# Density, Viscosity, Refractive Index, and Speed of Sound in Binary Mixtures of 1-Chloronaphthalene with Benzene, Methylbenzene, 1,4-Dimethylbenzene, 1,3,5-Trimethylbenzene, and Methoxybenzene at (298.15, 303.15, and 308.15) K

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Experimental values of densities, viscosities, and refractive indices at 298.15, 303.15, and 308.15 K and while speed of sound at 298.15 K for the binary mixtures of 1-chloronaphthalene with benzene, methylbenzene, 1,4-dimethylbenzene, 1,3,5-trimethylbenzene, and methoxybenzene are presented over the entire mole fraction range. From these data, excess molar volume, deviations in viscosity, speed of sound, isentropic compressibility, and Lorenz−Lorentz molar refractivity have been calculated. These results are fitted to the Redlich−Kister type polynomial of the third degree to derive the binary coefficients. The standard deviations are also estimated for the calculated and experimental data points.

## Introduction

1-Chloronaphthalene (1-CNP) is a versatile organic liquid that finds applications as a raw material for dyes and as a wood preservative with fungicidal and insecticidal properties (Dressler, 1979). In the earlier literature, the binary mixtures containing 1-CNP have been studied with considerable interest because these mixtures exhibit varying molecular interactions in the presence of liquids such as alkanes, alkanols, and ketones (Bendiab et al., 1994; Grolier et al., 1981; Wilhelm et al., 1986; Costas et al., 1988; Comelli and Francesconi, 1992; Aminabhavi and Banerjee, 1997; Aminabhavi and Patil, 1998a,b). In continuation of our ongoing program of research, we now present the experimental data on density, $\rho$, refractive index, $n_D$, for the sodium D-line, and viscosity, $\eta$, at 298.15, 303.15, and 308.15 K and the speed of sound, $u$, at 298.15 K for the binary mixtures of 1-CNP with benzene, methylbenzene, 1,4-dimethylbenzene, 1,3,5-trimethylbenzene, and methoxybenzene. From these data, excess molar volume, $V^E$, deviations in the viscosity, $\Delta\eta$, speed of sound, $\Delta u$, and isentropic compressibility, $\Delta k_S$, have been calculated. To the best of our knowledge, none of these mixtures have been studied in the earlier literature. The results of $V^E$, $\Delta\eta$, $\Delta u$, $\Delta k_S$, and $\Delta R$ are fitted to the Redlich and Kister equation (1948) to derive the binary coefficients and estimate the standard errors, $\sigma$, between the experimentally calculated and the computed values.

## Experimental Section

***Materials.*** All the monocyclic aromatic liquid samples (purchased from s.d. fine Chemicals, Ltd., Mumbai, India) were used without further purification because their purities exceeded 99 mol % as tested by gas chromatography (HP 6890 series) using a flame ionization detector with a packed column (see Table 1). The purity of 1-CNP is only 90.06 mol % as determined by gas chromatography. The remaining 9.94 mol % consists of 2-chloronaphthalene (2-CNP), which is a solid. It is very difficult to separate these two isomers (Dressler, 1979). The thermophysical properties of mixtures containing 1-CNP and 2-CNP are expected to be similar, and hence in this paper we have reported the physical property data for a mixture of 1-CNP + 2-CNP at $x$(1-CNP) = 0.9006 with other components. In our earlier papers (Aminabhavi and Patil, 1998a,b) we reported incorrectly the mole fraction purity of 1-CNP as 0.98% when in fact the material was 0.90% 1-CNP + 0.099% 2-CNP. The properties of all the mixtures reported are not expected to be significantly different from mixtures of pure 1-CNP.

**Table 1. Comparison of Experimental Densities ($\rho$) and Refractive Indices ($n_D$) of Pure Liquids with the Literature Values at 298.15 K**

| | $\rho$/(g·cm$^{-3}$) | | $n_D$ | |
|---|---|---|---|---|
| liquid (mol % purity) | expt | lit. | expt | lit. |
| 1-chloronaphthalene (90.06)[a] | 1.1880 | 1.1881[b] | 1.6300 | 1.6303[c] |
| benzene (99.8) | 0.8728 | 0.837[d] | 1.4982 | 1.4978[e] |
| methylbenzene (99.7) | 0.8614 | 0.8622[d] | 1.4946 | 1.4941[f] |
| 1,4-dimethylbenzene (99.0) | 0.8566 | 0.8567[d] | 1.4939 | 1.4933[f] |
| 1,3,5-trimethylbenzene (99.0) | 0.8606 | 0.8611[f] | 1.4978 | 1.4968[f] |
| methoxybenzene (99.0) | 0.9892 | 0.9893[f] | 1.5154 | 1.5143[f] |

[a] Impurity is 2-chloronaphthalene. [b] Comelli and Francesconi (1992). [c] Marsh (1994). [d] Singh et al. (1994). [e] Tasic et al. (1995). [f] Riddick et al. (1986).

