Predict Isothermal Bulk Modulus Values For Liquid Hydrocarbons With More Certainty

Background Of the Paper

All fluids are compressible under the application of pressure . The degree or extent of compressibility of a fluid is measured by its bulk modulus (reciprocal of the compressibility). The effect of fluid compressibility must be accounted for in those problems of fluid motion in which large changes in pressure occur.

A very practical application of the use of the bulk modulus is in the simulation (modeling) of waterhammer phenomena. Waterhammer may occur in a closed conduit or pipe line flowing full of liquid when there is either retardation or acceleration of the flow, such as with the closing or opening of a valve located somewhere in the line. The starting and stopping of a pump can cause a similar phenomenon.. These effects, due to waterhammer, may cause the pressure rating of the piping material to be exceeded.

When the flow in a hydraulic network is varied, disturbances are propagated through the system as shock waves. The velocity of these waves is simply called the wave velocity or the celerity, **a**. It is an important parameter used in the computer simulation of waterhammer effects. A necessary property used in calculating **a** is the isothermal bulk modulus B_T along with additional properties such as the liquid specific gravity and the Young's modulus for the pipe wall material.

Another important application of the bulk modulus is in the calculation of the speed of sound in a fluid medium. The speed of sound is related to the bulk modulus via the relationship:

$$c = \sqrt{\frac{k\,B_T}{\rho}}$$

$$\begin{aligned} \textit{where} \quad & k = \textit{the specific heat capacity ratio } (C_p / C_v) \\ & \rho = \textit{the liquid density} \end{aligned}$$

In this paper an empirical correlation based on three-parameter corresponding states theory is presented for predicting liquid hydrocarbon isothermal bulk modulus values with a statistical trend of – 0.8 percent and an absolute average deviation of 7.6 percent. In addition, a separate but specific correlation is presented for water based on two-parameter theory, and it produces an insignificant trend with an average absolute deviation of 2.7 percent.

"Predict Isothermal Bulk Modulus Values For Liquid Hydrocarbons With More Certainty"

An empirical three-parameter corresponding states equation can be used to quickly estimate bulk modulus values for hydrocarbon liquids

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All fluids are compressible under the application of pressure. The degree or extent of compressibility of a fluid is measured by its bulk modulus. The effect of fluid compressibility must be accounted for in those problems of fluid motion in which large changes in pressure occur. The calculation of bulk modulus is also an integral part in determining the velocity of sound in a fluid medium.

Bulk modulus can be defined as the ratio of pressure (stress) to volumetric strain. When a specific volume, v, of fluid under a pressure, P, is subjected to an increase in pressure ΔP, the specific volume decreases by an amount Δv. The bulk modulus is then defined by the ratio,

$$B = \lim(\Delta v \rightarrow 0)\left[\Delta P / \Delta v / v\right] = -dP / dv / v \qquad (1)$$

If we further require the temperature be kept constant, the resulting quantity is called the isothermal bulk modulus and is denoted by,

$$B_T = - v \, (\partial P / \partial v)_T \qquad (2)$$

It should be noted here that the bulk modulus is simply the reciprocal of the isothermal compressibility ($k_T = -(1/v)(\partial v/\partial P)_T$). Bulk modulus is expressed in the same units as pressure i.e. psia, atm, Pa, bars, etc.

An empirical correlation is presented for predicting liquid hydrocarbon bulk modulus values. It was developed from available isothermal compressibility data in the literature and is based on three-parameter corresponding states theory. In addition a separate but specific correlation is presented for water based on two-parameter corresponding states theory.

Database. An experimental isothermal liquid compressibility database consisting of 191 points for 14 different hydrocarbons and 33 points for water was extracted from the literature. The specific components and range of conditions covered are summarized in Table 1. Table 2 provides a detailed list of the source references cited in Table 1.

