THERMODYNAMIC EFFICIENCY OF HEAT EXCHANGERS

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Expressions are obtained to determine the exergetic efficiency of heat exchangers $\eta_э$ as a function of such dimensionless parameters as the energetic efficiency of the heat exchangers, the relationship between the thermal equivalents of the thermal carriers, the dimensionless initial temperature of the hot heat carrier $\overline{T}_1 = T_1/\Delta T_m$ and the temperature of the environment $\overline{T}_0 = T_0/\Delta T_m$. In the domain of high environment temperature the quantity $\eta_э$ rises with the increase in the value of the parameter $\overline{T}_1$ while in the domain of low environment temperature the dependence $\eta_э = f(\overline{T}_1)$ is extremal in nature and reached maximal values for $\overline{T}_1 = 1.75$-2.25.

The exergetic method permits estimation of the thermodynamic efficiency of a heat exchanger most objectively by taking account of not only the quantitative but also the qualitative characteristics of the thermal carriers [1, 2]. Exergy losses during heat transfer are associated primarily with heat transmission for a finite temperature difference between the heat carriers $\Delta T \neq 0$. Consequently, for instance, the exergy increment ΔE of the thermal carrier being heated in a heat exchanger operating in the high temperature domain of the environment T_0 is less than the reduction in exergy ∇E of the heating thermal carrier.

A heat exchanger in which $\Delta T \to 0$, i.e., there are no exergy losses ($\Delta E = \nabla E$), is taken as ideal in [1, 3] for estimation of the thermodynamic efficiency of a heat exchanger. The assumption is made here that in this case the maximal quantity of transmittable exergy will equal the magnitude of the exergy reduction in the heating thermal carrier in the present heat exchanger with fixed heat exchange surface. Actually to achieve the condition $\Delta T \to 0$ in an ideal heat exchanger it is necessary that the heat exchange surface be infinitely large ($F \to \infty$). The final temperatures of not only the heated but also the heating thermal carriers change in such a heat exchanger. Consequently, the final temperature of the heated thermal carrier reaches the initial temperature of the heating carrier. From the viewpoint of the first law of thermodynamics, when just the thermal carrier energy is taken into account, the energetic efficiency of the heat exchanger is defined as the ratio between the actually transferred quantity of heat and the quantity of heat that would be transferred in an ideal heat exchanger.

The problem is posed in this paper of examining the efficiency of heat exchangers on the basis of the second law of thermodynamics by taking a heat exchanger with $F \to \infty$ as ideal. For a heat exchanger with initial thermal carrier temperatures T_1, T_4 and final T_2, T_3 (Fig. 1), the exergetic heat exchanger efficiency (by analogy with the heat exchanger energetic efficiency [4]) with the fact that heating of a cold thermal carrier for heat exchange occurring above the environment temperature and cooling a warmer heat carrier for heat transfer occurring below the environment temperature taken into account is a useful effect can be written:

for $T_4 > T_0$

$$\eta_э^x = \frac{W_x (e_3 - e_4)}{W_{min} (e_1 - e_4)}, \tag{1}$$

for $T_1 < T_0$

$$\eta_э^r = \frac{W_r (e_2 - e_1)}{W_{min} (e_4 - e_1)}. \tag{2}$$

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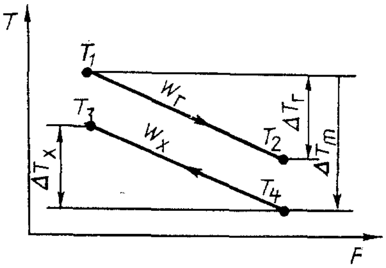

Fig. 1. Thermal carrier temperature distribution in a heat exchanger.