Experimental values of $\rho$ and $n_D$ of the pure liquids are compared in Table 1 at 298.15 K, and these values agree well with the published results. Mixtures were prepared by mass in specially designed glass stoppered bottles, and the properties were measured on the same day. An electronic Mettler balance, Model AE 240, with a precision of ±0.01 mg was used for the mass measurements. The error in mole fraction is around ±0.0002.

***Measurements.*** Densities of single liquids and their binary mixtures were measured using the pycnometer having a bulb volume of 15 cm$^3$ and a capillary bore with an internal diameter of 1 mm. Density values are accurate

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**Table 2. Experimental Values of Density ($\rho$), Refractive Index ($n_D$), Viscosity ($\eta$), and Speed of Sound ($u$) of the Binary Mixtures at Different Temperatures**

| $x_1$ | $\rho$/(g·cm$^{-3}$) | $n_D$ | $\eta$/(mPa·s) | $u$/(m·s$^{-1}$) | $x_1$ | $\rho$/(g·cm$^{-3}$) | $n_D$ | $\eta$/(mPa·s) | $u$/(m·s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1-Chloronaphthalene (1) + Benzene (2) | | | | | | | | | |
| 298.15 K | | | | | | | | | |
| 0.0000 | 0.8728 | 1.4982 | 0.552 | 1301 | 0.5982 | 1.0932 | 1.5942 | 1.475 | 1398 |
| 0.0989 | 0.9187 | 1.5200 | 0.655 | 1309 | 0.7022 | 1.1205 | 1.6038 | 1.731 | 1418 |
| 0.2022 | 0.9628 | 1.5434 | 0.792 | 1325 | 0.7973 | 1.1437 | 1.6134 | 2.022 | 1436 |
| 0.3275 | 1.0100 | 1.5606 | 0.960 | 1346 | 0.8976 | 1.1664 | 1.6217 | 2.380 | 1456 |
| 0.3981 | 1.0339 | 1.5696 | 1.078 | 1359 | 1.0000 | 1.1880 | 1.6300 | 2.783 | 1476 |
| 0.5035 | 1.0666 | 1.5846 | 1.294 | 1380 | | | | | |
| 303.15 K | | | | | | | | | |
| 0.0000 | 0.8678 | 1.4955 | 0.518 | | 0.5982 | 1.0888 | 1.5921 | 1.349 | |
| 0.0989 | 0.9139 | 1.5181 | 0.609 | | 0.7022 | 1.1161 | 1.6034 | 1.586 | |
| 0.2022 | 0.9581 | 1.5378 | 0.727 | | 0.7973 | 1.1392 | 1.6119 | 1.833 | |
| 0.3275 | 1.0048 | 1.5580 | 0.903 | | 0.8976 | 1.1618 | 1.6202 | 2.126 | |
| 0.3981 | 1.0291 | 1.5678 | 0.994 | | 1.0000 | 1.1835 | 1.6285 | 2.502 | |
| 0.5035 | 1.0620 | 1.5827 | 1.188 | | | | | | |
| 308.15 K | | | | | | | | | |
| 0.0000 | 0.8624 | 1.4927 | 0.493 | | 0.5982 | 1.0849 | 1.5881 | 1.242 | |
| 0.0989 | 0.9091 | 1.5146 | 0.571 | | 0.7022 | 1.1123 | 1.6006 | 1.452 | |
| 0.2022 | 0.9530 | 1.5366 | 0.679 | | 0.7973 | 1.1354 | 1.6102 | 1.669 | |
| 0.3275 | 1.0001 | 1.5560 | 0.843 | | 0.8976 | 1.1579 | 1.6185 | 1.928 | |
| 0.3981 | 1.0244 | 1.5651 | 0.922 | | 1.0000 | 1.1793 | 1.6266 | 2.259 | |
| 0.5035 | 1.0577 | 1.5780 | 1.098 | | | | | | |
| 1-Chloronaphthalene (1) + Methylbenzene (2) | | | | | | | | | |
| 298.15 K | | | | | | | | | |
| 0.0000 | 0.8614 | 1.4946 | 0.506 | 1310 | 0.5970 | 1.0781 | 1.5860 | 1.357 | 1400 |
