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# Study of Excess Volumetric and Thermodynamic Properties and Viscosity Modeling for Binary Liquid Mixtures of Isopropyl Benzene (cumene) with Aromatic Hydrocarbons at Temperature 298.15 K and Under Atmospheric Pressure

**Dhirendra Kumar Sharma**
Department of Chemistry, Institute of Basic Science,
Bundelkhand University, Jhansi (U.P), India

**Chandra Pal Prajapati**
Research Scholar, Department of Chemistry,
Institute of Basic Science, Bundelkhand University, Jhansi (U.P), India

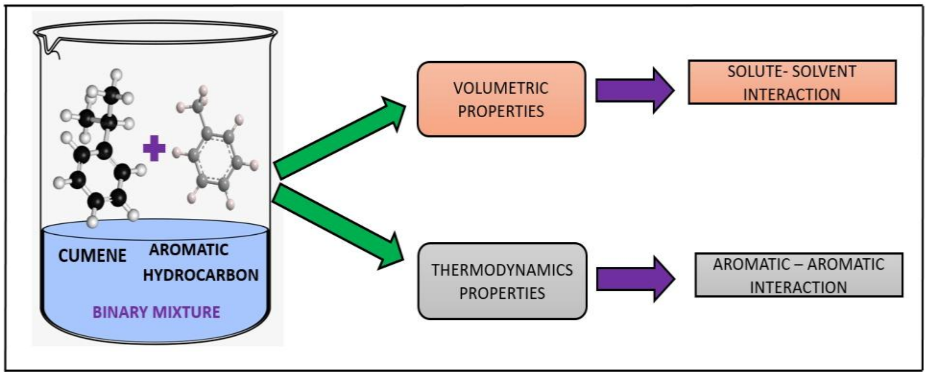
**Suneel Kumar**
Research Scholar, Department of Chemistry,
Institute of Basic Science, Bundelkhand University, Jhansi (U.P), India

## ABSTRACT

**The present discussion embodies the studies on binary mixtures containing isopropyl benzene (cumene) + ethyl benzene, isopropyl benzene (cumene) + toluene, isopropyl benzene (cumene) + mesitylene, isopropyl benzene (cumene) + *n*-propyl benzene, isopropyl benzene (cumene) + *tert*-butyl benzene, and isopropyl benzene (cumene) + biphenyl at the 298.15 K. For this purpose, the density, viscosity and speed of sound for pure liquids and their binary mixtures were measured within the temperature range 298.15K. Various excess and deviation parameters have been calculated using the measured properties. These properties provide valuable insight into molecular interactions and help predict the behaviour of complex chemical systems. Excess and deviation parameters were fitted to the Redlich–Kister polynomial.**

**Keywords:** Density, viscosity, speed of sound, excess properties, excess free volume, excess internal pressure, Cumene, binary systems, aromatic hydrocarbon.

## GRAPHICAL ABSTRACT



## INTRODUCTION

Thermodynamic studies of binary solvent systems remain fundamentally important in chemical engineering and industrial chemistry. Rigorous data on properties like density, speed of sound, and viscosity are essential for understanding intermolecular interactions, optimizing process design, and developing efficient separation techniques or solvent formulations [1]. The comprehensive study of binary liquid mixtures offers valuable insights into their behavior, which is essential for both a fundamental scientific understanding and practical engineering applications. In summary, the study of thermodynamic and acoustical properties plays a crucial role in unraveling the physical behavior and molecular interactions in both pure liquids, [2−6] binary liquid mixtures, [7-8] and electrolytic solutions. By examining the excess functions from ideality, researchers can gain insights into the nature and strength of molecular interactions in the binary mixtures. The volumetric and thermodynamic properties are very important for obtaining the fundamental data of various molecular liquids mixtures from different classes of compounds and for understanding the behaviour of interactions occurred between the components of these mixtures. These data are useful in chemical and petrochemical engineering designs with diverse applications: for phase separation processes and waste materials recycling, for surface facilities production operations and pipeline systems, etc., as well as in solutions theory and molecular thermodynamics for confirmation and development of theoretical and empirical models of pure fluids and mixtures. ]The strength of the chemical interactions between molecules in a binary mixture is indeed reflected in the fluctuation in the values of the excess parameters. These interactions can manifest through phenomena such as hydrogen bonding, solvation, self association, or other types of molecular recognition as a function of the composition, the molecular sizes, and the shapes of the components and the temperature. A number of studies have been conducted by researchers over the years on mixtures involving isopropyl benzene (cumene) + ethyl benzene, isopropyl benzene (cumene) + toluene, isopropyl benzene (cumene) + mesitylene, isopropyl benzene (cumene) + *n*-propyl benzene, isopropyl benzene (cumene) + *tert*-butyl benzene, and isopropyl benzene (cumene) + biphenyl. Thermophysical and in particular volumetric properties of aqueous mixtures of diols have been measured by various authors since some time ago [9–11]. The thermo physical properties such as the densities, speeds of sound, kinematic andv/or dynamic viscosities and the refractive indices, as well as their related magnitudes (the excess/deviation thermodynamic quantities and volumetric/apparent molar quantities) are largely revealed in open literature. In recent years the studies of the thermo physical properties and thermodynamic behavior of n-alkane with long chain, both pure and in mixture with different organic compounds, have received a considerable interest. The experimental values of sound velocity (u), density (ρ) and viscosity (η) are useful in evaluating thermodynamic properties such as enthalpy (H), free volume ($V_f$), internal pressure ($P_i$) and several excess parameters which will be very much useful in concerning the nature of intermolecular forces between the component molecules. Excess properties defined as deviations from ideal-solution behaviour are particularly valuable for verifying and developing theoretical models of dissolution and molecular interactions [12]. Excess properties quantify the extent of non-ideality in liquid mixtures and arise from molecular association or other specific intermolecular interactions. A variety of forces may act between unlike molecules, including dispersion forces, charge-transfer interactions, hydrogen bonding, and dipole–dipole or dipole–induced-dipole interactions. In many systems, more than one type of interaction operates simultaneously. Dispersion forces present in all mixtures generally contribute positively to excess values, whereas charge-transfer interactions, dipole–

