NOTATION

P, pressure; A, amplitude of the concentrator displacement; f, frequency; I, energy intensity of the ultrasonic oscillations; d, inner diameter; Δ, wall thickness of the capillary tube; δ*, magnitude of the effective gap; ρ, density; μ, coefficient of dynamic viscosity; c, speed of sound in air.

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SPEED OF ULTRASOUND IN WATER OVER A WIDE RANGE OF PRESSURE AND TEMPERATURE

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UDC 534.22

Experimental data are used to derive a formula for determination of the speed of sound in water over a wide range of state parameters.

The speed of sound in water was studied over a wide range of temperature and pressure in [1], which presented its experimental results in the form of a table for the pressure range of 3-30°C at pressures to 70 MPa, and from 75 to 374°C for pressures to 50 MPa. As the authors noted, the method proposed therein allows determination of the speed of sound in water with quite high accuracy.

The present author has attempted to use the experimental data of [1] to define the speed of sound in water as an analytical function of temperature and density.

The speed of sound in liquid n-alkanes [2] has been described by a formula

$$u = u_s' + B(\rho - \rho_s). \tag{1}$$

Tests showed that the speed of sound isotherms in water as a function of $(\rho - \rho_s)$, according to Eq. (1) for 11 isotherms (0, 10, 20, 30, 100, 130, 150, 200, 250, 300, and 350°C) presented in the study, were straight lines. The ρ values for these isotherms at corresponding pressures, presented in Table 1, were calculated from the equation of the isotherm [3]

$$\frac{pv}{RT} = 1 + B\rho + E\rho^4. \qquad (2)^*$$

It should be noted that the specific volumes calculated with Eq. (2), as is evident from Table 2, agree quite well with the tolerances of the International Table for water and water vapor [4].

The saturated water densities were taken from [4], since Eq. (2) does not provide the required accuracy for ρ_s at high temperatures.

Commencing from the linearity of the isotherms, according to Eq. (1), the least-squares method was used to find the speed of sound values u_s' for saturated water and the acoustical coefficient B for all 11 isotherms.

Considering the complex form of the curves $u_s' = f(t)$ and $B = \varphi(t)$ shown in Fig. 1, it was necessary to employ polynomials for their description with satisfactory accuracy. These polynomials are easily solved by a Horner type $\Sigma a_i t^i$ system. Seventh-order polynomials were

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*For water, $R = 4.6151$ bar·cm³/g/deg.

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TABLE 1. Comparison of Speed of Sound in Water Calculated by Eq. (1) with Experimental Data of [1]

t = 0 °C				t = 10°C				t = 20°C				t = 30°C				t = 100°C			
p, MPa	$\rho-\rho_s$	u, m/sec		p, MPa	$\rho-\rho_s$	u, m/sec		p, MPa	$\rho-\rho_s$	u, m/sec		p, MPa	$\rho-\rho_s$	u, m/sec		p, MPa	$\rho-\rho_s$	u, m/sec	
	(2)—[4]	[1]*	(1)		(2)—[4]	[1]*	(1)		(2)—[4]	[1]*	(1)		(2)—[4]	[1]*	(1)		(2)—[4]	[1]*	(1)
p_s	0	—	1400	p_s	0	—	1442	p_s	0	—	1477	p_s	0	—	1504	p_s	0	—	1544
5,093	2,639	1410	1409	5,0923	0,2388	1455	1451	5,0958	2222	1490	1486	5,0931	2,190	1518	1513	5,0968	2,123	1554	1554
10,868	5,589	1419	1420	10,867	5132	1464	1462	10,870	4849	1500	1496	9,888	4,338	1526	1522	10,872	4,818	1566	1566
15,766	8,050	1427	1429	15,764	7427	1472	1470	15,768	7066	1508	1505	14,787	6,487	1534	1531	15,769	7,084	1576	1577
25,561	12,873	1443	1446	25,560	11,928	1489	1487	25,565	11,373	1524	1522	24,582	10,705	1550	1548	20,668	9,311	1586	1587
30,459	15,218	1451	1455	30,458	14,144	1497	1496	30,461	13,481	1533	1531	30,459	13,176	1560	1558	25,566	11,498	1596	1597
35,357	17,561	1459	1463	35,356	16,332	1505	1504	35,360	15,581	1541	1539	35,357	15,207	1567	1567	30,465	13,646	1606	1607
40,255	19,836	1468	1771	40,254	18,481	1513	1512	40,258	17,651	1549	1547	40,254	17,229	1577	1575	35,362	15,794	1615	1617
50,059	24,327	1485	1487	50,038	22,700	1530	1528	50,062	21,685	1565	1563	50,946	21,183	1593	1591	40,260	17,864	1625	1626
59,862	28,702	1503	1503	59,862	26,839	1547	1544	59,865	25,658	1582	1579	54,946	23,127	1601	1599	50,065	22,005	1644	1645
70,640	33,389	1523	1520	69,666	30,863	1564	1560	69,669	29,525	1599	1595	59,746	25,011	1609	1607	—	—	—	—