| 0.0995 | 0.9036 | 1.5124 | 0.596 | 1312 | 0.6945 | 1.1068 | 1.5978 | 1.614 | 1420 |
| 0.1995 | 0.9426 | 1.5300 | 0.711 | 1327 | 0.7972 | 1.1356 | 1.6090 | 1.941 | 1440 |
| 0.3037 | 0.9811 | 1.5449 | 0.838 | 1344 | 0.8918 | 1.1612 | 1.6196 | 2.321 | 1458 |
| 0.3973 | 1.0140 | 1.5585 | 0.979 | 1360 | 1.0000 | 1.1880 | 1.6300 | 2.783 | 1476 |
| 0.4962 | 1.0466 | 1.5722 | 1.160 | 1380 | | | | | |
| 303.15 K | | | | | | | | | |
| 0.0000 | 0.8569 | 1.4920 | 0.479 | | 0.5970 | 1.0742 | 1.5848 | 1.249 | |
| 0.0995 | 0.8991 | 1.5106 | 0.561 | | 0.6945 | 1.1030 | 1.5961 | 1.484 | |
| 0.1995 | 0.9384 | 1.5275 | 0.665 | | 0.7972 | 1.1318 | 1.6078 | 1.764 | |
| 0.3037 | 0.9768 | 1.5423 | 0.788 | | 0.8918 | 1.1573 | 1.6187 | 2.091 | |
| 0.3973 | 1.0097 | 1.5576 | 0.910 | | 1.0000 | 1.1835 | 1.6285 | 2.502 | |
| 0.4962 | 1.0425 | 1.5718 | 1.074 | | | | | | |
| 308.15 K | | | | | | | | | |
| 0.0000 | 0.8523 | 1.4901 | 0.453 | | 0.5970 | 1.0697 | 1.5827 | 1.153 | |
| 0.0995 | 0.8945 | 1.5086 | 0.529 | | 0.6945 | 1.0985 | 1.5948 | 1.361 | |
| 0.1995 | 0.9338 | 1.5255 | 0.626 | | 0.7972 | 1.1274 | 1.6064 | 1.616 | |
| 0.3037 | 0.9723 | 1.5412 | 0.727 | | 0.8918 | 1.1530 | 1.6170 | 1.880 | |
| 0.3973 | 1.0052 | 1.5560 | 0.849 | | 1.0000 | 1.1793 | 1.6266 | 2.259 | |
| 0.4962 | 1.0380 | 1.5700 | 0.995 | | | | | | |
| 1-Chloronaphthalene (1) + 1,4-Dimethylbenzene (2) | | | | | | | | | |
| 298.15 K | | | | | | | | | |
| 0.0000 | 0.8566 | 1.4939 | 0.551 | 1311 | 0.5970 | 1.0649 | 1.5810 | 1.360 | 1410 |
| 0.0966 | 0.8926 | 1.5092 | 0.635 | 1328 | 0.7003 | 1.0978 | 1.5949 | 1.614 | 1424 |
| 0.1961 | 0.9288 | 1.5246 | 0.737 | 1346 | 0.7974 | 1.1277 | 1.6066 | 1.899 | 1440 |
| 0.2964 | 0.9644 | 1.5395 | 0.847 | 1363 | 0.8991 | 1.1585 | 1.6192 | 2.294 | 1458 |
| 0.3991 | 0.9998 | 1.5536 | 1.002 | 1380 | 1.0000 | 1.1880 | 1.6300 | 2.783 | 1476 |
| 0.4981 | 1.0328 | 1.5672 | 1.160 | 1395 | | | | | |
| 303.15 K | | | | | | | | | |
| 0.0000 | 0.8522 | 1.4917 | 0.519 | | 0.5970 | 1.0608 | 1.5792 | 1.250 | |
| 0.0966 | 0.8883 | 1.5072 | 0.596 | | 0.7003 | 1.0934 | 1.5932 | 1.475 | |
| 0.1961 | 0.9245 | 1.5224 | 0.687 | | 0.7974 | 1.1236 | 1.6048 | 1.723 | |
| 0.2964 | 0.9602 | 1.5377 | 0.789 | | 0.8991 | 1.1543 | 1.6172 | 2.072 | |
| 0.3991 | 0.9955 | 1.5524 | 0.926 | | 1.0000 | 1.1835 | 1.6285 | 2.502 | |
| 0.4981 | 1.0286 | 1.5666 | 1.074 | | | | | | |
| 308.15 K | | | | | | | | | |
| 0.0000 | 0.8480 | 1.4892 | 0.490 | | 0.5970 | 1.0565 | 1.5770 | 1.158 | |
| 0.0966 | 0.8841 | 1.5056 | 0.562 | | 0.7003 | 1.0894 | 1.5909 | 1.357 | |
| 0.1961 | 0.9202 | 1.5210 | 0.644 | | 0.7974 | 1.1194 | 1.6035 | 1.576 | |
| 0.2964 | 0.9558 | 1.5358 | 0.738 | | 0.8991 | 1.1502 | 1.6157 | 1.882 | |
| 0.3991 | 0.9912 | 1.5502 | 0.863 | | 1.0000 | 1.1793 | 1.6266 | 2.259 | |
| 0.4981 | 1.0242 | 1.5648 | 0.997 | | | | | | |

