An Improved Approximation for DIPPR-Based Predicting Speed of Sound in Long-Chained \textit{n}-Alkanes

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In this short communication, we revise a correlation for the saturated liquid isothermal compressibility based on the data available in DIPPR (Postnikov, 2016) which considers the molecular non-sphericity and addresses a problem of predicting speeds of sound in saturated long-chained alkanes. In addition, we correct a misprint appeared in the cited work and provide programming code used for the realisation of the proposed calculations.

**Keywords:** \textit{n}-alkanes; isothermal compressibility; speed of sound.

1. Introduction

DIPPR (DIPPR 801 Database) is one of the most popular databases on thermophysical properties of substances. However, due to the lacking of pertinent experimental data, it does not include several important properties, such as the isothermal compressibility, isobaric thermal expansion coefficient, and speeds of sound of saturated liquids. In the previous study (Postnikov, 2016) it was demonstrated that these properties can be estimated in a raw manner while implementing the available in the DIPPR data on vapour pressures, saturated liquid densities, and isobaric heat capacities. That approach was based on the Brelvi-O’Connel correlation for the isothermal compressibility (\(\kappa T\)):

\[
\frac{\mu_0}{RT \rho e T} = \exp \left[ -0.42704 (\xi \rho_r - 1) + 2.089 (\xi \rho_r - 1)^2 - 0.42367 (\xi \rho_r - 1)^3 \right] - 1. \tag{1}
\]

In Eq. (1) \(\rho_r = \rho / \rho_c\) (the reduced density), \(\rho_c\) is the critical density, \(\xi\) is an adjustment parameter determined using the internal pressure at the boiling point (Chorążewski et al., 2015); \(\mu_0\), \(R\), \(T\) are the molar mass, the gas constant, and the temperature, respectively. A major shortcoming of this correlation is a non-monotonic character of the cubic polynomial in respect of the reduced density. In particular, this equation exhibits a drastic decay for large reduced densities \(\rho_r > 4.18\). Such reduced densities are typical for the long-chained hydrocarbons, whose saturated liquid sound velocities have not been predicted in an accurate manner (Postnikov, 2016). Moreover, \(\xi \neq 1\) leads to the unphysical negative isothermal compressibility in the critical point because Eq. (1) does not reproduce accurately the transition to power law character of the isothermal compressibility in the sub-critical region.

This study aims at correcting these issues. Here we propose a more physically reasonable correlation for the isothermal compressibility resulting in more accurate predictions of speeds of sound for a larger variety of compounds.

2. The improved correlation for the isothermal compressibility

Instead of improving the dimensionless combination (1), we directly consider the isothermal compress-
satisfies the same functional form in the subcritical region. Indeed, Eq. (2) can be represented as $\rho = \rho_c \exp(-t^D \log B)$ because $C = T_c, A/B = \rho_c$. Consequently, using the expansion $\exp(x) \approx 1 + x$ for $t \ll 1$, we get $\rho - \rho_c = \rho_c \log B^{-1} \cdot t^D$. The latter means that the DIPPR’s density coefficient $D$ is in fact the Widom’s density critical index, while the corresponding isothermal compressibility index is equal to $\gamma = 2(1 - D)$. Since the power law is valid within the subcritical region only, we can obtain the isothermal compressibility as a function of the deviation of the reduced temperature from unity $\kappa_T = \kappa_0 (t - 1)^{-\gamma}$, where $g(t) \to 1$ at $t \to 0$, and $\kappa_0 = \text{const}$.

Within a general framework of the crossovers from long range to short range correlations, we have investigated the correcting function $g(t) = \exp(\gamma_1 t)$. We have used the standard thermodynamic expression for the isothermal compressibility

$$\kappa_T = \frac{1}{\rho} \left( \frac{1}{u^2} + \frac{T \alpha_F^2}{C_P} \right)$$

with the substituted warrant speed of sound data $u$ (Neruchev et al., 2005) and DIPPR correlations (DIPPR 801 Database) for other thermodynamic parameters (the density $\rho$ and its isobaric coefficient of expansion $\alpha_F$ and the isobaric heat capacity $C_P$) for short-chained $n$-alkanes from $n$-pentane to $n$-dodecane and evaluated two-stage fitting, which included minimisation of the deviation between experimental and calculated data with the subsequent polynomial interpolation of the obtained individual values of $\gamma_1$. This fitting evaluated using the build-in statistical function of SigmaPlot software has yielded the following function (the correlation coefficient 99.98%, see Fig. 1 as illustration):

