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Bubble-Point Measurements of *n*-Propane + *n*-Decane Binary Mixtures with Comparisons of Binary Mixture Interaction Parameters for Linear Alkanes

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Abstract

To develop comprehensive models for multicomponent natural gas mixtures, it is necessary to have binary interaction parameters for each of the pairs of constituent fluids that form the mixture. The determination of accurate mixture interaction parameters depends on reliably collected experimental data. In this work, we have carried out an experimental campaign to measure the bubble-point pressures of mixtures of *n*-propane and *n*-decane, a mixture that has been thus far poorly studied with only four existing data sets. The experimental measurements of bubble-point states span a composition range (in *n*-propane mole fraction) from 0.269 to 0.852, and the bubble-point pressures are measured in the temperature range from 270 K to 370 K. These data, in conjunction with data from a previous publication on mixtures of *n*-butane + *n*-octane and *n*-butane + *n*-nonane, are used to determine binary interaction parameters. The newly-obtained binary interaction parameters for the mixture of *n*-propane and *n*-decane represent the experimental bubble-point pressures given here to within 8% (coverage factor, $k=2$), as opposed to previous deviations up to 19%.

Introduction

Many of the separation processes in the energy industry require some knowledge of the vapor-liquid equilibria of hydrocarbon mixtures. A testament to this is the work done by the GERG (a consortium of European gas companies) to develop an equation of state for the thermodynamic properties of natural gases covering the gas and liquid regions including the vapor-liquid phase equilibrium.^{1,2} The GERG equation enables the prediction of thermal and caloric properties of 21 natural gas components and mixtures of these components. In the absence of experimental data, empirical equations of state, such as the GERG, may fail to produce accurate property predictions. This is especially true for the predictions of mixture properties.

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Supporting Information Available

A javascript-based 3D rendering of the *n*-propane + *n*-decane phase envelope usable in all modern browsers is provided. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

In this work, data for *n*-propane + *n*-decane binary systems, along with previously published data on *n*-butane + *n*-octane and *n*-butane + *n*-nonane binary systems³, are utilized to fit mixture parameters. Very few data sets of these mixtures exist in the literature^{4–7} and comparisons to the GERG-2008 equation showed considerable deviations, prompting the need for additional measurements and improved mixture modeling.

The thermodynamic properties of the mixture are modeled by the use of a multi-parameter mixture model. The GERG equation of state form is widely utilized in-part because it is a Helmholtz-energy based model, and therefore all other thermodynamic properties can be obtained from derivatives of the Helmholtz energy^{1,2,8,9}. For instance, the pressure of the mixture can be obtained from

$$p = \rho RT \left(1 + \delta \frac{\partial \alpha^r}{\partial \delta} (\tau, \delta) \right). \quad (1)$$

The non-dimensionalized residual Helmholtz energy α^r is expressed in terms of the reduced density $\delta = \rho / \rho_r \left(\bar{x} \right)$ and the reciprocal reduced temperature $\tau = T_r \left(\bar{x} \right) / T$. The reducing functions $\rho_r \left(\bar{x} \right)$ and $T_r \left(\bar{x} \right)$ contain the binary interaction parameters as described below.

Materials and Methods

Materials

n-Propane and *n*-decane were obtained from commercial sources and used without further purification. The stated manufacturer purities were as follows: *n*-propane 99,999 % and *n*-decane > 99 %. These purities were confirmed in our laboratory by analysis with gas chromatography-mass spectrometry (GC-MS) (Table 1). Spectral peaks were interpreted with guidance from the NIST/EPA/NIH Mass Spectral Database,¹⁰ Water content by mass was verified for *n*-decane using coulometric Karl Fischer titrations according to ASTM Standard Test Method E1064-00¹¹ as 20 ± 20 ppm, ¹H NMR and ¹³C NMR were also used to verify the purity of *n*-decane.