Let us examine heat exchanger operation in the domain above the environment temperature ($T_4 > T_0$). Let us substitute the value of the dimensionless thermal equivalent of a cold thermal carrier $\overline{W}_x = W_x/W_{min}$ and let us express the magnitude of the specific thermal carrier exergies in terms of their temperatures

$$\eta_э^x = \overline{W}_x \frac{(T_3 - T_0 - T_0 \ln T_3/T_0) - (T_4 - T_0 - T_0 \ln T_4/T_0)}{(T_1 - T_0 - T_0 \ln T_1/T_0) - (T_4 - T_0 - T_0 \ln T_4/T_0)}. \tag{3}$$

For $W_x < W_\Gamma$, $\overline{W}_x = 1$, while for $W_x > W_\Gamma$, $\overline{W}_x = W_x/W_\Gamma$.

If the magnitudes of the change in temperature of the heated thermal carrier $\Delta T_x = T_3 - T_4$ and the maximal heat carrier temperature difference $\Delta T_m = T_1 - T_4$ are substituted into (3), then after appropriate manipulations we can write

$$\eta_э^x = \overline{W}_x \frac{\Delta T_x - T_0 \ln T_3/T_4}{\Delta T_m - T_0 \ln T_1/T_4}. \tag{4}$$

The quantity ΔT_x in (4) can be determined in terms of the energetic efficiency η_x of the heat exchanger according to the heated thermal carrier [6]

$$\Delta T_x = \eta_x \Delta T_m. \tag{5}$$

The quantity η_x is determined from known expressions [5, 6] as a function of the thermal carrier motion scheme (forward current, countercurrent) and two dimensionless parameters; the relationship of the thermal equivalents of the thermal carriers W_x/W_Γ and the degree of heat transfer according to the heated thermal carrier $\vartheta_x = KF/W_x$. In fact, the quantity ϑ_x is analogous to the number of transfer units NTU utilized to compute the heat exchanger energetic efficiency [4].

We select the final and initial temperatures T_3 and T_4 of the heated thermal carrier in terms of the initial temperature of the warming thermal carrier T_1 and the maximal thermal carrier temperature difference ΔT_m: $T_3 = T_1 - \Delta T_m + \Delta T_x = T_1 - \Delta T_m + \eta_x \Delta T_m$; $T_4 = T_1 - \Delta T_m$ in conformity with Fig. 1. Substituting the values T_3 and T_4 of the thermal carrier temperatures as well as the dimensionless initial temperature $\overline{T}_1 = T_1/\Delta T_m$ of the hot thermal carrier and the dimensionless environment temperature $\overline{T}_0 = T_0/\Delta T_m$ into (4), we obtain after appropriate manipulations

$$\eta_э^x = \overline{W}_x \frac{\eta_x - \overline{T}_0 \ln \left(1 + \dfrac{\eta_x}{\overline{T}_1 - 1}\right)}{1 - \overline{T}_0 \ln \left(\dfrac{\overline{T}_1}{\overline{T}_1 - 1}\right)}. \tag{6}$$

The expression (6) permits determination of the exergetic heat exchanger efficiency in the domain above the environment temperature T_0 as a function of the dimensionless parameters $\overline{T}_1$, $\overline{T}_0$, η_x, and $\overline{W}_x$ given just by the initial conditions. The graphical dependence $\eta_э^x = f(\overline{T}_1, \eta_x)$ constructed according to (6) for $T_0 = 273$ K, $\Delta T_m = 100$ K ($\overline{T}_0 = 273/100 = 2.73$) and $\overline{W}_x = 1$ is represented in Fig. 2. Within the limits of values of the dimensionless temperature $\overline{T}_1 > 6$ ($T_1 > 600$ K), the quantity $\eta_э^x$ is practically independent of the value of $\overline{T}_1$ and is determined mainly by the magnitude of the heat exchanger energetic efficiency η_x, actually reaching its value. Thus, for $\overline{T}_1 = 20$ and $\eta_x = 0.8$ the quantity is

