Thermodynamic Properties of Propanol and Butanol as Oxygenate Additives to Biofuels

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Abstract

Alternative and renewable energy technologies are being sought throughout the world to reduce pollutant emissions and increase the efficiency of energy use. Oxygenate second-generation biofuels fuels lead to a reduction in pollutant emissions and their thermodynamic and transport properties allow that the facilities for transport, storage and distribution of fuels could be used without modification. Higher alcohols, like propanol and butanol, enhance the octane number, boosting the anti-knock effect in gasoline. Then the compression ratio of the engines can be increased without risk of knocking, leading to higher delivery of power. From the combustion point of view, the production of carbon monoxide and volatile hydrocarbons from the combustion of alcohols is less than the one of gasoline. This chapter covers mixtures of butanol and propanol with hydrocarbons. The properties reviewed are excess volume or density (VE), vapour-liquid equilibrium (VLE), and heat capacity (C_p).

Keywords: butanol, propanol, biofuel, density, enthalpy, phase equilibrium, heat capacity

1. Introduction

Biofuels, as environmental friendly fluids, have been paid much attention over the last decades. They contribute to diminish the greenhouse gas emissions due to its neutral carbon dioxide balance. Moreover, some oxygenated compounds are used as biofuel additives as they lead to
a reduction in pollutant emissions and to an increase in the energy efficiency of vehicle engines [1, 2].

Some alcohols and ethers, as oxygenated compounds additives, are added to present gasoline with the aim of reducing the emission of gases that produce environmental impact. The advantages of these oxygenates can be classified into several categories. First, they can be obtained from renewable, agricultural and raw materials, reducing the dependence of fossil sources [3]. Second, they enhance the octane number, boosting the anti-knock effect in gasoline. Then, the compression ratio of the engines can be increased without risk of knocking, leading to higher delivery of power. From the combustion point of view, the production of carbon monoxide and volatile hydrocarbons from the combustion of alcohols is less than the one of gasoline. Amongst the thermodynamic properties, the heat of vaporization of alcohols is high and leads to a reduction in the peak temperature of combustion, which means lower emissions of nitrogen oxides.

Alternative and renewable energy technologies are being sought to reduce pollutant emissions and increase the efficiency of energy use. Propanol and butanol have been proposed as an alternative to conventional gasoline and diesel fuels [4, 5]. They are higher member of the series of alcohols with each molecule containing three or four carbon atoms rather than two as in ethanol. The EN standards of the European Union (EU) and the World-Wide Fuel Charter (WWFC) for gasoline include, for example, 2-propanol, 2-methyl-2 propanol (also known as tert-butyl alcohol, TBA), and 2-methyl-1 propanol [6, 7] as gasoline components.

The traditional production and consumption of bioethanol have found an alternative with the second-generation biofuels, such as biobutanol. For example, 85% ethanol, E85, needs some modification of the internal combustion engines specifications, unlike butanols, which can work directly in present engines. The energy content per volume unit of butanol is similar to the one of gasoline, and higher than the same for ethanol. Concerning the contribution to the anti-knocking effect, butanol behaves almost the same as other alcohols like methanol or ethanol. And in the presence of water, the mixture butanol/gasoline shows lesser tendency to separation of phases than the mixture ethanol/gasoline. Then, all the facilities for transport, storage and distribution of fuels can be used without modification. Butanol, which can be synthesized chemically or biologically, is an alternative transportation fuel since it has properties that would allow its use in existing engines with minor hardware modifications [5]. For practical purposes, ASTM D7862 [8] gives specifications for blends of butanol with gasoline at 1–12.5% in volume for automotive spark ignition engines. Three butanol isomers are covered by the specification, 1-butanol, 2-butanol, and 2-methyl-1-propanol, while specifically excludes 2-methyl-2-propanol (TBA).

Besides its use as fuel component, its industrial uses covers a broad range of applications as solvent or as reactive for the production of other chemicals. Applications, chemicals and products that use butanol include solvents, plasticizers, coatings, chemical intermediate or raw material, textiles, cleaners, cosmetics, drugs and antibiotics, hormones, and vitamins.

Since the 1950s, most butanol is obtained from fossil sources [6]. 1-butanol and/or 2-butanol could be obtained from reduction of butyraldehyde with hydrogen, which is previously
obtained by hydroformulation reaction of propene (propylene). Meanwhile, propylene oxide production leads to isobutene, from which TBA could be derived. Butanol from biomass is called biobutanol [9], and it can be used in unmodified gasoline engines. Biobutanol can be produced by fermentation of biomass by the ABE process [9, 10]. The process uses the bacterium Clostridium acetobutylicum, the bacterium for the production of acetone from starch. The butanol was a by-product of this fermentation. Other by-products as acetic, lactic and propionic acids, isopropanol and ethanol, as well as a certain amount of H₂, are generated by the process. Ralstonia eutropha can also be used to produce biobutanol, by means of an electro-bioreactor and the input of carbon dioxide and electricity.

According to DuPont [11], existing bioethanol plants can be converted to biobutanol production with low economic cost. The main modification could affect to the fermentation process, with minor changes in distillation, as both alcohols use the same stocks: food energy crops (sugar beets, sugar cane, corn grain, wheat, etc.), non-food energy crops (switchgrass, cellulose, etc.) and agricultural by-products (straw, corn stalks, etc.).

Biopropanol is a rarely discussed biofuel. Tough propanol is included as regular component of gasolines [6], its frequent use as chemical solvent makes it rare to consider it as a fuel. Biopropanol could be produced from microbial fermentation of biomass (cellulose), but the process is extremely inefficient [12]. The issues with microbial production of biopropanol are analogous to the issues with microbial production of biobutanol, so if biobutanol becomes a more practical biofuel to produce, then biopropanol will also become more feasible.

This paper concerns thermodynamic properties of 1-propanol, 2-propanol, 1-butanol, 2-butanol and TBA. Accurate experimental data on thermodynamic properties should be available to check and develop predictive empirical equations, models and simulation programs. Industrial processes as storage, transport, separation and mixing processes also need reliable data for its design. As a result, the experimental literature reviews on properties of pure compounds and its mixtures with characteristic hydrocarbons can provide valuable information about the fluid behaviour under various temperature and pressure conditions.

The paper presents the literature review of available data on thermodynamic properties (density, vapour-liquid equilibrium, specific heat,) of the mixtures of 1-propanol, 1-butanol, TBA and its mixtures with hydrocarbons representatives of gasoline. Density has to do with the volumetric behaviour of the mixtures under pressure and temperature conditions and is the primary data to check equations of state. The vapour-liquid equilibria, which allows the calculation of the Gibbs function, deal with the equilibrium between the liquid and vapour phase under fixed pressure and temperature conditions. And the heat capacity gives information related to the sensible energy storage of the liquids. The review includes only the interval of temperature and pressure of every property reported. The wider is the range of pressure and temperature of the measured properties, so it would be the reliability of the applications of predictive and equations and models. Discussion of further data (uncertainties, experimental apparatus, etc.) would require more space than available. Interested readers should access the literature references to check these issues.
2. The literature review

Thermodynamic properties of liquid propanol and butanol and its liquid mixtures with some hydrocarbon have been obtained from the literature search using online library databases (Web of Science®, Scopus®, NIST® Standard Reference Database) and high impact electronic journals.

Special attention is given to alcohol + hydrocarbon mixtures. As stated, 1-propanol, 1-butanol and TBA have been selected as alcohols. As representative of hydrocarbons, n-heptane, 2,2,4 trimethylpentane (iso-octane), cyclohexane, methyl-cyclohexane, benzene, toluene and 1-hexene have been chosen. They represent linear, branched and cyclic alkanes, aromatics, as well as olefins, which are regular components of gasoline. **Table 1** presents the list of selected compounds.

| Compound                          | CAS number | Chemical formula |
|-----------------------------------|------------|------------------|
| **Alcohols**                      |            |                  |
| 1-Propanol                        | 71-23-8    | C₃H₇O            |
| 1-Butanol                         | 71-36-3    | C₄H₁₀O           |
| Tert-butyl alcohol (TBA)          | 75-65-0    | C₄H₁₀O           |
| **Hydrocarbons**                  |            |                  |
| Heptane                           | 142-82-5   | C₇H₁₆             |
| 2,2,4 trimethylpentane (TMP)      | 540-84-1   | C₈H₁₈             |
| Cyclohexane                       | 110-82-7   | C₆H₁₂             |
| Methyl cyclohexane                | 108-87-2   | C₇H₁₄             |
| Benzene                           | 71-43-2    | C₇H₈              |
| Toluene                           | 108-88-3   | C₇H₈              |
| 1-Hexene                          | 592-41-6   | C₆H₁₂             |

**Table 1.** Selected alcohols and hydrocarbons.

Concerning properties, there is a huge amount of available thermodynamic data for pure compounds. With respect to the mixtures, density data are shown in **Table 2** for binary mixtures alcohol (1) + hydrocarbon (2). **Tables 3 and 4** present the vapour-liquid equilibria selected for mixtures alcohol (1) + hydrocarbon (2) and alcohol (1) + hydrocarbon (2) + hydrocarbon (3). Finally, heat capacity data for binary mixtures alcohol (1) + hydrocarbon (2) are provided in **Table 5**.