$$\gamma_1 = -0.663r_g + 0.0859r_g^2 - 0.00432r_g^3,$$  \hspace{1cm} (3)

where $r_g$ is the molecule gyration radius given in DIPPR database multiplied by the factor $10^{10}$. This selection of the control parameter has been motivated by the physical assumption that the non-spherical molecular shapes should influence the packing properties, and, correspondingly, the isothermal compressibility.

Fig. 1. Coefficients in the exponential correcting factor for the isothermal compressibility for short-chained $n$-alkanes from $n$-pentane to $n$-dodecane as a function of the gyration radii and their fitting by Eq. (3).

The constant $\kappa_0$ can be determined expressing the isothermal compressibility $\kappa_T = \kappa_0 g(t) (t - 1)^{-\gamma}$ included in the respective inverse density fluctuations parameter $\nu_b = \mu_0 \left( \frac{RT_b \kappa_T}{\rho_b} \right)^{-1}$ via the internal pressure at the boiling point (Postnikov, 2016)

$$P_b = \frac{(24.5T_b - 1400)(4.44 - 0.78\omega)\rho_b}{\mu_0},$$

where $\omega$ is Pitzer’s acentric factor and $T_b$ is the boiling temperature.

Here we report that Eqs. (10) and (11) in (Postnikov, 2016) contain a misprint: there is no $T_b$ in their denominators. However, this textual misprint did not appear in the programming code used for calculations. It is freely accessible now (Postnikov et al., 2018) and all numerical and graphical results of (Postnikov, 2016) are valid. Thus, the correct form of the modified Srivastava’s correlation is Eq. (4).

It should be pointed out that many long-chained hydrocarbons decompose below their boiling temperatures. Consequently, the reported by DIPPR $T_b$ values often present raw estimations rather than experimental measurements. For this reason, we have adopted the following criterion:

$$T_b = \begin{cases} T_b \text{ [DIPPR]} > 0.82T_c, & T_b \text{ [DIPPR]}, \\ T_b = 0.82T_c, & \text{otherwise}, \end{cases}$$

(5)

This correcting replacement should be applied to $n$-alkanes $C_nH_{2n+2}$ with $n \geq 23$ because the DIPPR-provided boiling temperature results in a sufficient overestimating of the speed of sound. An example of such overestimation is shown in Fig. 2, where one can see that the dash-dotted line representing the speed of sound in squalane calculated using the DIPPR-provided boiling temperature is practically parallelly shifted into the region of higher values with respect to experimental data (upward triangles) and the calculations reproducing them using the correction (5) (solid line).
In addition, the differentiated logarithm of Eq. (2) yields the following expression for the isobaric thermal expansion coefficient:

$$\alpha_p = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_P = -\frac{d \log \rho}{dT} = -\frac{D}{C} T^{D-1} \log B. \quad (6)$$

Therefore, utilising the thermodynamic definition of the internal pressure

$$P_i = T \frac{\alpha_p}{\kappa_T} - P \quad (7)$$

and neglecting the atmospheric pressure $P = P_a$ in the right-hand side, we obtain the following expression for the isothermal compressibility in the boiling point (i.e. $P_i = P^b_i$ here):

$$\kappa_0 = -\frac{T_b}{T_c} e^{-\gamma_1(1-\frac{T_b}{T_c})} D \left( 1 - \frac{T_b}{T_c} \right)^{1-D} \log B. \quad (8)$$

In addition to the DIPPR’s expression for the saturated liquid densities (Eq. (2)), the proposed approach requires the data on isobaric heat capacities, which are also available in the databank. These data should be interpreted as:

$$C_p = \begin{cases} C_a = \sum_{n=0}^{4} c_n T^n, & \text{if } T \leq T_b, \\ C_a - \alpha P \frac{dP}{dT}, & \text{otherwise}, \end{cases} \quad (9)$$

where $c_n$ are the DIPPR coefficients for the liquid phase isobaric heat capacity, $C_a$ is the isobaric heat capacity of saturated liquid and

$$\frac{dP}{dT} = \left( \frac{B_T}{T^2} + \frac{C_T}{T} + D_T E_T T^{E_T-1} \right) \cdot \exp \left( A_T + \frac{B_T}{T} + C_T \log(T) + D_T T^{E_T} \right) \quad (10)$$

is a temperature derivative of the DIPPR’s expression for the vapour pressures, whose coefficients are $A_T$, $B_T$, $C_T$, $D_T$, $E_T$, respectively.