These data are also conveniently summarized in the general reference handbooks CRC Handbook of Chemistry and Physics (1) and Perry's Chemical Engineers' Handbook (2).

By definition, the bulk modulus is simply the reciprocal of the compressibility, k_T. The experimental compressibilities were reported in two different sets of units- m^2/N (Pa^{-1}) or bar^{-1}. The sample calculations below illustrate how these data were converted to bulk modulus values expressed in units of atmospheres (atm).

Case 1: At 1 atm pressure and 25 ° C (77 ° F) an isothermal liquid compressibility of $9.67 \times 10^{-10}\ m^2/N$ (Pa^{-1}) is reported for benzene. The isothermal bulk modulus in atm would then be:

$$B_T = (10^{10}/9.67)\ N/m^2\ (9.87\text{x}10^{-6}\ atm/\ N/m^2)$$

$$= (9.87/9.67) \times 10^4 = \underline{10{,}206.8\ atm}$$

Case 2: At 197 atm and 20 ° C(68 ° F) the measured compressibility of liquid n-hexane is reported as $117 \times 10^{-6}\ bar^{-1}$. Therefore the corresponding value of B_T would be:

$$B_T = (10^6/117)\ bar\ (\ 0.987\ atm/bar) = \underline{8436\ atm}$$

Equations of state. A preliminary investigation of three existing equations of state was made to see how well they would predict liquid hydrocarbon B_T values. The first equation has been adapted specifically to compressed hydrocarbon liquids and is based on three-parameter corresponding states theory. It is referred to as the Buehler equation and was developed by Hirschfelder et. al. (3).

For the "normal" liquid region, the Buehler equation is written as,

$$(P_r - p_o)\ (\rho_o - \rho_r) = M \qquad (3)$$

The temperature-dependent functions p_o, ρ_o and M were taken to be linear and fitted to the generalized tables of Lydersen, Greenkorn and Hougen (4). As a result, the following expressions were obtained:

$$p_o = -20 + 15\ T_r \qquad (4)$$

$$\rho_o = 8.284 - 18.07\ Z_c - (4.482 - 14.1\ Z_c)\ T_r \qquad (5)$$

$$M = -3.1 + 10\ T_r \qquad (6)$$

Z_c is the third parameter here and is called the critical compressibility factor. It generally varies between 0.25 and 0.29 for most hydrocarbons.

Equation 3 has been found suitable in the range $T_r = 0.50$ to 0.95 and for $P_r = 1$ to 30. Its main advantage is simplicity in that it can be solved explicitly for either pressure or density. Using Equation 3, the required expression for isothermal bulk modulus is derived as follows:

First, Equation 2 must be expressed in terms of the reduced corresponding-states parameters reduced pressure, P_r, reduced temperature, T_r, and the reduced density ρ_r.

$$\rho = 1/v$$

Therefore $$B_T = -(1/\rho)\,[\partial P/\partial (1/\rho)]_T = \partial P/[\rho\,\partial \rho/\rho^2]_T$$

Or $$B_T = [\partial P/(\partial \rho/\rho)]_T = [\partial P/\partial \mathrm{Ln}\,\rho]_T \qquad (7)$$

However, $P = P_r P_c$, $\rho = \rho_r \rho_c$ and $T = T_r T_c$ where P_c, ρ_c and T_c are the critical pressure, density and temperature respectively. After the following substitutions are made, we get,

$$B_T = P_c\,[\partial P_r/\partial \mathrm{Ln}\,\rho_r]_{Tr} \qquad (8)$$

Equation 3 can readily be solved for either P_r or ρ_r,

$$P_r = M/(\rho_o - \rho_r) + p_o \quad \text{or} \quad \rho_r = \rho_o - M/(P_r - p_o) \qquad (9\text{ a,b})$$

Then $$(\partial P_r/\partial \rho_r)_{Tr} = M/(\rho_o - \rho_r)^2 \qquad (10)$$

After substituting Equations 9b and 10 into 8, we get,

$$B_T = P_c\,\rho_r\,(\partial P_r/\partial \rho_r)_{Tr} = P_c\,[M/(\rho_o-\rho_r)^2][\rho_o-M/(P_r-p_o)] \qquad (11)$$

The remaining two equations of state investigated are closed-cubic equations and are applicable to either the vapor or liquid phase. These are the Soave and Peng Robinson equations.

