ENERGY ANALYSIS OF THE ENGINEERING-ECONOMIC OPTIMIZATION OF CONVECTIVE HEAT-TRANSFER SURFACES

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The influence of the specific costs of the heat transfer surface, 1 kW of installed power of the blower and motor, 1 kW·h of electrical energy consumption by it, operating time of the surface, and other factors on the optimum specific power expenditure to force heat-transfer fluids through the ducts of heat-transfer surfaces is investigated. The minimum engineering-economically justified operating time of the surface is determined.

Introduction

The comparison of heat-transfer surfaces and the determination of their optimal operating conditions are among the most crucial problems of modern times. The main reasons for the heightened interest of designers and operations specialists in these problems are the demands of the world economy of material and energy resources in the manufacture and utilization of various engineering facilities, including such ubiquitous equipment as heat exchangers, and also the existence of an enormous data base on heat-transfer laws and functional relations.

A great many papers have been devoted to the comparison of convective heat-transfer surfaces. Noteworthy among the earliest pioneering studies is the work of Gukhman [1], Kirpichev [2], Yudin [7, 8], Mitskevich [9], Kuznetsov and Lipatov [10], and other researchers.

The materials of Kays and London's book [11] are distinguished by outstanding depth of analysis and broad coverage of diverse modifications of the compared heat-transfer surfaces.

Methods for the augmentation of convective heat transfer in ducts of intricate configuration have been investigated in close coordination with the energy efficiency of heat-transfer surfaces by Kalinin in collaboration with fellow workers and students [12-14] and by other authors.

A significant number of papers have also been published on the optimization of convective heat-transfer processes and heat exchangers [15, 16, etc.]. One of the most profound studies of this topic, in our opinion, is the work of Kalafati and Popalov [17], in which the heat-transfer processes, flow resistances, and cost characteristics of heat-transfer surfaces are analyzed from a unified energy point of view.

The present study is also based on the energy approach and represents an elaboration of the basic principles of our earlier work [18].

Foundation of the Analytical Relations

One of the primary means of augmenting heat transfer in the forced motion of a heat-transfer fluid (HTF) is to increase its velocity, whereupon greater power is spent in forcing the HTF through the ducts of the heat-transfer surface.

An analysis of experience in the design and operation of tubular-jacket and finned heat exchangers for various applications has shown that the specific power expenditures in forcing through the HTFs in specification regimes range from 2.0 W/m^2 to 1000 W/m^2. Additional information on this problem may be found in [19].

The objective of the present study is to determine the optimum specific power expenditures in forcing HTFs through the ducts of heat-transfer surfaces as a function of their principal cost and performance characteristics.

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The optimum specific power expenditure in forcing a HTF through the ducts of a heat-transfer surface in engineering-economic optimization are determined from the condition

$$\frac{d(e_N)}{d\left(\frac{N}{F}\right)}=0, \tag{1}$$

where

$$e_N=\frac{E_s}{Q_a}+\frac{E_b}{Q_a}+\frac{E_o}{Q_a}. \tag{2}$$

Allowing for the fact that the capital expenditures for construction of the heat-transfer surface E_s and for construction and installation of the blower and its motor E_b, the operating expenditures E_o, and the per annum quantity of heat transmitted by the heat-transfer surface Q_a can be represented by the equations

$$E_s=(a+p)k_sF;\quad E_b=\frac{(a+p)k_b\left(\frac{N}{F}\right)^{Ee}_{opt}rF}{10^3\eta_e};$$

$$E_o=\frac{k_o\left(\frac{N}{F}\right)\tau F}{10^3\eta_e};\quad Q_a=\alpha\Delta t\tau F,$$

we write the one-way heat-transfer equation (2) in the form

$$e_N=\frac{(a+p)k_s10^3}{\alpha\Delta t\tau}+\frac{(a+p)k_b\left(\frac{N}{F}\right)^{Ee}_{opt}r}{\alpha\Delta t\tau\eta_e}+\frac{k_o\left(\frac{N}{F}\right)}{\alpha\Delta t\eta_e}. \tag{3}$$