The choice between two expressions given in Eq. (9) corresponds to the explanation to the correlations provided in (DIPPR 801 Database): for temperatures lower than the boiling point, they describe the heat capacity at the constant (normal atmospheric) pressure, i.e. $C_p$, directly; otherwise it is the saturated heat capacity.

The isobaric expansion coefficient can be obtained as a derivative of Eq. (2) (with an additional correction for the saturation curve for temperatures larger than the boiling one):

$$\alpha_p = \begin{cases} \frac{-D}{C} \left( 1 - \frac{T}{C} \right)^{1-D} \log B, & \text{if } T \leq T_b, \\ \frac{-D}{C} \left( 1 - \frac{T}{C} \right)^{1-D} \log B + \frac{\kappa_T}{C_T} \frac{dP}{dT}, & \text{otherwise}, \end{cases} \quad (11)$$

The isothermal compressibility should be determined as follows:

$$\kappa_T = \exp \left( a + \frac{b}{T} + c \log(T) + d T^e \right) \quad (12)$$

and $a = \log(\kappa_0)$, $b = 0$, $c = -\gamma$, $d = \gamma_1$, $e = 1$.

Note that Eq. (12) has the form called DIPPR-equation 101 and mathematically equivalent to the form $\kappa_T = \kappa_0 \exp(\gamma_1 T)^{-\gamma}$ discussed above.

All these quantities can be combined for the final calculation of the speed of sound via the standard thermodynamic formula

$$u = \left( \kappa_T \rho - \frac{T a^2}{C_p} \right)^{-1/2}, \quad (13)$$

which can be practically used step-by-step as follows:

(i) take coefficients for a chosen liquid from DIPPR 801 database and compute for each temperature the density, the isobaric heat capacity, and the isobaric expansion coefficients of expansion using DIPPR correlation formulae and their derivatives (2), (9)–(11);

(ii) compute the amplitude factor using Eqs. (4) and (8) as well as the exponential coefficients $\gamma = 2(1-D)$, $\gamma_1$ given by Eq. (3) using the parameters from the same source (DIPPR 801 Database);

(iii) substitute the obtained numerical parameters into Eq. (12) obtaining the isothermal compressibility;

(iv) substitute all these calculated functions into Eq. (13) that gives the desired value for the speed of sound.
To automate this procedure, we provide a free programming library (Postnikov et al., 2018) for MATLAB/OCTAVE, which evaluates these calculations and exports the obtained speed of sound values into a text file. DIPPR parameters may be entered using an Excel spreadsheet. An example for n-hexane filled with the data freely available due to courtesy of DIPPR AICHE demo database (dippr.aiche.org) is provided for guidance of formatting.

3. Results

Let us evaluate the predictions yielded by the proposed approach for the speeds of sound of saturated liquid hydrocarbons. The experimental data have been reported by several sources: Neruchev et al., 2005 for n-alkanes from n-octane to n-tetracosen (with exception of n-tetradecane). The latter substance was investigated by Khasanshin et al. (2001). The data on n-pentadecane and n-heptadecane were published by Daridon et al. (2002), n-octadecane – by Dutour et al. (2000), n-triacontane (squalane) – by Korotkovskih et al. (2012).

The coefficients used in Eqs. (2), (6), (10) are taken from (DIPPR 801 Database). In addition, the DIPPR density coefficient $D$ directly gives the isothermal compressibility critical index as $\gamma = 2(1 - D)$.

Table 1 presents the average absolute deviations (AAD) of speed of sound predictions for alkanes. As it can be seen, these deviations do not exceed the experimental uncertainties, regardless of the chain length. The latter confirms our assumption made in Eq. (3) that the gyration radius representing the molecular non-sphericity is in fact a control parameter for the isothermal compressibility of chained hydrocarbons due to its influence on their packing properties in the liquids bulk. Moreover, the proposed approach also removes the flaws in the Brebli-O’Connell correlation characteristic for large reduced densities (Postnikov, 2016).