**Table 2. Continued**

| $x_1$ | $\rho$/(g·cm$^{-3}$) | $n_D$ | $\eta$/(mPa·s) | $u$/(m·s$^{-1}$) | $x_1$ | $\rho$/(g·cm$^{-3}$) | $n_D$ | $\eta$/(mPa·s) | $u$/(m·s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1-Chloronaphthalene (1) + 1,3,5-Trimethylbenzene (2) | | | | | | | | | |
| 298.15 K | | | | | | | | | |
| 0.0000 | 0.8606 | 1.4978 | 0.600 | 1340 | 0.6008 | 1.0592 | 1.5795 | 1.476 | 1416 |
| 0.0983 | 0.8931 | 1.5114 | 0.688 | 1350 | 0.6999 | 1.0915 | 1.5923 | 1.706 | 1430 |
| 0.2041 | 0.9287 | 1.5257 | 0.807 | 1362 | 0.8017 | 1.1246 | 1.6054 | 2.019 | 1445 |
| 0.2992 | 0.9602 | 1.5388 | 0.929 | 1374 | 0.9016 | 1.1562 | 1.6183 | 2.376 | 1460 |
| 0.3988 | 0.9931 | 1.5522 | 1.086 | 1387 | 1.0000 | 1.1880 | 1.6300 | 2.783 | 1476 |
| 0.4984 | 1.0257 | 1.5656 | 1.251 | 1401 | | | | | |
| 303.15 K | | | | | | | | | |
| 0.0000 | 0.8567 | 1.4959 | 0.564 | | 0.6008 | 1.0549 | 1.5776 | 1.346 | |
| 0.0983 | 0.8892 | 1.5098 | 0.644 | | 0.6999 | 1.0873 | 1.5908 | 1.551 | |
| 0.2041 | 0.9249 | 1.5240 | 0.753 | | 0.8017 | 1.1199 | 1.6039 | 1.826 | |
| 0.2992 | 0.9560 | 1.5370 | 0.863 | | 0.9016 | 1.1524 | 1.6166 | 2.138 | |
| 0.3988 | 0.9887 | 1.5505 | 1.003 | | 1.0000 | 1.1835 | 1.6285 | 2.502 | |
| 0.4984 | 1.0216 | 1.5643 | 1.150 | | | | | | |
| 308.15 K | | | | | | | | | |
| 0.0000 | 0.8514 | 1.4943 | 0.530 | | 0.6008 | 1.0505 | 1.5758 | 1.239 | |
| 0.0983 | 0.8852 | 1.5080 | 0.605 | | 0.6999 | 1.0830 | 1.5891 | 1.419 | |
| 0.2041 | 0.9198 | 1.5230 | 0.703 | | 0.8017 | 1.1143 | 1.6022 | 1.661 | |
| 0.2992 | 0.9512 | 1.5356 | 0.803 | | 0.9016 | 1.1465 | 1.6096 | 1.935 | |
| 0.3988 | 0.9840 | 1.5485 | 0.927 | | 1.0000 | 1.1793 | 1.6266 | 2.259 | |
| 0.4984 | 1.0171 | 1.5623 | 1.062 | | | | | | |
| 1-Chloronaphthalene (1) + Methoxybenzene (2) | | | | | | | | | |
| 298.15 K | | | | | | | | | |
| 0.0000 | 0.9892 | 1.5154 | 0.917 | 1416 | 0.5959 | 1.1187 | 1.5914 | 1.720 | 1445 |
| 0.0985 | 1.0132 | 1.5299 | 1.025 | 1420 | 0.6962 | 1.1370 | 1.6019 | 1.896 | 1450 |
| 0.1969 | 1.0361 | 1.5432 | 1.116 | 1425 | 0.7827 | 1.1522 | 1.6106 | 2.096 | 1456 |
| 0.2977 | 1.0585 | 1.5568 | 1.262 | 1430 | 0.8985 | 1.1717 | 1.6218 | 2.425 | 1466 |
| 0.3974 | 1.0796 | 1.5687 | 1.409 | 1435 | 1.0000 | 1.1880 | 1.6300 | 2.783 | 1476 |
| 0.4997 | 1.1002 | 1.5806 | 1.568 | 1440 | | | | | |
| 303.15 K | | | | | | | | | |
| 0.0000 | 0.9846 | 1.5134 | 0.848 | | 0.5959 | 1.1143 | 1.5902 | 1.566 | |
| 0.0985 | 1.0087 | 1.5281 | 0.946 | | 0.6962 | 1.1326 | 1.6000 | 1.724 | |
| 0.1969 | 1.0316 | 1.5415 | 1.045 | | 0.7827 | 1.1479 | 1.6093 | 1.891 | |
| 0.2977 | 1.0540 | 1.5552 | 1.159 | | 0.8985 | 1.1673 | 1.6202 | 2.180 | |
| 0.3974 | 1.0751 | 1.5672 | 1.291 | | 1.0000 | 1.1835 | 1.6285 | 2.502 | |
| 0.4997 | 1.0959 | 1.5790 | 1.430 | | | | | | |
| 308.15 K | | | | | | | | | |
| 0.0000 | 0.9797 | 1.5117 | 0.788 | | 0.5959 | 1.1099 | 1.5882 | 1.431 | |
| 0.0985 | 1.0039 | 1.5268 | 0.878 | | 0.6962 | 1.1283 | 1.5986 | 1.570 | |
| 0.1969 | 1.0269 | 1.5404 | 0.966 | | 0.7827 | 1.1435 | 1.6080 | 1.717 | |
| 0.2977 | 1.0495 | 1.5534 | 1.069 | | 0.8985 | 1.1631 | 1.6188 | 1.973 | |
| 0.3974 | 1.0707 | 1.5657 | 1.185 | | 1.0000 | 1.1793 | 1.6266 | 2.259 | |
| 0.4997 | 1.0914 | 1.5774 | 1.312 | | | | | | |

to ±0.0002 g·cm$^{-3}$.