induced-dipole interactions, dipole–dipole interactions, and hydrogen bonding typically contribute negatively. The measurement of internal pressure is essential for understanding the thermodynamic behaviour of liquids. Internal pressure represents the net cohesive force within a liquid, arising from the balance between intermolecular attractive and repulsive forces. This cohesive nature generates an intrinsic pressure that strongly influences the liquid's structural and interactional characteristics. Consequently, internal pressure provides valuable insight into solubility behaviour, as dissolved solutes experience the intrinsic pressure of the surrounding medium. The interactions between solutes and solvent molecules may involve hydrogen bonding, charge-transfer interactions, Coulombic forces, or van der Waals interactions, all of which contribute to the overall cohesiveness and stability of the liquid system.

## EXPERIMENTAL PROCEDURE

### Chemical

The chemicals used in this study, along with their suppliers, are listed in Table 1. All chemicals possessed high purity; therefore, no additional purification procedures were undertaken. The purity of each chemical was further verified by measuring key physical properties ultrasonic velocity (u), density (ρ), and viscosity (η) and comparing the results with corresponding literature values. These comparisons, presented in Table 2, show excellent agreement, confirming the reliability and suitability of the chemicals for the experimental work.

**Table 1: The details of the chemicals used, including their CAS Registry Numbers and mass fraction purities, are provided in Table 1.**

| Component | Formula | CAS Reg. No. | Supplier | Mass Fraction Purity (%) | Water Content | Method Purity analysis method |
|---|---|---|---|---|---|---|
| Cumene | $C_9H_{12}$ | 80-15-9 | CDH, (P) Ltd. New Delhi, India | 99.0% | 0.1% | Double distillation |
| Mesitylene | $C_9H_{12}$ | 108-67-8 | CDH, (P) Ltd. New Delhi, India | 99.8% | 0.01% | Double distillation |
| Ethyl benzene | $C_8H_{10}$ | 100-41-4 | CDH, (P) Ltd. New Delhi, India | 99.8% | 0.1% | Double distillation |
| Toluene | $C_7H_8$ | 108-88-3 | CDH, (P) Ltd. New Delhi, India | 99.0% | 0.1% | Double distillation |
| n-Propyl benzene | $C_9H_{12}$ | 103-65-1 | CDH, (P) Ltd. New Delhi, India | 99.0% | 0.01% | Double distillation |
| t-Butyl benzene | $C_{10}H_{14}$ | 98-06-6 | CDH, (P) Ltd. New Delhi, India | 99.0% | 0.1% | Double distillation |
| Biphenyl | $C_{12}H_{10}$ | 92-52-4 | CDH, (P) Ltd. New Delhi, India | 99.0% | 0.05% | Double distillation |

### Measurements

Six binary systems were studied: isopropyl benzene (cumene) + ethylbenzene, isopropyl benzene (cumene) + toluene, isopropyl benzene (cumene) + mesitylene, isopropyl benzene (cumene) + n-propylbenzene, isopropyl benzene (cumene) + tert-butylbenzene, and isopropyl benzene (cumene) + biphenyl. All chemicals were stored over sodium hydroxide pellets for several days and fractionally distilled twice, following the procedure reported in the literature [13]. The purification method described by Zhao et al. [14] was also adopted: for example, ethyl acetate was dried over $K_2CO_3$, filtered, and distilled, with the initial and final fractions discarded. All purified chemicals were stored in dark bottles over freshly activated molecular sieves to minimize moisture adsorption. Each sample mixture was prepared gravimetrically by mixing accurately calculated masses of the pure components in specially designed glass-stoppered bottles. Binary mixtures covering the entire mole fraction range were prepared by injecting the required amounts of each component into sealed glass vials using gas-tight syringes to minimize evaporation losses. The pure liquids were weighed using a digital electronic balance (Citizen Scale (I) Pvt. Ltd., Mumbai, India) with a precision of ±0.1 mg, and the overall uncertainty in mole fraction was estimated to be within ±0.0005. For each binary system, five mixture compositions were prepared, and measurements of density, viscosity, and ultrasonic velocity were carried out on the same day in order to minimize compositional and environmental variations.