In 1971, G. Soave (5) proposed what is probably the most popular and extensively used cubic EOS. Like its predecessor the Redlich-Kwong equation, the Soave equation attributes its basic roots to the celebrated van der Waals equation found in every textbook on Physical Chemistry. The Soave equation may be written as:

$$P = RT/(v-b) - a(T)/v(v+b) \qquad (12)$$

and when expanded out becomes a cubic polynomial in specific volume, v. The compressibility factor form (Z-form) of Equation 12 is derived by making the following substitutions:

$$v = ZRT/P \;;\; A = aP/R^2T^2 \;;\; B = bP/RT \qquad (13\ a,b,c)$$

with the result being,

$$Z^3 - Z^2 + Z(A-B-B^2) - AB = 0 \qquad (14)$$

Specifically at the critical point, the constants a_c and b can be obtained by setting the first and second derivatives of pressure with respect to volume to zero. When these criteria are applied to Equation 12, the results are:

$$a(T_c) = a_c = 0.42747\ R^2T_c^2/P_c \;;\; b = 0.08664\ RT_c/P_c \qquad (15\ a,b)$$

Also $$Z_c = 0.333 \qquad (15\ c)$$

The key feature of the work by Soave is the comprehensive correlation of the term a as a function of temperature. At temperatures other than the critical ($T < T_c$),

$$a(T) = a_c\,\alpha\,(T) \qquad (16)$$

where $\alpha \rightarrow 1$ as $T \rightarrow T_c$

Values of α for a given substance were generated from vapor pressure data by regression. When values of $\alpha^{0.5}$ were plotted against $1 - T_r^{0.5}$, nearly straight lines were obtained for a host of hydrocarbons. Since all “lines” must pass through the same point ($T_r=\alpha=1$), Soave then proceeded to write,

$$\alpha^{0.5} = 1 + m\,(1 - T_r^{0.5}) \;;\; T_r = T/T_c \qquad (17)$$

m, the slope, is a parameter characteristic of the component i.d. The author then successfully cross-correlated it against the acentric factor ω for a host of hydrocarbons with the result,

$$m = 0.48508 + 1.55171\,\omega - 0.15613\,\omega^2 \qquad (18)$$

The coefficients in Equation 18 are different that those originally derived by Soave. They were recorrelated and modified by Graboski and Daubert (6) using a more comprehensive vapor pressure data bank compiled by the American Petroleum Institute (API).

When Equation 12 is substituted into Equation 2, the desired expression for the isothermal bulk modulus is obtained based on the Soave EOS. This turns out to be,

$$B_T = vRT/(v-b)^2 - a\,v(2v+b)/[v(v+b)]^2 \qquad (19)$$

where $v = ZRT/P$ and $a = \alpha\, a_c$

Before Equation 19 can be evaluated, we must solve Equation 14 for the proper root (Z). For a cubic equation, as many as three real roots may be found. For the liquid phase, the smallest positive real root will be sought.