| Substance 1 | Substance 2 | References | Year | T_min/K | T_max/K | P_min/kPa | P_max/kPa |
|-------------|-------------|------------|------|---------|---------|-----------|-----------|
| 1-Propanol  | Heptane     | [13]       | 1967 | 298.15  | 298.15  | 101       | 101       |
| Heptane     | Heptane     | [14]       | 1967 | 348.15  | 348.15  | 101       | 101       |
| Heptane     | Heptane     | [15]       | 1977 | 298.15  | 298.15  | 101       | 101       |
| Heptane     | Heptane     | [16]       | 1982 | 423.11  | 523.11  | 422       | 5495      |
| Heptane     | Heptane     | [17]       | 1983 | 298.15  | 298.15  | 101       | 101       |
| Substance 1  | Substance 2                  | References | Year | $T_{\text{m}}$/K | $T_{\text{m}}’$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|-------------|------------------------------|------------|------|------------------|------------------|----------------------|----------------------|
| Heptane     | [18] Heptane                 | 1993       | 313.15 | 313.15           | 101              | 101                  |                      |
| Heptane     | [19] Heptane                 | 1994       | 278.15 | 308.15           | 101              | 101                  |                      |
| Heptane     | [20] Heptane                 | 1995       | 298.15 | 298.15           | 101              | 101                  |                      |
| Heptane     | [21] Heptane                 | 1996       | 298.15 | 308.15           | 101              | 101                  |                      |
| Heptane     | [22] Heptane                 | 1997       | 298.15 | 298.15           | 101              | 101                  |                      |
| Heptane     | [23] Heptane                 | 1998       | 278.15 | 308.15           | 101              | 101                  |                      |
| Heptane     | [24] Heptane                 | 2003       | 308.15 | 308.15           | 101              | 101                  |                      |
| Heptane     | [25] Heptane                 | 2004       | 293.15 | 318.21           | 101              | 101                  |                      |
| Heptane     | [26] Heptane                 | 2005       | 298.15 | 298.15           | 101              | 101                  |                      |
| Heptane     | [27] Heptane                 | 2005       | 298.15 | 298.15           | 101              | 101                  |                      |
| 2,2,4 trimethylpentane | [28] 2,2,4 trimethylpentane | 2001       | 298.15 | 298.15           | 101              | 101                  |                      |
| 2,2,4 trimethylpentane | [29] 2,2,4 trimethylpentane | 2007       | 298.15 | 298.15           | 101              | 101                  |                      |
| 2,2,4 trimethylpentane | [30] 2,2,4 trimethylpentane | 2007       | 303.15 | 303.15           | 101              | 101                  |                      |
| 2,2,4 trimethylpentane | [31] 2,2,4 trimethylpentane | 2012       | 298.15 | 298.15           | 101              | 101                  |                      |
| 2,2,4 trimethylpentane | [32] 2,2,4 trimethylpentane | 2015       | 298.15 | 323.15           | 101              | 101                  |                      |
| Cyclohexane | [33] Cyclohexane             | 1979       | 298.15 | 298.15           | 101              | 101                  |                      |
| Cyclohexane | [34] Cyclohexane             | 1980       | 298.15 | 298.15           | 101              | 101                  |                      |
| Cyclohexane | [35] Cyclohexane             | 1991       | 298.15 | 298.15           | 101              | 101                  |                      |
| Cyclohexane | [36] Cyclohexane             | 1996       | 298.15 | 308.15           | 101              | 101                  |                      |
| Cyclohexane | [37] Cyclohexane             | 1997       | 298.15 | 303.15           | 101              | 101                  |                      |
| Cyclohexane | [38] Cyclohexane             | 1998       | 303.15 | 303.15           | 101              | 101                  |                      |
| Cyclohexane | [39] Cyclohexane             | 2004       | 298.15 | 298.15           | 101              | 101                  |                      |
| Cyclohexane | [40] Cyclohexane             | 2005       | 298.15 | 298.15           | 101              | 101                  |                      |
| Cyclohexane | [41] Cyclohexane             | 2007       | 293.15 | 303.15           | 101              | 101                  |                      |
| Cyclohexane | [42] Cyclohexane             | 2008       | 303.15 | 303.15           | 101              | 101                  |                      |
| Cyclohexane | [43] Cyclohexane             | 2016       | 303.15 | 313.15           | 101              | 101                  |                      |
| Methylcyclohexane | [44] Methylcyclohexane      | 1977       | 303.15 | 303.15           | 101              | 101                  |                      |
| Methylcyclohexane | [45] Methylcyclohexane      | 1996       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [46] Benzene                 | 1969       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [33] Benzene                 | 1979       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [34] Benzene                 | 1980       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [47] Benzene                 | 1993       | 308.15 | 308.15           | 101              | 101                  |                      |
| Benzene     | [58] Benzene                 | 1994       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [59] Benzene                 | 2001       | 303.15 | 303.15           | 101              | 101                  |                      |
| Benzene     | [24] Benzene                 | 2003       | 308.15 | 308.15           | 101              | 101                  |                      |
| Benzene     | [39] Benzene                 | 2004       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [50] Benzene                 | 2007       | 288.15 | 313.15           | 101              | 101                  |                      |
| Benzene     | [51] Benzene                 | 2008       | 298.15 | 298.15           | 101              | 101                  |                      |
| Benzene     | [52] Benzene                 | 2009       | 298.15 | 298.15           | 101              | 101                  |                      |
| Substance 1 | Substance 2 | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|------------|-------------|------------|------|-----------------|-----------------|-----------------|-----------------|
| Benzene    |             | [53]       | 2015 | 303.15          | 303.15          | 101             | 101             |
| Toluene    |             | [54]       | 1980 | 298.15          | 298.15          | 101             | 101             |
| Toluene    |             | [47]       | 1993 | 308.15          | 308.15          | 101             | 101             |
| Toluene    |             | [48]       | 1994 | 298.15          | 298.15          | 101             | 101             |
| Toluene    |             | [55]       | 2000 | 303.15          | 313.15          | 101             | 101             |
| Toluene    |             | [24]       | 2003 | 308.15          | 308.15          | 101             | 101             |
| Toluene    |             | [56]       | 2005 | 303.15          | 333.15          | 100             | 30000           |
| Toluene    |             | [57]       | 2006 | 298.15          | 298.15          | 101             | 101             |
| Toluene    |             | [58]       | 2006 | 303.15          | 333.15          | 101             | 101             |
| Toluene    |             | [59]       | 2008 | 298.15          | 298.15          | 101             | 101             |
| Toluene    |             | [53]       | 2015 | 303.15          | 303.15          | 101             | 101             |
| 1-Hexene   |             | [60]       | 1993 | 298.15          | 298.15          | 101             | 101             |
| 1-Hexene   |             | [61]       | 2010 | 298.15          | 298.15          | 101             | 101             |
| 1-Butanol  | n-Heptane   | [15]       | 1977 | 298.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [62]       | 1979 | 298.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [17]       | 1983 | 298.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [63]       | 1984 | 298.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [64]       | 1994 | 313.15          | 313.15          | 101             | 101             |
| n-Heptane  |             | [21]       | 1996 | 298.15          | 308.15          | 101             | 101             |
| n-Heptane  |             | [65]       | 1997 | 293.15          | 293.15          | 101             | 101             |
| n-Heptane  |             | [66]       | 1997 | 288.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [24]       | 2003 | 308.15          | 308.15          | 101             | 101             |
| n-Heptane  |             | [67]       | 2003 | 316.85          | 458.15          | 4930            | 4930            |
| n-Heptane  |             | [26]       | 2005 | 298.15          | 298.15          | 101             | 101             |
| n-Heptane  |             | [68]       | 2006 | 288.15          | 308.15          | 101             | 101             |
| n-Heptane  |             | [69]       | 2009 | 288.15          | 308.15          | 101             | 101             |
| 2,2,4 trimethyloctane | | [65] | 1997 | 293.15 | 293.15 | 101 | 101 |
| 2,2,4 trimethyloctane | | [66] | 1997 | 288.15 | 298.15 | 101 | 101 |
| 2,2,4 trimethyloctane | | [31] | 2012 | 298.15 | 298.15 | 101 | 101 |
| 2,2,4 trimethyloctane | | [70] | 2013 | 298.15 | 328.15 | 101 | 101 |
| Cyclohexane |             | [33]       | 1979 | 298.15          | 298.15          | 101             | 101             |
| Cyclohexane |             | [34]       | 1980 | 298.15          | 298.15          | 101             | 101             |
| Cyclohexane |             | [71]       | 1983 | 298.15          | 318.15          | 101             | 101             |
| Cyclohexane |             | [72]       | 1995 | 293.15          | 313.15          | 101             | 101             |
| Cyclohexane |             | [38]       | 1998 | 303.15          | 303.15          | 101             | 101             |
| Cyclohexane |             | [73]       | 2001 | 298.15          | 298.15          | 101             | 101             |
| Cyclohexane |             | [24]       | 2003 | 308.15          | 308.15          | 101             | 101             |
| Cyclohexane |             | [74]       | 2005 | 298.15          | 313.15          | 101             | 101             |
| Cyclohexane |             | [40]       | 2007 | 293.15          | 303.15          | 101             | 101             |
| Cyclohexane |             | [75]       | 2010 | 293.15          | 293.15          | 101             | 101             |
| Cyclohexane |             | [76]       | 2014 | 293.15          | 333.15          | 100             | 100000          |
| Substance 1         | Substance 2     | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|---------------------|-----------------|------------|------|-------------------|-------------------|---------------------|---------------------|
| Cyclohexane         | [42]            | 2016       | 303.15 | 313.15            | 101               | 101                 |
| Methylcyclohexane   | [43]            | 1977       | 303.15 | 303.15            | 101               | 101                 |
| Methylcyclohexane   | [77]            | 1989       | 298.15 | 298.15            | 101               | 101                 |
| Methylcyclohexane   | [78]            | 2004       | 303.15 | 303.15            | 101               | 101                 |
| Methylcyclohexane   | [45]            | 2006       | 298.15 | 308.15            | 101               | 101                 |
| Benzene             | [46]            | 1969       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [33]            | 1979       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [34]            | 1980       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [79]            | 1993       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [80]            | 1994       | 298.15 | 308.15            | 101               | 101                 |
| Benzene             | [81]            | 1996       | 308.15 | 308.15            | 101               | 101                 |
| Benzene             | [49]            | 2001       | 303.15 | 303.15            | 101               | 101                 |
| Benzene             | [21]            | 2003       | 308.15 | 308.15            | 101               | 101                 |
| Benzene             | [82]            | 2004       | 303.15 | 303.15            | 101               | 101                 |
| Benzene             | [83]            | 2008       | 288.15 | 313.15            | 101               | 101                 |
| Toluene             | [84]            | 1940       | 298.15 | 298.15            | 101               | 101                 |
| Toluene             | [54]            | 1980       | 298.15 | 298.15            | 101               | 101                 |
| Toluene             | [81]            | 1996       | 308.15 | 308.15            | 101               | 101                 |
| Toluene             | [55]            | 2000       | 303.15 | 313.15            | 101               | 101                 |
| Toluene             | [24]            | 2003       | 308.15 | 308.15            | 101               | 101                 |
| Toluene             | [70]            | 2013       | 298.15 | 328.15            | 101               | 101                 |
| Toluene             | [85]            | 2015       | 298.15 | 328.15            | 101               | 101                 |
| 1-Hexene            | [86]            | 2013       | 273.15 | 333.15            | 101               | 101                 |
| TBA                 |                 |            |       |                   |                   |                     |
| n-Heptane           | [62]            | 1979       | 299.15 | 299.15            | 101               | 101                 |
| n-Heptane           | [64]            | 1994       | 313.15 | 313.15            | 101               | 101                 |
| n-Heptane           | [87]            | 2011       | 303.15 | 323.15            | 101               | 101                 |
| 2,2,4 trimethylpentane | [88]       | 1999       | 298.15 | 298.15            | 101               | 101                 |
| 2,2,4 trimethylpentane | [89]       | 2001       | 298.15 | 298.15            | 101               | 101                 |
| 2,2,4 trimethylpentane | [90]       | 2005       | 298.15 | 318.15            | 101               | 101                 |
| Cyclohexane         | [71]            | 1983       | 298.15 | 318.15            | 101               | 101                 |
| Cyclohexane         | [72]            | 1995       | 293.15 | 313.15            | 101               | 101                 |
| Methylcyclohexane   | [88]            | 1999       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [79]            | 1993       | 298.15 | 298.15            | 101               | 101                 |
| Benzene             | [91]            | 1995       | 313.15 | 313.15            | 101               | 101                 |
| Benzene             | [81]            | 1996       | 308.15 | 308.15            | 101               | 101                 |
| Benzene             | [82]            | 2004       | 303.15 | 303.15            | 101               | 101                 |
| Toluene             | [81]            | 1996       | 308.15 | 308.15            | 101               | 101                 |
| Toluene             | [88]            | 1999       | 298.15 | 298.15            | 101               | 101                 |
| Toluene             | [55]            | 2000       | 303.15 | 313.15            | 101               | 101                 |

