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SHIROKOV'S FORMULA CONNECTING THE TRANSFER PROPERTIES OF
LIQUIDS WITH THE VELOCITY OF SOUND

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According to existing data for u , η , λ , it is established that Shirokov's formula can become a quantitative relation if we introduce into it a dimensionless quantity ε , which depends on the temperature and pressure.

Starting from the idea of heat transfer by means of hyperacoustic oscillations of the medium, and assuming the mean free paths of the molecules in these processes to be equal, Shirokov [1] established a relation between the translational properties and the velocity of sound in liquids:

$$\frac{\eta}{\lambda} = \frac{T}{u^2}. \quad (1)$$

Our investigations have shown that the Shirokov complex $u^2\eta/T\lambda^*$ at any temperature and pressure for different liquids always differs from unity. Denoting the deviations of this complex by ε , Eq. (1) can be represented in the form

$$\frac{u^2\eta}{T\lambda} = \varepsilon. \quad (2)$$

*The Shirokov complex in [2] is represented as $\lambda/\eta = u^{m(T)}/A(T)$.

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TABLE 1. Values of the Constants a and b of Eq. (3) for a Series of Isotherms of Toluene and Water

$t, ^\circ\text{C}$	For toluene		For water	
	a	b	a	b
0	—	—	22,756	0,0470
25	24,877	1,3982	—	—
50	15,205	0,9165	6,287	0,2691
75	9,908	0,6800	—	—
100	6,593	0,5344	2,666	0,1667
125	4,373	0,4440	—	—
150	2,930	0,3552	0,199	0,0857
175	1,886	0,3036	—	—
200	1,169	0,2666	0,752	0,0934
225	0,710	0,2259	—	—
250	0,374	0,1979	0,419	0,0849

TABLE 2. Values of $\varepsilon_{\tau, \pi}$ — the Shirokov Complex, for $\tau = T^*/T_{cr} = 0.603$ and $\pi = p^*/p_{cr} = 2.740$ for Five Liquids

Material	Corresponding parameters					$\frac{u^2 \eta}{T \lambda} = \varepsilon_{\tau, \pi}$
	$t, ^\circ\text{C}$	P, bar	$10^7 \cdot \eta, \text{Pa} \cdot \text{sec}$	$10^4 \cdot \lambda, \text{W}/\text{m}^2 \cdot \text{K}$	$u, \text{m}/\text{sec}$	
Benzene	66	134,8	4126 [15]	1364 [14]	1241 [11]	13,73
Toluene	85	111	3365 [5]	1177 [7]	1125 [3]	10,10
m-Xylene	100	100	3121 [13]	1134 [16]	1093 [12]	8,81
n-Heptane	52,57	74,97	3245 [9]	1248 [9]	1080 [10]	9,31
Water	117,15	606,09	2542 [6]	7205 [8]	1662 [4]	2,50

*The critical parameters are taken from [9].

Typical calculations carried out for two liquids — toluene over the temperature range 25–250°C at pressures from p_s to 250 bar, and water from 0 to 250°C and from p_s to 500 bar, according to existing data for u [3, 4], η [5, 6], and λ [7, 8], have shown that isotherms of the values of the deviation ε depend linearly on the pressure. Since the quantity ε is dimensionless, we will express it in terms of the reduced pressure

$$\varepsilon = a + b\pi, \quad (3)$$

where a and b are constants obtained by the least-squares method, the numerical values of which are given in Table 1 for a series of isotherms.

Curves of these coefficients for toluene and water in terms of the reduced temperature $\tau = T/T_{cr}$ are shown in Fig. 1. As can be seen from Fig. 1, if the anomalous part of water is ignored, the form of their variation is identical.

In the range $\tau = 0.502$ – 0.630 we can only express the initial parts of ε for toluene in terms of the following empirical relations:

$$a = \frac{\tau}{0.121416\tau - 0.04871} - 16.175, \quad (4)$$

$$b = \frac{\tau}{3.64074\tau - 1.53112} - 0.2948 \quad (5)$$

with a mean error of 0.34 and 0.20%, respectively. Taking (4) and (5) into account, Eq. (3) takes the form

$$\varepsilon = a(\tau) + b(\tau)\pi. \quad (6)$$

Hence, the Shirokov complex $u^2 \eta / T \lambda$, denoted in Eq. (2) by the dimensionless quantity ε , is a function of the temperature and pressure.

Since Eq. (2) gives the relations between the parameters u , η , λ quite accurately, it can be regarded as a qualitative and quantitative relationship. This suggests that in deriving Eq. (1) all the conditions during the heat-transfer process were ignored, and a correction is therefore necessary, which we carried out by introducing the dimensionless quantity ε , depending on the temperature and pressure.