Refractive indices for the sodium D-line were measured using a thermostatically controlled Abbe Refractometer (Atago 3T). A minimum of three independent readings was taken for each composition. The refractive index values are accurate to ±0.0001 units. Calibration procedures of the pycnometer and refractometer are the same as those given earlier (Aminabhavi et al., 1993; Aminabhavi and Bindu, 1994; Aralaguppi et al., 1991).

Viscosities were measured using a Schott-Gerate viscometer, Model AVS 350. The unit performs automated measurements of the flow-through times in capillary viscometers. Efflux times were determined on a digital display at an accuracy of ±0.01 s. An AVS/S measuring stand was used for optoelectronic sensing of the meniscus. The LED in the upper part of the measuring stand generates light in the near-infrared range which is transmitted through a glass fiber cable to the measuring levels. The light beam passes through the viscometer and reaches the input end of another light guide cable on the other side which conducts light to a receiver in the upper part of the measuring stand. When the liquid meniscus passes through the measuring level, the light beam is darkened briefly by the optical lens effect of the meniscus and thereafter intensified for a brief period. This fluctuation of the light beam produces a measuring signal which can be evaluated precisely.

The temperature of the bath (Schott-Gerate, Model CT 050/2) was maintained constant within ±0.01 K. Approximately, a 5 cm$^3$ volume of the liquid was taken in the viscometer. The liquid was allowed to equilibrate to the desired bath temperature ranging from 7 to 10 min, depending upon the viscosity of the liquid. The viscosity of the liquid/mixture was calculated using

$$\eta = tk\rho \qquad (1)$$

where $k$ is the viscometer constant (0.010 35 mm$^2$/s$^2$), $\rho$ is the density of the liquid, and $t$ is the efflux time in seconds. The viscometer constant, $k$, was determined by using comparative measurements with the reference viscometers, of which the constants were determined from the Physikalisch-Technischen Bundesanstalt, Braunschweig, Germany. The instrument constant is valid for liquids with a surface tension of 20−30 mN/m and an acceleration of the fall of 9.8125 m/s$^2$. The estimated error in the viscosity measurement is ±0.001 mPa·s.

The speed of sound values were measured using a variable path single crystal interferometer (Mittal Enter-

prises, Model M-84, New Delhi, India) as described earlier by Aralaguppi et al. (1991). The interferometer was used at a frequency of 4 kHz and was calibrated using water and benzene. The speed of sound values are accurate to ±2 m·s$^{-1}$. From the speed of sound data, isentropic compressibilities, $k_S$, have been calculated as follows: $k_S = 1/u^2\rho$. This relation was used earlier by other investigators (Aralaguppi et al., 1991; Afanasyev and Zyatkova, 1996).

In all the property measurements except viscosity, an INSREF Model 016 AP thermostat was used and the desired temperature in this thermostat was controlled to ±0.01 K. The results of $\rho$, $\eta$, $n_D$, and $u$ compiled in Table 2 represent the averages of three independent measurements for each composition of the mixture.

The Julabo immersion cooler (FT 200), Julabo Labortechnik Gmbh, was used to cool the water bath. The unit was installed at the intake of a heating circulator to draw the heat away from the circulating liquid. The immersion probe was connected to the instrument with a flexible and insulated tube. To prevent the immersion of the probe from icing, it was completely immersed with the liquid surface of the bath.

## Results and Discussion

From the results of densities given in Table 2, excess molar volumes have been calculated as

$$V^E = V_m - V_1x_1 - V_2x_2 \quad (2)$$

where $V_m$ is the mixture molar volume; $V_1$ and $V_2$ are the molar volumes of components 1 and 2 of the mixture; and $x_i$ represents the mole fraction of the $i$th component in the mixture. From the values of $\eta$, $n_D$, $u$, and $k_S$ of the individual components as well as of the binary mixtures, $\Delta\eta$, $\Delta R$, $\Delta u$, and $\Delta k_S$ have been calculated from

$$\Delta Y = Y_m - Y_1C_1 - Y_2C_2 \quad (3)$$

For calculating $\Delta\eta$ and $\Delta u$, we have used mole fraction $x_i$ for $C_i$. Similarly, following the conventional practice in the literature (Aralaguppi et al., 1991), to compute $\Delta R$ and $\Delta k_S$, the volume fraction, $\phi_i$ [$=x_iV_i/\sum_i x_iV_i$] was used.

Each set of functions computed from eqs 2 and 3 have been fit to the Redlich and Kister (1948) polynomial equation,

$$V^E(\text{or } \Delta Y) = C_1C_2\sum_{j=1}^{k=3} A_{j-1}(C_2 - C_1)^{j-1} \quad (4)$$

to estimate the parameter values $A_0$, $A_1$, and $A_2$ by the method of least squares using Marquardt algorithm (1963). It was found that the best fits were obtained for the solution of eq 4 with only three adjustable parameters for all of the functions.