Table 2. Reported density (g⋅cm$^{-3}$) for binary mixtures alcohol (1) + hydrocarbon (2).
| Substance 1        | Substance 2        | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|-------------------|-------------------|------------|------|-------------------|-------------------|---------------------|---------------------|
| 1-propanol        | Heptane           | [92]       | 1966 | 357.72            | 371.52            | 101.32              | 101.32              |
|                   | Heptane           | [14]       | 1967 | 347.97            | 347.97            | 39.72               | 73.63               |
|                   | Heptane           | [13]       | 1967 | 303.13            | 333.12            | 3.92                | 39.81               |
|                   | Heptane           | [93]       | 1980 | 278.16            | 303.14            | 1.67                | 10.17               |
|                   | Heptane           | [16]       | 1982 | 423.15            | 573.15            | 200                 | 5066                |
|                   | Heptane           | [94]       | 1991 | 313.15            | 313.15            | 10.95               | 16.52               |
|                   | Heptane           | [95]       | 1992 | 313.15            | 313.15            | 9.638               | 16.428              |
|                   | Heptane           | [96]       | 1993 | 303.15            | 303.15            | 5.42                | 10.24               |
|                   | Heptane           | [97]       | 1995 | 379.38            | 475.45            | 204.5               | 1032.8              |
|                   | Heptane           | [98]       | 1995 | 316.78            | 357.58            | 19.60               | 101.33              |
|                   | Heptane           | [99]       | 2000 | 298.15            | 298.15            | –                   | –                   |
|                   | Heptane           | [100]      | 2004 | 303.15            | 343.15            | –                   | –                   |
| 2,2,4, trimethylpentane | [28]   | 1981      | 328.36 | 348.50          | 15.98             | 72.75               |                     |
| 2,2,4, trimethylpentane | [101] | 1994      | 357.88 | 365.46          | 101.3             | 101.3               |                     |
| 2,2,4, trimethylpentane | [102] | 1994      | 343.15 | 343.15          | 42.04             | 60.07               |                     |
| 2,2,4, trimethylpentane | [29]   | 2007      | 303.15 | 303.15          | 4.88              | 10.45               |                     |
| 2,2,4, trimethylpentane | [103] | 2011      | 318.15 | 318.15          | 9.00              | 21.13               |                     |
| Cyclohexane       | [104]            | 1977      | 298.15 | 298.15          | 2.79              | 14.29               |                     |
| Cyclohexane       | [105]            | 1986      | 347.66 | 369.17          | 101.33            | 101.33              |                     |
| Cyclohexane       | [98]             | 1995      | 347.58 | 347.58          | 101.33            | 101.33              |                     |
| Cyclohexane       | [106]            | 1996      | 298.15 | 308.15          | 2.63              | 22.1                |                     |
| Cyclohexane       | [107]            | 1997      | 323.15 | 333.15          | 27.92             | 61.17               |                     |
| Cyclohexane       | [99]             | 2000      | 313.15 | 343.15          | –                 | –                   |                     |
| Cyclohexane       | [108]            | 2000      | 298.15 | 298.15          | 101.32            | 101.32              |                     |
| Methylcyclohexane | [109]            | 1969      | 360.13 | 366.83          | 101               | 101                 |                     |
| Methylcyclohexane | [110]            | 1989      | 332.98 | 332.98          | 29.12             | 38.60               |                     |
| Methylcyclohexane | [111]            | 1997      | 358.75 | 373.60          | 101.3             | 101.3               |                     |
| Benzene           | [112]            | 1947      | 298.94 | 363.52          | 13.33             | 99.99               |                     |
| Benzene           | [113]            | 1963      | 349.12 | 365.92          | 101               | 101                 |                     |
| Benzene           | [114]            | 1964      | 493.16 | 558.18          | 2419.4            | 4904.2              |                     |
| Benzene           | [104]            | 1977      | 298.15 | 298.15          | 2.79              | 13.04               |                     |
| Benzene           | [105]            | 1986      | 350.03 | 361.85          | 101.33            | 101.33              |                     |
| Benzene           | [115]            | 1987      | 313.15 | 313.15          | 7.01              | 25.98               |                     |
| Benzene           | [107]            | 1997      | 323.15 | 333.15          | 22.02             | 56.70               |                     |
| Benzene           | [116]            | 2001      | 313.15 | 313.15          | 7.047             | 26.069              |                     |
| Benzene           | [117]            | 2006      | 313.15 | 313.15          | 7.01              | 25.91               |                     |
| Benzene           | [52]             | 2008      | 323.15 | 323.15          | 17.98             | 39.89               |                     |
| Benzene           | [51]             | 2008      | 329.45 | 368.35          | 50                | 94                  |                     |
| Toluene           | [115]            | 1987      | 313.15 | 313.15          | 7.01              | 11.35               |                     |
| Toluene           | [118]            | 1996      | 298.15 | 298.15          | 2.63              | 5.39                |                     |
| Toluene           | [119]            | 2003      | 323.15 | 370.15          | –                 | –                   |                     |
| Substance 1 | Substance 2 | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|------------|------------|------------|------|----------------|----------------|----------------|----------------|
| Toluene    |            | [59]       | 2008 | 333.15         | 333.15         | 20.27          | 27.41          |
| Toluene    |            | [120]      | 2009 | 323.15         | 323.15         | 13.42          | 17.85          |
| 1-butanol  | Heptane    | [121]      | 1966 | 361.92         | 376.92         | 91.2           | 91.2           |
| Heptane    |            | [122]      | 1967 | 387.93         | 434.34         | 192.65         | 496.63         |
| Heptane    |            | [63]       | 1984 | 333.15         | 363.15         | 8.01           | 89.49          |
| Heptane    |            | [123]      | 1990 | 353.15         | 373.15         | 101.32         | 101.32         |
| Heptane    |            | [124]      | 1994 | 313.15         | 313.15         | 4.39           | 13.22          |
| Heptane    |            | [98]       | 1995 | 312.34         | 357.58         | 12.93          | 74.47          |
| Heptane    |            | [125]      | 1996 | 328.45         | 366.55         | 25.63          | 101.38         |
| Heptane    |            | [126]      | 1997 | 303.15         | 303.15         | 1.35           | 8.26           |
| Heptane    |            | [99]       | 2000 | 298.15         | 298.15         | –              | –              |
| Heptane    |            | [127]      | 2001 | 365.05         | 389.05         | 95             | 95             |
| Heptane    |            | [100]      | 2004 | 303.15         | 343.15         | –              | –              |
| Heptane    |            | [138]      | 2010 | 349.00         | 387.75         | 53.3           | 91.3           |
| Heptane    |            | [129]      | 2012 | 313.15         | 313.15         | 2.51           | 13.22          |
| 2,2,4-trimethylpentane |    | [130]      | 2006 | 308.15         | 318.15         | 2              | 17             |
| 2,2,4-trimethylpentane |    | [103]      | 2011 | 318.15         | 318.15         | 7.2            | 16.4           |
| 2,2,4-trimethylpentane |    | [129]      | 2012 | 313.15         | 313.15         | 2.55           | 13.71          |
| 2,2,4-trimethylpentane |    | [131]      | 2013 | 313.15         | 313.15         | 11.55          | 13.50          |
| Cyclohexane |            | [132]      | 1968 | 353.15         | 383.12         | 21.23          | 229.21         |
| Cyclohexane |            | [133]      | 1982 | 293.15         | 293.15         | –              | –              |
| Cyclohexane |            | [71]       | 1983 | 318.15         | 318.15         | 3.41           | 30.59          |
| Cyclohexane |            | [134]      | 1990 | 312.8          | 389.9          | –              | –              |
| Cyclohexane |            | [98]       | 1995 | 352.7          | 352.7          | 101.33         | 101.33         |
| Cyclohexane |            | [108]      | 2000 | 298.15         | 298.15         | 101.32         | 101.32         |
| Cyclohexane |            | [99]       | 2000 | 313.15         | 343.15         | –              | –              |
| Cyclohexane |            | [135]      | 2001 | 350.95         | 389.05         | 95             | 95             |
| Cyclohexane |            | [136]      | 2002 | 325.6          | 386.12         | 40.0           | 101.3          |
| Cyclohexane |            | [129]      | 2012 | 313.15         | 313.15         | 2.51           | 24.83          |
| Methylcyclohexane |      | [109]      | 1969 | 369.75         | 385.65         | 101            | 101            |
| Methylcyclohexane |      | [110]      | 1989 | 332.98         | 332.98         | 11.07          | 29.77          |
| Methylcyclohexane |      | [111]      | 1997 | 368.45         | 390.50         | 101.3          | 101.3          |
| Benzene    |            | [137]      | 1939 | 298.15         | 298.15         | 0.85           | 12.59          |
| Benzene    |            | [128]      | 1963 | 353.21         | 390.83         | 101.32         | 101.32         |
| Benzene    |            | [114]      | 1964 | 513.17         | 558.18         | 2032.6         | 4751.2         |
| Benzene    |            | [115]      | 1987 | 313.15         | 313.15         | 2.52           | 24.37          |
| Benzene    |            | [79]       | 1993 | 298.15         | 298.15         | 0.82           | 12.83          |
| Benzene    |            | [139]      | 1995 | 354.03         | 425.26         | 105            | 303            |
| Benzene    |            | [140]      | 2004 | 308.15         | 308.15         | 4.03           | 20.28          |
| Benzene    |            | [141]      | 2006 | 313.15         | 313.15         | 2.49           | 24.37          |
| Toluene    |            | [84]       | 1940 | 376.12         | 390.83         | 101            | 101            |
### Table 3. Reported vapour-liquid equilibria for binary mixtures alcohol (1) + hydrocarbon (2).

