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APPROXIMATION OF TRANSFER PROPERTIES AND THE SOUND SPEED OF WATER BY A DEPENDENCE OF THE TAIT ISOTHERM EQUATION TYPE

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The heat conduction and speed of sound of water are described with great accuracy by dependences of the Tait isotherm equation type on the basis of available literature data.

The possibility of approximating the heat conduction and viscosity coefficients and the speed of sound of water by dependences of the Tait isotherm equation type [1]*

$$v = v_s' \left[1 - A \ln \frac{p + B}{p_s + B} \right]. \tag{1}$$

is examined in this paper.

To find the empirical coefficients of the heat conduction equation

$$\lambda = \lambda_s' \left[1 - A_\lambda \ln \frac{p + B_\lambda}{p_s + B_\lambda} \right] \tag{2}$$

we write it for two states and then obtain by dividing one by the other

*We have replaced the parameters p_0, v_0 in the Tait equations by the parameters p_S, v_S of a saturated liquid.

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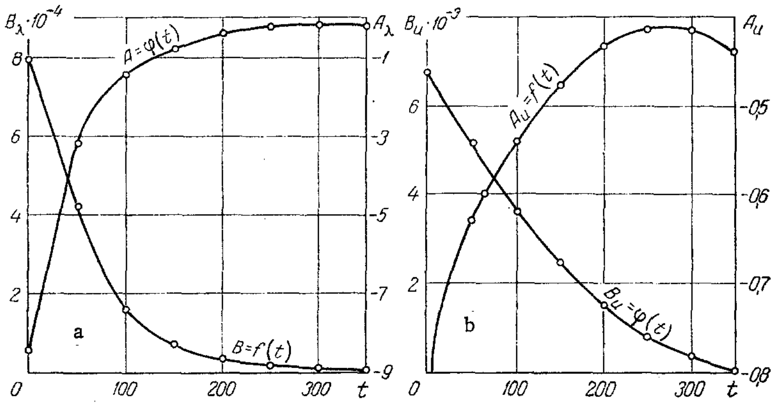

Fig. 1. Temperature dependences of the empirical coefficients: a) equations (2), and b) equation (4); t,°C.

$$\frac{\lambda_s' - \lambda_1}{\ln(p_1 + B_\lambda) - \ln(p_s + B_\lambda)} = \frac{\lambda_s' - \lambda_2}{\ln(p_2 + B_\lambda) - \ln(p_s + B_\lambda)} . \quad (2')$$

This equation for B_λ can be solved by the method of inspection or graphically by constructing the functions

$$\varphi_1(B_\lambda) = \frac{\lambda_s' - \lambda_1}{\ln(p_1 + B_\lambda) - \ln(p_s + B_\lambda)} , \quad (2'')$$

$$\varphi_2(B_\lambda) = \frac{\lambda_s' - \lambda_2}{\ln(p_2 + B_\lambda) - \ln(p_s + B_\lambda)} \quad (2''')$$

in the coordinate system $\varphi(B_\lambda)$, B_λ.

The abscissa of the intersection of the curves $\varphi_1(B_\lambda)$ and $\varphi_2(B_\lambda)$ will be a solution of (2). The other coefficients A_λ can be found from (2) when B_λ is available.

It must be noted that we executed the approximation of the transfer properties [2, 3] by formulas of the type of the equation of state

$$\frac{pv}{BT} = 1 + B\rho + E\rho^4 \quad (3)$$

on the basis of data from the International Skeleton Tables for Water and Steam from 1964. The English International Conference on the Properties of Water and Steam, held in Gien (France), established that the "MST of 1964 is insufffciently accurate and should be considered obsolete" [5]. Hence, the recommended values of the heat conduction [6] and the experimental data on the speed of sound in water, from with high accuracy [7], are the basis of the approximation in this paper.

The recommended values of the heat conduction of water and steam are presented in [6] in two tables. The first, including data on water and steam for pressures to 500 bar and temperature to 700°C, is a graphical treatment of test results. Data only on water at pressures to 2500 bar and temperatures to 350°C are in the second and it is the result of processing a number of test results found by Soviet and foreign scientists between 1968 and 1974.

