losses be determined in the following way:

$$\Delta P = \Delta P_0 + A\tau^n,$$

where, in dependence on the geometry of the finning, the mass velocity, and the relative air humidity, more than thiry values for A and n are given. Yavnel' [2] presented the relative pressure losses in the form of dependences on the amount of frost settling on the surface of the air cooler, but there is no information on the method of determining this amount. On the other hand, the author recommends calculating the losses by formulas obtained without frost, and taking into account the reduction of the cross section for the passage of air. Calculations by this method are very difficult because for their realization it is required that the regularities of the growth of frost be known, and in addition, the cross section of the channels and the air speed in them have to be continuously recalculated. Lotz [3] correlated the aerodynamic losses with the density of the frost. Thus there does not exist so far a single method of calculating pressure losses in finned air coolers during frost formation that takes into account design features of the apparatuses as well as their operating conditions.

The present article represents an attempt at refining the regularities of the increase of pressure losses in finned air coolers with the object of generalizing them and of working out substantiated methods of calculation. In a wind tunnel 400 × 400 mm in size we investigated the operation of air coolers with finning pitches of 8, 11, 13.4, 17.5, and 20 mm. Frost formation in these air coolers had been investigated earlier [5]. The characteristics of the air coolers are presented in Table 1, and the experimental installation, the regimes and method of the experiments were described in [5, 6].

Vinnitsa Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 896-899, June, 1986. Original article submitted February 25, 1985.

TABLE 1. Characteristics of Air Coolers

Indicator	Air coolers				
	1	2	3	4	5
Finning pitch, mm	8	11	13,4	17,5	20
No. of pipes in depth	20	20	20	20	20
Cross section of slotted channel, m^2	0,0032	0,0044	0,00536	0,07	0,008
Hydr. diam. of channel, mm	15,686	21,4	25,92	33,5	38
Ratio of length of apparatus to hydraulic diameter	108	79,4	65,6	50,4	44
Full surface, m^2	38,5	29	24	78,9	16,8
Coeff. of finning β	13	9,6	7,85	6,3	5,5
Parameter σ	0,645	0,5	0,423	0,33	0,275

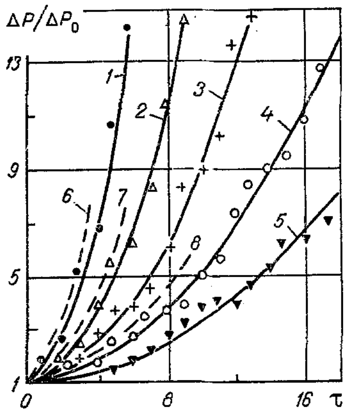

Fig. 1

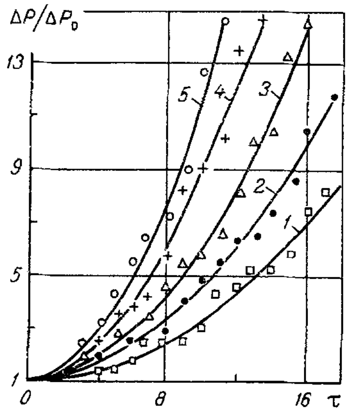

Fig. 2

Fig. 1. Relative pressure losses: 1-5) author's experiments with φ = 0.9, c_t = 0.97 (the numbers of the curves correspond to the numbers of the air coolers in Table 1); 6-8) [1] with φ = 0.88, c_t = 0.974; 6) σ = 0.66; 7) 0.485; 8) 0.37. τ, h.

Fig. 2. The effect of φ on $\Delta P/\Delta P_0$ with σ = 0.423, c_t = 0.97; 1) φ = 0.75; 2) 0.79; 3) 0.85; 4) 0.91; 5) 0.96.

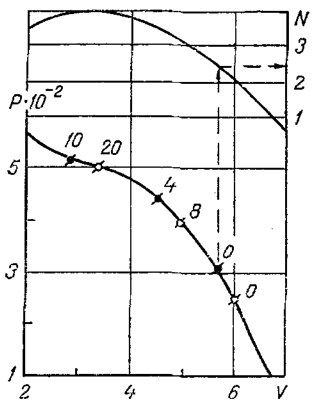

Fig. 3

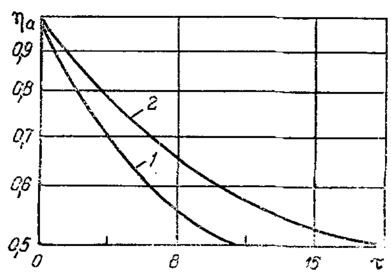

Fig. 4

Fig. 3. Running working points of air coolers with different finning pitch with φ = 0.9; c_t = 0.97. P, Pa; V, m^3/sec; N, kW.

Fig. 4. Running values of η_a of air coolers: 1) s_r = 11 mm; 2) 17.5.