| Substance 1 | Substance 2 | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|-------------|-------------|------------|------|-------------------|-------------------|-------------------|-------------------|
| Toluene     | [142]       | 1963       | 378.63 | 390.83            | 101.33            | 101.33            |
| Toluene     | [115]       | 1987       | 313.15 | 313.15            | 2.52              | 8.48              |
| Toluene     | [134]       | 1990       | 349.5  | 389.9             | –                 | –                 |
| Toluene     | [143]       | 1997       | 360.9  | 389.1             | 56.4              | 94.0              |
| Toluene     | [119]       | 2003       | 323.15 | 390.15            | –                 | –                 |
| Toluene     | [140]       | 2004       | 308.15 | 308.15            | 2.49              | 6.39              |
| Toluene     | [129]       | 2012       | 313.15 | 313.15            | 2.49              | 8.39              |
| 1-hexene    | [131]       | 2013       | 313.15 | 313.15            | 2.48              | 44.99             |

### Table 4. Reported vapour-liquid equilibria for ternary mixtures alcohol (1) + hydrocarbon (2) + hydrocarbon (3).

| Substance 1 | Substance 2 | Substance 3 | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|-------------|-------------|-------------|------------|------|-------------------|-------------------|-------------------|-------------------|
| 1-butanol   | 2,2,4-trimethylpentane | 1-hexene  | [131] | 2013 | 313.15 | 313.15 | 2.48 | 44.99 |
| 1-butanol   | toluene     | 1-hexene   | [144] | 2015 | 313.15 | 313.15 | 2.51 | 44.99 |
| TBA         | Cyclohexane | Benzene    | [98]   | 1995 | 294.91 | 344.25 | 13.61 | 101.36 |
| Substance 1  | Substance 2            | References | Year | $T_{\text{min}}$/K | $T_{\text{max}}$/K | $P_{\text{min}}$/kPa | $P_{\text{max}}$/kPa |
|------------|------------------------|-----------|------|-------------------|-------------------|-------------------|-------------------|
| 1-propanol | Heptane                | [157]     | 1976 | 298.15            | 298.15            | 101               | 101               |
|            | Heptane                | [158]     | 1981 | 184.97            | 184.97            | 101               | 101               |
|            | Heptane                | [159]     | 1993 | 298.15            | 298.15            | 101               | 101               |
| 1-butanol  | Heptane                | [159]     | 1993 | 298.15            | 298.15            | 101               | 101               |
|            | 2,2,4 Trimethylpentane | [160]     | 2012 | 293.15            | 313.15            | 101               | 25,000            |
|            | Cyclohexane            | [76]      | 2014 | 293.15            | 313.15            | 101               | 25,000            |
|            | Toluene                | [161]     | 1991 | 298.15            | 368.15            | 101               | 101               |
|            | 1-Hexene               | [86]      | 2013 | 293.15            | 313.15            | 101               | 25,000            |

Table 5. Reported heat capacity for binary mixtures alcohol (1) + hydrocarbon (2).

3. Discussion

3.1. Density of mixtures 1-propanol, or 1-butanol, + hydrocarbon

Table 2 presents density data for the selected mixtures alcohol (1) + hydrocarbon (2). Fifty-nine references correspond to mixtures 1-propanol (1) + hydrocarbon (2) and 51 to the one 1-butanol (1) + hydrocarbon (2), while only 16 references have been found for TBA (1) + hydrocarbon (2). For 1-propanol (1) + hydrocarbon (2), only atmospheric pressure density data have been found for the binary mixtures, except Refs. [16, 56] that are above 5 MPa. The highest pressure, 30 MPa, is reported by Zeberg-Mikkelsen and Andersen [56]. Temperatures above 350 K are only measured by Zawisza and Vejrosta [16]. Concerning 1-butanol (1) + hydrocarbon (2), Refs. [67, 76] report pressure above the atmospheric pressure. Hundred Megapascal is the maximum pressure measured in Ref. [76]. Reference [67] also reports temperature above 350 K. Finally, mixtures TBA (1) + hydrocarbon are reported only at atmospheric pressure and moderate temperatures, being 323.15 K the highest measured temperature [87]. No data were found for the mixture TBA (1) + 1-hexene (2).

3.2. Vapour-liquid equilibrium of mixtures 1-propanol, or 1-butanol, + hydrocarbon

With respect to the binary mixtures, Table 3 shows 43 references for VLE data on 1-propanol (1) + hydrocarbon (2), 47 for 1-butanol (1) + hydrocarbon (2) and 24 for TBA (1) + hydrocarbon (2). No references for the mixtures 1-propanol (1) + 1-hexene (2) and TBA (1) + 1-hexene (2) were found, while [131] was the only one for 1-butanol (1) + 1-hexene (2). Most references were found for pressures lower or equal to atmospheric pressure. Studies done in Refs. [97, 122, 132] were measured at moderate pressures, below 1.0 MPa, and only Ref. [114] reports pressure close to 5 MPa for both mixtures 1-propanol (1), or 1-butanol (1), + benzene (2).
Concerning temperature, most measurements were performed at low and moderate temperatures. Within the interval 350–400 K, we found a limited number of 27 set of data [51, 63, 84, 98, 105, 109, 111–113, 119, 121, 123, 125, 127, 128, 132, 134–136, 142, 143, 146–150, 155]. Only Refs. [16, 97, 114, 122, 139] report temperatures between 400 and 573 K.

Only three references were found reporting VLE data of ternary mixtures, as shown in Table 4, at atmospheric or lower pressures. Temperatures were moderate, with maximum at 344 K measured in Ref. [98]. No ternary mixture with 1-propanol was found.

3.3. Heat capacity of mixtures 1-propanol, or 1-butanol, + hydrocarbon

Only eight references reporting heat capacity of binary mixtures alcohol (1) + hydrocarbon (2) are cited. Three of them correspond to the binary mixture 1-propanol (1) + heptane (2) at atmospheric pressure and at moderate temperatures (up to 300 K). No other mixture of 1-propanol with the any of selected hydrocarbons was found.

While the heat capacity of 1-butanol with heptane, 2,2,4 trimethylpentane, cyclohexane, toluene and 1-hexane was measured by several authors. It must be pointed out that some measurements [86, 160, 161] have been performed at pressures up to 25 MPa and temperature of 313 K.

4. Conclusion

The literature review on thermodynamic properties of liquid mixtures of 1-propanol, 1-butanol and TBA with representative hydrocarbons has been reported. Seven hydrocarbons (linear, branched and cyclic alkanes, aromatics, and olefins) have been selected as representative of present and future unleaded gasoline. The review covers density, vapour-liquid equilibrium and heat capacity of mixtures.

The review of density data shows a big amount of data at low pressure and moderate temperatures. Only two references report data above 30 MPa at a maximum temperature of 333 K. And at temperatures above 450 K, the maximum pressure is 5.5 MPa. With respect to the vapour-liquid equilibrium, only one reference shows measurements over 555 K at 5 MPa. Heat capacity data of mixtures are very scarce, tough some high pressure and high temperature data can be found for some alcohol + hydrocarbon mixtures.

The performance of fuels and biofuels in engines and other devices shows a trend of increasing pressure and temperature, which leads to the need of more reliable predictive models for complex mixtures at such conditions. Availability of high pressure and high temperature thermodynamic properties is then a requisite for the implementation of these equation and models. The review shows a lack of reliable data at high pressure and high temperature thermodynamic data, which serve as a basis for the development of predictive equations and models.
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References

[1] Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.

[2] Directive 2009/30/EC of the European Parliament and of the Council as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions.

[3] Ezeji TC, Blaschek HP. Butanol Production from Lignocellulosic Biomass. In: Blaschek HP, Ezeji TC, Sheffran J, editors. Biofuels from Agricultural Wastes and Byproducts. Ames: Wiley-Blackwell; 2010. pp. 19–37.

[4] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Progress in Energy and Combustion Science. 2007; 33: 233–271. doi:10.1016/j.pecs.2006.08.003

[5] Surisetty VR, Dalai AK, Kozinski J. Alcohols as alternative fuels: An overview. Applied Catalysis A: General. 2011; 404: 1–11. doi:10.1016/j.apcata.2011.07.021

[6] Elvers B, editor. Handbook of Fuels: Energy for Transportation. Weinheim: Wiley-VCH; 2008. 356 p.

[7] De Klerk A. Fischer-Tropsch Refining. Weinheim: Wiley-VCH; 2011. 620 p.

[8] ASTM D7862 – 13. Standard Specification for Butanol for Blending with Gasoline for Use as Automotive Spark-Ignition Engine Fuel.

[9] Köpke M, Dürre P. Biochemical Production of Biobutanol. In: Luque R, Campelo J, Clark J, editors. Handbook of Biofuels Production. Cambridge, UK: Woodhead; 2011. pp. 221–257.

[10] Mousdale D. Introduction to Biofuels. Boca Raton: CRC Press; 2010. 429 p.

[11] Butamax: The Biofuel Company [Internet]. 2016. Available from: http://www.butamax.com/ [Accessed: 2016-09-12]
Minteer SD. Biochemical Production of Other Bioalcohols: Biomethanol, Biopropanol, Bioglycerol and Bioethylene Glycol. In: Luque R, Campelo J, Clark J, editors. Handbook of Biofuels Production. Cambridge, UK: Woodhead; 2011. pp. 258–265.

Van Ness HC, Soczek CA, Peloquin GL, Machado RL. Thermodynamic excess properties of three alcohol-hydrocarbon systems. Journal of Chemical and Engineering Data. 1967; 12: 217–224. doi:10.1021/je60033a017

Lee LL, Scheller WA. Isothermal vapor-liquid equilibrium data for the system heptane + 1-propanol at 75°C and decane + 1-butanol at 100°C. Journal of Chemical and Engineering Data. 1967; 12: 497. doi:10.1021/je60035a009

Tresczczanowicz AJ, Benson GC. Excess volumes for n-alkanols I. Binary mixtures of methanol, ethanol, n-propanol, and n-butanol + n-heptane. Journal of Chemical Thermodynamics. 1977; 9: 1189–1197. doi:10.1016/0021-9614(77)90119-7

Zawisza A, Vejrosta J. High-pressure liquid-vapor equilibria, critical stat, and p(V, T, x) up to 573.15 K and 5.066 MPa for (heptane + propan-1-ol). Journal of Chemical Thermodynamics. 1982; 14: 239–249. doi:10.1016/0021-9614(82)90014-3

Kumaran MK, Benson GC. Limiting partial molar volumes of ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, and hexan-1-ol in n-heptane at 298.15 K. Journal of Chemical Thermodynamics. 1983; 15: 245–248. doi:10.1016/0021-9614(83)90115-5

Zielkiewicz J. Excess molar volumes of (heptane + ethanol + propan-1-ol) at the temperature 313.15 K. Journal of Chemical Thermodynamics. 1993; 25: 1243–1248. doi:10.1006/jcht.1993.1122

Romani L, Peleteiro J, Iglesias TP, Carballo E, Escudero R, Legido JL. Temperature dependence of the volumetric properties of binary mixtures containing alcohols (1-propanol, 1-pentanol, 1-heptanol) + heptane. Journal of Chemical and Engineering Data. 1994; 39: 19–22. doi:10.1021/je00013a006