Taking into account the expression for the specific power expenditure to force the HTF through hydraulically smooth tubes:

$$\frac{N}{F}=\frac{A\,\mathrm{Re}^{3-m}\nu^3\rho}{8d_e^3}, \tag{4}$$

along with the equation for the heat-transfer coefficient

$$\alpha=\frac{\lambda}{d_e}c\left[\frac{8d_e^3\left(\frac{N}{F}\right)}{A\nu^3\rho}\right]^{\frac{n}{3-m}}\mathrm{Pr}^k\varepsilon_t \tag{5}$$

we can write Eq. (3) in the form

$$e_N=B\left[\frac{(a+p)k_s10^3}{\left(\frac{N}{F}\right)^{\frac{n}{3-m}}}+\frac{(a+p)k_b\left(\frac{N}{F}\right)^{Ee}_{opt}r}{\left(\frac{N}{F}\right)^{\frac{n}{3-m}}\eta_e}+\frac{k_o\tau\left(\frac{N}{F}\right)^{\frac{3-m-n}{3-m}}}{\eta_e}\right], \tag{6}$$

where

$$B=\frac{d_e\left[\frac{A\nu^3\rho}{8d_e^3}\right]^{\frac{n}{3-m}}}{\lambda c\,\mathrm{Pr}^k\varepsilon_t\Delta t}.$$

Executing the procedure for the differentiation of Eq. (6) according to condition (1) with allowance for the fact that $B \neq 0$, we obtain

$$\left(\frac{N}{F}\right)^{Ee}_{opt}=\frac{nk_s10^3\eta_e}{(3-m-n)\left[\frac{k_o\tau}{(a+p)}-\frac{k_br}{(3-m-n)}\right]}. \tag{7}$$

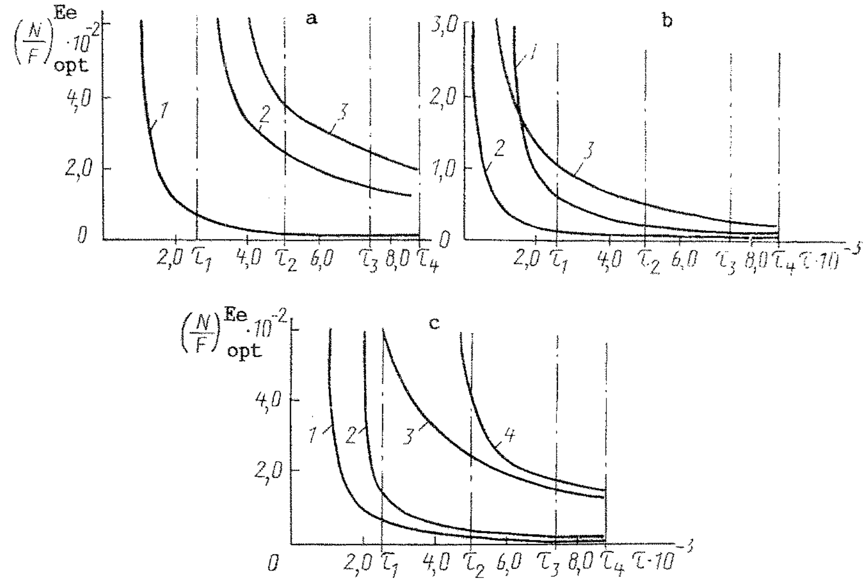

Fig. 1. Engineering-economic optimum specific power expenditure to drive the heat-transfer fluid $(N/F)_{opt}^{Ee}$, W/m², vs operating time of the heat-transfer surface τ, h/year (general characteristics of the surface: a = 0.1 year^{-1}, p = 0.12 year^{-1}; η_e = 0.7; r = 1.2; m = 0.8). a) k_o = 1.5 kop/kW·h; k_b = 100 rubles/kW: 1) k_s = 24 rubles/m²; 2) 240; 3) 380. b) k_b = 100 rubles/kW: 1) k_o = 1.5 kop/kW·h, k_s = 24 rubles/m²; 2) 6, 24; 3) 6, 240. c) k_o = 1.5 kop/kW·h: 1) k_b = 100 rubles/kW, k_s = 24 rubles/m²; 2) 200, 24; 3) 100, 240; 4) 200 and 240.

A more complete substantiation of the functional relation (7) is given in [18].