Mixture preparation

Mixtures were prepared gravimetrically in sealed 300 mL stainless steel cylinders. Mixture preparation has been previously explained in detail.³ Briefly, *n*-decane was added to the stainless steel cylinder, then degassed by freezing in liquid nitrogen and evacuating the headspace. This was repeated three times. After degassing, the mass of the *n*-decane in the cylinder was determined by use of a double-substitution weighing design.¹² The density of ambient air was calculated based on measurements of temperature, pressure, and relative humidity, and the sample masses were corrected for the effects of air buoyancy.¹³ *n*-Propane was transferred to the sample cylinder directly from the manufacturer's cylinder, and the sample mixture was degassed three times. The mass of *n*-propane was then determined. Sample cylinders were prepared with the goal of filling the sample cylinder to between 280 mL and the maximum volume of 300 mL at the target composition, at ambient temperature.

The standard deviation of the repeat weighings was at most 1.5 mg. The uncertainty of the measured mixture composition will be discussed in detail in a later section and is given in each data table.

Measurements

A schematic of the instrument used to make the measurements is shown in Figure 1 and has been previously described in detail.¹⁴ Briefly, a cylindrical stainless steel cell with an internal volume of 30 mL housed the sample. The cell and all of the system valves were housed inside a temperature-controlled, insulated aluminum block. Sample pressure measurements were recorded in 5 K increments from 270 K to 370 K. As the cell temperature was increased, the liquid inside the cell expanded, and it was necessary to periodically release a small amount of liquid from the bottom of the cell to maintain a vapor space. Repeat measurements were conducted at a minimum of two temperatures for each mixture composition to establish the repeatability of the measurements and to determine if the loss of small amounts of the liquid phase affected the sample composition to the extent that duplicate measurements at a given temperature yielded different bubble-point pressures.

Under this measurement configuration, efforts were made to ensure that the most accurate bubble points of the sample were measured, but assumptions were made. These assumptions include: (1) the liquid composition in the cell is equal to the bulk composition of the mixture in the sample bottle, and (2) by loading the cell almost full of liquid with only a very small vapor space remaining, the pressure of the vapor phase is the bubble-point pressure of the liquid composition at a given temperature.

Uncertainty Analysis

Mixture uncertainty analyses were performed with REFPROP Version 9.1.1¹⁵ and with the GERG-2008 equation of state¹ for comparison. The interaction parameters used for the mixtures are given in Table 2.

The expanded uncertainty for our bubble-point measurements was previously reported. Briefly, the uncertainty is calculated by the root-sum-of-squares method, taking into account five principle sources of uncertainty: temperature, pressure, sample composition, measurement repeatability, and head pressure correction.¹⁶ The standard platinum resistance thermometer (SPRT) and the pressure transducer used for our measurements were calibrated immediately prior to starting the measurements. A difference of pressure at 0.03 K from the measured temperature was factored into the calculation to account for uncertainty in the temperature measurement. The manufacturer's stated uncertainty of the pressure transducer is 0.01 % of full range, or 0.7 kPa. As a conservative estimate of the pressure uncertainty, the greater of 0.7 kPa or 0.1 % has been used in the calculation of the overall combined uncertainty of the bubble-point pressures reported here. The uncertainty in the composition of the mixture is by far the most difficult to estimate accurately. Sample purity, uncertainty in the determined masses during sample preparation, and the transfer of the mixture sample into the measuring system affect the composition of the fluid mixture. To account for the possibility that the degassing of the samples was not complete, a calculation was done

assuming that air represented a 0.001 mol fraction impurity in each of the mixtures. Nitrogen was used to represent air in the calculations.

The repeatability of our bubble-point measurements was determined by repeating measurements at a minimum of two temperatures for each sample studied. The standard deviation was then taken as the repeatability. To be conservative in our uncertainty estimates, the largest of the standard deviation values for each mixture was used as the repeatability value in the calculation of overall combined uncertainty for each point in that mixture. The pressure transducer was maintained at 313 K during measurements. For temperatures of 315 K and above, the head pressure was calculated for each point and treated as an uncertainty in the calculation of the overall uncertainty in the reported bubble-point pressures. The reported overall combined uncertainty for each point was calculated by taking the root sum of squares of the pressure equivalents of the temperature and composition uncertainties, the uncertainty in pressure, the measurement repeatability, and head pressure corrections. This number was multiplied by two (coverage factor, $k=2$) and is reported as an uncertainty in pressure as well as a percent uncertainty for each bubble point.