Keller M, Schnabel S, Heintz A. Thermodynamics of the ternary mixture propan-1-ol + tetrahydrofuran + n- heptane at 298.15 K. Experimental results and ERAS model calculations of GE, HE and VE. Fluid Phase Equilibria. 1995; 110: 231–265. doi:10.1016/0378-3812(95)02757-6

Sastry NV, Valand MK. Densities, speeds of sound, viscosities, and relative permittivities for 1-propanol + and 1-butanol + heptane at 298.15 K and 308.15 K. Journal of Chemical and Engineering Data. 1996; 41: 1421–1425. doi:10.1021/je960135d

Orge B, Iglesias M, Rodriguez A, Canosa JM, Tojo J. Mixing properties of (methanol, ethanol, or 1-propanol) with (n-pentane, n-hexane, n-heptane and n-octane) at 298.15 K. Fluid Phase Equilibria. 1997; 133: 213–227. doi:10.1016/S0378-3812(97)00031-9

Jiménez E, Franjo C, Segade L, Legido JL, Paz Andrade MI. Viscosities and densities for the 1-propanol + n-heptane system at several temperatures. Journal of Solution Chemistry. 1998; 27: 569–579. doi:10.1023/A:1022686707250
[24] Bahadur PNV, Sastry NV. Densities, sound speeds, excess volumes, and excess isentropic compressibilities of methyl acrylate + 1-propanol (or 1-butanol) + hydrocarbons (n-hexane, n-heptane, cyclohexane, benzene, and toluene) at 308.15 K. International Journal of Thermophysics. 2003; 24: 447–462. doi:10.1023/A:1022920005042

[25] Dzida M. The effect of pressure on the thermodynamic properties of propan-1-ol + n-heptane mixtures. Journal of Solution Chemistry. 2004; 33: 529–548. doi:10.1023/B:JOSL.0000037774.94690.d1

[26] El-Hefnawy M, Sameshima K, Matsushita T, Tanaka R. Apparent dipole moments of 1-alkanols in cyclohexane and n-heptane, and excess molar volumes of (1-alkanol + cyclohexane or n-heptane) at 298.15 K. Journal of Solution Chemistry. 2005; 34: 43–69. doi:10.1007/s10953-005-0272-1

[27] Mato MM, Cebreiro SM, Verdes PV, Pallas AV, Legido JL, Paz Andrade MI. Experimental and predicted excess molar volumes of the ternary system tertbutylmethyl ether +1-propanol+n-heptane at 298.15 K. Journal of Thermal Analysis and Calorimetry. 2005; 80: 345–349. doi:10.1007/s10973-005-0658-x

[28] Berro C, Neau E, Rogalski M. Vapor-liquid equilibrium of the systems 1-propanol + 2,2,4-trimethylpentane and 2-propanol + n-hexane. Fluid Phase Equilibria. 1981; 7: 41–54. doi:10.1016/0378-3812(81)87004-5

[29] Hwang IC, Lim HM, Park SJ, Han KJ, Park IH. Isothermal vapor liquid equilibrium at 303.15 K and excess molar volumes at 298.15 K for the ternary system of propyl vinyl ether + 1-propanol + 2,2,4-trimethyl-pentane and its binary sub-systems. Fluid Phase Equilibria. 2007; 259: 146–152. doi:10.1016/0378-3812(81)87004-5

[30] Hwang IC, Jo MY, Kwak HY, Park SJ, Han KJ. Isothermal VLE and VE at 303.15 K for the binary and ternary mixtures of Di-isopropyl ether (DIPE) + 1-propanol + 2,2,4-trimethylpentane. Journal of Chemical and Engineering Data. 2007; 52: 2503–2508. doi:10.1021/je700460w

[31] Faneite AM, Garces SI, Aular JA, Urdaneta MR, Soto D. Excess molar volumes, excess molar enthalpies and refractive index deviations for binary mixtures of propan-1-ol, butan-1-ol and pentan-1-ol with 2,2,4-trimethylpentane at 298.15 K. Fluid Phase Equilibria. 2012; 334: 117–127. doi:10.1016/j.fluid.2012.06.031

[32] Wang X, Wang X, Song B. Densities and viscosities of binary mixtures of 2,2,4-trimethylpentane + 1-propanol, + 1-pentanol, + 1-hexanol, and + 1-heptanol from (298.15 to 323.15) K. Journal of Chemical and Engineering Data. 2015; 60: 1664–1673. doi:10.1021/je501041r

[33] Edward JT, Farrell PG, Shahidi F. Effect of solvent (benzene, ethanol, cyclohexane) on the partial molar volumes of organic compounds. Canadian Journal of Chemistry. 1979; 57: 2887–2891. doi:10.1139/v79-469
[34] Arce A, Blanco A, Antorrena G, Quintela MD. Excess physical properties of ternary mixtures. Benzene-cyclohexane-alcohol systems at 25°C. Anales de Química. 1980; 76: 405–413.

[35] Letcher TM, Mercer-Chalmers J. Excess molar volumes of (a cycloalkane + an alkanol) at 298.15 K. Canadian Journal of Chemistry. 1991; 69: 1259–1260. doi:10.1139/v91-188

[36] Singh KC, Kalra KC, Maken S, Gupta V. Excess enthalpies and volumes of mixing of 1-propanol or 2-propanol + cyclohexane at 298.15 and 308.15 K. Fluid Phase Equilibria. 1996; 123: 271–281. doi:10.1016/S0378-3812(96)90037-0

[37] Lee LS, Chuang ML. Excess volumes of cyclohexane with 2-propanone, 2-butanone, 3-pentanone, 4-methyl-2-pentanone, 1-propanol, and 2-propanol and ethanoic acid + 1-propanol systems. Journal of Chemical and Engineering Data. 1997; 42: 850–853. doi:10.1021/je9603335

[38] Oswal SL, Prajapati KD. Speeds of sound, isentropic compressibilities, and excess molar volumes of an alkanol + cycloalkane at 303.15 K. 1. Results for alkan-1-ols + cyclohexane. Journal of Chemical and Engineering Data. 1998; 43: 367–372. doi:10.1021/je970235z

[39] Tanaka R, Yokoyama T. Apparent dipole moments of 1-butanol, 1-propanol, and chlorobenzene in cyclohexane or benzene, and excess molar volumes of (1-propanol or chlorobenzene + cyclohexane or benzene) at T = 298.15 K. Journal of Solution Chemistry. 2004; 33: 1061–1072. doi:10.1021/bj049116p

[40] González B, Calvar N, Domínguez A, Tojo J. Dynamic viscosities of binary mixtures of cycloalkanes with primary alcohols at T = (293.15, 298.15, and 303.15) K: New UNIFAC-VISCO interaction parameters. Journal of Chemical Thermodynamics. 2007; 39: 322–334. doi:10.1016/j.jct.2006.06.008

[41] Gardas RL, Oswal S. Volumetric and transport properties of ternary mixtures containing 1-propanol, triethylamine or tri-n-butylamine and cyclohexane at 303.15 K: Experimental data, correlation and prediction by ERAS model. Thermochimica Acta. 2008; 479: 17–27. doi:10.1016/j.tca.2008.09.006

[42] Umadevi M, Kesavasamy R, Rathina K, Mahalakshmi R. Studies on liquid-liquid interactions of some ternary mixtures by density, viscosity and ultrasonic speed measurements. Journal of Molecular Liquids. 2016; 219: 820–828. DOI: 10.1016/j.molliq.2016.03.085.

[43] Rao MVP, Naidu PR. Viscosities of binary liquid mixtures of 1-propanol, 1-butanol, 1-pentanol and 1-hexanol with methylcyclohexane, cyclopentanone and cyclohexanone. Indian Journal of Chemistry - Section A: Inorganic, Bio-inorganic, Physical, Theoretical & Analytical Chemistry. 1977; 15: 239.

[44] Letcher TM, Nevine JA. Excess molar volumes of chloro- or methylcyclohexane + an alkanol at 298.15 K. Thermochimica Acta. 1996; 287: 287–292. doi:10.1016/S0040-6031(96)03001-8
[45] Aralaguppi MI, Baragi JG. Physico-chemical and excess properties of the binary mixtures of methylcyclohexane + ethanol, + propan-1-ol, + propan-2-ol, + butan-1-ol, + 2-methyl-1-propanol, or 3-methyl-1-butanol at T = (298.15, 303.15, and 308.15) K. Journal of Chemical Thermodynamics. 2006; 38: 434–442. doi:10.1016/j.jct.2005.06.011

[46] Coca Prados J. Physical-chemical properties of liquid binary mixtures. Viscosity and heat of mixture. Acta Salmanticensia. Ciencias. 1969; 33: 7–39.

[47] Yadav BL, Maken S, Kalra KC, Singh KC. Excess volumes of (an alkanol + an aromatic hydrocarbon) at the temperature 308.15 K. Journal of Chemical Thermodynamics. 1993; 25: 1345–1350. doi:10.1006/jcht.1993.1135

[48] Singh KC, Kalra KC, Maken S, Yadav BL. Excess volumes of 1-propanol and 2-propanol with aromatic hydrocarbons at 298.15 K. Journal of Chemical and Engineering Data. 1994; 39: 241–244. doi:10.1021/je00014a011

[49] Kumar KS, Reddy NV. Excess volumes of binary mixtures of benzene 1-alkanols at 303.15 K. Physics and Chemistry of Liquids. 2001; 39: 117–123. doi:10.1080/00319100108030331

[50] Kijevcanin ML, Puric IM, Radovic IR, Djordjevic BD, Serbanovic SP. Densities and excess molar volumes of the binary 1-propanol + chloroform and 1-propanol + benzene and ternary 1-propanol + chloroform + benzene mixtures at (288.15, 293.15, 298.15, 303.15, 308.15, and 313.15) K. Journal of Chemical and Engineering Data. 2007; 52: 2067–2071. doi:10.1021/je700254t

[51] Mejía A, Segura H, Cartes M. Vapor-liquid equilibrium, densities, and interfacial tensions for the system benzene + propan-1-ol. Physics and Chemistry of Liquids. 2008; 46: 185–200. doi:10.1080/00319100701459350

[52] Kim HD, Hwang IC, Park SJ. Isothermal vapor liquid equilibrium at 323.15 K and excess molar volumes and refractive indices at 298.15 K for the ternary system propyl vinyl ether + 1-propanol + benzene and its binary sub-systems. Fluid Phase Equilibria. 2008; 274: 73–79. doi:10.1016/j.fluid.2008.09.005

[53] Gahlyan S, Rani M, Lee I, Moon I, Maken SK. Measurement and correlation of excess molar volumes for mixtures of 1-propanol and aromatic hydrocarbons. Korean Journal of Chemical Engineering. 2015; 32: 168–177. DOI : 10.1007/s11814-014-0200-6