Peng and Robinson (7) attempted to shore up some of the shortcomings of Soave's equation by modifying the second term. They proposed the equation,

$$P = RT/(v-b) - a(T)/[\,v(v+b) + b(v-b)] \qquad (20)$$

The term b(v-b) was not present in the original Soave equation. It was incorporated in order to improve the prediction of liquid density and produce a more realistic value for the universal critical compressibility factor. Once again, we can place this equation into the more convenient cubic form, explicit in Z.

$$Z^3 - (1-B)Z^2 + (A - 3B^2 - 2B)Z - (AB - B^2 - B^3) = 0 \qquad (21)$$

where $A = a\,P/R^2T^2$; $B = bP/RT$; $Z = Pv/RT$ (22 a,b,c)

and $a(T_c) = 0.45724\, R^2T_c^2/P_c$ (23)

$b = 0.07780\, RT_c/P_c$; $Z_c = 0.307$ (24 a,b)

At temperatures other than T_c,

$$a(T) = a(T_c)\,\alpha\,(T_r,\omega) \qquad (25)$$

$b(T) = b(T_c)$ with no temperature dependency (26)

Using regression techniques with vapor pressure data, in a similar manner as did Soave, Peng and Robinson arrived at the following correlation for $\alpha(Tr,\omega)$,

$$\alpha^{0.5} = 1 + \kappa\,(1 - T_r^{0.5}) \qquad (27)$$

$$\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2 \qquad (28)$$

Both the Redlich-Kwong and Soave equations predict a universal critical compressibility factor Z_c of 0.333 whereas the Peng-Robinson equation yields a value of 0.307. This is a little more realistic in that the majority of hydrocarbons have a true Z_c value around 0.270.

The Peng-Robinson expression for isothermal bulk modulus is then obtained by inserting Equation 20 into Equation 2 with the result,

$$B_T = vRT/(v-b)^2 - 2av\,(v+b)/(\,v^2 + 2bv - b^2)^2 \qquad (29)$$

In this case, we must solve Equation 21 first for the lowest positive real root (liquid compressibility factor).

Some typical results of comparing the equation of state predictions against the corresponding measured values of B_T are presented in Table 3. For the two hydrocarbons, at 1 atm pressure, all of the equations predict B_T values that are consistently too low. As the pressure is increased, so do the percentage deviations in the positive (high) direction. At 1000 atm total pressure, the predictions of the Buehler equation exceed several hundred percent on the high side whereas the two cubic equations give deviations that vary from over 30 percent to about 98 percent. For water all of the correlations predict excessively high regardless of pressure level. In all cases the errors exceed 200 percent.

These comparisons are fairly typical of the entire hydrocarbon and water data sets and show that the prediction accuracy of the three equations of state tested is clearly unacceptable.

Predicting isothermal bulk modulus with accuracy either directly from experimental PVT data or by evaluating the slope $(\partial P/\partial v)_T$ from an equation of state is difficult since, fundamentally, the calculations require taking differences of data points or differentiation. As a result, much of the accuracy of the original data is lost or quite a strain is placed on the equation.

Proposed hydrocarbon correlation. Because of the failure of the three equations of state to adequately predict liquid hydrocarbon bulk modulus apriori, an empirical correlation based on the three parameter corresponding states principle was developed. The three independent variables chosen are T_r, P_r and ω. T_r and P_r have been previously defined. ω is the Pitzer acentric factor and is defined by,

$$\omega = -1. - \mathrm{Log}_{10}\,(P^S/P_c)_{Tr=0.7} \qquad (30)$$

The last term in Equation 30 is simply the reduced vapor pressure evaluated at a reduced temperature of 0.7. Acentric factor is a very good characterization because it reflects the relative size and shape of the molecule in question. For simple fluids such as Ar or CH_4, $\omega \cong 0$and for more complex fluids $\omega > 0$. Acentric factors for some typical hydrocarbons are given below:

Benzene	0.2125
n-heptane	0.3498
n-octane	0.4018
n-decane	0.4885
n-hexadecane	0.742

The Linear Regression Procedure found in the PC spreadsheet program EXCEL was used to fit the 191 experimental bulk modulus data points for the liquid hydrocarbons listed in Table 1. It was determined that a simple multi-variable linear equation could satisfactorily be fit to the data. The result is Equation 31.