Using the data from the tables in [6] and [7] for the heat conduction and speed of sound in water, we determined the empirical coefficients A_λ, B_λ of (2) and A_u, B_u by the method described above from the formula

$$u = u_s' \left[1 - A_u \ln \frac{p + B_u}{p_s + B_u}\right] . \quad (4)$$

These coefficients are represented in Fig. 1a, b and are approximated by the following dependences:

for the heat conduction of water between 0 and 50°C

$$A_\lambda = -8.500 + 0.1090\,t,\ B_\lambda = 79800 + 756\,t,$$

from 50 to 300°C

$$A_\lambda = \sum_0^5 a_i (t-50)^i, \quad B_\lambda = \sum_0^5 b_i (t-50)^i,$$

where $a_0 = -3050000 \cdot 10^{-6}$; $b_0 = +42000000 \cdot 10^{-3}$; $a_1 = +4854166 \cdot 10^{-8}$; $b_1 = -83165833 \cdot 10^{-5}$; $a_2 = -4371166 \cdot 10^{-10}$; $b_2 = +82847500 \cdot 10^{-7}$; $a_3 = +2569333 \cdot 10^{-12}$; $b_3 = -48025000 \cdot 10^{-9}$; $a_4 = -8673333 \cdot 10^{-15}$; $b_4 = +14930000 \cdot 10^{-11}$; $a_5 = +1200000 \cdot 10^{-17}$; $b_5 = -18866667 \cdot 10^{-14}$;

from 300 to 350°C

$$A_\lambda = -0.250 + 0.00126(t-300), \quad B_\lambda = 450 - 9.94(t-300),$$

for the speed of sound in water from 0 to 350°C

$$A_u = \sum_0^7 a_i t^i, \quad B_u = \sum_0^7 b_i t^i,$$

where $a_0 = -8307800 \cdot 10^{-7}$; $b_0 = +66700000 \cdot 10^{-4}$; $a_1 = +6729641 \cdot 10^{-9}$; $b_1 = -29972381 \cdot 10^{-6}$; $a_2 = -8239298 \cdot 10^{-11}$; $b_2 = -59922200 \cdot 10^{-9}$; $a_3 = +7045160 \cdot 10^{-13}$; $b_3 = +11342200 \cdot 10^{-10}$; $a_4 = -3434811 \cdot 10^{-15}$; $b_4 = -74722200 \cdot 10^{-13}$; $a_5 = +8943067 \cdot 10^{-18}$; $b_5 = +29755600 \cdot 10^{-15}$; $a_6 = -1119911 \cdot 10^{-20}$; $b_6 = -63555600 \cdot 10^{-18}$; $a_7 = +4792381 \cdot 10^{-24}$; $b_7 = +54603200 \cdot 10^{-21}$.

The formula (2) proposed describes the values of λ exceptionally well in the 0–350°C temperature and p_s to 500 bar pressure ranges, where deviations are less than 1%. Hence, it can be used successfully to compile detailed tables* of the heat conduction of water in the mentioned ranges of p and t.

In addition, it should be noted that the approximate values of the heat conduction of water in the 0–350°C temperature and p_s up to 500 bar pressure ranges proposed in [8] also agree with the recommended data [6] within 1% limits, with the exception of two isotherms 0 and 50°C, for which these deviations reach 2.3% at high pressures and are not within the limits of the probable error for the recommended values of the heat conduction of water, that is 1% for $0 \le t \le 200$°C, $1 \le p \le 25$ bar, 1.5% for $25 < p \le 500$ bar 2% for $200 \le t \le 300$°C, p = 1–500 bar and 3% for $300 < t \le 350$°C, p = 1–500 bar.

To clarify the possibility of extrapolating (2) to the domain $p > 500$ bar, we constructed heat conduction isotherms in Fig. 2 for both the data from [6] and the results calculated by means of (2). It is seen from Fig. 2 that both values almost agree on all isotherms up to 500 bar, but discrepancies appear for $p > 500$ bar, where it can easily be established up to what pressure and to what accuracy the proposed formula (2) can be applied.