### Density:

Densities of the pure liquids and their binary mixtures were determined using a 25 $cm^3$ relative density (R.D.) bottle. The bottle containing the sample was immersed in a thermostated water bath to maintain thermal stability, which was monitored using a calibrated thermometer under equilibrium conditions. Calibration of the R.D. bottle at 298.15 K was performed using triply distilled water and purified methanol, with density values taken from the literature. Conductivity water (specific conductance less than $1\times10^6$ $ohm^{-1}$) was used to verify the calibration, assuming densities of 0.9970 and 0.9940 g $cm^{-3}$ at 298.15 K, respectively. Before each measurement, the R.D. bottle was filled with bubble-free liquid and placed in a thermo stated water bath (MSI Goyal Scientific, Meerut, India) to ensure proper thermal equilibration. The uncertainty in the density measurements was found to be less than ±0.0004 $g.cm^{-3}$.

### Sound Velocity:

Ultrasonic velocities were measured using a multi-frequency ultrasonic interferometer (Model F80D, Mittal Enterprise, New Delhi, India) operating at a fixed frequency of 3 MHz. The instrument was calibrated at 298.15 K using water, methanol, and benzene. The measurement technique, described in detail elsewhere, is based on the accurate determination of the wavelength of ultrasonic waves of known frequency generated by a quartz crystal inside the measuring cell. The interferometer cell was filled with the test liquid, and a constant-temperature water bath was used to circulate water around the cell to maintain thermal stability. The uncertainty in speed of sound was estimated to be ±1 $m.s^{-1}$. The ultrasonic velocities measured for pure isopropyl benzene (cumene), ethylbenzene, toluene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl were found to be in good agreement with literature values. The ultrasonic velocity (U) was calculated using the following formula:

$$U = \lambda .\ F \tag{1}$$

### Viscosity:

The viscosities of the pure liquids and their binary mixtures were measured using a suspended Ostwald viscometer with a capacity of approximately 15 mL, a capillary length of about 90 mm, and an internal diameter of 0.5 mm. The viscometer was calibrated at 298.15 K using triply distilled water, methanol, and benzene, following standard procedures reported in the literature. The efflux time of each sample was measured with an electronic stopwatch (Racer) with a resolution of ±0.015 s, and the average of at least four consistent flow-time readings was used for each determination. A glass stopper was placed at the viscometer opening during measurements to minimise evaporation losses. The instrument's design, with two reservoir bulbs connected by a U-shaped capillary, ensures free liquid flow under atmospheric pressure. The viscosity (η) of the pure liquids and their binary mixtures was calculated using the standard viscometric relation based on measured flow times and calibrated constants.

$$\frac{\eta}{\rho} = at - \frac{b}{t} \tag{2}$$

Where t is the efflux time and a and b are viscometric constants.

The measured viscosities with an uncertainty of ±0.008 mPa.s. The viscosity values obtained for pure isopropyl benzene (cumene), ethylbenzene, toluene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl were found to be in good agreement with literature data.

**Table 2: Comparison of Experimental and Literature Values of Density (ρ), Sound Velocity (u), and Viscosity (η) for Pure Components at 298.15 K and Atmospheric Pressure.**

| **Compound** | **ρ (g.cm$^{-3}$)** | | **u (m.s$^{-1}$)** | | **η (m Pa s)** | |
|---|---|---|---|---|---|---|
| | **Observed** | **Literature** | **Observed** | **Literature** | **Observed** | **Literature** |
| Cumene | 0.8532 | 0.8581[26] | 1326 | 1325[31] | 0.7337 | 0.7337[26] |
| | | 0.5574[27] | | 1308[35] | | 0.7390[27] |
| Mesitylene | 0.8616 | 0.8612[23] | 1338 | 1336[23] | 0.6449 | 0.6486[32] |
| | | 0.8611[24] | | 1336[25] | | 0.6600[37] |
| Ethyl benzene | 0.8674 | 0.8620[16] | 1324 | 1312[16] | 0.6345 | 0.6280[16] |
| | | 0.8626[17] | | 1318[36] | | 0.6373[16] |
| Toluene | 0.8576 | 0.8624[15] | 1306 | 1307[19] | 0.5527 | 0.5525[21] |
| | | 0.8622[18] | | 1309[20] | | 0.5531[22] |
| n-Propyl benzene | 0.8624 | 0.8577[28] | 1315 | 1320[33] | 0.7931 | 0.7995[30] |
| | | 0.8577[29] | | 1320[34] | | 0.7827[28] |
| t-butyl benzene | 0.8624 | 0.8624[24] | 1316 | 1315[23] | 0.7449 | NA |
| | | 0.8622[23] | | 1315[25] | | NA |
| Biphenyl | 0.7920 | NA | 1118 | NA | 0.6108 | NA |

NA: Data not available.

## Modelling

### Redlich-Kister Equation:

The Redlich–Kister (RK) equation [38] is a widely used algebraic expression for correlating the excess properties of chemical mixtures. It expresses the excess property $Y^E$ as a function of the mole fractions ($x_1$ and $x_2$) of the components. The Redlich–Kister (RK) equation is given by:

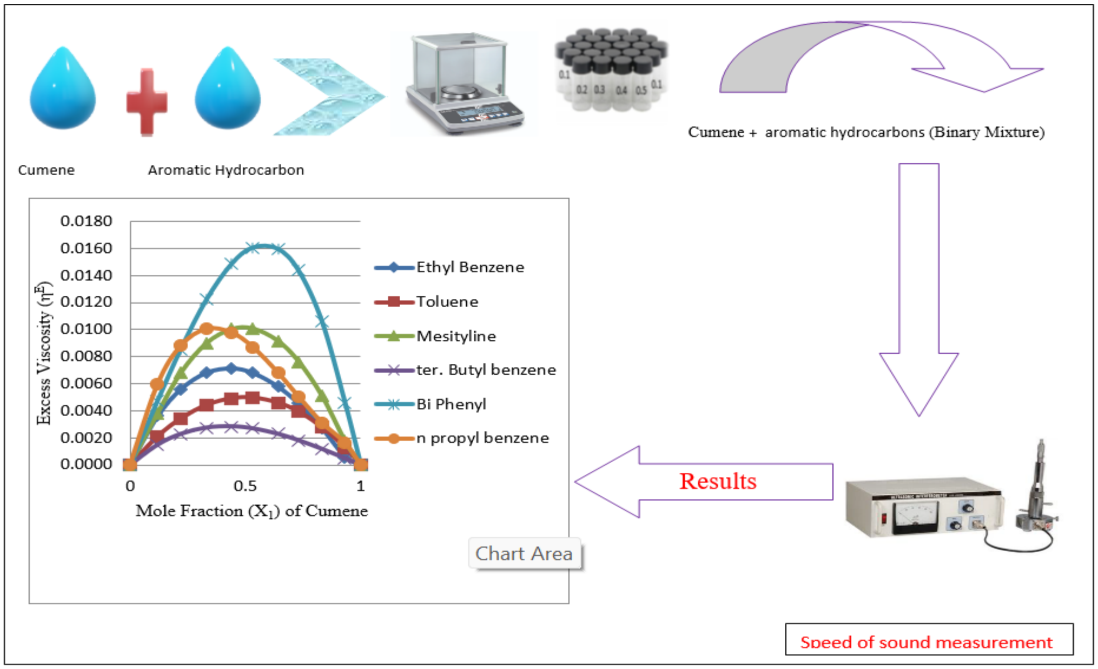
$$Y = x_1 x_2 \sum_{j=1}^{p} A_{j-1}(x1 - x2)^{j-1} \tag{3}$$

Where $Y$ is $V_m^E$, $V_f^E$, $p_i^E$ and $H^E$) and $x_1$ and $x_2$ are the mole fractions of pure components 1 and 2, respectively. $a_{j-1}$ is the polynomial coefficient, and $p$ is the polynomial degree.

The goodness of fit of the regression is evaluated using statistical indicators, such as the standard deviation, which reflect the accuracy and reliability of the correlation.

## RESULTS AND DISCUSSION

The experimental values of ultrasonic velocity (u), density (ρ), viscosity (η), and refractive index (n) for binary mixtures of isopropyl benzene (cumene) with ethylbenzene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl at 298.15 K are summarized in Table 3. Using these measured values, various derived thermodynamic parameters including molar volume ($V_m$), enthalpy (H), internal pressure ($P_i$), and free volume ($V_f$) were calculated and are also presented in Table 3.



**Scheme 1: Interactions between Isopropyl Benzene (Cumene) with Aromatic Hydrocarbons at 298.15K**

**Table 3: Density (ρ), Sound Velocity (u) and Viscosity (η) of Binary Mixtures of Isopropyl Benzene with Aromatic Hydrocarbons at 298.15 K.**