Results and Discussion

Experimental Data

Bubble-point pressures for five compositions of *n*-propane + *n*-decane binary mixtures were measured from 270 K to 370 K (Tables 3, 4, 5, 6, 7). The uncertainty in the pressure was calculated and reported for each point and is given as an absolute value, as well as a percentage. The deviation from the GERG-2008 equation of state as implemented in REFPROP 9.1.1 is given in the final column. As seen previously for mixtures of low molar mass linear alkanes with high molar mass linear alkanes,³ the deviation from the GERG-2008 predicted value increases with higher *n*-decane composition. Figure 2 illustrates the temperature and pressure range of our data, as compared to existing literature data. It can be seen that the data presented here are mostly at lower temperatures and pressures than that of the literature. The experimental data of Tiffin and coworkers is solid-liquid-vapor phase data.⁴ It is provided here for comparison, but not used further in the text.

Mixture Parameters

According to the most recent formulation used in all state-of-the-art libraries, the reducing parameters for the mixture (T_r and $v_r = 1/\rho_r$) can be given in a common form by

$$Y_r(\bar{x}) = \sum_{i=1}^N x_i^2 Y_{c,i} + \sum_{i=1}^{N-1} \sum_{j=i+1}^N 2x_i x_j \frac{x_i + x_j}{\beta_{Y,y}^2 x_i + x_j} Y_{ij} \quad (2)$$

where Y represents the parameter of interest, either T or V , with the parameters T_r or v_r are defined by

$$\frac{Y_r}{T_r} \frac{Y_{c,i}}{T_{c,i}} \frac{\beta_{Y,ij}}{\beta_{T,ij}} \frac{Y_{ij}}{\beta_{T,ij} \gamma_{T,ij} (T_{c,i} T_{c,j})^{0.5}} \\ v_r \frac{1}{\rho_{c,i}} \beta_{v,ij} \beta_{v,ij} \gamma_{v,ij} \frac{1}{8} \left(\frac{1}{\rho_{c,i}^{1/3}} + \frac{1}{\rho_{c,j}^{1/3}} \right)^3$$

These mixture reducing models are simply weighting functions of the critical properties of the pure fluids that form the mixture. There is an additional adjustable parameter in the excess function F_{ij} that is applied to the binary-specific excess function, though here the excess terms are not employed because there are insufficient experimental data to fit the excess terms. One important point to note is that the γ parameters are symmetric ($\gamma_{Y,ij} = \gamma_{Y,ji}$), while the β parameters are not symmetric ($\beta_{Y,ij} = 1/\beta_{Y,ji}$), and thus the order of fluids in the binary pair is important and must be handled carefully when implementing the binary interaction parameters in the user's code.

For the ij pair, there are a total of four adjustable parameters - $\beta_{T,ij}$, $\gamma_{T,ij}$, $\beta_{v,ij}$, and $\gamma_{v,ij}$. The parameters fit here ($\beta_{T,ij}$, $\gamma_{T,ij}$) have the strongest impact on the prediction of bubble points and can generally be fit with a relatively small dataset size. New interaction parameters are given for the n -propane + n -decane binary system studied here, as well as for the previously published n -butane binary systems (n -butane + n -octane, n -butane + n -nonane).³ The fitting of these new interaction parameters involved the use of an evolutionary optimization approach as described in Bell¹⁷.

The database REFPROP 9.1¹⁵ developed by the National Institute of Standards and Technology contains the current state-of-the-art mixture binary parameters, with interaction parameters for 697 mixtures, where approximately 200 of these are available in the literature^{1,2,8,18–22} as well as mixture interaction parameters that were fit using in-house code. Other libraries that implement a significant number of binary interaction parameters for high-accuracy mixture models are the open-source library CoolProp 5.1²³ comprising 220 binary pairs and the TREND 2.0 package from the University of Bochum, Germany²⁴ comprising approximately 215 binary pairs.