$$B_T/P_c = 722.4032 - 1215.44\, T_r + 9.284182\, P_r + 664.6927\, \omega \qquad (31)$$

where the dimensionless ratio B_T/P_c is defined as the reduced isothermal bulk modulus. Critical constants and values for the acentric factor were taken from two sources- the Technical Data Book of the American Petroleum Institute (8) and from Reid, Sherwood and Prausnitz (9). The correlation (Equation 31) predicts B_T values that trend slightly low overall by 0.8 percent and with an average absolute deviation of 7.6 percent. This insignificant trend indicates that the data must exhibit a significant degree of scatter. Consequently, we didn't think it worthwhile to attempt to fit more complex equation forms (power law, etc.) In round numbers, the range of valid application of Equation 31 is,

T_r from 0.35 to 0.70

P_r up to 84 (nC_{18})

ω from 0.2 to 0.8 (nC_{18})

In Equation 31, the coefficient of reduced temperature is negative, but those of the reduced pressure and acentric factor are positive. This indicates that the bulk modulus of liquid hydrocarbons decreases with increasing temperature and increases if either or both the pressure and acentric factor is increased. The smallest coefficient is associated with P_r and indicates that pressure is the least significant of the three independent variables.

Mixtures. Because of the paucity of liquid hydrocarbon mixture data, it is suggested that Kay's pseudocritical rules simply be used to obtain the mixture critical constants and acentric factors.

$$P_{pc} = \sum x_i P_{ci} \qquad (32)$$

$$T_{pc} = \sum x_i T_{ci} \qquad (33)$$

$$\omega = \sum x_i \omega_i \qquad (34)$$

These mixing rules are especially good for mixtures of like-hydrocarbons such as a blend of aliphatics only or aromatics only.

Petroleum fractions. In developing new charts which provide a more accurate representation of the effect of pressure on petroleum fraction enthalpies, Kesler and Lee (10) also developed some correlations and charts for estimating the critical constants, acentric factor and molecular weight. In their paper, each parameter is graphically represented as a function of API gravity (60/60) and the Watson characterization factor, K_w (Figure 12, Page 156). In addition, they present these correlations analytically on Page 157 of their paper as Equations 3 through 6.

We recommend that these correlations be used in conjunction with Equation 31 to estimate B_T for petroleum fraction cuts such as typical naphthas and gas oils. Kesler and Lee state that their correlations give best results for petroleum cuts which are less than 200 deg. F in boiling width.

Water. When Equation 31 was used to predict the bulk modulus for water, it produced values that exceeded the experimental values by over 150 percent. Using 33 experimental data points specific to water, we performed a similar regression analysis as we did for the liquid hydrocarbons. Only the parameters T_r and P_r were considered with the final result given by Equation 35.

$$B_T/P_c = 90.05466 + 17.53697\ T_r + 7.329067\ P_r \qquad (35)$$

Equation 35 is valid over a rather modest range of pressure and temperature, namely,

T_r between 0.40 and 0.60

P_r up to 4.6

The correlation predicts B_T values for water with an overall trend of only + 0.12 percent and absolute average deviation of 2.7 percent. The sign of both coefficients in Equation 35 are positive. Thus, the bulk modulus of water increases if either or both the temperature and pressure increases. The relative magnitude of the coefficients shows that the B_T of water is more strongly affected by temperature than by pressure.

Examples. The three examples provided below illustrate the use of the empirical corresponding states correlations proposed in this paper.

Example 1 – Benzene. It is desired to estimate the isothermal bulk modulus of liquid benzene at 131 deg. F and 1000 atm.

For benzene Pc = 710.4 psia, Tc = 552.2 deg. F and $\omega = 0.2125$ as read from the Technical Data Book of the API (8).