In the course of the investigations it was established that the roughness of the frost affects the pressure losses only during the initial period of operation of the apparatus ($\tau < 2$). As the frost grows, its surface becomes smoothened, and the effect of roughness practically vanishes; this is in agreement with [2]. The increase of aerodynamic losses is due to the increased air speed in the channels of the air cooler in proportion to the increased thickness of the layer of frost. To shed light on the regularities of the increase ΔP, the experiments, like in previous works, were carried out with constant air flow rate. It was discovered that ΔP increases with rising temperature of the air supplied to the apparatus and with decreasing temperature of the finned surface. The effect of these temperatures was taken into account by the coefficient c_t which is the ratio of the absolute temperatures of the finned surface and the supplied air [5]. The change of relative pressure losses in air coolers with different finning pitch is shown in Fig. 1. Here, the magnitude of ΔP_0 corresponds to the pressure loss in an apparatus operating with the same air flow rate but without frost. The formulas for calculating ΔP_0 are presented in [6]. The dashed lines in Fig. 1 represent the theoretical data of [1] calculated for the same experimental conditions. The agreement between the results of the present authors and [1] may be regarded as perfectly satisfactory since the divergence between them does not exceed ± 12%. The data of [3] were found to be 40-50% too high.

Previously it was noted [1, 3, 4] that the principal factor affecting the processes of frost formation and the increase ΔP is the relative air humidity. Nevertheless, the degree of the effect of φ on ΔP was not evaluated quantitatively. The nature of the effect of the relative air humidity on the magnitude of $\Delta P/\Delta P_0$ is shown in Fig. 2. The increase of the relative losses with increasing φ is due to the great intensity of frost deposition [5]. Analogous dependences were also obtained for other air coolers. Generalization of the experimental data made it possible to obtain a formula suitable for practical calculations:

$$\Delta P/\Delta P_0 = 1 + 2.327\sigma^{3,4}\varphi^4 c_t^{-3}\tau^2, \tag{1}$$

yielding an error within the limits ± 6%.

The calculation operations are simplified if the value of $\Delta P/\Delta P_0$ is correlated with the thickness of the layer of frost. The correlation between relative pressure losses and the thickness of the frost has the form

$$\Delta P/\Delta P_0 = \exp[0.7\sigma^{1,5}(\delta_f \cdot 10^3)^2]. \tag{2}$$

The running values of δ_f can be easily determined by the formula or the nomograph from [5].

The obtained results express only the general tendencies of the change of $\Delta P/\Delta P_0$ in finned air coolers during frost formation. Under real operating conditions of a cooling system, the absolute values of the aerodynamic losses are smaller than the theoretical ones, and they depend on the shape of the fan characteristic since the delivery of the fan decreases simultaneously with increasing ΔP. Therefore, to evaluate the effectiveness of operation of a given air cooler with a certain type of fan, the running position of the working points on the fan characteristic has be found. When the characteristic of the fan is described by an equation, then this problem can be easily realized on a computer with the aid of formula (1). For industrial air coolers axial fans of the Central Aerohydrodynamic Institute of different series are used. On the characteristic of the fan of the Central Aerohydrodynamic Institute series UK-2M in Fig. 3 the theoretical working points of air coolers with a heat-exchange surface of 200 m² are shown. The dark dots correspond to an apparatus with s_r = 11 mm, the light dots to s_r = 17.5 mm. The numbers above the dots indicate the time of operation in hours. It can be seen from Fig. 3 that within twenty hours of operation of an air cooler with s_r = 17.5 mm the delivery of the fan drops by a factor of 1.8, and the required pressure head doubles. The same change of V and P for an apparatus with s_r = 11 mm is attained already after 10 hours of operation. In the first air cooler the theoretical thickness of the frost in the first sections is 4.8 mm [5], and in the second one 3.5 mm. It can also be seen from Fig. 3 that expenditures on the transport of refrigerant increase constantly, in spite of the reduced delivery of the fan. The relative increase of power required for the supply of air can be evaluated by the aerodynamic efficiency, i.e.,

$$\eta_a = N_0/N. \tag{3}$$

The time-dependent change of η_a for the air coolers under consideration is shown in Fig. 4. The investigations show that under conditions of frost formation air coolers with smaller finning pitch, in which η_a is lower and the work cycle to thawing is shorter, operate more poorly from the aerodynamic point of view. However, a final evaluation of the effectiveness of operation of air coolers has to be carried out with the thermal efficiency taken into account:

$$\eta_T = Q/Q_0, \tag{4}$$

and if its running values are to be determined, the regularities of the processes of heat transfer under conditions of growing frost have to be known.

NOTATION

P, pressure; ΔP, pressure losses; τ, time; φ, relative air humidity; δ_f, thickness of frost; V, volumetric flow rate; N, power; Q, refrigerating capacity; δ_r, thickness of the fin; s_r, finning pitch; d, outer pipe diameter; s_1, transverse pitch between pipes; d_h, hydraulic diameter of slotted air cooler channels; β, degree of finning; $\sigma = 2\delta_r s_r s_1 \beta \cdot (d^2 d_h)^{-1}$, parameter taking into account the design features of finned surfaces [6]. The subscript 0 denotes the initial values of magnitudes for $\tau = 0$.

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