The standard deviations, $\sigma$, between the experimental (eq 4) and the computed quantities (eqs 2 and 3) have been calculated using

$$\sigma = \left[\sum (V^E_{calc}(\text{or } \Delta Y_{calc}) - V^E_{obs}(\text{or } \Delta Y_{obs}))^2/(n - m)\right]^{1/2} \quad (5)$$

where $n$ represents the number of data points and $m$ the number of coefficients. The fitted parameter values along with the standard deviations are presented in Table 3. Smoothed curves of the various quantities, viz., $V^E$, $\Delta\eta$, $\Delta R$, $\Delta u$, and $\Delta k_S$, vs mixture compositions, presented respectively in Figures 1−5, have been calculated from eq 4, while the points represent those calculated from eqs 2 and 3.

**Table 3. Estimated Parameters of Various Functions for the Binary Mixtures**

| function | temp/K | $A_0$ | $A_1$ | $A_2$ | $\sigma$ |
|---|---|---|---|---|---|
| 1-Chloronaphthalene (1) + Benzene (2) | | | | | |
| $V^E/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −0.921 | −0.683 | 0.384 | 0.030 |
| | 303.15 | −1.002 | −0.694 | 0.386 | 0.021 |
| | 308.15 | −1.281 | −0.433 | 0.122 | 0.009 |
| $\Delta R/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −8.102 | −2.405 | −0.221 | 0.060 |
| | 303.15 | −8.166 | −1.940 | −0.181 | 0.026 |
| | 308.15 | −8.317 | −2.427 | 0.025 | 0.051 |
| $\Delta\eta$/(mPa·s) | 298.15 | −1.593 | 0.478 | −0.081 | 0.011 |
| | 303.15 | −1.351 | 0.421 | −0.243 | 0.008 |
| | 308.15 | −1.165 | 0.345 | −0.265 | 0.007 |
| $\Delta u$/(m·s$^{-1}$) | 298.15 | −37.8 | −40.7 | −36.7 | 0.568 |
| $\Delta k_S$/(TPa$^{-1}$) | 298.15 | −29.61 | −19.04 | 23.26 | 0.448 |
| 1-Chloronaphthalene (1) + Methylbenzene (2) | | | | | |
| $V^E/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −1.404 | −0.330 | −0.567 | 0.024 |
| | 303.15 | −1.651 | −0.058 | −0.912 | 0.022 |
| | 308.15 | −1.653 | −0.063 | −1.001 | 0.024 |
| $\Delta R/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −3.886 | −0.085 | −0.130 | 0.025 |
| | 303.15 | −3.717 | −0.344 | 0.018 | 0.034 |
| | 308.15 | −3.607 | −0.271 | 0.069 | 0.019 |
| $\Delta\eta$/(mPa·s) | 298.15 | −1.953 | 0.627 | 0.031 | 0.011 |
| | 303.15 | −1.671 | 0.537 | −0.018 | 0.008 |
| | 308.15 | −1.443 | 0.457 | −0.090 | 0.006 |
| $\Delta u$/(m·s$^{-1}$) | 298.15 | −48.3 | −77.3 | −35.9 | 1.371 |
| $\Delta k_S$/(TPa$^{-1}$) | 298.15 | −48.6 | −50.4 | 28.68 | 1.055 |
| 1-Chloronaphthalene (1) + 1,4-Dimethylbenzene (2) | | | | | |
| $V^E/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −1.467 | −0.308 | 0.025 | 0.013 |
| | 303.15 | −1.650 | −0.272 | −0.140 | 0.013 |
| | 308.15 | −1.683 | −0.183 | −0.308 | 0.014 |
| $\Delta R/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −0.711 | 0.185 | 0.621 | 0.017 |
| | 303.15 | −0.617 | −0.136 | 0.618 | 0.046 |
| | 308.15 | −0.534 | −0.125 | 0.612 | 0.024 |
| $\Delta\eta$/(mPa·s) | 298.15 | −2.005 | 0.854 | −0.352 | 0.005 |
| | 303.15 | −1.737 | 0.738 | −0.336 | 0.005 |
| | 308.15 | −1.497 | 0.618 | −0.296 | 0.005 |
| $\Delta u$/(m·s$^{-1}$) | 298.15 | 6.8 | 27.1 | −17.6 | 0.668 |
| $\Delta k_S$/(TPa$^{-1}$) | 298.15 | −116.22 | 38.93 | 8.18 | 0.455 |
| 1-Chloronaphthalene (1) + 1,3,5-Trimethylbenzene (2) | | | | | |
| $V^E/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −2.001 | −0.201 | 0.260 | 0.023 |
| | 303.15 | −1.986 | −0.202 | −0.150 | 0.029 |
| | 308.15 | −2.272 | −1.078 | 0.557 | 0.087 |
| $\Delta R/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | 0.633 | 0.212 | 0.219 | 0.014 |
| | 303.15 | 0.685 | 0.156 | 0.104 | 0.017 |
| | 308.15 | 0.747 | −0.110 | −0.938 | 0.102 |
| $\Delta\eta$/(mPa·s) | 298.15 | −1.730 | 0.525 | −0.125 | 0.007 |
| | 303.15 | −1.506 | 0.483 | −0.147 | 0.005 |
| | 308.15 | −1.307 | 0.419 | −0.146 | 0.004 |
| $\Delta u$/(m·s$^{-1}$) | 298.15 | −26.7 | −8.7 | −10.5 | 0.249 |
| $\Delta k_S$/(TPa$^{-1}$) | 298.15 | −87.5 | 6.64 | 8.12 | 0.152 |
| 1-Chloronaphthalene (1) + Methoxybenzene (2) | | | | | |
| $V^E/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −0.236 | 0.052 | 0.187 | 0.002 |
| | 303.15 | −0.315 | 0.086 | 0.158 | 0.006 |
| | 308.15 | −0.411 | 0.035 | 0.170 | 0.007 |
| $\Delta R/10^{-6}$ (m$^3$·mol$^{-1}$) | 298.15 | −2.959 | −0.222 | 0.345 | 0.015 |
| | 303.15 | −2.926 | −0.383 | 0.173 | 0.040 |
| | 308.15 | −2.894 | −0.255 | 0.782 | 0.016 |
| $\Delta\eta$/(mPa·s) | 298.15 | −1.156 | 0.590 | −0.489 | 0.010 |
| | 303.15 | −0.996 | 0.577 | −0.428 | 0.005 |
| | 308.15 | −0.867 | 0.521 | −0.384 | 0.005 |
| $\Delta u$/(m·s$^{-1}$) | 298.15 | −24.0 | 18.7 | −14.8 | 0.274 |
| $\Delta k_S$/(TPa$^{-1}$) | 298.15 | −3.15 | 12.76 | 12.46 | 0.123 |