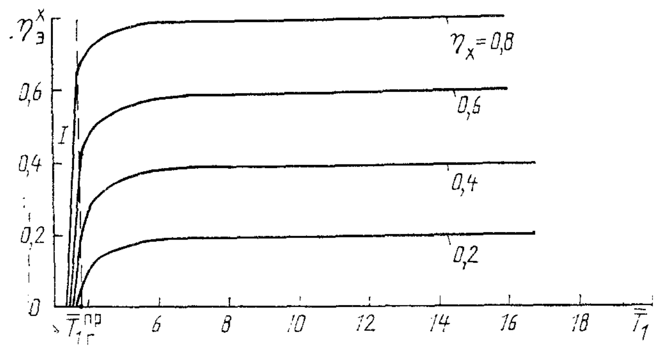

Fig. 2. Dependence of $\eta_э^x$ on $\overline{T}_1$ and η_x for $T_4 > T_0$; $\Delta T_m = 100$ K; $T_0 = 273$ K; $\overline{T}_0 = 2.73$; $\overline{W}_x = 1$; I) domain of technically inexpedient heat exchanger operation.

$\eta_э^x = 0.7993$. In this regime the heat exchanger exergetic efficiency reaches 99.9% of the magnitude of the energetic efficiency. For lower values of the dimensionless temperature $\overline{T}_1$ ($\overline{T}_1 < 6$) and lower initial temperatures of the thermal carrier T_1 ($T_1 < 600$ K), the influence of the dimensionless temperature $\overline{T}_1$ on the quantity $\eta_э^x$ is already noticeable. As the value of the dimensionless temperature $\overline{T}_1$ is lowered for η_x = const the quantity $\eta_э^x$ is also diminished. Thus, for $\overline{T}_1 = 4$ and $\eta_x = 0.8$ the quantity is $\eta_э^x = 0.7206$, i.e., is 90.7% of the quantity η_x. As η_x is lowered, the ratio $\eta_э^x/\eta_x$ diminishes also. For instance, for $\overline{T}_1 = 4$ and $\eta_x = 0.2$ the quantity $\eta_э^x$ is just 55% of the quantity η_x.

The influence of the environment temperature on the magnitude of the exergetic heat exchanger efficiency can be estimated by using the dimensionless temperature $\overline{T}_0$. As computations show, for conditions of Fig. 2 as well as values $\overline{T}_0 = 2.73$ ($T_0 = 2.73 \cdot 100 = 273$ K), $\overline{T}_1 = 5.0$ ($T_1 = 5 \cdot 100 = 500$ K) of the dimensionless temperatures and $\eta_x = 0.8$ the quantity is $\eta_э^x = 0.773$. As the environment temperature is lowered to $T_0 = 243$ K ($\overline{T}_0 = 243/100 = 2.43$) the quantity $\eta_э^x$ is raised to 0.798. A rise in the environment temperature to $T_0 = 303/100 = 3.03$) results in lowering the quantity η^x to 0.784. Therefore, a 60 K rise in the environment temperature lowers the heat exchanger exergetic efficiency by the quantity $\nabla\eta_э^x = 0.034$ or by 4.4%. In the domain of low values of the heat exchanger energetic efficiency $\eta_э^x = 0.2$ an analogous rise in the environment temperature will result in lowering the heat exchanger exergetic efficiency by a lower quantity $\nabla\eta_э^x = 0.1779-0.1611 = 0.0168$, or by 9.8%. Therefore, if an approximately two times reduction of the quantity $\nabla\eta_э^x$ is present in absolute values, then a more than two times growth in the reduction of the heat exchanger exergetic efficiency occurs in relative quantities as compared with the regime for $\eta_x = 0.8$.

The influence of the environment temperature on the quantity $\eta_э^x$ is reduced significantly as the initial temperature of the hot heat carrier rises. Thus for $T_1 = 2000$ K ($\overline{T}_1 = 2000/100 = 20$) a 60 K rise in the environment temperature (from 243 to 303 K) results in lowering the heat exchanger exergetic efficiency by just $\nabla\eta_э^x = 0.002$ independently of the magnitude of the heat exchanger energetic efficiency. This reduction is 1-2.5% in relative quantities.