Then $T_r = (131 + 459.7)/(552.2 + 459.7) = 0.584$

$$P_r = (1000)(14.7)/(710.4) = 20.693$$

Using Equation 31, we calculate,

$$B_T/P_c = 722.4032 - 1215.44(0.584) + 9.284182(20.693) + 664.6927(0.2125)$$

$$= 722.4032 - 709.817 + 192.118 + 141.247 = 346.0$$

$B_T = (346.0)(710.4)/(14.7) =$ **16721 atm**

The measured value derived from experimental compressibility data at this condition is 17225 atm. Comparison of these two values indicates that the predicted bulk modulus is low by about 3 percent.

Example 2 – Petroleum Cut Let us estimate the isothermal bulk modulus at 100 deg. F and 40 psia for a gas oil with average boiling point (T_b) of 540 deg. F and specific gravity 0.8483 ($60^o/60^o$).

From the well-known definitions of the Watson Factor and API gravity, we first compute,

$$K_w = (T_b, \text{deg. R})^{1/3} / \text{S.G.} \qquad (36)$$

$$= (540+459.7)^{1/3} / 0.8483 = 11.8$$

$$^o\text{API} = 141.5 / \text{S.G.} - 131.5 \qquad (37)$$

$$= 141.5 / 0.8483 - 131.5 = 35.3$$

From Figure 12, Page 156, of the paper by Kesler and Lee (10) we read,

$P_c = 260$ psia ; $T_c = 1322$ deg. R ; $\omega = 0.673$

Then $P_r = 40 / 260 = 0.154$; $T_r = 559.7 / 1322 = 0.423$

By Equation 31 we can now estimate B_T for this gas oil to be,

$$B_T/P_c = 722.4032 - 1215.44(0.423) + 9.284182\,(0.154) \qquad (31)$$

$$+ 664.6927\,(0.673) = 657.$$

$B_T = (657)\,(260) / 14.7 =$ **11621 atm.**

Example 3 – Water. Finally let us predict B_T for liquid water at 104 deg. F and 987 atm.

From the steam tables of Keenan et. al. (11) we first obtain the critical constants for water,

$P_c = 3204$ psia ; $T_c = 705.4$ deg. F

Then $P_r = (987)(14.7)/ 3204 = 4.53$

$T_r = (104+459.7)/(705.4+459.7) = 563.7/1165.1 = 0.484$

Using Equation 35 which is specific for water,

$$B_T/P_c = 90.05466 + 17.53697\,(0.484) + 7.32906\,(4.53) = 131.7 \qquad (35)$$

$B_T = (131.7)(3204)/14.7 =$ **28705 atm.**

The corresponding experimental value is 29909 atm. Therefore, the predicted B_T is about 4 percent low.

Example 4 – Water. In Example 3 we calculated an isothermal bulk modulus value of 28705 atm for compressed liquid water at 104 deg. F and 987 atm total pressure. If we compress liquid water from an initial pressure of 10,000 psia (680 atm) to 20,000 psia (1360 atm) under conditions of constant temperature (104 deg. F), what is the approximate change in the specific volume of water ? In addition, let us estimate the speed of sound in water under these conditions.

From the steam tables of Keenan et. al. (11) we read:

v = 0.015684 cuft/ Lb at 10,000 psia and 104 deg. F

Using this volume as a basis we calculate,

$$\Delta P = \frac{20,000-10,000}{14.7} = 680.3 \; atm$$

$$\Delta v = -v\frac{\Delta P}{B_T} = -\;(0.015684)\left(\frac{680.3}{28705}\right) = -0.000372\, cuft/Lb$$

which represents a decrease of

$$-\frac{0.000372}{0.015684}(100) = -\;2.4 \; \textit{percent in the specific volume.}$$

The rigorous expression for the speed of sound is:

$$c = \sqrt{\frac{k\,B_T}{\rho}g_c}$$

where $k = heat\ capacity\ ratio = C_p/C_v = 1.36$ *for water at these condtions*