After the fitting procedure was carried out, the binary interaction parameters from Table 8 were obtained.

In this work, we have fit the binary interaction parameters $\beta_{Y,ij}$ and $\beta_{T,ij}$ while setting the other binary interaction parameters $\beta_{v,ij}$ and $\gamma_{v,ij}$ to 1. The fitting algorithm described in Bell¹⁷ was used to carry out the optimization of the binary interaction parameters. The totality of the available bubble-point data is used to fit the binary interaction parameters with an evolutionary optimization approach. For more information on the algorithm, the user is directed to the work of Bell¹⁷.

Impact of New Interaction Parameters

The new interaction parameters were implemented to determine deviations from the equation of state (EOS). Deviations from predicted values with the mixture interaction parameters in Table 2 were as high as 20 % for mixtures with a low n -propane composition

(Figure 3, top). When the new mixture interaction parameters (Table 8) were implemented, this deviation dropped to less than 10 % for the low *n*-propane compositions, without a significant shift in deviation for most of the reported literature data (Figure 3, bottom). To better visualize the *n*-propane + *n*-decane data and the projected phase envelope with the new interaction parameters, a 3-dimensional projection of the phase envelope is given (Figure 4); this 3D projection can be manipulated in the website given in the Supporting Information.

The interaction parameters were adjusted for the literature measurements of *n*-butane + *n*-octane systems (Figure 5).^{3,25,26} For the *n*-butane + *n*-octane systems, measurements by Mansfield and Outcalt had not been included previously and deviations were up to -20 % from the predicted values and only in the negative direction. With the new interaction parameters, these deviations are more uniformly centered around zero and are well distributed with other measurements reported in the literature. The previous literature measurements^{25,26} show little change with the new parameters.

Finally, for the binary system of *n*-butane + *n*-octane, there is only one data set in the literature.³ The deviations from the predicted values were reported to deviate as much as 131 %. With the new interaction parameters, deviations are less than 2 % and are centered around zero (Figure 6).

Conclusions

In this work, bubble-point pressures of mixtures of *n*-propane and *n*-decane were measured over the temperature range of 270 K to 370 K for a composition range (in *n*-propane mole fraction) from 0.269 to 0.852. These data, in conjunction with data from a previous publication on mixtures of *n*-butane + *n*-octane and *n*-butane + *n*-nonane, were used to determine binary interaction parameters. A new and entirely automatic evolutionary optimization fitting procedure was employed for obtaining the binary interaction parameters. The newly-obtained binary interaction parameters for *n*-propane + *n*-decane systems represent the experimental bubble-point pressures to within 8 % where previous deviations were on the order of 19 %. It is expected that the new binary interaction parameters obtained with the fitting algorithm published by Bell¹⁷ will better represent bubble-point data in linear alkane systems, such as those studied here.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Schematic of the apparatus used to make bubble-point measurements

Figure 2.
Experimental data (open circles) plotted with literature data⁴⁻⁷

Figure 3.

Deviations between experimental and calculated values as a function of *n*-propane composition, with the mixture interaction parameters from GERG-2008 (top) and this work (bottom) for the *n*-propane and *n*-decane mixture.⁵⁻⁷

Figure 4.
Three-dimensional rendering of *n*-propane + *n*-decane phase envelope

Figure 5.

Deviations between experimental and calculated values as a function of *n*-butane composition, with the mixture interaction parameters from GERG-2008 (top) and this work (bottom) for *n*-butane + *n*-octane mixtures.^{3,25,26}

Figure 6. Deviations between experimental and calculated values as a function of *n*-butane composition, with the mixture interaction parameters from GERG-2008 and this work for *n*-butane + *n*-nonane mixture.³

Table 1

Measured and manufacturer determined purity of mixture components

Chemical	Manufacturer Specification	GC-MS	^1H NMR	^{13}C NMR
<i>n</i> -propane	99.999 %	99.9999 %		
<i>n</i> -decane	>99%	99.57 %	(99.99 $\pm$ 0.02) %	(99.8 $\pm$ 0.1) %