Figure 2 demonstrates that the accuracy of the proposed approach is independent from the reduced densities. We have chosen the same liquids which illustrated the fail of the reduced density approach in (Postnikov, 2016) and added two of them, n-hexadecane, and squalene to provide a comparative picture of the old and new approaches. One can see that the correction proposed in this work accurately predicts the decrease of the saturated speed of sound slopes with the increasing chain lengths. The main feature resulting in such an improvement is connected with the rejection of the reduced density, which was considered earlier as a main parameter and acted incorrectly for heavy molecules (see Fig. 2 for the example of squalene which demonstrates a drastic error, and n-hexadecane for which this error is smaller but exists anyway) in favour of a direct correlation of the isothermal compressibility as a function of temperature based on some scaling arguments of statistical physics. The latter appropriately fixes the basic governing property.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Temperature interval [K]</th>
<th>AAD [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$<em>8$H$</em>{18}$</td>
<td>233.15–433.15</td>
<td>0.65</td>
</tr>
<tr>
<td>C$<em>9$H$</em>{20}$</td>
<td>233.15–433.15</td>
<td>0.81</td>
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<tr>
<td>C$<em>{10}$H$</em>{22}$</td>
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<td>0.42</td>
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<tr>
<td>C$<em>{11}$H$</em>{24}$</td>
<td>293.15–433.15</td>
<td>0.51</td>
</tr>
<tr>
<td>C$<em>{12}$H$</em>{26}$</td>
<td>293.15–433.15</td>
<td>0.24</td>
</tr>
<tr>
<td>C$<em>{13}$H$</em>{28}$</td>
<td>303.15–453.15</td>
<td>0.25</td>
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<tr>
<td>C$<em>{14}$H$</em>{30}$</td>
<td>303.15–433.15</td>
<td>0.99</td>
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<tr>
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</tr>
<tr>
<td>C$<em>{16}$H$</em>{34}$</td>
<td>293.15–533.15</td>
<td>0.52</td>
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<tr>
<td>C$<em>{17}$H$</em>{36}$</td>
<td>303.15–383.15</td>
<td>1.10</td>
</tr>
<tr>
<td>C$<em>{18}$H$</em>{38}$</td>
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<tr>
<td>C$<em>{19}$H$</em>{40}$</td>
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<td>0.82</td>
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<tr>
<td>C$<em>{20}$H$</em>{42}$</td>
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<tr>
<td>C$<em>{21}$H$</em>{44}$</td>
<td>333.15–473.15</td>
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<tr>
<td>C$<em>{22}$H$</em>{46}$</td>
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<tr>
<td>C$<em>{23}$H$</em>{48}$</td>
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<tr>
<td>C$<em>{24}$H$</em>{50}$</td>
<td>353.15–473.15</td>
<td>0.48</td>
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<tr>
<td>C$<em>{30}$H$</em>{62}$</td>
<td>298.15–413.15</td>
<td>0.30</td>
</tr>
</tbody>
</table>

4. Conclusion

In the previous study (Postnikov, 2016) it was shown that saturated liquid phase properties included in the DIPPR database provide a sufficient basis for predicting the pertinent speed of sound while using the Brebli-O’Connell correlation for the reduced isothermal compressibility. Although this approach can be implemented for different classes of organic liquids, it is restricted by the upper range of densities $\rho < 3.5\rho_c$, where $\rho_c$ is the critical density. As a result, it could not be applied for the industrially important substances such as heavy alkanes.

In this work, we have developed a correction solving this problem and expanding the applicability range of the model. The proposed approach directly operates with the isothermal compressibility, fulfills the exact scale invariance conditions in the subcritical region, and admits expectable functional dependence of transitions between critical and non-critical states. For the latter ones, we have proposed a numerical correlation based on the gyration radius, which is a natural measure for the molecular non-sphericity. In addition, we have revealed the interplay between Widom’s density critical index and one of the DIPPR reference con-
stants. The proposed approach can be successfully implemented for a wide range of saturated state parameters, which can be particularly important for various practical purposes.

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References