It follows from this equation that the optimum value of the specific power expenditure to drive the HTF is determined entirely by the flow regime of the HTF n, m, the specific cost of the heat-transfer surface k_s, the cost of 1 kW·h of electrical energy consumption by the blower and its motor k_o, the specific cost of 1 kW·h k_b, the installed power reserve r and effective efficiency η_e of the blower and its motor, the operating time τ, and the net return of the heat-transfer surface (a + p); it does not depend on the type of HTF and its thermophysical characteristics or on the specific structural characteristics of the heat-transfer surface.

Analysis of Engineering-Economic Optimization Conditions

The analysis of Eq. (7) on the basis of realistic values of the above-indicated characteristics of the surfaces is of major importance. To set up a numerical experiment, following the recommendations of Yufa and Ioffe [20], we adopt the following base values of the governing variables: k_s = 24 rubles/m²; k_b = 100 rubles/kW; k_o = 1.5 kop/kW·h [1 kopeck = 1/100 ruble]; a = 0.1 year^{-1} and p = 0.12 year^{-1}; η_e = 0.7.

In all the computations we assume turbulent flows of the HTF in hydraulically smooth ducts of the heat-transfer surface (n = 0.8, m = 0.25) and a 20% installed power reserve of the blower and its motor (r = 1.2).

A good starting point for the analysis of Eq. (7) for the engineering-economic optimization of convective heat-transfer surfaces is to determine the influence of the operating time and specific cost of the heat-transfer surface. In studying the results of the analysis, we bear in mind that round-the-clock operation of the surface for 365 days per year amounts to 8760 h/year (τ_4), triple-shift operation of the surface for 310 days per year, i.e., exclusive of Sundays and holidays, comes to 7440 h/year (τ_3), double-shift operation for 310 days is 4960 h/year (τ_2), and single-shift operation for 310 days per years is 2480 h/year (τ_1).

The results of our determination of the optimum specific power expenditures to drive the HTF in engineering-economic optimization of the heat-transfer surface for once-through (noncirculating) flow under the above-stated conditions are shown in Fig. 1. It is evident from the figure that an increase in the operating time of the heat-transfer surface is accompanied by a reduction in the optimum specific power expenditure to drive the HTF through the ducts of this surface. It follows from Fig. 1a that when the specific cost of the heat-transfer surface increases, the values of the optimum specific power expenditure to drive the HTF, given equal operating time of the compared surfaces, also increases.

For example, in double-shift operation (τ_2) the factor $(N/F)_{opt}^{Ee}$ is equal to 24.4 W/m² for surfaces with k_s = 24 rubles/m², 244 W/m² for surfaces with k_s = 240 rubles/m², and 390 W/m² for surfaces with k_s = 380 rubles/m². It is evident from the figure that when the operating time of the heat-transfer surface falls below 900 h/year (or, more precisely, below 902.3 h/year), the function $(N/F)_{opt}^{Ee} = f(\tau)$ (curve 1) suffers a discontinuity. This means that in order to ensure optimal engineering-economic operating conditions for the given heat-transfer surface at $\tau \le 900$ h/year, the specific power expenditure to overcome the flow resistance of the ducts of the heat-transfer surface must be infinite and, accordingly, an infinite velocity must be imparted to the HTF in the ducts, all of which, of course, is absurd.

It is certain, however, that optimal engineering-economic operating conditions cannot possibly be ensured for the investigated heat-transfer surface if it operates less than 900 h/year.

The minimum engineering-economically justified operating time of the heat-transfer surface can be determined from relation (7). Thus, $\tau_{opt.min}^{Ee}$ is achieved for

$$\left(\frac{N}{F}\right)_{opt}^{Ee} = \infty, \tag{8}$$

which is feasible under the condition

$$\frac{k_o \tau_{opt.min}^{Ee}}{(a+p)} - \frac{k_b}{(3-m-n)} = 0, \tag{9}$$

so that

$$\tau_{opt.min}^{Ee} = \frac{k_b (a+p)}{k_o (3-m-n)}. \tag{10}$$

It is evident from Eq. (10) that curves 1, 2, and 3 in Fig. 1a have the same minimum engineering-economically justified operating time for the analyzed surfaces, since $\tau_{opt.min}^{Ee}$ does not depend on the specific cost of the heat-transfer surface, but is determined entirely by the quantities involved in Eq. (10).