Comparing values on the speed of sound in water calculated by means of (4), with experimental results shows that (4) yields values of the speed of sound in water to 0.1–0.4% accuracy in the 0–350°C temperature and p_s up to 700 bar pressure ranges.

Verification by means of the results in [8, 9] showed that the formula

$$\eta = \eta_s' \left[1 - A_\eta \ln \frac{p + B_\eta}{p_s + B_\eta} \right] \tag{5}$$

can be used successfully to describe the viscosity of water also. In must be assumed that the other above-mentioned thermophysical quantities can also be approximated by the same method. It should be noted that the coefficients obtained in our approximations depend sufficiently strongly on the temperature, while there coefficients are constants for the heat conduction of oil in [10].

In conclusion, let us note that (2), (4), and (5) are unable to establish dependences between their empirical coefficients A_λ, B_λ; A_η, B_η; A_u, B_u although they yield values of λ, η and u with high accuracy. It is true that if we start from the differential dependence of the Tait isotherm equation

$$-\left(\frac{\partial v}{\partial p}\right)_T = \frac{A v_s'}{B + p} \tag{6}$$

and

$$-\left(\frac{\partial p}{\partial v}\right)_T = a_v + b_v p, \tag{6'}$$

*We have compiled such a table with a 10° step, but it not presented here because of the limited space in the paper.

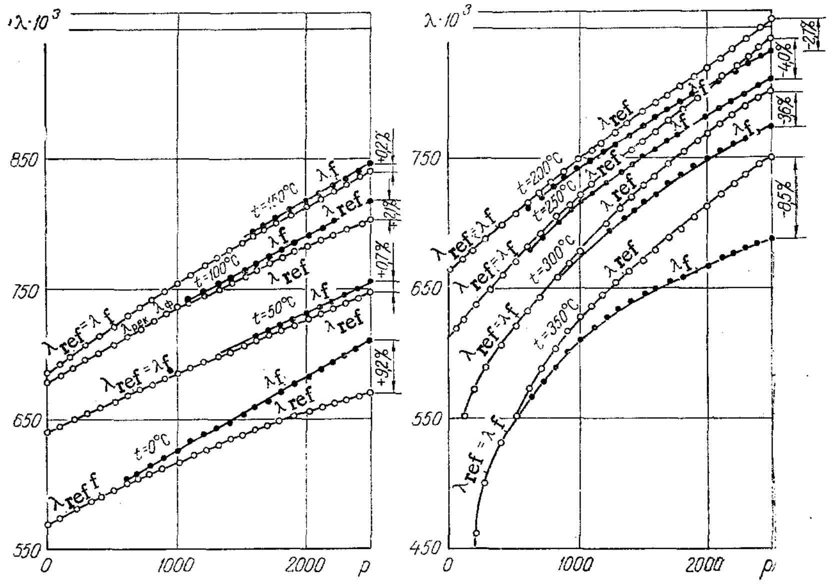

Fig. 2. Heat conduction isotherms according to the recommended data and according to (2).

we can obtain the following linear dependences for the heat conduction and the speed of sound:

$$-\left(\frac{\partial p}{\partial \lambda}\right)_T = a_\lambda + b_\lambda p \tag{7}$$

and

$$-\left(\frac{\partial p}{\partial u}\right)_T = a_u + b_u p, \tag{8}$$

where

$$a_\lambda = \frac{B_\lambda}{A_\lambda v_s'}\ ;\ b_\lambda = \frac{1}{A_\lambda v_s'}\ ;\ a_u = \frac{B_u}{A_u v_s'}\ ;\ b_u = \frac{1}{A_u v_s'}\ .$$

NOTATION

ρ, liquid density; v, specific volume of liquid; v_s, the same for a saturated liquid; p, pressure; p_s, the same for a saturated liquid; R, gas constant; λ, heat conduction coefficient of a liquid; λ_s', the same for the saturated liquid; η, coefficient of dynamic viscosity of the liquid; η_s', the same for a saturated liquid; u, speed of sound of the liquid; u_s', the same for the saturated liquid; A_λ, B_λ; A_u, B_u temperature-dependent coefficients.

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