[54] Swamy GN, Dharmaraju G, Raman GK. Excess volumes of toluene mixtures with some alcohols at 303.15 K. Canadian Journal of Chemistry. 1980; 58: 229–230. doi:10.1139/v80-037

[55] Nikam PS, Jagdale BS, Sawant AB, Hasan M. Densities and viscosities of binary mixtures of toluene with methanol, ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, and 2-methylpropan-2-ol at (303.15, 308.15, 313.15) K. Journal of Chemical and Engineering Data. 2000; 45: 559–563. doi:10.1021/je990317i
[56] Zeberg-Mikkelsen CK, Andersen SI. Density measurements under pressure for the binary system 1-propanol + toluene. Journal of Chemical and Engineering Data. 2005; 50: 524–528. doi:10.1021/je049685z

[57] Atik Z. Experimental and predicted volumetric and refractive index properties of ternary mixtures of iodoethane with toluene and alcohols at temperature 298.15 K and pressure 101 kPa. Journal of Chemical Thermodynamics. 2006; 38: 201–208. doi:10.1016/j.jct.2005.05.004

[58] Zéberg-Mikkelsen CK, Lugo L, Fernandez J. Corrigendum to “Density measurements under pressure for the binary system (ethanol + methylcyclohexane)”. Journal of Chemical Thermodynamics. 2006; 38: 649. doi:10.1016/j.jct.2005.11.006

[59] Hwang IC, Park SJ, Lee SY, Ahn HS. Isothermal vapor liquid equilibrium at 333.15 K and excess molar volumes at 298.15 K for the ternary system di-isopropyl ether + n-propyl alcohol + toluene and its binary subsystems. Fluid Phase Equilibria. 2008; 270: 103–108. doi:10.1016/j.fluid.2008.06.019

[60] Letcher TM, Mercer-Chalmers J, Govender UP, Radloff S. Excess molar enthalpies and excess molar volumes of binary mixtures of 1-alkenes with 1-propanol and 2-propanol. Thermochemica Acta. 1993; 224: 33–38. doi:10.1016/0040-6031(93)80151-Y

[61] Treszczanowicz A, Pawlowski TS, Treszczanowicz T, Szafranski AM. Excess volume of the 1-propanol + 1-alkene systems in terms of an equation of state with association. Journal of Chemical and Engineering Data. 2010; 55: 5478–5482. doi:10.1021/je100595s

[62] Kumar A, Pradhan SD, Katti SS. Volume change on mixing of isomeric butanols with normal heptane. Proc. Indian Acad. Sci. (Chem. Sci.). 1979; 88: 249–255. DOI:10.1007/BF02880931

[63] Berro C, Peneloux A. Excess gibbs energies and excess volumes of 1-butanol-n-heptane and 2-methyl-1-propanol-n-heptane binary systems. Journal of Chemical and Engineering Data. 1984; 29: 206–210. doi:10.1021/je00036a033

[64] Zielkiewicz J. Excess volumes of (heptane + propane-2-ol or butan-1-ol or 2-methylpropan-1 -ol or 2-methylpropan-2-ol or pentan-1-ol) at the temperature 313.15 K. Journal of Chemical Thermodynamics. 1994; 26: 959–964. doi:10.1006/jcht.1994.1112

[65] Nath J. Speeds of sound in and isentropic compressibilities of (n-butanol + n-pentane, or n-hexane, or n-heptane, or n-octane, or 2,2,4-trimethylpentane, or carbon tetrachloride) at T=293.15 K. Journal of Chemical Thermodynamics. 1997; 29: 853–863. doi: 10.1006/jcht.1997.0200

[66] Nath J, Pandey JG. Binary mixtures of butanol + pentane, +hexane, +heptane, +octane, +2,2,4-trimethylpentane, and + carbon tetrachloride. 1. Excess molar volumes at 288.15 K and 298.15 K and refractive indexes at 298.15 K. Journal of Chemical and Engineering Data. 1997; 42: 128–131. doi:10.1021/je960229n
[67] Westwood BM, Kabadi VN. A novel pycnometer for density measurements of liquids at elevated temperatures. Journal of Chemical Thermodynamics. 2003; 35: 1965–1974. doi:10.1016/j.jct.2003.08.005

[68] Vijande J, Pineiro MM, Garcia J, Valencia JL, Legido JL. Density and surface tension variation with temperature for heptane + 1-alkanol. Journal of Chemical and Engineering Data. 2006; 51: 1778–1782. doi:10.1021/je060179e

[69] Kijevcanin ML, Radovic IR, Serbanovic SP, Tasic AZ. Experimental determination and modelling of densities and excess molar volumes of ternary system (1-butanol + cyclohexylamine + n-heptane) and corresponding binaries from 288.15 to 323.15 K. Thermochimica Acta. 2009; 496: 71–86. doi:10.1016/j.tca.2009.07.002

[70] Moravkova L, Troncoso J, Machanova K, Sedlakova Z. Volumetric behaviour of the (2,2,4-trimethylpentane + methylbenzene + butan-1-ol) ternary system and its binary sub-systems within the temperature range (298.15-328.15) K. Journal of Chemical Thermodynamics. 2013; 64: 137–150. doi:10.1016/j.jct.2009.07.002

[71] French HT. Thermodynamic functions of the systems 1-butanol, 2-butanol, and t-butanol + cyclohexane. Journal of Solution Chemistry. 1983; 12: 869. doi:10.1007/BF00643927

[72] Artigas H, Sanz ML, Mainar AM, Royo FM, Urieta JS. Excess volumes and excess viscosities of binary mixtures of cyclohexane + an isomer of butanol at several temperatures. Physics and Chemistry of Liquids. 1995; 30: 17–28. doi:10.1080/00319109508028430

[73] Mascato E, Mosteiro L, Pineiro MM, Garcia J, Iglesias TP, Legido JL. Thermodynamic properties of mixing for (1-alkanol + an-alkane + a cyclic alkane) at T = 298.15 K. I. (n-Hexane + cyclohexane + 1-butanol). Journal of Chemical Thermodynamics. 2001; 33: 269–285. doi:10.1006/jcht.2000.0732

[74] Haro M, Gascón I, Cea P, Lafuente C, Royo FM. Volumetric and acoustic properties of the ternary system (1-butanol+1,4-dioxane+cyclohexane). Journal of Thermal Analysis and Calorimetry. 2005; 79: 51–57. DOI: 10.1007/s10973-004-0561-x.

[75] Bebek K, Strugala-Wilczek A. Acoustic and thermophysical properties of binary liquid mixtures of primary butanols with hexane and cyclohexane at 293.15 K. International Journal of Thermophysics. 2010; 31: 8–15. doi:10.1007/s10765-009-0665-4

[76] Torin-Ollarves GA, Martín MC, Chamorro CR, Segovia JJ. Densities, viscosities, and isobaric heat capacities of the system (1-butanol + cyclohexane) at high pressures. Journal of Chemical Thermodynamics. 2014; 74: 153–160. doi:10.1016/j.jct.2014.01.020

[77] Alonso R, Corrales JA. Excess molar volumes of (methylcyclohexane + an alkanol) at 298.15 K. I. Results for n-butanol, n-pentanol, and n-hexanol. Journal of Chemical Thermodynamics. 1989; 21: 515–518. doi:10.1016/0021-9614(89)90168-7

[78] Oswal SL, Prajapati KD, Ghael NY, Ijardar SP. Speeds of sound, isentropic compressibilities and excess molar volumes of an alkanol + cycloalkane at 303.15 K. II. Results for
alkan-2-ols + cyclohexane and alkan-1-ols + methylcyclohexane and theoretical interpretation. Fluid Phase Equilibria. 2004; 218: 131–140. doi:10.1016/j.fluid.2003.11.012

[79] Rodríguez V, Lafuente C, López MC, Royo FM, Urieta JS. Excess molar volumes and vapor pressures of (benzene + each of several isomers of butanol). Journal of Chemical Thermodynamics. 1993; 25: 679–685. doi:10.1006/jcht.1993.1065

[80] Yu CH, Tsai FN. Excess volumes of binary mixtures of benzene + 1-alkanols at 298.15 and 308.15 K. Journal of Chemical and Engineering Data. 1994; 39: 441–443. doi:10.1021/je00015a008

[81] Bhardwaj U, Maken S, Singh KC. Excess molar volumes of (an isomer of butanol + benzene or toluene) at the temperature 308.15 K. Journal of Chemical Thermodynamics. 1996; 28: 1173–1177. doi:10.1006/jcht.1996.0103

[82] Ali A, Nain AK, Lal B, Chand D. Densities, viscosities, and refractive indices of binary mixtures of benzene with isomeric butanols at 30°C. International Journal of Thermophysics. 2004; 25: 1835–1847. doi:10.1007/s10765-004-7738-1

[83] Smiljanić JD, Kijevčanin ML, Djordjević BD. Temperature dependence of densities and excess molar volumes of the ternary mixture (1-butanol + chloroform + benzene) and its binary constituents (1-butanol + chloroform and 1-butanol + benzene). International Journal of Thermophysics. 2008; 29: 586–609. doi:10.1007/s10765-008-0390-4

[84] Litkenhous EE, Van Arsdale JD, Hutchison IW. The physical properties of the ternary system butyl alcohol-ethyl acetate-toluene. Journal of Physical Chemistry. 1940; 44: 377–388. doi:10.1021/j150399a010

[85] Moravkova L, Troncoso J, Skvorova M, Havlica J, Petrus P, Sedlakova Z. Volumetric behavior of the ternary system (methyl tert-butyl ether + methylbenzene + butan-1-ol) and its binary sub-system (methyl tert-butyl ether + butan-1-ol) within the temperature range (298.15 to 328.15) K. Journal of Chemical Thermodynamics. 2015; 90: 59–70. doi:10.1016/j.jct.2015.06.009

[86] Torín-Ollarves GA, Segovia JJ, Martín MC, Villamañán MA. Density, viscosity, and isobaric heat capacity of the mixture (1-butanol + 1-hexene). Journal of Chemical and Engineering Data. 2013; 58: 2717–2723. doi:10.1021/je301301j

[87] Radovic IR, Serbanovic SP, Djordjevic BD, Kijevcanin ML. Experimental determination of densities and refractive indices of the ternary mixture 2-methyl-2-propanol + cyclohexylamine + n-heptane at T = (303.15 to 323.15) K. Journal of Chemical and Engineering Data. 2011; 56: 344–349. doi:10.1021/je100484n

[88] Peña MP, Martínez-Soria V, Montón JB. Densities, refractive indices, and derived excess properties of the binary systems tert-butyl alcohol + toluene, +methylcyclohexane, and + isooctane and toluene + methylcyclohexane, and the ternary system tert-butyl alcohol
+ toluene + methylcyclohexane at 298.15 K. Fluid Phase Equilibria. 1999; 166: 53–65. doi: 10.1016/S0378-3812(99)00284-8