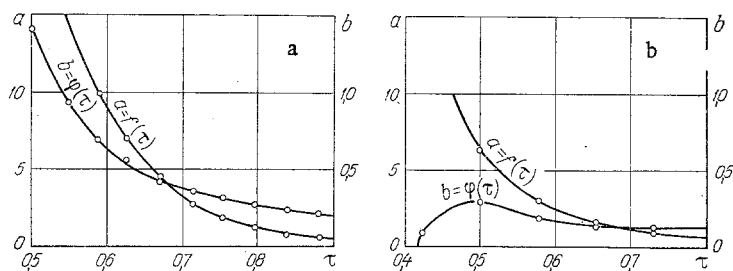


Fig. 1. Dependence of the coefficients α and b of Eq. (3) on τ for toluene (a) and water (b).

It should be noted that Eq. (1), when the deviation factor ϵ is introduced into it, by becoming the quantitative relationship (2), loses its universality and depends on the individual feature of the liquid, since the Shirokov complex $u^2\eta/T\lambda = \epsilon_{\tau,\pi}$ for different liquids, as can be seen from Table 2, has different values for corresponding states. This means that for two different liquids even of the same class, for corresponding states, the Shirokov complexes are not equal, i.e., when $\tau_2 = \tau_1$ and $\pi_2 = \pi_1$ $(u^2\eta/T\lambda)_2 \neq (u^2\eta/T\lambda)_1$.

In conclusion, it should be noted that despite the above advantage of Eq. (2), the fact that it is not possible to obtain the correction coefficient ϵ using any physical-chemical constants of a given liquid makes it difficult to use.

In fact, Eq. (2) must be regarded as an interpolation relationship, ensuring both a qualitative and quantitative relationship between the most important thermal parameters, u , η , and λ .

It can be seen from a typical calculation for toluene that Eq. (2) can be extrapolated to higher pressures up to $6p_{cr}$ bar. A check for water showed that it could be extrapolated up to 1000 bar. With regard to the extrapolation of Eq. (2) to increased temperatures, it involves a disturbance of the linearity of the correction factor $\epsilon = \alpha(t) + b_1(t)p$. A typical calculation for water showed that linearity at 350°C is obtained at pressures above 250 bar. Hence, the upper limit of the extrapolation can be taken as $\sim 0.9T_{cr}$ K.

NOTATION

η , dynamic viscosity; λ , thermal conductivity; u , velocity of sound; T , absolute temperature; ϵ , deviation factor for the Shirokov complex; τ , reduced temperature; and π , reduced pressure.

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EFFECTIVE THERMAL CONDUCTIVITY COEFFICIENTS OF A
GRAINY MEDIUM

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An exact solution is presented for the problem of determination of effective thermal conductivity coefficients of a composite medium with regularly spaced spherical grains.

1. The grainy layer considered consists of an isotropic matrix and spherical grains of radius R , the centers of which form a three-dimensional orthogonal lattice with periods a , b , and c . We denote by λ_1 and λ_2 the thermal conductivities of the matrix and grain materials. We introduce a Cartesian coordinate system x, y, z such that its origin coincides with the center of one grain, and the coordinates of the center 0_{pqs} of an arbitrary pqs -th grain are $p\alpha, qb, sc$ (where $p, q, s = 0, \pm 1, \pm 2, \dots$). We denote the temperature field within the matrix by $T(x, y, z)$, and within the pqs -th grain by $T_{pqs}(r_{pqs}, \theta_{pqs}, \Phi_{pqs})$. Here $r_{pqs}, \theta_{pqs}, \Phi_{pqs}$ are spherical coordinates corresponding to the above Cartesian system and $x_{pqs} = x - p\alpha, y_{pqs} = y - qb, z_{pqs} = z - sc$ ($x_{000} \equiv x, y_{000} \equiv y, z_{000} \equiv z$).

The problem consists of integrating the Laplace equation

$$\Delta t = 0 \quad (1)$$

at $t = T$ in the volume outside the grains and $t = T_{pqs}$ in the region occupied by the pqs -th grain under the condition of ideal thermal contact between matrix and grains:

$$T = T_{pqs}, \lambda_1 \frac{\partial T}{\partial r_{pqs}} = \lambda_2 \frac{\partial T_{pqs}}{\partial r_{pqs}}, r_{pqs} = R. \quad (2)$$

We will first determine the effective thermal conductivity of the grainy layer in the z direction.

The essence of the method to be employed is the construction of an explicit expression for the temperature $T(x, y, z)$ in a layer of thickness c , selected from the grainy medium. The faces of this layer are perpendicular to the z axis, and it contains a double-period system of grains with indices $pq0$. The upper face is removed from the plane xy by a distance h_1 , and the lower, by a distance h_2 , so that $h_1 + h_2 = c$ and $h_1, h_2 > R$.

We write the temperature field within the layer in the form

$$T = \gamma z + T_1(x, y, z), \quad (3)$$

where T_1 is a periodic function of arguments x and y with periods a and b , respectively,

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