t = 130°C				t = 200°C				t = 300°C				t = 350°C			
p_s	0	—	1503	p_s	0	—	1330	p_s	0	—	908	p_s	0	—	575
5,0973	2,627	1516	1515	5,0961	2,645	1343	1343	8,827	1,067	910	912	16,753	2,885	584	585
10,872	5,556	1529	1529	10,870	6,864	1364	1363	10,874	5,675	930	932	20,671	28,654	676	672
15,770	8,027	1541	1541	15,777	10,340	1381	1379	15,771	15,073	972	972	25,569	53,007	754	755
20,668	10,401	1552	1552	20,666	13,738	1397	1396	20,667	23,502	1009	1008	30,466	70,679	814	815
25,566	12,783	1564	1563	25,563	17,020	1413	1411	25,566	31,451	1043	1142	35,364	85,366	864	865
30,463	15,127	1574	1574	30,460	20,263	1428	1427	30,463	38,834	1074	1173	40,261	98,013	908	908
36,362	17,392	1585	1585	35,359	23,426	1443	1442	35,361	45,748	1103	1103	45,163	109,045	947	946
40,259	19,658	1596	1596	40,255	26,512	1458	1457	40,258	52,272	1131	1131	50,066	118,711	982	979
50,063	24,111	1617	1617	50,059	32,489	1486	1485	50,061	64,303	1180	1182	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

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*u values presented are rounded.

TABLE 2. Comparison of Specific Volume of Water v, cm^3/g, Calculated by Eq. (2) with Data of International Tables [4]

p, bar	$t = 0°C$		50		100		150		200		250		300		350	
	$B = -6{,}3778$ $E = 3{,}3810$		$B = -6{,}3897$ $E = 5{,}5767$		$B = -5{,}6116$ $E = 5{,}1976$		$B = -4{,}7194$ $E = 4{,}7109$		$B = -3{,}8567$ $E = 4{,}1915$		$B = -3{,}1575$ $E = 3{,}7844$		$B = -2{,}5862$ $E = 3{,}4437$		$B = -2{,}2195$ $E = 3{,}4457$	
	[4]	(2)	[4]	(2)	[4]	(2)	[4]	(2)	[4]	(2)	[4]	(2)	[4]	(2)	[4]	(2)
1	1,0002 1	1,0002	1,0121 2	1,0121	—	—	—	—	—	—	—	—	—	—	—	—
10	0,9997 2	0,9997	1,0117 2	1,0119	1,0433 2	1,0435	1,0903 3	1,0902	—	—	—	—	—	—	—	—
50	0,9976 2	0,9976	1,0099 2	1,0099	1,0410 2	1,0414	1,0878 3	1,0876	1,1531 3	1,1531	1,2495 4	1,2494	—	—	—	—
100	0,9952 2	0,9951	1,0077 2	1,0077	1,0386 4	1,0389	1,0846 4	1,0843	1,1483 4	1,1482	1,2409 4	1,2409	1,397 1	1,397	—	—
200	0,9904 2	0,9902	1,0033 2	1,0033	1,0336 4	1,0340	1,0782 4	1,0780	1,1399 4	1,1390	1,2251 5	1,2254	1,360 1	1,361	1,665 2	1,664
300	0,9856 2	0,9854	0,9992 2	0,9991	1,0289 4	1,0292	1,0721 4	1,0720	1,1304 4	1,1304	1,2111 5	1,2115	1,331 1	1,333	1,555 2	1,555
400	0,9811 2	0,9809	0,9951 2	0,9950	1,0244 4	1,0247	1,0664 4	1,0663	1,1224 4	1,1223	1,1981 6	1,1987	1,308 1	1,309	1,489 3	1,492
500	0,9766 2	0,9765	0,9912 3	0,9911	1,0200 4	1,0203	1,0609 5	1,0608	1,1148 5	1,1147	1,1868 6	1,1871	1,288 1	1,288	1,443 3	1,447
600	0,9723 3	0,9722	0,9873 3	0,9873	1,0157 4	1,0161	1,0556 5	1,0555	1,1075 5	1,1074	1,1760 6	1,1763	1,270 1	1,270	1,407 3	1,412
800	0,9642 3	0,9642	0,9800 3	0,9800	1,0076 4	1,0079	1,0456 5	1,0456	1,0941 5	1,0940	1,1568 8	1,1569	1,239 1	1,239	1,355 3	1,358
1000	0,9566 3	0,9566	0,9731 3	0,9731	1,0000 4	1,0003	1,0363 5	1,0363	1,0818 5	1,0818	1,1398 12	1,1398	1,214 3	1,213	1,314 4	1,318