| Mole fraction Cumene ($x_1$) | Density (ρ) $g.cm^{-3}$ | Viscosity (η) mPa.s | Speed of Sound (u) $ms^{-1}$ | Molar volume $V_m$ ($cm^3mol^{-1}$) | Free Volume $V_f$ × $10^{-7}$ $M^3mol^{-1}$ | Internal pressure $p_i$ × $10^5$/ N $m^{-2}$ | Enthalpy (H) × $10^{-6}$ ($J.mol^{-1}$) |
|---|---|---|---|---|---|---|---|
| isopropyl benzene + ethyl benzene | | | | | | | |
| 0.0000 | 0.8630 | 0.6345 | 1308 | 123.02 | 0.3512 | 2.8014 | 3.4463 |
| 0.1193 | 0.8612 | 0.6472 | 1310 | 125.16 | 0.3526 | 2.7754 | 3.4737 |
| 0.2209 | 0.8600 | 0.6633 | 1314 | 126.98 | 0.3537 | 2.7541 | 3.4973 |
| 0.3312 | 0.8596 | 0.6715 | 1316 | 128.97 | 0.3549 | 2.7294 | 3.5202 |
| 0.4397 | 0.8592 | 0.3882 | 1317 | 130.94 | 0.3561 | 2.7064 | 3.5438 |
| 0.5319 | 0.8588 | 0.6931 | 1318 | 132.61 | 0.3571 | 2.6853 | 3.5610 |
| 0.6395 | 0.858 | 0.7042 | 1320 | 134.52 | 0.3582 | 2.6608 | 3.5794 |
| 0.7301 | 0.8572 | 0.7124 | 1321 | 136.13 | 0.3591 | 2.6378 | 3.5908 |
| 0.8315 | 0.8564 | 0.7198 | 1322 | 137.90 | 0.3601 | 2.6119 | 3.6018 |
| 0.9313 | 0.8554 | 0.7249 | 1324 | 139.66 | 0.3611 | 2.5875 | 3.6137 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |
| isopropyl benzene + toluene | | | | | | | |
| 0.0000 | 0.8672 | 0.5527 | 1312 | 106.25 | 0.3462 | 3.1354 | 3.3313 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.1193 | 0.8628 | 0.5801 | 1314 | 110.26 | 0.3481 | 3.0683 | 3.3875 |
| 0.2209 | 0.8612 | 0.6046 | 1315 | 113.82 | 0.3498 | 3.0110 | 3.4302 |
| 0.3312 | 0.8600 | 0.6293 | 1316 | 117.53 | 0.3516 | 2.9488 | 3.4725 |
| 0.4397 | 0.8592 | 0.6457 | 1318 | 121.23 | 0.3534 | 2.8878 | 3.5100 |
| 0.5319 | 0.8584 | 0.6706 | 1390 | 124.43 | 0.3548 | 2.8356 | 3.5375 |
| 0.6395 | 0.8576 | 0.6869 | 1320 | 128.18 | 0.3564 | 2.7745 | 3.5643 |
| 0.7301 | 0.8568 | 0.7032 | 1321 | 131.44 | 0.3577 | 2.7228 | 3.5824 |
| 0.8315 | 0.8556 | 0.7191 | 1322 | 134.95 | 0.3592 | 2.6652 | 3.5998 |
| 0.9313 | 0.8544 | 0.7266 | 1324 | 138.42 | 0.3606 | 2.6085 | 3.6130 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |
| isopropyl benzene + meistylene | | | | | | | |
| 0.0000 | 0.8616 | 0.6449 | 1338 | 139.50 | 0.4753 | 2.3605 | 3.2715 |
| 0.1193 | 0.8612 | 0.6216 | 1336 | 139.59 | 0.4698 | 2.3875 | 3.3161 |
| 0.2209 | 0.8608 | 0.6384 | 1335 | 139.66 | 0.4618 | 2.4092 | 3.3527 |
| 0.3312 | 0.8604 | 0.6551 | 1334 | 139.74 | 0.4546 | 2.4324 | 3.3913 |
| 0.4397 | 0.86 | 0.6718 | 1333 | 139.76 | 0.4486 | 2.4556 | 3.4302 |
| 0.5319 | 0.8596 | 0.6885 | 1332 | 139.85 | 0.4356 | 2.4756 | 3.4633 |
| 0.6395 | 0.8592 | 0.6967 | 1331 | 139.89 | 0.4216 | 2.4975 | 3.4999 |
| 0.7301 | 0.8588 | 0.7048 | 1330 | 140.05 | 0.4085 | 2.5158 | 3.5304 |
| 0.8315 | 0.8584 | 0.7130 | 1329 | 140.38 | 0.3942 | 2.5364 | 3.5647 |
| 0.9313 | 0.8576 | 0.7293 | 1328 | 140.54 | 0.3751 | 2.5568 | 3.5985 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |
| isopropyl benzene + n-propyl benzene | | | | | | | |
| 0.0000 | 0.8624 | 0.7931 | 1315 | 138.61 | 0.3167 | 2.7143 | 3.7622 |
| 0.1193 | 0.8620 | 0.7896 | 1316 | 138.90 | 0.3236 | 2.6986 | 3.7483 |
| 0.2209 | 0.8618 | 0.7884 | 1317 | 139.17 | 0.3298 | 2.6846 | 3.7363 |
| 0.3312 | 0.8614 | 0.7724 | 1318 | 139.45 | 0.3361 | 2.6698 | 3.7230 |
| 0.4397 | 0.8604 | 0.7664 | 1319 | 139.70 | 0.3417 | 2.6550 | 3.7090 |
| 0.5319 | 0.8596 | 0.7626 | 1320 | 139.95 | 0.3462 | 2.6421 | 3.6976 |
| 0.6395 | 0.8588 | 0.7558 | 1321 | 140.10 | 0.3508 | 2.6258 | 3.6788 |
| 0.7301 | 0.8584 | 0.7524 | 1322 | 140.30 | 0.3544 | 2.6111 | 3.6634 |
| 0.8315 | 0.8576 | 0.74630 | 1324 | 140.52 | 0.3578 | 2.5956 | 3.6474 |
| 0.9313 | 0.8560 | 0.7422 | 1325 | 140.74 | 0.3602 | 2.5808 | 3.6323 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |
| isopropyl benzene + t-butyl benzene | | | | | | | |
| 0.0000 | 0.8624 | 0.7449 | 1316 | 154.77 | 0.4105 | 2.3043 | 3.5665 |
| 0.1193 | 0.8620 | 0.7445 | 1317 | 153.17 | 0.4055 | 2.3372 | 3.5798 |
| 0.2209 | 0.8612 | 0.7440 | 1318 | 151.78 | 0.4012 | 2.3648 | 3.5895 |
| 0.3312 | 0.8604 | 0.7436 | 1390 | 150.27 | 0.3978 | 2.3948 | 3.5986 |
| 0.4397 | 0.8596 | 0.7420 | 1320 | 148.78 | 0.3946 | 2.4242 | 3.6066 |
| 0.5319 | 0.8586 | 0.7398 | 1321 | 147.56 | 0.3906 | 2.4488 | 3.6136 |
| 0.6395 | 0.8572 | 0.7389 | 1322 | 146.01 | 0.3846 | 2.4768 | 3.6164 |
| 0.7301 | 0.8564 | 0.7373 | 1323 | 144.72 | 0.3788 | 2.5003 | 3.6185 |
| 0.8315 | 0.8556 | 0.7364 | 1324 | 143.30 | 0.3722 | 2.5266 | 3.6206 |
| 0.9313 | 0.8548 | 0.7351 | 1325 | 141.90 | 0.3656 | 2.5521 | 3.6215 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |
| isopropyl benzene + Biphenyl | | | | | | | |
| 0.0000 | 0.7920 | 0.6108 | 1118 | 177.91 | 0.6809 | 1.6766 | 2.9829 |
| 0.1193 | 0.7956 | 0.6215 | 1144 | 173.45 | 0.6498 | 1.7844 | 3.0951 |
| 0.2209 | 0.8036 | 0.6357 | 1174 | 169.70 | 0.6314 | 1.8761 | 3.1839 |
| 0.3312 | 0.8084 | 0.6510 | 1186 | 165.65 | 0.6124 | 1.9754 | 3.2722 |
| 0.4397 | 0.8144 | 0.6710 | 1198 | 161.66 | 0.5875 | 2.0732 | 3.3516 |
| 0.5319 | 0.8248 | 0.6932 | 1212 | 158.31 | 0.5576 | 2.1553 | 3.4120 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.6395 | 0.8276 | 0.7308 | 1242 | 154.27 | 0.5202 | 2.2509 | 3.4725 |
| 0.7301 | 0.8324 | 0.7161 | 1274 | 150.90 | 0.4827 | 2.3315 | 3.5183 |
| 0.8315 | 0.8436 | 0.7215 | 1286 | 147.14 | 0.4428 | 2.4210 | 3.5623 |
| 0.9313 | 0.8484 | 0.7295 | 1300 | 143.44 | 0.4006 | 2.5095 | 3.5997 |
| 1.0000 | 0.8532 | 0.7337 | 1326 | 140.87 | 0.3616 | 2.5691 | 3.6191 |

