Reduced flow rate of plasma-forming gas and reduced power of the electric arc cause more rapid equalization of the heat flux in the cross sections of the reactor. However, in that case the absolute value of the heat flux density and the fraction of the reactor filled with high-enthalpy gas are reduced.

## NOTATION

N, electric power of the plasmatrons, kW; G, flow rate of the plasma-forming gas, kg/sec; q, heat flux density from the gas to the probe, W/m$^2$; L, length of the reactor, m; $\alpha$, angle of insertion of the probe in the cross section of the reactor, deg; h, range of the plasma jet, m; d, diameter of the anode channel, m; K, experimental coefficient equal to 2.2; $v_1$, $v_2$, linear velocity of the total flux and of the plasma jet, respectively, m/sec; $\rho_1$, $\rho_2$, gas density in the total flux and in the plasma jet, respectively, kg/m$^3$.

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# THERMODYNAMIC PROPERTIES OF NORMAL PROPYL ALCOHOL AT ATMOSPHERIC PRESSURE


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Data from the literature on density, speed of sound, and isobaric specific heat are analyzed and approximated. Isochoric specific heat and adiabatic and isothermal compression coefficients are calculated for normal propyl alcohol at atmospheric pressure for the temperature range 146.95-370.35°K.


The systematization and compact presentation of information (compression of experimental data) on experimental studies of the thermodynamic properties of aliphatic alcohols over wide temperature and pressure ranges, and especially at atmospheric pressure, is a task of great practical importance.

There exist only a few review articles and handbooks [1-4] containing collections of experimental data on the density and isobaric specific heat of normal propyl alcohol at atmospheric pressure, encompassing the temperature range 253-363°K. The most complete is handbook [3]. But it should be noted first, that not all properties are presented in those studies, and second, the collected results encompass only the time period up to 1970. Practically no one had reported data on the speed of sound previously. The literature contains no in-

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TABLE 1. Calculated Specific Volume and Density of Propyl Alcohol

| $T$ | $v$ | $\rho$ | $T$ | $v$ | $\rho$ |
|---|---|---|---|---|---|
| 146,95 | 1,08356 | 0,92289 | 263,15 | 1,20926 | 0,82695 |
| 153,15 | 1,09050 | 0,91701 | 273,15 | 1,22068 | 0,81922 |
| 163,15 | 1,10132 | 0,90801 | 283,15 | 1,23234 | 0,81147 |
| 173,15 | 1,11188 | 0,89938 | 293,15 | 1,24432 | 0,80365 |
| 183,15 | 1,12237 | 0,89098 | 298,15 | 1,25047 | 0,79970 |
| 193,15 | 1,13288 | 0,88271 | 303,15 | 1,25674 | 0,79571 |
| 203,15 | 1,14348 | 0,87453 | 313,15 | 1,26971 | 0,78758 |
| 213,15 | 1,15418 | 0,86642 | 323,15 | 1,28335 | 0,77921 |
| 223,15 | 1,16499 | 0,85838 | 333,15 | 1,29779 | 0,77054 |
| 233,15 | 1,17589 | 0,85042 | 343,15 | 1,31312 | 0,76154 |
| 243,15 | 1,18690 | 0,84253 | 353,15 | 1,32943 | 0,75220 |
| 253,15 | 1,19801 | 0,83471 | 363,15 | 1,34674 | 0,74253 |
| | | | 370,35 | 1,35982 | 0,73539 |

formation on isochoric specific heat, and the presentation of adiabatic and isothermal compression coefficients is limited.

Specific Volume and Density. The present study makes use of experimental data on the density of liquid propanol at atmospheric pressure obtained at various times and contained in [1-3, 5-15]. The International Critical Tables [1] and Timmerman's handbook [2] present results over the temperature interval 273-303°K. Density measurements were performed in the low temperature range in [7, 8, 12]. In the absence of reliable data in the interval from 303°K to the boiling point, experimental data on the saturation curve [3, 13-15] were used in the processing. Since the isothermal compressibility of alcohols is significantly greater than that of water, recalculation of density on the saturation curve to density at atmospheric pressure was performed with the expression

$$\rho = \rho' \exp[\beta_T (0.101325 - P_S)] \tag{1}$$

with the assumption that over the pressure interval from $P_S$, the saturation pressure, to atmospheric, the quantity $\beta_T$ is constant. This is quite permissible, since the pressure difference is less than 0.1 MPa, and the correction to the density does not exceed 0.015%. The values of $\beta_T$ are taken from [6], in which they were experimentally determined at temperatures of 283-363°K to an accuracy of 1%. For the final processing, a set of reliable original experimental data [1-3, 12-15] was collected.