The results of $V^E$ vs $x_1$ for all of the binary mixtures at 298.15 K are presented in Figure 1. It is observed that, for all of the mixtures, the values of $V^E$ are negative over the entire range of mixture composition and these values follow the sequence methoxybenzene > benzene > methylbenzene > 1,4-dimethylbenzene > 1,3,5-trimethylbenzene, showing a clear-cut dependence on the size of the monocyclic aromatic molecules. This proves that $V^E$ decreases with increasing methyl group substitution on benzene. For mixtures of 1-chloronaphthalene + methylbenzene, or +

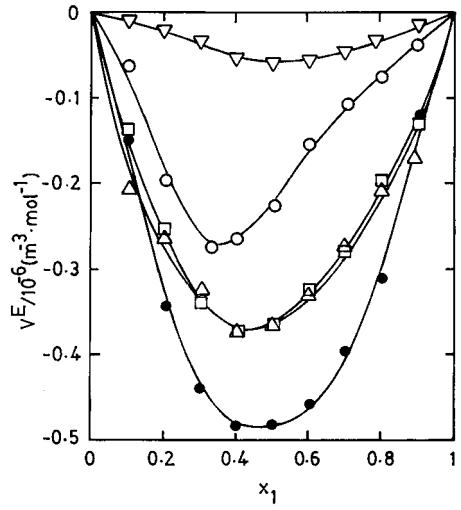


**Figure 1.** Excess molar volume vs mole fraction of 1-chloronaphthalene with (○) benzene, (△) methylbenzene, (□) 1,4-dimethylbenzene, (●) 1,3,5-trimethylbenzene, and (▽) methoxybenzene at 298.15 K.

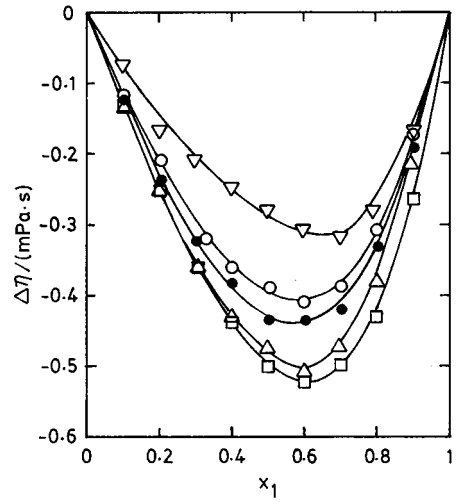


**Figure 2.** Deviation in viscosity vs mole fraction of binary mixtures of 1-chloronaphthalene at 298.15 K. Symbols are the same as those given in Figure 1.

1,4-dimethylbenzene, the $V^E$ vs $x_1$ curves vary almost identically.

The results of $\Delta\eta$ vs $x_1$ for all of the binary mixtures are presented at 298.15 K in Figure 2. The variation of $\Delta\eta$ follows the sequence methoxybenzene > benzene > 1,3,5-trimethylbenzene > methylbenzene > 1,4-dimethylbenzene, indicating that $\Delta\eta$ values do not show any regular trend with the size of the second component in the binary mixtures considered.