$\rho = fluid\ density, lbm/cu\ ft$

$g_c = 32.17\ \ ft-lbm/lbf-\sec^2$

$$c = \sqrt{\frac{(1.36)(28705)(14.7)(144)(32.17)}{1/0.015684}} = 6460\ \ ft/\sec$$

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Table 1

Summary Of Data Bank
Isothermal Compressibilities Of
Liquid hydrocarbons

Hydrocarbon	Temp. Range deg. F	Overall Range In Tr	Press Range Atm Abs	Overall Range In Pr	Data* Source Ref.
Benzene	32 to 176 63 to 68 77	0.49 to 0.63	1, 1000 5,197, 395 98, 196, 294	0.021 to 20.7	1,3,6,10,15
Carbon Tetrachloride	minus 9 to 167 77	0.45 to 0.63	1, 1000 98, 196, 294	0.022 to 22.2	1,3,7,10,12, 15,16
Cyclohexane	77 to 167	0.54 to 0.63	1	0.025	15,16
n-decane	77 to 140	0.48 to 0.54	1	0.048	16
n-dodecane	77 to 275	0.45 to 0.62	1	0.055	16
n-heptane	77 to 140 77	0.55 to 0.62	1 1000	0.037 to 37	8, 17
n-hexane	77 to 140 68 77	0.58 to 0.66	1 197, 395 1000	0.034 to 33.6	8
n-nonane	77 to 140	0.5 to 0.56	1	0.044	8
n-octadecane	140 to 275	0.45 to 0.55	1, 1000	0.084 to 84	13
n-octane	77 to 140	0.52 to 0.59	1	0.041	8
n-pentadecane	100 to 275	0.44 to 0.58	1, 1000	0.067 to 66.7	13
Toluene	minus 75 to 158 68 77	0.36 to 0.58	1 197, 395 115, 231, 355	0.025 to 9.74	1, 3, 9
m-xylene	32 to 176 68	0.44 to 0.57	1 197, 395	0.029 to 11.3	1
n-hexadecane	77 to 122	0.42 to 0.45	1	0.071	17
Water	32 to 212 68 104	0.42 to 0.58	1, 1000 13, 197,395, 494 494, 987	0.0046 to 4.59	1, 7, 9

* Cited in Table 2.

Table 2*

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*This list of references was extracted from page F-15 of the 65th Edition of the CRC Handbook of Chemistry and Physics (1984-1985)

Table 3 - Comparison Of Isothermal Bulk Modulus Values

Comp.	Press. Atm	Temp. deg. F	Exper. BT, Atm	Buehler EOS BT, Atm	% Dev	Peng-Robinson EOS BT, Atm	% Dev	Soave EOS BT, Atm	% Dev
Benzene	1	77	10207	9008	-11.7	9179	-10.1	7544	-26.1
Benzene	98.1	77	11850	12372	4.4	10788	-9.0	9025	-23.8
Benzene	196.2	77	12670	16310	28.7	12484	-1.5	10580	-16.5
Benzene	294.3	77	13600	20791	52.9	14232	4.6	12197	-10.3
Benzene	1000	77	19467	69033	254.6	28521	46.5	25709	32.1
n-penta	1	275	5875	2320	-60.5	4474	-23.8	3693	-37.1
decane	1000	275	15422	115352	648.0	no soln.	-	30457	97.5
water	1	77	21597	85568	296.2	82154	280.4	66105	206.1
water	1000	77	28362	157192	454.2	104571	268.7	86724	205.8

AUTHOR'S BACKGROUND

Dr. Charles R. Koppany is a retired chemical engineer formerly employed by C F Braun & Co/ Brown & Root, Inc. from 1965 to 1994. While at Braun he served in both the Research and Process Engineering departments. Dr. Koppany has also done part-time teaching in the Chemical Engineering Departments at Cal Poly University Pomona and the University of Southern California. He holds B.S., M.S. and PhD degrees in Chemical Engineering from the University of Southern California and is a registered professional engineer (Chemical) in the state of California.

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