ESTIMATION OF THE HEAT TRANSFER TO SUPERCRITICAL FREONS

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An approximate equation is proposed for estimating the heat transfer to supercritical freons.

The promising outlook for freon power plants raises the question of determining the optimum parameters of the heat-transfer surfaces.

In this connection in the case of certain heat exchangers it is necessary to estimate the heat transfer to freons with supercritical parameters in the presence of forced motion in the tubes.

The use of criterial formulas [1–3] for this purpose requires a knowledge of the physical properties. However, in most cases the lack of necessary data precludes the use of criterial formulas.

At the same time, fairly accurate information [4, 5] on the principal thermodynamic characteristics P_{cr}, T_{cr}, and μ is available for all the freons of interest. Accordingly, relations that make it possible to estimate the coefficient of heat transfer to freons on the basis of the available information on P_{cr}, T_{cr}, and μ acquire special significance.

For the coefficient of heat transfer α to substances with supercritical parameters, in the case of forced motion in tubes, we can write

$$\psi(\alpha,\ w,\ d,\ q,\ \varepsilon) = 0. \tag{1}$$

By analogy with [7–9], Eq. (1) can also be represented in the form

$$\alpha = A\, w^{n_1}\, d^{n_2}\, q^{n_3}\, \lambda^{n_4}\, \eta^{n_5} \ldots, \tag{2}$$

where λ, η, etc. are physical properties; A is a constant coefficient determined from the experimental data.

The theory of thermodynamic similarity [4, 7–10] establishes the general approximate form of notation for any physical characteristic:

$$X = \varphi(\mu,\ P_{cr},\ T_{cr},\ R_0)\, f(\pi,\ \tau,\ K_1,\ K_2). \tag{3}$$

Using (3), we reduce relation (2) to the form

$$\alpha = A w^{n_1}\, d^{n_2}\, q^{n_3}\, \mu^{m_1}\, P_{cr}^{m_2}\, T_{cr}^{m_3}\, R_0^{m_4}\, f(\pi,\ \tau,\ K_1,\ K_2). \tag{4}$$

In (4) the entire complex preceding the function f must have the dimension of the heat-transfer coefficient. The exponents n and m for all the factors in this complex can be determined by dimensional analysis.

However, the exponents for the regime parameters must be taken from the experimental data [9, 10].

In our case, the principal regime parameters are the velocity of forced motion and the geometric characteristic of the heat-transfer surface—the inside diameter of the tube.

It follows from [1–3, 11, 12] that the exponent of w must be not less than 0.8. McAdams [2] found that $n_1 = 0.89$ best corresponds to the experimental data. In the correlations of Swenson-Carver-Kakarala and Bishop [2], the exponent of w is equal to 0.923 and 0.9, respectively. In this case $n_2 \simeq -0.1$.

Using the Swenson-Carver-Kakarala correlation [2], we obtain the following values of the exponents in (4): $n_1 = 12/13$; $n_2 = -3/26$; $n_3 = -1/13$; $m_1 = -1/13$; $m_2 = -27/26$; $m_3 = -23/26$; $m_4 = 3/26$.

Thus, Eq. (4) takes the form

$$\alpha = A\, \frac{w^{12/13}\, R_0^{3/26}\, P_{cr}^{27/26}}{d^{3/26}\, \mu^{1/13}\, T_{cr}^{23/26}\, q^{1/13}}\, f(\pi,\ \tau,\ K_1,\ K_2). \tag{5}$$

Here, the quantities have the following dimensions: w, m/sec; d, m; q, W/m^2; molecular mass μ, Nsec^2/m; P_{cr}, N/m^2; T_{cr}, °K; α, W/m^2·deg.

We denote

$$Y = P_{cr}^{27/26} / (\mu^{1/13}\, T_{cr}^{23/26}); \tag{6}$$

then

$$\alpha = A\, \frac{w^{12/13}\, R_0^{3/26}}{d^{3/26}\, q^{1/13}}\, Y f(\pi,\ \tau,\ K_1,\ K_2). \tag{7}$$

The quantity Y (table) is a universal multiplier and characterizes the effect of μ, P_{cr}, and T_{cr} on the heat-transfer process.

Thermodynamic Characteristics and Values of the Universal Multipliers of Certain Substances

Working medium	$P_{cr}\cdot 10^{-5}$, N/m^2	T_{cr} °K	μ	$Y\cdot 10^{-4}$
H_2O	221.4	647.3	18.0	11.07
F-11	43.7	471.0	137.4	2.33
F-12	41.2	385.0	121.0	2.69
F-21	51.7	451.6	103.0	2.94
F-22	49.4	369.0	86.5	3.40
F-142	41.9	410.0	100.0	2.58
F-114	32.8	419.0	171.0	1.88
F-C318	28.1	388.5	200.0	1.69
F-12B1	41.2	428.0	165.4	2.35
F-12B2	40.9	471.0	210.0	2.10
F-114B2	35.7	487.0	260.0	1.74
F-31-10	23.3	386.3	238.0	1.38
F-113	34.2	487.2	187.4	1.71

The function f is universal for thermodynamically similar substances and characterizes the effect of the reduced parameters on heat transfer.