[89] Bernatova S, Wichterle I. Isothermal vapour-liquid equilibria in the ternary system tert-butyl methyl ether + tert-butanol + 2,2,4-trimethylpentane and the three binary subsystems. Fluid Phase Equilibria. 2001; 180: 235–245. doi:10.1016/S0378-3812(01)00349-1

[90] Wang CC, Chen HW, Tu C-H. Densities, viscosities, and refractive indices for binary and ternary mixtures of ethanol, 2-methylpropan-2-ol, and 2,2,4-trimethylpentane. Journal of Chemical and Engineering Data. 2005; 50: 1687–1693. doi:10.1021/je0501639

[91] Rived F, Roses M, Bosch E. Densities, refractive indices, absolute viscosities, and static dielectric constants of 2-methylpropan-2-ol + hexane, + benzene, + propan-2-ol, + methanol, + ethanol, and + water at 303.2 K. Journal of Chemical and Engineering Data. 1995; 40: 1111–1114. doi:10.1021/je00021a017

[92] Gurukul SMKA, Raju BN. Isobaric vapor liquid equilibria of the 1-propanol-n-heptane system. Journal of Chemical and Engineering Data. 1966; 11: 501–502. doi:10.1021/je60031a013

[93] Sipowska J, Wieczorek S. Vapor pressures and excess gibbs free energies of propan-1-ol + n-heptane between 278.164 and 303.147 K. Journal of Chemical Thermodynamics. 1980; 12: 459–464. doi:10.1016/0021-9614(80)90059-2

[94] Zielkiewicz J. (Vapor + liquid) equilibria in (propan-1-ol + n-hexane + n-heptane) at the temperature 313.15 K. Journal of Chemical Thermodynamics. 1991; 23: 605–612. doi: 10.1016/S0021-9614(91)80103-X

[95] Zielkiewicz J. (Vapor + liquid) equilibria in (propan-1-ol + heptane + octane) at the temperature 313.15 K. Journal of Chemical Thermodynamics. 1992; 24: 455–462. doi: 10.1016/S0021-9614(92)80117-X

[96] Pradhan AG, Bhethanabotla VR, Campbell SW. Vapor-liquid equilibrium data for etanol-n-heptane-1-propanol and etanol-n-heptane-2-propanol and their interpretation by a simple association model. Fluid Phase Equilibria. 1993; 84: 183–206. doi: 10.1016/0378-3812(93)85123-4

[97] Olson JD. Thermodynamics of hydrogen-bonding mixtures II. GE, HE, and SE of 1-propanol + n-heptane. International Journal of Thermophysics. 1995; 16: 215–226. doi: 10.1007/BF01438972

[98] Chen G, Wang Q, Zhang L-Z, Bao J, Han S-J. Study and applications of binary and ternary azeotropes. Thermochimica Acta. 1995; 253: 295–305. doi: 10.1016/0040-6031(94)02078-3

[99] Dobrjakov YG, Balashova IM, Maurer G. Experimental results for the limiting activity coefficients in some binary and ternary mixtures of organic components. Journal of Chemical and Engineering Data. 2000; 45: 185–193. doi:10.1021/je990204z
Vrbka P, Dohnal V, Arlt W. Limiting activity coefficients by comparative tensimetry: 1-propanol and 1-butanol in heptane and in octane. Journal of Chemical and Engineering Data. 2004; 49: 867–871. doi:10.1021/je0302295

Hiaki T, Takahashi K, Tsuji T, Hongo M, Kojima K. Vapor-liquid equilibria of 1-propanol or 2-propanol with 2,2,4-trimethylpentane at 101.3 kPa. Journal of Chemical and Engineering Data. 1994; 39: 602–604. doi:10.1021/je00015a047

Hiaki T, Takahashi K, Tsuji T, Hongo M, Kojima K. Vapor-liquid equilibria of etanol + 2,2,4-trimethylpentane at 333.15 K and 1-propanol + 2,2,4-trimethylpentane at 343.15 K. Journal of Chemical and Engineering Data. 1994; 39: 605–607. doi:10.1021/je00015a048

Garces SI, Faneite AM, Soto D, Álvarez CA, Urdaneta MR. Isothermal vapor liquid equilibrium data of propan-1-ol + 2,2,4-trimethylpentane and butan-1-ol + 2,2,4-trimethylpentane at 318.15 K. Journal of Chemical and Engineering Data. 2011; 56: 3346–3350. doi:10.1021/je200279q

Hwang S-C, Robinson Jr RL. Vapor-liquid equilibria at 25°C for nine alcohol-hydrocarbon binary systems. Journal of Chemical and Engineering Data. 1977; 22: 319–325. doi:10.1021/je60074a025

Hiaki T, Tochigi K, Kojima K. Measurement of vapor-liquid equilibria and determination of azeotropic point. Fluid Phase Equilibria. 1986; 26: 83–102. doi:10.1016/0378-3812(86)85006-3

Gupta V, Maken S, Kalra KC, Singh KC. Molar excess free energy of mixing of 1-propanol or 2-propanol with cyclohexane at 298.15 and 308.15 K in terms of association model with a Flory contribution term. Fluid Phase Equilibria. 1996; 120: 195–203. doi:10.1016/0378-3812(96)03001-4

Kurihara K, Uchiyama M, Kojima K. Isothermal vapor-liquid equilibria for benzene + cyclohexane + 1-propanol and for three constituent binary systems. Journal of Chemical and Engineering Data. 1997; 42: 149–154. doi:10.1021/je9602475

Castells CB, Eikens DI, Carr PW. Headspace gas chromatographic measurements of limiting activity coefficients of eleven alkanes in organic solvents at 25°C. 1. Journal of Chemical and Engineering Data. 2000; 45: 369–375. doi:10.1021/je990146h

Raju BN, Rao DP. Isobaric vapor-liquid equilibrium data for the systems 1-propanol-methylcyclohexane and methylcyclohexane-1-butanol. Journal of Chemical and Engineering Data. 1969; 14: 283–286. doi:10.1021/je60042a019

Nagata I. Isothermal vapour-liquid equilibria for binary mixtures of methylcyclohexane with alcohols. Thermochimica Acta. 1989; 144: 95–107. doi:10.1016/0040-6031(89)85088-9

Loras S, Monton JB, España FJ. Vapor-liquid equilibria for the binary systems of methylcyclohexane with 1-propanol, 2-propanol, 1-butanol and 2-butanol at 101.3 kPa. Journal of Chemical and Engineering Data. 1997; 42: 914–918. doi:10.1021/je970079w
[112] Britton EC, Nutting HS, Horsley LH. Vapor-liquid equilibrium diagrams of alcohol-ketone azeotropes as a function of pressure. Analytical Chemistry. 1947; 19: 601–602. doi:10.1021/ac60008a003

[113] Prabhu PS, Van Winkle M. Effect of polar components on the relative volatility of the binary system n-hexane-benzene. Journal of Chemical and Engineering Data. 1963; 8: 210–214. doi:10.1021/je60017a022

[114] Skaates JM, Kay WB. The phase relations of binary systems that form azeotropes: N-alkyl alcohol-benzene systems: Metanol through n-butanol. Chemical Engineering Science. 1964; 19: 431–444. doi:10.1016/0009-2509(64)85070-3

[115] Oracz P, Kolasinska G. Vapour-liquid equilibria-III. Total vapour pressure measurements for binary mixtures of metanol, etanol, 1-propanol and 1-butanol with benzene, toluene and p-xylene at 313.15 K. Fluid Phase Equilibria. 1987; 35(1–3): 253–278. doi:10.1016/0378-3812(87)80016-X

[116] Rhodes JM, Griffin TA, Lazzaroni MJ, Bhethanabotla VR, Campbell SW. Total pressure measurements for benzene with 1-propanol, 2-propanol, 1-pentanol, 3-pentanol, and 2-methyl-2-butanol at 313.15 K. Fluid Phase Equilibria. 2001; 179: 217–229. doi:10.1016/S0378-3812(00)00502-1

[117] Villamañán RM, Chamorro CR, Villamañán MA, Segovia JJ. Total pressure and excess Gibbs energy for the ternary mixture di-isopropyl ether + 1-propanol + benzene and its corresponding binary systems at 313.15 K. Fluid Phase Equilibria. 2006; 239: 183–187. doi:10.1016/j.fluid.2005.11.014

[118] Gupta V, Maken S, Kalra KC, Singh KC. Molar excess free energy of 1-propanol or 2-propanol + aromatic hydrocarbons at 298.15 K in terms of an association model with a Flory contribution term. Thermochimica Acta. 1996; 277: 187–198. doi:10.1016/0040-6031(95)02745-9

[119] Vrbka P, Rozbroj D, Vladimirov DA. Limiting activity coefficients in binary mixtures of 1-alkanols and toluene. Fluid Phase Equilibria. 2003; 209(2): 265–280. doi:10.1016/S0378-3812(03)00114-6

[120] Hwang I-C, Park S-J, Lee J-Y. Binary and ternary vapor-liquid equilibrium at 323.15 K and excess molar volumes at 298.15 K for the mixtures of propyl vinyl ether + 1-propanol + toluene. Journal of Chemical and Engineering Data. 2009; 54: 1041–1045. doi:10.1021/je800972b

[121] Vijayaraghavan SV, Deshpande PK, Kuloor NR. Isobaric vapor-liquid equilibrium of n-heptane-n-butanol system. Journal of Chemical and Engineering Data. 1966; 11: 147–149. doi:10.1021/je60029a004

[122] Vijayaraghavan SV, Deshpande PK, Kuloor NR. Vapor-liquid equilibrium data for the system n-heptane-butyl-alcohol at medium pressures. Journal of Chemical and Engineering Data. 1967; 12: 13–15. doi:10.1021/je60032a004
[123] Pividal KA, Sandler SI. Neighbor effects on the group contribution method: Infinite dilution activity coefficients of binary systems containing primary amines and alcohols. Journal of Chemical and Engineering Data. 1990; 35: 53–60. doi:10.1021/je00059a018

[124] Zielkiewicz J. (Vapor + liquid) equilibria in (heptane + propan-2-ol or butan-1-ol or 2-methylpropan-1-ol or 2-methylpropan-2-ol or pentan-1-ol) at the temperature 313.15 K. Journal of Chemical Thermodynamics. 1994; 26: 919–923. doi:10.1006/jcht.1994.1109

[125] Gmehling J, Boelts R. Azeotropic data for binary and ternary systems at moderate pressures. Journal of Chemical and Engineering Data. 1996; 41: 202–209. doi:10.1021/je950228f

[126] Powell JR, McHale MER, Kauppila AS-M, Acree WE, Flanders PH, Varanasi VG, Campbell SW. Prediction of anthracene solubility in alcohol + alkane solvent mixtures using binary alcohol + alkane VLE data. Comparison of Kretschmer-Wiebe and mobile order models. Fluid Phase Equilibria. 1997; 134: 185–200. doi:10.1016/S0378-3812(97)00039-3