To describe the temperature dependence of specific volume and density at atmospheric pressure the equation

$$v = \sum_{i=0}^{6} a_i \tau^i; \quad \rho = \frac{1}{\sum_{i=0}^{6} a_i \tau^i} \tag{2}$$

was used, where $\tau$ = T/1000; T is temperature in °K by the MPShT-68 standard scale.

Calculations of the coefficients $a_i$ for Eq. (2) were performed by a "Minsk-32" computer using the method of least squares. The following values were obtained: $a_0 = 0.210135586$; $a_1 = 0.192839148 \cdot 10^2$; $a_2 = -0.188755691 \cdot 10^3$; $a_3 = 0.102147830 \cdot 10^4$; $a_4 = -0.304567531 \cdot 10^4$; $a_5 = 0.473538893 \cdot 10^4$; $a_6 = -0.297870150 \cdot 10^4$.

Values of density and specific volume for the range from the freezing point (T = 146.95°K [3]) to the boiling point (T = 370.35°K [3]) as calculated by Eq. (2) are presented in Table 1. Figure 1a shows the deviation of the experimental values from those calculated by Eq. (2), together with deviations of values from [5, 9], which were not considered in Eq. (2). As is evident from the figure, Eq. (2) describes the most reliable results of [1-3, 12, 14] with an error not exceeding 0.02% at 263-363°K and 0.03% below 263°K, which generally corresponds to the experimental uncertainty of the original authors, so that it may be assumed that this agreement between experiment and calculation results defines the accuracy of the recommended density and specific volume values (Table 1).

As for the results of other authors, the deviations, as would be expected, are more significant, since these results are of relatively low accuracy and show large systematic divergences from the other data analyzed,

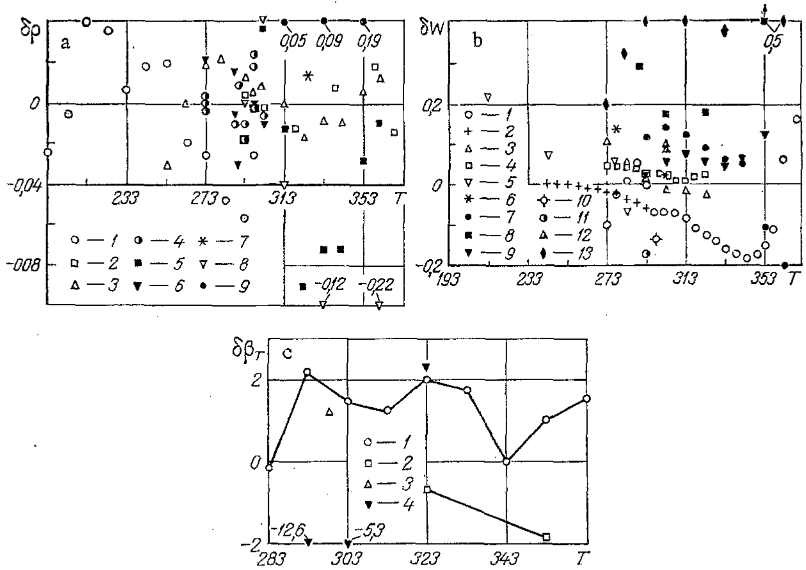

Fig. 1. Comparison of calculated values of density (a), speed of sound (b), isothermal compression coefficient (c) with data of other authors: a) $\delta\rho = (\rho\,[i] - \rho\,[av])\,100/\rho\,[av]$; % (1 – [12]; 2 – [14]; 3 – [3]; 4 – [2]; 5 – [13]; 6 – [1]; 7 – [15]; 8 – [9]; 9 – [5]); b) $\delta W = (W[i] - W[av])\,100/W[av]$; % (1 – [21]; 2 – [29]; 3 – [24]; 4 – [30]; 5 – [7]; 6 – [17]; 7 – [20]; 8 – [27]; 9 – [25]; 10 – [28]; 11 – [18]; 12 – [22, 26]; 13 – [31]); c) $\delta\beta_T = (\beta_T[i] - \beta_T[av])\,100/\beta_T[av]$; % (1 – [16]; 2 – [39]; 3 – [37]; 4 – [38]).

apparently produced by the varying purity of the alcohols studied (which was often not indicated). As an example, the results of [5-8, 10-11] lie systematically above the present calculated values by average amounts of 0.1, 0.2, 0.25, 0.5, 0.2, and 0.15%, respectively, while the data of [9] are low, the deviation increasing with temperature until it reaches 0.22% at 363°K.