## Table 4: Excess thermodynamic parameter $V_m^E$, $V_f^E$, $p_i^E$ and $H^E$) for binary mixture of isopropyl benzene (1) + aromatic hydrocarbons (2) at 298.15K

| **Mole fraction 1,3-Dioxolane ($x_1$)** | **Excess molar volume ( $V_m^E$) (cm$^3$mol$^{-1}$)** | **Excess Free Volume $V_f^E$ × 10$^{-7}$ M$^3$mol$^{-1}$** | **Excess Internal pressure $p_i^E$ × 10$^5$/ N m$^{-2}$** | **Excess Enthalpy $H^E$ × 10$^{-4}$ (J.mol$^{-1}$)** |
|---|---|---|---|---|
| isopropyl benzene + ethyl benzene | | | | |
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.1193 | 0.0130 | 0.0123 | 21.1098 | 0.6857 |
| 0.2209 | 0.0293 | 0.0206 | 39.5149 | 1.2822 |
| 0.3312 | 0.0487 | 0.0281 | 56.1230 | 1.6668 |
| 0.4397 | 0.0658 | 0.0333 | 67.6464 | 2.1499 |
| 0.5319 | 0.0763 | 0.0356 | 72.6363 | 2.2788 |
| 0.6395 | 0.0804 | 0.0351 | 71.6712 | 2.2607 |
| 0.7301 | 0.0748 | 0.0316 | 64.2368 | 1.8323 |
| 0.8315 | 0.0557 | 0.0238 | 47.6727 | 1.1871 |
| 0.9313 | 0.0211 | 0.0117 | 21.7987 | 0.6445 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| isopropyl benzene + toluene | | | | |
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.1193 | 0.0224 | 0.0119 | 4.8505 | 2.1838 |
| 0.2209 | 0.0396 | 0.0226 | 8.2950 | 3.5351 |
| 0.3312 | 0.0549 | 0.0311 | 10.9872 | 4.5909 |
| 0.4397 | 0.0654 | 0.0360 | 12.5109 | 5.2191 |
| 0.5319 | 0.0695 | 0.0373 | 12.8830 | 5.3108 |
| 0.6395 | 0.0676 | 0.0351 | 12.1922 | 4.8930 |
| 0.7301 | 0.0595 | 0.0302 | 10.6290 | 4.0998 |
| 0.8315 | 0.0424 | 0.0210 | 7.7685 | 2.9161 |
| 0.9313 | 0.0160 | 0.0080 | 3.7605 | 1.3671 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| isopropyl benzene + meistylene | | | | |
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.1193 | 0.0331 | 0.0078 | 16.0060 | 0.3054 |
| 0.2209 | 0.0562 | 0.0133 | 25.0779 | 0.4347 |
| 0.3312 | 0.0752 | 0.0177 | 32.3845 | 0.4615 |
| 0.4397 | 0.0867 | 0.0202 | 36.7306 | 0.5849 |
| 0.5319 | 0.0902 | 0.0209 | 38.0133 | 0.6884 |
| 0.6395 | 0.0863 | 0.0199 | 36.4840 | 0.6146 |
| 0.7301 | 0.0758 | 0.0173 | 32.4910 | 0.5135 |
| 0.8315 | 0.0553 | 0.0126 | 24.8903 | 0.4163 |
| 0.9313 | 0.0257 | 0.0058 | 13.9802 | 0.3266 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| isopropyl benzene + n-propyl benzene | | | | |
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.1193 | 0.0098 | 0.0015 | 12.7856 | 0.3183 |
| 0.2209 | 0.0188 | 0.0032 | 21.7225 | 0.5700 |