Table 2

Current state-of-the-art binary interaction parameters from NIST REFPROP

Mixture	$\beta_{T,ij}$	$\gamma_{T,ij}$	$\beta_{v,ij}$	$\gamma_{v,ij}$
<i>n</i> -propane + <i>n</i> -decane	0.985331233	1.1409053	0.984104227	1.053040574
<i>n</i> -butane + <i>n</i> -octane	1	1.0331801	1	1.046905515
<i>n</i> -butane + <i>n</i> -nonane	1	1.0140964	1	1.049219137

Table 3

Measured bubble-point pressures for the system *n*-propane(1) + *n*-decane(2) at temperature *T*, pressure *P*, and liquid mole fraction $x_1 = 0.731$. Standard uncertainties *u* are $u(T) = 0.03$ K and $u(x_1) = 1.78 \times 10^{-5}$. The values for $u(P)$ are given in the table.

<i>T</i> /K	<i>P</i> /kPa	x_1	$u(P)$ /kPa	$(u(P)/P) \times 100$	$(1-P_{EOS}/P_{exp}) \times 100$
270.00	313.52	0.731	4.13	1.32	-1.81
275.00	365.03	0.731	4.21	1.15	-1.45
280.00	421.76	0.731	4.29	1.02	-1.26
285.00	483.56	0.731	4.37	0.90	-1.28
285.00	483.62	0.731	4.37	0.90	-1.27
290.00	551.33	0.731	4.45	0.81	-1.33
290.00	552.15	0.731	4.45	0.81	-1.18
295.00	626.26	0.731	4.53	0.72	-1.23
300.00	707.93	0.731	4.62	0.65	-1.15
300.00	707.79	0.731	4.62	0.65	-1.17
305.00	796.24	0.731	4.76	0.60	-1.11
310.00	891.91	0.731	4.91	0.55	-1.06
315.00	991.98	0.731	6.18	0.62	-1.30
315.00	993.51	0.731	6.18	0.62	-1.15
320.00	1100.52	0.731	6.35	0.58	-1.40
320.00	1100.05	0.731	6.35	0.58	-1.44
325.00	1203.46	0.731	6.52	0.54	-2.59
325.00	1192.51	0.731	6.51	0.55	-3.53
330.00	1309.73	0.731	6.65	0.51	-3.91
330.00	1309.68	0.731	6.65	0.51	-3.92
335.00	1439.13	0.731	6.80	0.47	-3.90
340.00	1576.56	0.731	7.02	0.45	-3.84
345.00	1721.22	0.731	7.21	0.42	-3.81
350.00	1872.35	0.731	7.40	0.40	-3.83
355.00	2030.24	0.731	7.66	0.38	-3.87
360.00	2197.17	0.731	7.95	0.36	-3.82
365.00	2370.02	0.731	8.19	0.35	-3.81
370.00	2550.34	0.731	8.45	0.33	-3.76

Table 4

Measured bubble-point pressures for the system *n*-propane(1) + *n*-decane(2) at temperature *T*, pressure *P*, and liquid mole fraction $x_1 = 0.726$, Standard uncertainties *u* are $u(T) = 0.03$ K and $u(x_1) = 8.36 \times 10^{-4}$, The values for $u(P)$ are given in the table.