One should note the good agreement within ±0.01% of the calculated density value at 298.15°K and the most reliable data from [3, 14].

Speed of Sound. A large number of studies have dealt with the speed of sound in propanol [17-31]. Basically, results were obtained over the temperature range 273-363°K. There are also a number of studies in which the speed of sound was measured in alcohols with a high water content. When results are compared the differences in speed reach as high as 10 m/sec or more. Today these studies are of historic interest and will not be considered further. At temperatures below 273°K the speed of sound was measured only in [7, 29]. In [7] the temperature range studied was 128-275°K at frequencies of 1-52.5 MHz. It was established that beginning at 173°K the speed of sound is frequency-dependent, i.e., dispersion occurs. The latter exists even in the low absorption frequency range (1, 3, and 5 MHz). The value of the dispersion step in the curve of speed of sound versus frequency at 1 and 3 MHz is 0.12% at 173°K, reaching 1.4% with decrease in temperature to 148°K. Since determination of the speed of sound at zero frequency at temperatures of 148-173°K is practically impossible, the present study employed data obtained at 1 MHz in its data base. However, since the data of [7] are unique for this temperature range, a graph of the function $W = \varphi(F)$ for temperatures of 173, 163, 158, and 148°K was used to estimate the possible effect of dispersion on the speed of sound when the latter was reduced to zero frequency (to the frequency where the corresponding curves becomes horizontal). With consideration of these estimates, the speed of sound values corresponding to these temperatures and 1-MHz frequency were given lower weighting in the calculations.

Comparison of speed of sound values of the various authors reveals that the majority agree within 0.1-0.2%. The most reliable are the measurements of [24, 29-30]. However it should be noted that the results of [29, 30], obtained by the same method, agree with each other where their ranges overlap within 0.08-0.09%, with the measurement accuracy being estimated at 0.01%. The cause of this divergence was not explained. It should be kept in mind that [29, 30] do not directly present experimental data, but offer coefficients for a third degree polynomial in temperature, constructed by the authors on the basis of experimental data.

TABLE 2. Calculated Values of Thermodynamic Properties of Propyl Alcohol

| $T$ | $C_P$ | $C_V$ | $\beta_S \cdot 10^5$ | $\beta_T \cdot 10^5$ | $W$ |
|---|---|---|---|---|---|
| 146,95 | 1,7663 | 1,3450 | 31,85 | 41,83 | 1844,4 |
| 153,15 | 1,7721 | 1,3737 | 33,19 | 42,82 | 1812,6 |
| 163,15 | 1,7827 | 1,4082 | 35,47 | 44,90 | 1762,2 |
| 173,15 | 1,7957 | 1,4338 | 37,89 | 47,46 | 1713,0 |
| 183,15 | 1,8120 | 1,4558 | 40,48 | 50,38 | 1665,1 |
| 193,15 | 1,8321 | 1,4781 | 43,24 | 53,60 | 1618,6 |
| 203,15 | 1,8564 | 1,5033 | 46,19 | 57,04 | 1573,4 |
| 213,15 | 1,8853 | 1,5332 | 49,34 | 60,67 | 1529,5 |
| 223,15 | 1,9192 | 1,5688 | 52,68 | 64,45 | 1487,0 |
| 233,15 | 1,9586 | 1,6106 | 56,25 | 68,40 | 1445,9 |
| 243,15 | 2,0040 | 1,6587 | 60,04 | 72,54 | 1406,0 |
| 253,15 | 2,0561 | 1,7131 | 64,07 | 76,90 | 1367,4 |
| 263,15 | 2,1156 | 1,7736 | 68,37 | 81,56 | 1329,9 |
| 273,15 | 2,1832 | 1,8398 | 72,97 | 86,59 | 1293,4 |
| 283,15 | 2,2595 | 1,9115 | 77,89 | 92,07 | 1257,8 |
| 293,15 | 2,3450 | 1,9885 | 83,19 | 98,10 | 1223,0 |
| 298,15 | 2,3913 | 2,0288 | 86,00 | 101,36 | 1205,9 |
| 303,15 | 2,4400 | 2,0703 | 88,92 | 104,80 | 1188,8 |
| 313,15 | 2,5444 | 2,1567 | 95,17 | 112,28 | 1155,0 |
| 323,15 | 2,6573 | 2,2472 | 102,04 | 120,67 | 1121,5 |
| 333,15 | 2,7773 | 2,3412 | 109,66 | 130,10 | 1087,9 |
| 343,15 | 2,9021 | 2,4379 | 118,20 | 140,71 | 1054,0 |
| 353,15 | 3,0281 | 2,5364 | 127,87 | 152,66 | 1019,6 |
| 363,15 | 3,1503 | 2,6351 | 138,95 | 166,12 | 984,5 |
| 370,35 | 3,2322 | 2,7051 | 148,01 | 176,86 | 958,5 |