| | | | | |
|---|---|---|---|---|
| 0.3312 | 0.0265 | 0.0045 | 28.9243 | 0.8204 |
| 0.4397 | 0.0329 | 0.0053 | 33.2048 | 0.9713 |
| 0.5319 | 0.0341 | 0.0056 | 34.4569 | 1.1496 |
| 0.6395 | 0.0315 | 0.0054 | 32.9167 | 0.8108 |
| 0.7301 | 0.0258 | 0.0049 | 28.9318 | 0.5731 |
| 0.8315 | 0.0174 | 0.0038 | 21.3551 | 0.4211 |
| 0.9313 | 0.0095 | 0.0017 | 10.4797 | 0.3376 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

isopropyl benzene + t-butyl benzene

| | | | | |
|---|---|---|---|---|
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0 |
| 0.1193 | 0.0472 | 0.0012 | 14.1506 | 0.7048 |
| 0.2209 | 0.0815 | 0.0026 | 24.3469 | 1.1378 |
| 0.3312 | 0.1107 | 0.0038 | 32.6084 | 1.4736 |
| 0.4397 | 0.1298 | 0.0047 | 37.5872 | 1.6979 |
| 0.5319 | 0.1372 | 0.0052 | 39.1406 | 1.9101 |
| 0.6395 | 0.1340 | 0.0051 | 37.5850 | 1.6254 |
| 0.7301 | 0.1204 | 0.0045 | 33.2588 | 1.3577 |
| 0.8315 | 0.0921 | 0.0032 | 24.9198 | 1.0356 |
| 0.9313 | 0.0494 | 0.0011 | 12.8774 | 0..6028 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

isopropyl benzene + Biphenyl

| | | | | |
|---|---|---|---|---|
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0.1193 | 0.0303 | 0.0125 | 16.5386 | 3.6277 |
| 0.2209 | 0.0550 | 0.0245 | 28.5802 | 6.0471 |
| 0.3312 | 0.0754 | 0.0349 | 37.8051 | 7.8560 |
| 0.4397 | 0.0878 | 0.0419 | 42.8483 | 8.8932 |
| 0.5319 | 0.0918 | 0.0448 | 43.8987 | 9.0729 |
| 0.6395 | 0.0879 | 0.0440 | 41.2588 | 8.2753 |
| 0.7301 | 0.0769 | 0.0394 | 35.7228 | 7.0948 |
| 0.8315 | 0.0555 | 0.0295 | 25.8405 | 5.0371 |
| 0.9313 | 0.0242 | 0.0142 | 12.2175 | 2.4339 |
| 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

The molar volume $V_m$ calculated from the measured values of density (ρ), molar volume ($V_m$) was calculated using the relation

$$V_m = \frac{(X_1 M_1 + X_2\, M_2)}{\rho} \qquad (4)$$

Where $X_1$ , $X_2$ and $M_1$, $M_2$ are the mole fraction and molecular weight of the component 1 and 2 respectively.

According to Bingham [39] and Macleod [40] free volume ($V_f$) can be calculated from the sound velocity and viscosity by the relation given below

$$V_f \;=\; (M\,U/\,k\,\eta)^{3/2} \qquad (5)$$

Where M is the molecular weight (gm)

- U is the sound velocity (cm/sec)
- η is the viscosity (poise)

- k is the constant, equal to $4.28\times10^{9}$, independence of temperature and $V_f$, the free volume is in milliliters per mole.

On the basis of dimensional analysis, using free volume concept, the following expression can be used for calculating internal pressure. The internal pressure of a liquid can also be evaluated by using the equation proposed by Suryanarayana [41-42]

$$p_i = \mathrm{bRT}\left(\frac{k\eta}{u}\right)^{\frac{1}{2}} \frac{\rho^{2/3}}{M_{eff}^{7/6}} \tag{6}$$

where b is the packing fraction of the liquid which is taken equal to 2 for most of the liquids, k is a constant equal to $4.28 \times 10^{9}$, $M_{eff}$ ($= x_1M_1 + x_2M_2$) is the effective molecular mass and M is the molar mass of the mixture of pure liquid and T is absolute temperature.

Enthalpy (H) can be calculated by the following equation [43]

$$H = V_m \times P_i \tag{7}$$

Where $V_m$ is molar volume and $P_i$ is internal pressure.

The excess thermodynamic function ($Y^E$) provide a way to represent directly the deviation of a solution from ideal behaviour. The difference between the thermodynamic function of mixing for a real system and the value corresponding to a perfect solution at the same temperature, pressure and composition is called the thermodynamic excess function, denoted by $Y^E$. Excess values for all the parameters are computed using the general formula

$$Y^E = Y_{exp} - (X_1Y_1 + X_2\,Y_2) \tag{8}$$

Where Y represents the parameter such as intermolecular free length, free volume, internal pressure, adiabatic compressibility and entropy and $X_1$ *and* $X_2$ are the mole fractions of components whose parameters.