[127] Prasad TEV, Satyakishore P, Ramserish GV, Prasad DHL. Boiling temperature measurements on the binary mixtures of n-heptane with some aliphatic alcohols. Journal of Chemical and Engineering Data. 2001; 46: 1266–1268. doi:10.1021/je010006j

[128] Mohsen-Nia M, Memarzadeh MR. Isobaric vapor-liquid equilibria of heptane + 1-butanol and heptane + 1-pentanol systems at (53.3 and 91.3) kPa. Journal of Chemical and Engineering Data. 2010; 55: 2140–2144. doi:10.1021/je9006629

[129] Belabbaci A, Villamañán RM, Negadi L, Martín MC, Ait Kaci A, Villamañán MA. Vapor-liquid equilibria of binary mixtures containing 1-butanol and hydrocarbons at 313.15 K. Journal of Chemical and Engineering Data. 2012; 57: 114–119. doi:10.1021/je200840e

[130] Hull A, Kronberg B, Stam JV, Golubkov I, Kristensson J. Vapor-liquid equilibrium of binary mixtures. 2. Ethanol + 2,2,4-trimethylpentane, 1-butanol + 2,2,4-trimethylpentane, and ethanol + o-xylene. Journal of Chemical and Engineering Data. 2006; 51: 2002–2008. doi:10.1021/je060005x

[131] Ghellai S, Belabbaci A, Villamañán RM, Martín MC, Villamañán MA, Negadi L. Vapour-liquid equilibria of binary and ternary mixtures containing 1-butanol, 2,2,4-trimethylpentane and 1-hexene at T = 313.15 K. Journal of Chemical Thermodynamics. 2013; 63: 164–168. doi:10.1016/j.jct.2013.04.003

[132] Ramalho RS, Delmas J. Isothermal and isobaric vapor-liquid equilibrium data and excess free energies by the total pressure method. Systems: 2,2,4-trimethylpentane-toluene, cyclohexane-1-butanol, and ethanol-n-heptane. Journal of Chemical and Engineering Data. 1968; 13: 161–164. doi:10.1021/je60037a005

[133] Thomas ER, Newman BA, Long TC, Wood DA, Eckert CA. Limiting activity coefficients of nonpolar and polar solutes in both volatile and nonvolatile solvents by gas chroma-
tography. Journal of Chemical and Engineering Data. 1982; 27: 399–405. doi:10.1021/je00030a010

[134] Trampe DM, Eckert CA. Limiting activity coefficients from an improved differential boiling point technique. Journal of Chemical and Engineering Data. 1990; 35: 156–162. doi:10.1021/je00060a018

[135] Prasad VTE, Naidu RP, Madhukiran D, Prasad DHL. Boiling temperature measurements on the binary mixtures of cyclohexane with some alcohols and chlorohydrocarbons. Journal of Chemical and Engineering Data. 2001; 46: 414–416. doi:10.1021/je000139p

[136] Gascón I, Martín S, Artigas H, López MC, Lafuente C. Isobaric vapour liquid equilibrium of binary and ternary mixtures containing cyclohexane, n-hexane, 1,3-dioloxane and 1-butanol at 40.0 and 101.3 kPa. Chemical Engineering Journal. 2002; 88: 1–9. doi:10.1016/S1385-8947(01)00258-3

[137] Allen BB, Lingo SP, Felsing WA. Total and partial pressures of binary solutions of the butyl alcohols in benzene at 25°C. Journal of Physical Chemistry. 1939; 43: 425–430. doi:10.1021/j150391a004

[138] Mann RS, Shemilt LW, Waldichuck M. Vapor-liquid equilibria at atm. pressure II. 1-butanol-benzene system. Journal of Chemical and Engineering Data. 1963; 8: 502–504. doi:10.1021/je60019a008

[139] Chen G, Wang Q, Ma Z-M, Yan X-H, Han S-J. Phase equilibria at superatmospheric pressures for systems containing halohydrocarbon, aromatic hydrocarbon, and alcohol. Journal of Chemical and Engineering Data. 1995; 40: 361–366. doi:10.1021/je00018a003

[140] Maken S, Park JJ, Bhardwaj U, Singh KC, Park J-W, Han SD, Deshwal BR. (Vapour + liquid) equilibria of (1-butanol + benzene, or toluene, or o-, or m-, or p-xylene) at T = 308.15 K. Journal of Chemical Thermodynamics. 2004; 36: 309–315. doi:10.1016/j.jct.2004.01.001

[141] Villamañán RM, Martín MC, Chamorro CR, Villamañán MA, Segovia JJ. Phase equilibrium properties of binary and ternary systems containing di-isopropyl ether + 1-butanol + benzene at 313.15 K. Journal of Chemical Thermodynamics. 2006; 38: 547–553. doi:10.1016/j.jct.2005.07.004

[142] Mann RS, Shemilt LW. Vapor-liquid equilibria at atm. pressure. 1-butanol-toluene system. Journal of Chemical and Engineering Data. 1963; 8: 189–190. doi:10.1021/je60017a013

[143] Darwish NA, Al-Khateib AA. Isobaric vapor-liquid equilibria of the system toluene + 1-butanol at 94.0, 70.5, and 56.4 kPa. Fluid Phase Equilibria. 1997; 132: 215–223. doi:10.1016/S0378-3812(97)00006-x

[144] Belabbaci A, Ghezouali C, Villamañán RM, Segovia JJ, Villamañán MA, Negadi L. Isothermal vapor liquid equilibrium and molar excess Gibbs energies of two ternary
systems containing either 1-butanol or 2-butanol + 1-hexene + methylbenzene at 313.15 K. Fluid Phase Equilibria. 2015; 386: 1–6. doi:10.1016/j.fluid.2014.11.010

[145] Janaszewski B, Oracz P, Goral M, Warycha S. Vapor-liquid equilibria: I. An apparatus for isothermal total vapor pressure measurements. Binary mixtures of ethanol and t-butanol with n-hexane, n-heptane and n-octane at 313.15 K. Fluid Phase Equilibria. 1982; 9: 295–310. doi:10.1016/0378-3812(82)80025-3

[146] Zong ZL, Yang XH, Zheng XY. Determination and correlation of vapor-liquid equilibria of alcohol solutions. Journal of Chemical Engineering of Japan. 1983; 16: 1–6. doi:10.1252/jcej.16.1

[147] Cheung Y-S, Chen Y-J, Ng CY, Chiu S-W, Li W-K. Combining theory with experiment: Assessment of the thermochemistry of SFₙ, SFₙ⁺, and and SFₙ⁻, n = 1-6. Journal of the American Chemical Society. 1995; 117: 9725–9733. doi:10.1021/ja00143a016

[148] Martínez-Soria V, Peña P, Montón JB. Vapor-liquid equilibria for the binary systems tert-butyl alcohol + toluene, + isoctane, and methylcyclohexane at 101.3 kPa. Journal of Chemical and Engineering Data. 1999; 44: 148–151. doi:10.1021/je980165b

[149] Prasad TEV, Sriram N, Raju AN, Prasad DHL. (Vapor + liquid) equilibria of binary mixtures formed by iso-octane with a variety of compounds at 95.8 kPa. Journal of Chemical Thermodynamics. 2006; 38: 119–122. doi:10.1016/j.jct.2005.04.006

[150] Tripathi RP, Krishna S, Gulati IB. Isobaric binary vapor-liquid equilibria in cyclohexane-tert-butyl alcohol and 2,4-dimethylpentane-tert-butyl alcohol systems. Journal of Chemical and Engineering Data. 1976; 21: 44–47. doi:10.1021/je00068a013

[151] Triday JO, Veas C. Vapor-liquid equilibria for the system cyclohexane-tert-butyl alcohol. Journal of Chemical and Engineering Data. 1985; 30: 171–173. doi:10.1021/je00040a011

[152] Young S, Fortey EC. LXXV. The properties of mixtures of the lower alcohols with benzene and with benzene and water. Journal of the Chemical Society, Transactions. 1902; 81: 739–752. doi:10.1039/CT9028100739

[153] Tongberg CO, Johnston F. Vapor-liquid equilibria for n-hexane-benzene mixtures. Industrial and Engineering Chemistry. 1933; 25: 733–735. doi:10.1021/ie50283a006

[154] Brown I, Fock W, Smith F. The thermodynamic properties of solutions of normal and branched alcohols in benzene and n-hexane. Journal of Chemical Thermodynamics. 1969; 1: 273–291. doi:10.1016/0021-9614(69)90047-0

[155] Govindaswamy S, Andiappan AN, Lakshmanan SM. Vapor-liquid equilibria of the binary and ternary systems containing n-hexane (1) + benzene (2) + tert-butyl alcohol (3) at 760 mmHg pressure. Journal of Chemical and Engineering Data. 1977; 22: 264–269. doi:10.1021/je60074a008
[156] Bhardwaj U, Singh KC, Maken S. Excess molar Gibbs energies of (2-methylpropan-2-ol + benzene, or toluene, or toluene, or o-, or m-, or p-xylene) at the temperature 308.15 K. Journal of Chemical Thermodynamics. 1998; 30: 109–115. doi:10.1006/jcht.1997.0281

[157] Fortier JL, Benson GC. Excess heat capacities of binary liquid mixtures determined with a Picker flow calorimeter. Journal of Chemical Thermodynamics. 1976; 8: 411–423. doi:10.1016/0021-9614(76)90061-6

[158] Kalinowska B, Jedlinska J, Stecki J, Woycicki W. Heat capacities of liquids in the temperature interval between 90 and 300 K and at atmospheric pressure II. Heat capacities and excess heat capacities of propan-1-ol+n-heptane and +n-hexane. Journal of Chemical Thermodynamics. 1981; 13: 357–366. doi:10.1016/0021-9614(81)90025-2

[159] Roux AH, Roux-Desgranges G, Grolier JPE. Excess molar heat capacities and enthalpies for 1-alkanol + N-alkane binary mixtures. New measurements and recommended data. Fluid Phase Equilibria. 1993; 89: 57–88. doi:10.1016/0378-3812(93)85045-N

[160] Torin-Ollarves GA, Segovia JJ, Martin MC, Villamañán MA. Thermodynamic characterization of the mixture (1-butanol + iso-octane): Densities, viscosities, and isobaric heat capacities at high pressures. Journal of Chemical Thermodynamics. 2012; 44: 75–83. doi:10.1016/j.jct.2011.08.012

[161] Cobos JC, Garcia I, Casanova C, Roux AH, Roux-Desgranges G, Grolier JPE. Excess heat capacities of 1-butanol + toluene from 298 to 368 K. Fluid Phase Equilibria. 1991; 69: 223–233. doi:10.1016/0378-3812(91)90035-6