A sign of thermodynamic similarity is the equality of a minimum of any two similarity criteria [4]. In this case Ri and σ_{cr} are characteristic [7].

Then for thermodynamically similar substances from (7) we obtain

$$(\alpha/Y)_{w,\ d,\ q,\ \pi,\ \tau,\ Ri,\ \sigma_{cr}} = \text{idem}. \tag{8}$$

In reality, discrepancies in Ri and σ_{cr} are unavoidable. Consequently, substances with approximately the same values of the criteria are assumed thermodynamically similar [4].

To estimate the heat transfer to freons from Eq. (8) it is necessary to have suitable similar base substances, for which the physical properties in the investigated range of the parameters are available. In practice it is difficult to employ (8) because the necessary data are lacking for most of the potential base substances.

For an approximate estimate of the heat transfer in accordance with (8), it may be satisfactory to use an approximate base substance, i.e., substitute for the equality of two like similarity criteria the condition that the difference between them be "not too great."

Below it will be shown that in this case acceptable results can be obtained for freons if water is used as the base substance.

Equation (8) is then written in the form

$$(\alpha_F/\alpha_{H_2O})_{\pi,\ \tau,\ w,\ d,q} = Y_F/Y_{H_2O}. \tag{9}$$

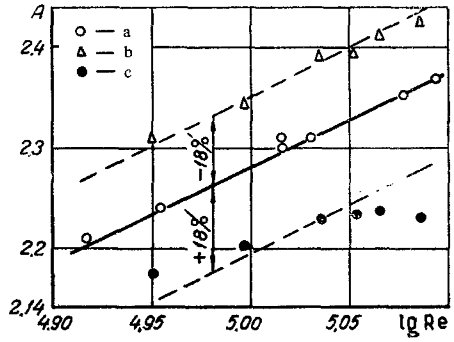
The determining criteria Ri and σ_{cr} for water differ from the corresponding criteria for freons by not more than 15% [4].

To check Eq. (9) we calculated the coefficient of heat transfer to water (figure) for the following starting data: $\pi = 1.01$; $\tau = 0.683-0.847$; $d = 0.0094$ m; $w = 6.3 \cdot 10^3$ m/hr. As the base substances we took F-113 and F-12. The physical constants needed for the calculation were taken from [4, 5] for F-113, while for F-12 they were determined by extrapolation with account for the recommendations of [4, 6].

The coefficients of heat transfer to the freons were calculated from the Swenson-Carver-Kakarala correlation [2]

$$\left\{\mathrm{Nu}/\left[(\overline{\mathrm{Pr}})^{0.613}(\bar{v})^{0.231}\right]\right\} = 4.59 \cdot 10^{-3}\,\mathrm{Re}^{0.923}. \tag{10}$$

In Eq. (10) the viscosity and thermal conductivity, which determine the criterion $\overline{\mathrm{Pr}}$, have been referred to the temperature of the inner face of the wall; the isobaric specific heat is equal to the ratio of the enthalpy difference at the temperatures at the inner face of the wall and in the flow core to the difference of those temperatures calculated for the substances in question starting from equality of the specific heat fluxes. The quantity $\bar{v}$ is determined by the ratio of the specific volume in the flow core to the specific volume at the temperature at the inner face of the wall.



Comparison of the coefficients α_{H_2O} according to [2] (a) and those calculated from Eq. (9) (b and c), base substances F-113 and F-12. $A = \lg[\mathrm{Nu}/(\overline{\mathrm{Pr}}^{0,613}\bar{v}^{0.231})]$.

Clearly, the α_{H_2O} obtained from Eq. (9) are in satisfactory agreement with the experimental values of α_{H_2O} [2]. The starting data for F-12 are less accurate, especially at high τ; therefore, the maximum deviation in the region in question reaches 25.7%.

Thus, the heat transfer to F-12 and F-113 can be approximately estimated from formula (9).

The satisfactory fulfillment of the conditions of thermodynamic similarity between freons [4] suggests that for them, too, the heat transfer can also be estimated from (9).

The next step is to refine formula (9) on the basis of a generalization of the experimental data.

NOTATION

P_{cr} is the critical pressure; T_{cr} is the critical temperature; μ is the molecular weight; R_0 is the universal gas constant; φ is a dimensional multiplier composed of μ, the molecular mass, numerically equal to the molecular weight, P_{cr}, T_{cr}, and R_0; f is a dimensionless function of the relative pressure π, the relative temperature τ, and the two similarity criteria K_1, K_2; $\pi = P/P_{cr}$, $\tau = T/T_{cr}$; P, T are variable pressure and temperature; α is the heat-transfer coefficient; w is the velocity; q is the specific heat flux; d is the inside diameter of tube; ε is a function of the physical properties determining heat transfer; $Ri = (\partial\pi/\partial\tau)_{\tau=1}$ is the Ridel number; $\sigma_{cr} = \mu P_{cr} v_{cr}/(R_0 T_{cr})$ is the critical coefficient; F is freon.

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