<i>T</i> /K	<i>P</i> /kPa	x_1	$u(P)$ /kPa	$(u(P)/P) \times 100$	$(1-P_{EOS}/P_{exp}) \times 100$
270.00	311.98	0.726	6.02	1.93	-1.70
275.00	361.33	0.726	6.08	1.68	-1.86
280.00	417.09	0.726	6.13	1.47	-1.75
285.00	478.50	0.726	6.19	1.29	-1.70
290.00	546.77	0.726	6.25	1.14	-1.50
295.00	621.12	0.726	6.32	1.02	-1.40
295.00	622.86	0.726	6.32	1.02	-1.11
300.00	703.77	0.726	6.39	0.91	-1.06
300.00	703.80	0.726	6.39	0.91	-1.06
305.00	789.97	0.726	6.51	0.82	-1.22
305.00	791.16	0.726	6.51	0.82	-1.06
305.00	792.09	0.726	6.51	0.82	-0.95
310.00	883.80	0.726	6.64	0.75	-1.27
315.00	986.17	0.726	7.67	0.78	-1.17
315.00	985.25	0.726	7.67	0.78	-1.27
315.00	986.82	0.726	7.67	0.78	-1.10
320.00	1092.67	0.726	7.80	0.71	-1.38
320.00	1092.77	0.726	7.80	0.71	-1.38
325.00	1182.63	0.726	7.93	0.67	-3.63
325.00	1182.62	0.726	7.93	0.67	-3.63
325.00	1186.52	0.726	7.93	0.67	-3.29
330.00	1307.04	0.726	8.17	0.62	-3.35
335.00	1431.75	0.726	8.34	0.58	-3.64
340.00	1571.75	0.726	8.57	0.55	-3.35
345.00	1721.82	0.726	8.82	0.51	-2.95
350.00	1865.24	0.726	9.03	0.48	-3.39
355.00	2027.28	0.726	9.41	0.46	-3.18
360.00	2192.82	0.726	9.66	0.44	-3.16
365.00	2354.31	0.726	10.04	0.43	-3.62
370.00	2533.71	0.726	10.41	0.41	-3.55

Table 5

Measured bubble-point pressures for the system *n*-propane(1) + *n*-decane(2) at temperature *T*, pressure *P*, and liquid mole fraction $x_1 = 0.512$. Standard uncertainties *u* are $u(T) = 0.03$ K and $u(x_1) = 7.77 \times 10^{-5}$. The values for $u(P)$ are given in the table.

<i>T</i> /K	<i>P</i> /kPa	x_1	$u(P)$ /kPa	$(u(P)/P) \times 100$	$(1 - P_{EOS}/P_{exp}) \times 100$
270.00	219.56	0.512	3.77	1.72	-5.69
275.00	253.73	0.512	3.89	1.53	-5.49
280.00	290.84	0.512	4.02	1.38	-5.53
285.00	332.58	0.512	4.17	1.25	-5.22
290.00	378.20	0.512	4.35	1.15	-4.94
295.00	427.64	0.512	4.57	1.07	-4.72
300.00	481.47	0.512	4.80	1.00	-4.45
300.00	481.91	0.512	4.69	0.97	-4.36
305.00	538.64	0.512	5.00	0.93	-4.37
305.00	539.51	0.512	5.00	0.93	-4.20
310.00	601.44	0.512	5.33	0.89	-4.04
310.00	601.28	0.512	5.33	0.89	-4.07
315.00	668.53	0.512	6.92	1.04	-3.75
315.00	665.85	0.512	6.92	1.04	-4.17
320.00	735.93	0.512	7.26	0.99	-4.06
325.00	810.90	0.512	7.65	0.94	-3.88
330.00	890.63	0.512	8.08	0.91	-3.66
335.00	974.55	0.512	8.49	0.87	-3.46
340.00	1057.58	0.512	9.14	0.86	-3.79
340.00	1056.73	0.512	9.14	0.86	-3.88
345.00	1143.83	0.512	9.65	0.84	-4.14

Table 6

Measured bubble-point pressures for the system *n*-propane(1) + *n*-decane(2) at temperature *T*, pressure *P*, and liquid mole fraction $x_1 = 0.305$. Standard uncertainties *u* are $u(T) = 0.03$ K and $u(x_1) = 8.69 \times 10^{-5}$. The values of $u(P)$ are given in the table.