The maximal thermal carrier temperature difference also influences the magnitude of the heat exchanger exergetic efficiency, it is here necessary to take into account that the dimensionless temperatures $\overline{T}_1$ and $\overline{T}_0$ depend on its magnitude in inverse proportion. Thus a reduction in ΔT_m from 100 to 50 K for $T_0 = 273$ K, $T_1 = 500$ K and $\eta_x = 0.8$ raises the heat exchanger exergetic efficiency by the quantity $\Delta\eta_э^x = 0.895-0.773 = 0.172$, that corresponds to a 22% rise in $\eta_э^x$ in relative quantities. A rise in ΔT_m from 100 to 150 K also results in growth of the heat exchanger exergetic efficiency but by a smaller quantity $\Delta\eta_э^x = 0.788-0.773 = 0.015$, that corresponds to a ~2% rise in $\eta_э^x$ in relative quantities. Therefore, the dependence of the heat exchanger exergetic efficiency on ΔT_m is of extremal nature, reaches minimal values of $\eta_э^x$ here for $\Delta T_m \approx 100$ K.

In the domain of higher values $T_1 \approx 2000$ K the influence of ΔT_m on $\eta_э^x$ is not felt in practice. Thus a reduction in ΔT_m from 100 to 50 K for $\eta_x = 0.8$ diminishes the exergetic efficiency by just $\nabla\eta_э^x = 0.7993-0.7984 = 0.0009$, while a rise in ΔT_m from 100 to 150 K also increases $\eta_э^x$ by the insignificant quantity $\Delta\eta_э^x = 0.7996-0.7993 = 0.0003$. In this case the reduction of ΔT_m by 100 K diminishes $\eta_э^x$ by $\nabla\eta_э^x = 0.7996-0.7984 = 0.0012$, which corresponds to a diminution in $\eta_э^x$ by 0.15% in relative quantities. For a reduction of η_x to 0.2 the quantity $\nabla\eta_э^x$ does not change and also equals $0.1996-0.1982 = 0.0014$. However, in relative quantities the reduction in $\eta_э^x$ is somewhat elevated and equals 0.6%.

The regime when $T_4 = T_0$ is the limit of a heat exchanger operating in the domain of high environment temperatures T_0. In such a regime the cold heat carrier goes to the heat exchanger with a temperature equal to the environment temperature (for instance, heating of the external air in the heating elements of tributary air conditioners). For $T_4 = T_0$ the dimensionless initial temperature of the warming thermal carrier equals

$$\overline{T}_{1r}^{np} = \frac{T_4 + \Delta T_m}{\Delta T_m} = \frac{T_0 + \Delta T_m}{\Delta T_m} = \overline{T}_0 + 1.$$

For the value $\overline{T}_0 = 2.73$ the quantity $\overline{T}_{1r}^{np}$ equals $2.73 + 1 = 3.73$ (the line $\overline{T}_{1r}^{np} = 3.73$ is superposed in Fig. 2). In fact this line bounds the domain of expedient heat exchanger operation that is determined by the condition $\infty > \overline{T}_1 \geq \overline{T}_0 + 1$. For $\overline{T}_1 = \overline{T}_{1r}^{np}$ the magnitude of the exergetic efficiency reaches the minimal values. Thus for $\eta_x = 0.2$ the quantity is $\eta_э^x = 0.0472$, i.e., is 24% of the magnitude of the heat exchanger energetic efficiency. For $\eta_x = 0.8$ the quantity is $\eta_э^x = 0.665$, i.e., is already 83% of the heat exchanger energetic efficiency.