The results of $\Delta u$ vs $x_1$ are presented in Figure 3. The negative $\Delta u$ values are observed for 1-chloronaphthalene with benzene, methylbenzene, 1,3,5-trimethylbenzene, or methoxybenzene. However, in the case of 1-chloronaphthalene + 1,4-dimethylbenzene, the $\Delta u$ values vary sigmoidally with the mole fraction of the mixture.

The results of $\Delta k_S$ vs $\phi_1$ at 298.15 K are presented in Figure 4. We find that large negative $\Delta k_S$ values are observed for the mixtures of 1-CNP + 1,4-dimethylbenzene. However, comparatively for 1-CNP + 1,3,5-trimethylbenzene, the $\Delta k_S$ values are slightly larger indicating lesser specific interactions. On the other hand, in the case of mixtures of 1-CNP + methylbenzene, the $\Delta k_S$ vs $\phi_1$ curve shows a sigmoidal trend. Similarly, for 1-CNP + methoxybenzene, the $\Delta k_S$ vs $\phi_1$ curve shows a sigmoidal trend and the values vary from negative to positive.

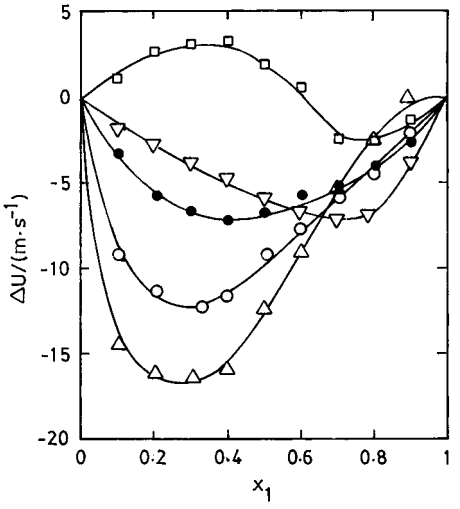


**Figure 3.** Deviation in speed of sound vs mole fraction of binary mixtures of 1-chloronaphthalene at 298.15 K. Symbols are the same as those given in Figure 1.

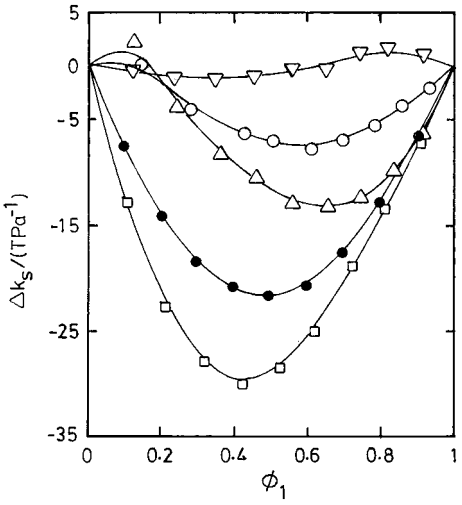


**Figure 4.** Deviation in isentropic compressibility vs volume fraction of binary mixtures of 1-chloronaphthalene at 298.15 K. Symbols are the same as those given in Figure 1.

The results of $\Delta R$ vs $\phi_1$ presented at 298.15 K in Figure 5 vary according to the sequence 1,3,5-trimethylbenzene > 1,4-dimethylbenzene > methoxybenzene > methylbenzene > benzene, a trend that is almost opposite to the behavior of $V^E$ vs $x_1$ curves. Except for 1-CNP + 1,3,5-trimethylbenzene, for all the other mixtures, the $\Delta R$ values are negative.

With regard to the temperature dependence of $V^E$, we find that the $V^E$ values decrease slightly with increasing temperature. On the other hand, the $\Delta\eta$ values show an increase with increasing temperature. However, the results of $\Delta R$ do not show much variations with temperature. To avoid overcrowding of the plots, we have not displayed these curves.

In conclusion, the present database on the binary mixtures of 1-chloronaphthalene with aromatics is not available in the earlier literature. However, all the physical property data were obtained at a purity of 90.06 mol % 1-chloronaphthalene as it was not possible to obtain any better purity and the impurity was only 2-chloronaphthalene (solid) whose properties are almost identical to 1-chloronaphthalene.

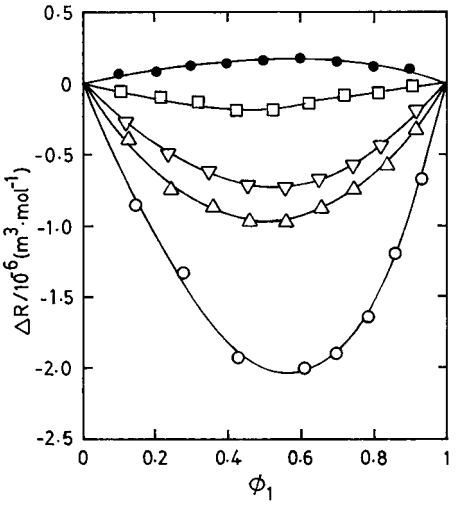


**Figure 5.** Deviation in molar refraction vs volume fraction of binary mixtures of 1-chloronaphthalene at 298.15 K. Symbols are the same as those given in Figure 1.

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