<i>T</i> /K	<i>P</i> /kPa	x_1	<i>u</i> (<i>P</i>)/kPa	$(u(P)/P) \times 100$	$(1-P_{EOS}/P_{exp}) \times 100$
270.00	128.26	0.305	7.12	5.55	-12.41
275.00	146.46	0.305	7.13	4.87	-12.76
280.00	167.81	0.305	7.15	4.26	-12.08
285.00	191.20	0.305	7.17	3.75	-11.41
290.00	216.65	0.305	7.19	3.32	-10.79
295.00	244.25	0.305	7.21	2.95	-10.19
300.00	274.06	0.305	7.23	2.64	-9.60
305.00	306.04	0.305	7.25	2.37	-9.05
310.00	340.33	0.305	7.27	2.14	-8.50
315.00	375.39	0.305	8.36	2.23	-8.41
315.00	376.87	0.305	8.36	2.22	-7.98
320.00	414.09	0.305	8.38	2.02	-7.90
325.00	454.83	0.305	7.33	1.61	-7.46
330.00	497.85	0.305	7.36	1.48	-7.03
335.00	538.68	0.305	7.38	1.37	-7.48
335.00	543.26	0.305	7.38	1.36	-6.58
340.00	585.45	0.305	7.40	1.26	-7.13
345.00	634.21	0.305	8.48	1.34	-6.80
350.00	684.98	0.305	8.50	1.24	-6.49
355.00	737.84	0.305	8.53	1.16	-6.17
360.00	792.61	0.305	8.57	1.08	-5.88
365.00	849.17	0.305	8.62	1.01	-5.60
370.00	907.62	0.305	8.73	0.96	-5.29

Table 7

Measured bubble-point pressures for the system *n*-propane(1) + *n*-decane(2) at temperature *T*, pressure *P*, and liquid mole fraction $x_1 = 0.148$. Standard uncertainties *u* are $u(T) = 0.03$ K and $u(x_1) = 3.22 \times 10^{-5}$. The values of $u(P)$ are given in the table.

<i>T</i> /K	<i>P</i> /kPa	x_1	$u(P)$ /kPa	$(u(P)/P) \times 100$	$(1-P_{EOS}/P_{exp}) \times 100$
270.00	62.80	0.148	3.02	4.80	-17.62
275.00	70.65	0.148	3.05	4.32	-18.95
280.00	80.52	0.148	3.09	3.84	-18.09
285.00	91.70	0.148	3.13	3.41	-16.73
290.00	103.63	0.148	3.16	3.05	-15.69
295.00	116.52	0.148	3.20	2.75	-14.72
300.00	130.49	0.148	3.24	2.48	-13.71
305.00	144.31	0.148	3.28	2.27	-13.65
305.00	145.39	0.148	3.28	2.25	-12.81
310.00	159.14	0.148	3.31	2.08	-13.47
310.00	161.30	0.148	3.31	2.05	-11.96
315.00	175.99	0.148	5.38	3.06	-12.55
320.00	193.56	0.148	5.40	2.79	-11.85
325.00	212.55	0.148	5.42	2.55	-10.96
325.00	212.41	0.148	5.42	2.55	-11.03
330.00	232.25	0.148	5.45	2.35	-10.26
330.00	231.47	0.148	5.45	2.35	-10.63
335.00	252.61	0.148	5.47	2.17	-9.75
335.00	253.43	0.148	5.47	2.16	-9.39
340.00	275.22	0.148	5.50	2.00	-8.73
340.00	274.77	0.148	5.50	2.00	-8.91
345.00	298.16	0.148	5.52	1.85	-8.05
350.00	320.88	0.148	5.55	1.73	-7.80
355.00	346.09	0.148	5.57	1.61	-7.06
360.00	371.70	0.148	5.60	1.51	-6.53
365.00	398.97	0.148	5.63	1.41	-5.83
370.00	426.05	0.148	5.65	1.33	-5.47

Table 8

New interaction parameters

Mixture	β_T	γ_T	$\beta_{v,ij}$	$\gamma_{v,ij}$
<i>n</i> -propane + <i>n</i> -decane	0.977575	1.15138	1.0	1.0
<i>n</i> -butane + <i>n</i> -octane	0.992865	1.04538	1.0	1.0
<i>n</i> -butane + <i>n</i> -nonane	0.989867	1.06894	1.0	1.0