We can also conclude from the analysis of Fig. 1a that the engineering-economic optimum for more expensive surfaces requires higher specific power expenditures to force the HTF through the ducts formed by these surfaces. As the operating time of the heat-transfer surface is increased, the engineering-economic optimum is attained under milder (less forced) operating conditions.

The investigation of the operating conditions of the heat-transfer surface according to Eq. (7) can yield information, for example, on the minimum operating time of the surface with assurance of the engineering-economic optimum if the specific power expenditure to drive the HTF has a set limit (e.g., 500 W/m²). According to Fig. 1a, this limit requires that a surface with k_s = 24 rubles/m² operate for a minimum time of 1050 h/year (curve 1), a surface with k_s = 240 rubles/m² for 2900 h/year (curve 2), and one with k_s = 380 rubles/m² for 4100 h/year (curve 3).

Figure 1b shows the results of a calculation of the optimum specific power expenditure to force the HTF through the ducts of the heat-transfer surface as a function of the operating time and the specific cost of the surface and as a function of the specific cost of the electrical energy consumption to drive the blower.

It is evident from a comparison of curves 1 and 2 in Fig. 1b that the behavior of the function $(N/F)_{opt}^{Ee} = f(\tau)$ has not changed, but the optimum specific power expenditure now depends strongly on the specific cost of electrical energy per kW·h. An increase in the kW·h cost of electrical energy, all other characteristics remaining the same, is accompanied

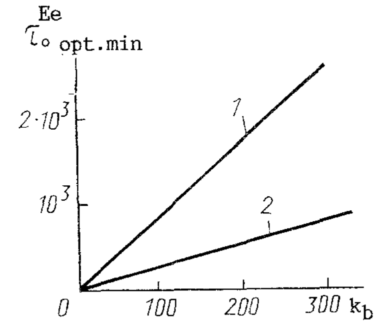

Fig. 2. Minimum engineering-economically justified optimum operating time of the heat-transfer surface $\tau_{opt.min}^{Ee}$, h/year, vs specific costs of 1 kW installed power of the blower and motor and 1 kW·h of electrical energy consumption k_b, rubles/kW. 1) k_o = 1.5 kop/kW·h; 2) 6 kop/kW·h.

by an appreciable reduction in the optimum specific power expenditure to drive the HTF, a diminution of the influence of the surface operating time on the optimum specific power expenditure, and a decrease in the minimum surface operating time at which the function $(N/F)_{opt}^{Ee} = f(\tau)$ becomes meaningless. Indeed, $\tau_{opt.min}^{Ee}$ = 902.3 h/year for k_o = 1.5 kop/kW·h and a specific cost of the surface equal to 24 rubles/m², and $\tau_{opt.min}^{Ee}$ = 225.6 h/year for k_o = 6 kop/kW·h and the same specific cost of the surface.

It should be noted that an energy cost of 6 kop/kW·h is typical of shipboard conditions, when electrical energy is produced by marine diesel-powered generators using diesel fuel.

Curve 3 in Fig. 1b represents the optimum specific power expenditure as a function of the surface operating time under the conditions k_s = 240 rubles/m² and k_o = 6 kop/kW·h. It follows from Eq. (10) that the minimum engineering-economically optimum operating times of the heat-transfer surfaces represented by curves 2 and 3 in Fig. 1b are identical.

One conclusion that might be drawn from the analysis of Fig. 1b is that more money spent on the electrical energy consumption of the blower motor will abate the demands on the forcing of heat transfer and on the operating time of the heat-transfer surface. Naturally, this "gain" is chimerical; even on purely intuitive grounds, it is extravagant.

Figure 1c shows the results of a calculation of the optimum specific power expenditures to drive the HTF as a function of the surface operating time and the specific cost per installed kilowatt of power of the blower and its motor. It is evident from the figure that curves 1 and 2 practically coincide when the heat-transfer surface operates for more than 4000 h/year. If the operating time of the investigated surfaces falls below τ_1, the differences between the optimum specific expenditures becomes very large. The function $(N/F)_{opt}^{Ee} = f(\tau)$ becomes meaningless at $\tau_{opt.min}^{Ee}$ = 1804.6 h/year (curve 2 in Fig. 1c), which means that this surface cannot possibly operate cost-effectively for any specific power expenditure to drive the HTF if it runs for less than 1800 h/year.