For temperatures $T_4 < T_0$ heating the cold thermal carrier by the hot one becomes irrational since heating the cold thermal carrier from T_4 to T_0 can be realized because of utilization of the external air. A regime is possible in the domain of relatively low values of the temperature T_4 when the quantity of exergy reproducible in the heat exchanger equals zero, i.e., $e_3 = e_4$. Using (6) this condition can be written as

$$\eta_x - \overline{T}_0 \ln\left(1 + \frac{\eta_x}{\overline{T}_{1r}^0 - 1}\right) = 0, \tag{7}$$

from which

$$\overline{T}_{1r}^0 = 1 + \frac{\eta_x}{e^{\eta_x/\overline{T}_0} - 1}. \tag{8}$$

Values of $\overline{T}_{1r}^0$ are found in Fig. 2 at the intersection of the lines $\eta_x = \text{const}$ with the lines $\eta_э^x = 0$. For the conditions of Fig. 2 the value of $\overline{T}_{1r}^0$ for $\eta_x = 0.2$ will equal 3.63 in conformity with (8), which corresponds to initial temperatures $T_1 = 3.63 \cdot 100 = 363$ K of the hot thermal carrier and $T_4 = 363-100 = 263$ K of the cold thermal carrier as well as the final temperature $T_3 = 263 + 0.2 \cdot 100 = 283$ K of the cold thermal carrier. For $\eta_x = 0.8$ the quantity is $\overline{T}_{1r}^0 = 3.35$ while values of the thermal carrier temperatures equal $T_1 = 3.35 \cdot 100 = 335$ K; $T_4 = 335-100 = 235$ K; $T_3 = 235 + 0.8 \cdot 100 = 315$ K, respectively.

Let us examine heat exchanger operation in the domain of low environment temperature ($T_1 < T_0$). We substitute the value of the dimensionless thermal equivalent of the cold (hot) thermal carrier into (2) and we represent the magnitudes of the specific thermal carrier exergies in terms of their temperatures

$$\eta_э^r = \overline{W}_r \frac{(T_2 - T_0 - T_0 \ln T_2/T_0) - (T_1 - T_0 - T_0 \ln T_1/T_0)}{(T_4 - T_0 - T_0 \ln T_4/T_0) - (T_1 - T_0 - T_0 \ln T_1/T_0)}. \tag{9}$$

For $W_r < W_x$, $\overline{W}_r = 1$, while for $W_r > W_x$, $\overline{W}_r = W_r/W_x$.

Let us substitute the magnitudes of the change in cold thermal carrier temperature $-\Delta T_r = T_2 - T_1$ and the maximal thermal carrier temperature difference $-\Delta T_m = T_4 - T_1$ into (9) and we obtain after appropriate manipulations

$$\eta_э^r = \overline{W}_r \frac{-\Delta T_r - T_0 \ln T_2/T_1}{-\Delta T_m - T_0 \ln T_4/T_1}. \tag{10}$$

Let us express the quantity (10) in terms of the magnitude of the heat exchanger energetic efficiency ΔT_r in the cold thermal carrier

$$\Delta T_r = \eta_r \Delta T_m. \tag{11}$$

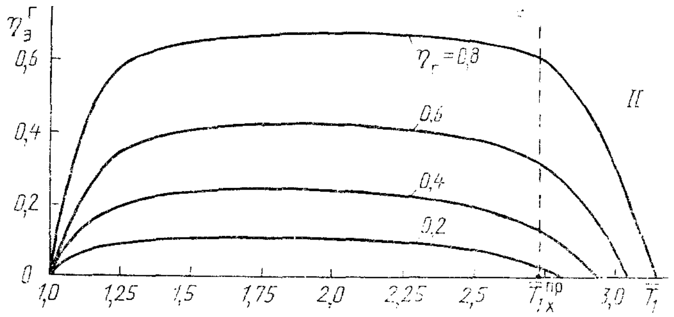

Fig. 3. The dependence of $\eta_э^Г$ on $\overline{T}_1$ and $\eta_Г$ for $T_1 < T_0$; $\Delta T_m = 100$ K; $\overline{T}_0 = 2.73$; $\overline{W}_Г = 1$; II is the domain of technically inexpedient heat exchanger operation.