Data from [7, 20-31] were processed with the equation

$$W = \sum_{i=0}^{4} c_i \tau^i, \tag{3}$$

where $c_0 = 0.261864027 \cdot 10^4$; $c_1 = -0.445597897 \cdot 10^4$; $c_2 = -0.135588172 \cdot 10^5$; $c_3 = 0.665899463 \cdot 10^5$; $c_4 = -0.814726249 \cdot 10^5$. Deviations of the original data from the value given by Eq. (3) are shown in Fig. 1b, from which it is evident that the deviations lie essentially within the range of measurement uncertainty of the various studies. Since in [7] sound dispersion was observed at low temperatures, the accuracy of the speed of sound calculations below 173°K can be estimated at 0.5-0.8%.

Isobaric Specific Heat. The broadest studies of isobaric specific heat in propanol, encompassing the temperature range of 154-361°K, were carried out in [32], in which 48 experimental points were obtained, with accuracy estimated at 0.1-0.15% by the authors. There also exist a number of studies [2, 20, 33-35], in which $C_P$ was studied over a narrower temperature interval, and with less accuracy (0.5-1.5%). The values of $C_P$ presented in [3] for the freezing and boiling points and at 298.15°K have an accuracy of the order of ±1%.

Preliminary analysis of the available material resulted in the data of [2, 3, 32, 33, 35] being used for the final processing, with values from [32] being assigned greater weight. Since [32] presented values of isobaric specific heat on the boundary curve $C_P^b$, these were recalculated to atmospheric pressure, the required correction not exceeding 0.01%.

The approximation equation for $C_P$ has the form

$$C_P = \sum_{i=0}^{6} b_i \tau^i, \tag{4}$$

in which $b_0 = -0.175022350 \cdot 10^1$; $b_1 = 0.985731021 \cdot 10^2$; $b_2 = -0.114177424 \cdot 10^4$; $b_3 = 0.694611721 \cdot 10^4$; $b_4 = -0.234156895 \cdot 10^5$; $b_5 = 0.419466257 \cdot 10^5$; $b_6 = -0.308111498 \cdot 10^5$. Equation (4) describes the original data with an error not exceeding the measurement error of the original studies, with the exception of a single point at 298.15°K [3], in which the deviation is 1.93% with an estimated measurement accuracy of 0.9%. Considering that the calculated $C_P$ values agree with the most reliable data of [32] at 147-361°K within ± 0.2%, while above 361°K they agree (with data of other authors) within ±0.7%, we may assume that the calculated $C_P$ values have the same accuracy.

The equations obtained for specific volume, speed of sound, and isobaric specific heat were used to calculate the isochoric specific heat, and adiabatic and isothermal expansion coefficients with the relationships presented in [36]. The calculated values of W, $C_P$, $C_V$, $\beta_S$, and $\beta_T$ are presented in Table 2. Figure 1c compares calculated $\beta_T$ values with experimental data of [16, 37, 38] and experimental $\beta_T$ values from [39], obtained from speed of sound measurements. As is evident from the figure, the divergence does not exceed 2%, except for the data of [38], for which the divergence is 12.6 and 5.3% at temperatures of 293 and 303°K respectively. The calculated $\beta_S$ agree with the calculated results of [39] within 1%, the results of that study for both $\beta_S$ and $\beta_T$ lying below the present values.

As for the temperature dependence of the thermal expansion coefficient $\alpha = (1/v)(dv/dT)_p$ the results of the present calculations show that this value increases with approach to the freezing point. This unique phenomenon was first noted in [12], in which the authors proposed that such an anomaly in the behavior of $\alpha$ was apparently related to a change in the structure of liquid alcohols near the freezing point.

## NOTATION

T, temperature, °K; v, specific volume, $cm^3/g$; $\rho$, $\rho'$, liquid density at atmospheric pressure and on saturation curve, $g/cm^3$; W, speed of sound, m/sec; $C_V$, $C_P$, isochoric and isobaric specific heats, kJ/(kg · °K); $\beta_S$, $\beta_T$, adiabatic and isothermal compression coefficients, 1/MPa; $P_S$, saturation pressure, MPa; $\alpha$, thermal expansion coefficient, 1/°K; F, frequency, MHz.

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