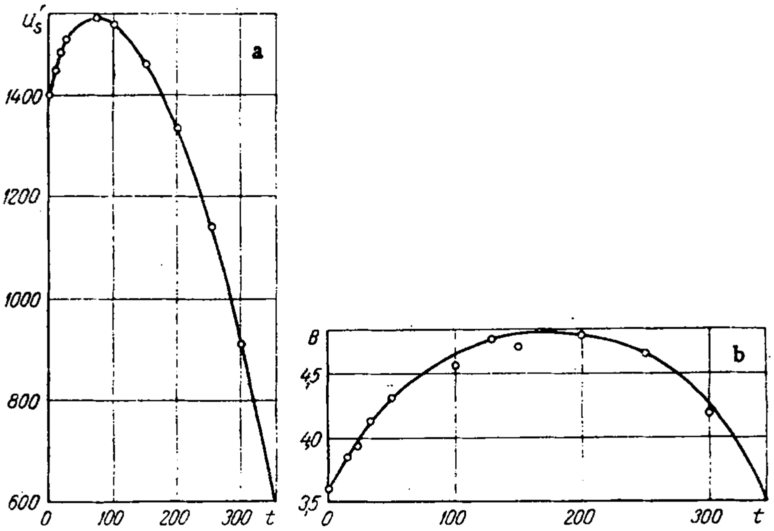

Fig. 1. Speed of sound in saturated liquid u_s', m/sec (a) and acoustical coefficient B, $m^4/kg \cdot sec$ (b) versus temperature, °C.

TABLE 3. Coefficients of Polynomials $u_s' = \sum_{i=0}^{i=7} a_i t^i$ and $B = \sum_{i=0}^{i=7} a_i t^i$ for Water

Coefficient	u_s'	B	Coefficient	u_s'	B
a_0	$140000 \cdot 10^{-2}$	$35900 \cdot 10^{-4}$	a_4	$945556 \cdot 10^{-12}$	$-23756 \cdot 10^{-12}$
a_1	$455419 \cdot 10^{-5}$	$25707 \cdot 10^{-6}$	a_5	$-516889 \cdot 10^{-14}$	$83556 \cdot 10^{-15}$
a_2	$-364378 \cdot 10^{-7}$	$-36566 \cdot 10^{-8}$	a_6	$118222 \cdot 10^{-16}$	$-15289 \cdot 10^{-17}$
a_3	$-688889 \cdot 10^{-12}$	$37876 \cdot 10^{-10}$	a_7	$-104127 \cdot 10^{-19}$	$11175 \cdot 10^{-20}$

TABLE 4. Parameters of Maximum Speed of Sound in Water

p, MPa	t, °C	u_{max}, m/sec	P, bar	t, °C	u_{max}, m/sec
10	77	1576	600	83	1671
20	78	1596	700	85	1688
30	79	1516	800	86	1705
40	80—81	1634	900	87	1723
50	82	1653	1000	88	1739

obtained, since u_s' and B values for eight isotherms from 0 to 350°C in 50°C steps were used to calculate them. The values of the constant polynomial coefficients are presented in Table 3.

Table 1 compares the values of the speed of sound in water calculated with Eq. (1) with the experimental data of [1]. As is evident from the table, Eq. (1) describes the values with a high accuracy, the maximum deviation from the experimental data being 4 m/sec (~0.2%), which is completely acceptable for engineering calculations.

Tests revealed that the polynomials for u_s' and B constructed from Fig. 1a,b every 5-10° over the temperature range from 0 to 350°C have no wave-shaped segments. Thus, Eq. (1), as is evident from Table 1, also gives correct results for intermediate temperatures (10, 20, 30, and 130°C).

It should be noted that the expression for the speed of sound may be obtained from differential thermodynamic relationships and the equation of state chosen here, Eq. (2), but will be nonlinear in density. Therefore, the formula used here, Eq. (1), is of an approximate character, but its value lies in the fact that within the state parameter limits considered it transforms a nonlinear dependence into a linear one.

It should also be noted that speed of sound values can be calculated with Eq. (1) up to 100 MPa.

It is to be expected that such extrapolation is justifiable, since for n-hexane* Eq. (1) is valid to $\sim 40 p_{cr}$, for water, the corresponding limit is an order of magnitude lower, being only $\sim 4.5 p_{cr}$.

It is known that the speed of sound in water at all pressures shows maxima. Our studies show that up to 100 MPa these maxima, as may be seen from Table 4, are located in the temperature range of 75–88°C.

NOTATION

u, speed of sound; u_s', speed of sound in saturated liquid; B, temperature dependent acoustical coefficient of Eq. (1); ρ, density; ρ_s, density of saturated liquid; p pressure, v, specific volume; T, absolute temperature; B and E, temperature-dependent coefficients of Eq. (2).

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*p_{cr} = 30.31 bar [5].