The quantity $\eta_Г$ is determined by analogy with η_x as a function of the dimensionless parameters, the relationships between the thermal heat carrier equivalents $W_Г/W_x$ and the degree of heat transfer $\vartheta_Г = KF/W_Г$ over the cold thermal carrier. We express the final temperature of the cold thermal carrier T_2 in conformity with Fig. 1 in terms of the initial temperature of the cold thermal carrier T_1 and the maximal temperature difference of the heat carriers ΔT_m: $T_2 = T_1 - \Delta T_Г = T_1 - \Delta T_m \eta_Г$. The temperature T_4 was determined as $T_1 - \Delta T_m$. Substituting values of the temperatures T_2 and T_4 and the dimensionless temperatures $\overline{T}_1$ and $\overline{T}_0$ into (10) we obtain after appropriate manipulations

$$\eta_э^Г = \overline{W}_Г \frac{\eta_Г + \overline{T}_0 \ln(1 - \eta_Г/\overline{T}_1)}{1 + \overline{T}_0 \ln(1 - 1/\overline{T}_1)} . \tag{12}$$

As the expression (6), the expression (12) permits determination of the heat exchanger exergetic efficiency but already as a function of the dimensionless parameters $\overline{T}_1$, $\overline{T}_0$, $\eta_Г$, and $\overline{W}_Г$ given just by the initial conditions in the domain of low environment temperatures T_0. The graphical dependence, constructed according to (12), is represented in Fig. 3 for the same conditions as for Fig. 2. The dependence $\eta_э^Г = f(\overline{T}_1)$ is extremal in nature. The quantity achieves the highest values at $\overline{T}_1 = 1.75$-2.25. In this regime the ratio $\eta_э^Г/\eta_Г$ reaches the value 0.49 for $\eta_Г = 0.2$ and 0.83 for $\eta_Г = 0.8$.

The environment temperature in terms of the dimensionless temperature $\overline{T}_1$ also influences the magnitude of the heat exchanger exergetic efficiency. For the conditions of Fig. 3, the heat exchanger exergetic efficiency equals 0.6606 for $\eta_Г = 0.8$ and $\overline{T}_1 = 2.25$ ($T_1 = 2.25 \cdot 100 = 225$ K). A reduction of the environment temperature from 273 to 243 K ($\overline{T}_0 = 243/100 = 2.43$) results in a diminution of the quantity $\eta_э^Г$ to 0.6249 while a rise in the environment temperature to 303 K ($\overline{T}_0 = 303/100 = 3.03$) increases $\eta_э^Г$ to 0.6803. Therefore, a 60 K rise in the environment temperature increases the heat exchanger exergetic efficiency by $\Delta\eta_э^Г = 0.0554$ and this increase equals 8.4% in relative quantities. For $\eta_Г$ the same 60 K rise in the environment temperature increases the heat exchanger exergetic efficiency from 0.0612 to 0.1051, i.e., $\Delta\eta_э^Г = 0.0439$. This quantity equals 49% in relative quantities. Therefore if a certain reduction in $\Delta\eta_э^Г$ occurs in absolute values, than an almost five times growth in the rise of the heat exchanger exergetic efficiency is present in relative quantities as compared with the regime for $\eta_Г = 0.8$.

As the initial temperature of the cooling thermal carrier is reduced to $T_1 = 125$ K ($\overline{T}_1 = 125/100 = 1.25$) for $\eta_Г = 0.8$ a 60 K rise in the environment temperature will result in an increase in the heat exchanger exergetic efficiency by the quantity $\Delta\eta_э^Г = 0.592$-$0.578 = 0.014$ while this increase equals 2.4% in relative quantities. For $\eta_Г = 0.2$ such a rise in the environment temperature results in an increase in the heat exchanger exergetic efficiency by the quantity $\Delta\eta_э^Г = 0.0847$-$0.0768 = 0.0079$, and this increase equals 9.7% in relative quantities. In this regime a reduction in $\Delta\eta_э^Г$ with diminution of $\eta_Г$ and growth of the rise in the quantity $\eta_э^Г$ in relative quantities also occurs.