Curve 4 in Fig. 1c is the most dramatic of all those discussed so far. According to this curve, under the assumed conditions of the analysis, for a specific cost of the heat-transfer surface k_s = 240 rubles/m², and for a specific cost of installed power of the blower and motor k_b = 200 rubles/kW, single-shift operation of the surface can never be optimum, owing to the exceedingly high value of the engineering-economic optimum; double-shift operation can ensure optimization, but only when the specific power expenditure to drive the HTF exceeds 500 W/m².

Figure 2 shows the minimum engineering-economically optimum operating time of the heat-transfer surface ($\tau_{opt.min}^{Ee}$) as a function of the specific costs per 1 kW·h electrical energy consumption and 1 kW installed power of the blower and motor at $a + p = 0.22$ year^{-1}, $r = 1.2$, and $3 - m - n = 1.95$.

It is evident from Fig. 2 that for equal cost of 1 kW·h of electrical energy $\tau_{opt.min}^{Ee}$ increases linearly with the specific cost of 1 kW of installed power of the blower and motor. For equal specific cost of 1 kW of installed power of the blower and motor the minimum engineering-economically justified operating time of the surface decreases linearly with increasing cost of 1 kW·h of electrical energy consumption, all other conditions remaining fixed.

The foregoing analysis of the equations for the engineering-economic optimization of convective heat-transfer surfaces does not exhaust the possibilities of these equations, nor is the analysis itself complete. The numerical data are of independent interest, because they provide realistic approximate values of the optimum energy and temporal characteristics of heat-transfer surfaces operating with turbulent motion of the HTFs.

Additional characteristics of the surface can be introduced in the proposed equations to make them more complete, but then naturally they will be more cumbersome.

CONCLUSIONS

Our energy analysis of the conditions for engineering-economic optimization of convective heat-transfer surfaces has enabled us to ascertain the influence of the specific cost of the heat-transfer surfaces, 1 kW of installed power of the blower and its drive motor, 1 kW·h of electrical energy consumption, and other factors on the optimum specific power expenditures to force the heat-transfer fluid through the ducts of the heat-transfer surface.

The results of the study can be used:

to establish the optimum specific power expenditure to force the HTF through the ducts of particular heat-transfer surfaces and, on the basis of this information, to execute optimal heat exchanger design;

to assess the influence of fiscal, operational (electrical and hydraulic), and temporal characteristics on the conditions of engineering-economic optimization of a heat exchanger in its design phase;

to establish the influence of the operating time of a heat-transfer surface in hours per year on the optimum loads of a heat exchanger and to determine the engineering-economically substantiated minimum operating time of the heat-transfer surface, setting the stage for the development of clearly defined recommendations for the optimal operating conditions of a projected heat exchanger installation;

to carry out an engineering-economic analysis of heat exchangers already in operation and to determine their optimal working conditions.

NOTATION

e_N, normalized per annum expenditures for construction and operation of heat-transfer surface; N/F, specific power expenditure to overcome fluid resistance of ducts in heat-transfer surface; d, differential symbol; E_s, E_b, E_o, per annum capital expenditures for construction of heat-transfer surface, construction and installation of blower and motor, and operation of the latter; Q_a, per annum quantity of heat transmitted through heat-transfer surface; k_s, k_b, k_o, specific costs of heat-transfer surface, 1 kW of installed power of blower and motor, and 1 kW·h of electrical energy; a, fraction of annual amortized deductions; p, efficiency factor of capital investiments; r, power reserve factor of blower and motor; τ, operating time of heat-transfer surface, h/year; η_e, efficiency of blower and motor; α, heat-transfer coefficient; Δt, average differential temperature; A, numerical coefficient of functional relation for determining hydraulic loss factor; ν, ρ, kinematic viscosity coefficient and density of heat-transfer fluid; d_e, equivalent diameter of duct in heat-transfer surface; Re, Pr, Reynolds and Prandtl numbers; $\varepsilon_t = (Pr_f/Pr_w)^{0.25}$, parameter characterizing direction of heat flux; λ, thermal conductivity of heat-transfer fluid; m, n, k, numbers appearing in similitude exponents. Indices: N, normalized, Ee, engineering-economic; opt, optimum; min, minimum; f, fluid; w, wall.

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