One of the limits for a heat exchanger operating in the domain of low environment temperatures T_0 is the regime when $T_1 = T_0$. In such a regime the cooling thermal carrier proceeds into the heat exchanger with a temperature equal to the environment temperature (for example, cooling of the external air in air coolers of air conditioning systems). For $T_1 = T_0$ the dimensionless initial temperature of the cooling thermal carrier will equal $\bar{T}_{1x}^{np} = \bar{T}_0$. For the value $\bar{T}_0 = 2.73$ the quantity $\bar{T}_{1x}^{np}$ will also equal 2.73 (the line $\bar{T}_{1x}^{np} = 2.73$ is superposed in Fig. 3). In the zone of lower temperatures of the exchanging media, the regime when $T_4 \to 0K$ corresponds to the limit regime. Since expenditure of infinitely large quantities of work is required to obtain such a temperature, then the specific exergy of the cooling thermal carrier e_4 will be $e_4 \to 0$ in this case, while the heat exchanger exergetic efficiency is $\eta_э\Gamma \to 0$. For $T_4 = 0$, $\bar{T}_{1x}^{np} = (T_4 + \Delta T_m)/\Delta T_m = (0 + \Delta T_m)/\Delta T_m = 1$. Therefore, the domain of expedient heat exchanger operations will be determined for temperatures below the environment temperature by the condition $\bar{T}_0 \geq \bar{T}_1 > 1$. For $\bar{T}^{np}_{\Gamma}$ the magnitude of the exergetic efficiency reaches the minimal values. Thus, for $\eta_\Gamma = 0.2$ the quantity is $\eta_э{}^\Gamma = 0.0314$, i.e., is ~16% of the magnitude of the heat exchanger energetic efficiency. For $\eta_\Gamma = 0.8$ the quantity is $\eta_э{}^\Gamma = 0.598$, i.e., is ~75% of the magnitude of the heat exchanger energetic efficiency. In the domain of maximal values of η^Γ these quantities would equal 49 and 83% as has already been noted.

Cooling of the warmer thermal carrier by coolant in the heat exchanger for temperatures $T_1 > T_0$ becomes irrational since cooling this thermal carrier from T_1 to T_0 can be realized by external air. For relatively high values of the temperature T_1 a regime is possible when the quantity of exergy produced in the heat exchanger will equal zero, i.e., $e_2 = e_1$. Taking (12) into account we can write

$$\eta_\Gamma + \bar{T}_0 \ln(1 - \eta_\Gamma/\bar{T}^0_{1x}) = 0, \tag{13}$$

from which

$$\bar{T}^0_{1x} = \frac{\eta_x}{1 - e^{-\eta_\Gamma/\bar{T}_0}}. \tag{14}$$

Values of $\bar{T}_{1x}{}^0$ are found in Fig. 3 at the intersection of the lines η_Γ = const with the lines $\eta_э{}^\Gamma = 0$. For the conditions of Fig. 3 the value of $\bar{T}_{1\Gamma}{}^0$ for $\eta_\Gamma = 0.2$ equals 2.83 in conformity with (14), which corresponds to the temperatures $T_1 = 2.83 \cdot 100 = 283$ and $T_2 = 283 - 100 \cdot 0.2 = 263$ K. For $\eta_\Gamma = 0.8$ the quantity is $\bar{T}_{1x}{}^0 = 3.15$ and the values of the thermal carrier temperatures are $T_1 = 3.15 \cdot 100 - 315$ K; $T_2 = 315\text{-}100 \cdot 0.8 = 235$ K.

The expressions obtained to determine the exergetic efficiency permit estimation of the effectiveness of applying heat exchangers in installations and systems utilizing heat as a function of the potential of the thermal carriers being used. Application of heat exchanger exergetic efficiency in industrial thermal engineering will stimulate more extensive utilization of low potential thermal carriers including VER. In the future when the cost of thermal carriers will depend to a definite extent on their energy, the thermodynamic efficiency criteria will be able to be utilized directly to compute the optimal heat exchanger surface.

NOTATION

T is the thermal carrier temperature; T_0 is the environment temperature, e is the specific thermal carrier exergy; W_x, W_Γ are the thermal equivalent of the cold and hot thermal carriers; W_{min} is the smaller of the two quantities W_x and W_Γ; $\bar{W}_x = W_x/W_{min}$, $\bar{W}_\Gamma = W_\Gamma/W_{min}$ are the relative thermal equivalents of the cold and hot thermal carriers; $\Delta T_x = T_3 - T_4$, $\Delta T_\Gamma = T_2 - T_1$ are changes in the cold and hot thermal carrier temperatures; $\Delta T_m = T_1 - T_4$ is the maximal thermal carrier temperature difference; $\bar{T}_0 = T_0/\Delta T_m$ is the dimensionless environment temperature; $\bar{T}_1 = T_1/\Delta T_m$ is the dimensionless initial temperature of the hot thermal carrier; η_x and η_Γ are the heat exchange energetic efficiencies in the hot and cold thermal carriers; K is the heat transfer coefficient, $W/(m^2 \cdot K)$; F is the heat exchange surface, m^2. Subscripts: 1, 2 are hot thermal carrier temperatures at the heat exchanger input and output; 3, 4 are the cold thermal carrier temperatures at the heat exchanger input and output.

LITERATURE CITED

1. V. M. Brodyanskii, V. Fratsher, and K. Mikhalek, Exergetic Method and Its Application [in Russian], Moscow (1988).
2. Ya. Shargut and R. Petela, Exergy [in Russian], Moscow (1968).
3. V. Fratsher and F. Otte, Energy and Exergy [in Russian], Moscow (1968), pp. 122-151.
4. W. M. Kays and A. L. London, Compact Heat Exchangers, McGraw-Hill (1967).

5. H. Hausen, Heat Transfer for Tributary, Direct Flow and Cross Flow [Russian translation], Moscow (1981).
6. O. N. Man'kovskii, A. R. Torchinskii, and R. V. Aleksandrov, Heat Exchange Apparatus of Chemical Production [in Russian], Leningrad (1976).

SOME PRINCIPLES OF COMBUSTION OF HOMOGENEOUS FUEL-AIR MIXTURES IN THE CYLINDER OF AN INTERNAL COMBUSTION ENGINE

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An algorithm is presented for the problem of flame propagation rate in combustion of a homogeneous fuel-air mixture in the cylinder of an internal combustion engine. It is assumed that the mixture is not "overturbulized" and that the flame front is spherical. The model used for the phenomenon is based on a turbulent transport mechanism. In the near-wall region the combustion mechanism follows a fine-scale mechanism, but in the core, a large-scale mechanism.

Experiments permitted determination of the character and numerical value of coefficients which consider the effect of turbulence on flame front propagation in the combustion chamber of a ZMZ-4021 engine.

The principles presented can be used as the basis of an algorithm for heat liberation rate in an internal combustion engine with external mixture formation.

Modeling of processes within an internal combustion engine with external mixture formation is hampered at present by lack of a clear physical picture of the heat liberation mechanism in fuel combustion. The situation is no better for engines with internal mixture formation. Heat liberation in the combustion process is a little studied area of internal combustion engine theory.

There have been numerous attempts to solve the problem of heat liberation during fuel burning in the engine cylinder, all of which we may divide into two groups. The first group includes studies of the physics of the combustion process, including chambers of variable volume [1-4]. These studies, while not pretending to create a method for calculating the combustion process in piston engines, do describe the basic principles of fuel combustion.

In the second group we have studies which attempt to formalize the complex combustion process [5, 6]. Usually this formalization is quite specialized and to a great extent empirical.

The principal differences between combustion in engines with internal and external mixture formation will not permit consideration of the unique features of the overall process within the scope of a single journal article. Herein we will only consider some aspects of the process of fuel-air mixture combustion in an engine with external mixture formation.

The majority of experimental studies of such engines has been carried out either with high speed cine photography of flame propagation, or with the aid of ionization sensors.

The studies that have been performed have to a great extent exposed the basic principles of fuel combustion in the variable volume engine chamber [4, 7, 8]. It has been

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