The molar volume ($V_m$) for the pure liquids isopropyl benzene (cumene), ethyl benzene, toluene, mesitylene, *n*-propyl benzene, *tert*-butyl benzene and biphenyl have been calculated using vide eq. 4. The calculated volumes for all the liquid are enlisted in Table 3. Determining the excess molar volume ($V_m^E$) of binary mixes depends on exact measurement of density. For this aim, several experimental approaches are extensively used, each with advantages and constraints [44]. Figures 1 represent variation of excess molar volume ($V_m^E$) with $x_1$ (isopropyl benzene (cumene)) at 298.15 yielding a U-shaped nature of the graph is attributed to the equilibria of State effects and steric factors arising from the change of orientation of cumene molecules with change in its mole fraction. For the solutions of cumene with ethyl benzene, toluene, mesitylene, *n*-propyl benzene, *tert*-butyl benzene and biphenyl the graphs are inverted v-shaped. Treszcznowicz et al. [45] and later Aminabhavi et al. [46] observed that excess molar volume ($V_m^E$) many be discussed in terms of several effects which may be arbitrarily divided into physical, chemical and geometrical contributions. The Physical interact involved mainly dispersion forces giving a positive contribution. The chemical or specific interactions result in a volume contraction and these include charge-transfer type forces.

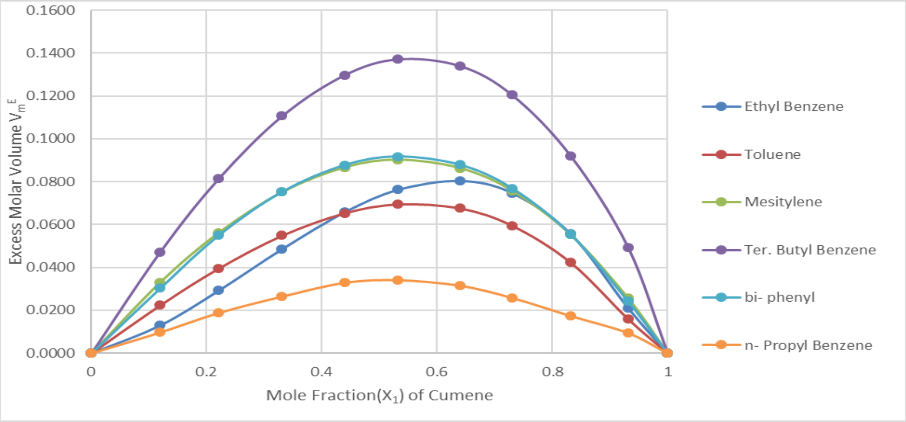


**Figure 1: Curves of excess molar volume ($V_m^E$) against the mole fraction of isopropyl benzene (cumene) $x_1$, for the binary mixture (isopropyl benzene (cumene) (1) + Aromatic Hydrocarbons (2) at 298.15K. The solid lines represent the values calculated from the Redlich–Kister equation.**

The experimental results are consistent with this explanation, as most of the studied mixtures exhibit positive excess volumes. This indicates that changes in intermolecular forces dominate over packing effects caused by geometrical constraints, which explains the variation in excess molar volumes among different hydrocarbons. When comparing maximum excess molar volumes at equimolar composition, several trends emerge: mixtures with flat or small-substituted hydrocarbons (e.g., ethyl benzene, mesitylene, biphenyl) tend to show positive excess molar volume ($V_m^E$) mixtures with non-flat or moderately substituted hydrocarbons (e.g., t-butylbenzene, isopropylbenzene) exhibit intermediate values; and the highest ($V_m^E$) is observed for cumene + mesitylene, where mesitylene has a flat geometry with three methyl groups in the meta positions around the aromatic ring. These observations can be interpreted qualitatively in terms of steric and electronic effects. Bulky substituents in the hydrocarbon molecules prevent close approach of the acetate groups, weakening interactions and increasing the excess volume. In contrast, flat molecules with few substituents (toluene, ethyl benzene, mesitylene, biphenyl) allow some residual interactions, resulting in($V_m^E$). The steric hindrance imposed by three methyl groups in mesitylene obstructs the approach of the cumene molecules, increasing the occupied volume and thus the excess molar volume. Similar trends in excess volume with molecular size and substitution have been observed in other non-polar + non-polar mixtures, including cumene with aromatic compounds [47–48]. These results highlight the importance of steric hindrance in controlling dispersive interactions and the progressive masking of non-polar effects of methyl groups during mixing.

The free volumes of the pure liquids isopropyl benzene (cumene), ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl were calculated using the method of Suryanarayana and Kuppusami (Eq. 5). The calculated values are listed in Table 3. Excess free volumes ($V_f^E$) were subsequently determined from the difference between the free volume of the mixture and the ideal free volume (Eq. 8), and these values are also presented in

Table 4. The variation of $(V_f^E)$ with the mole fraction of isopropyl benzene $(X_1)$ at 298.15 K for the six binary mixtures is illustrated in Figure 2. The observed excess free volume can be analyzed in terms of three contributions: physical, chemical, and geometrical. Physical interactions, primarily dispersion forces and other non-specific interactions, generally produce positive contributions to $(V_f^E)$. Chemical interactions, including the disruption of hydrogen-bonded structures, also tend to increase excess free volume, whereas specific interactions such as hydrogen bonding or charge-transfer complex formation lead to contraction of the mixture and negative contributions. Geometrical or structural contributions arise from the fitting of one component into the other; differences in molecular size and shape can lead to negative contributions to $(V_f^E)$. As shown in Figure 2, $(V_f^E)$ is positive across the entire composition range for all six binary mixtures at 298.15 K, indicating predominantly weak intermolecular interactions. For systems where dispersion, induction, and dipolar forces are operative, excess free volume and viscosity generally show positive deviations, while specific interactions leading to complex formation can further enhance these positive deviations.

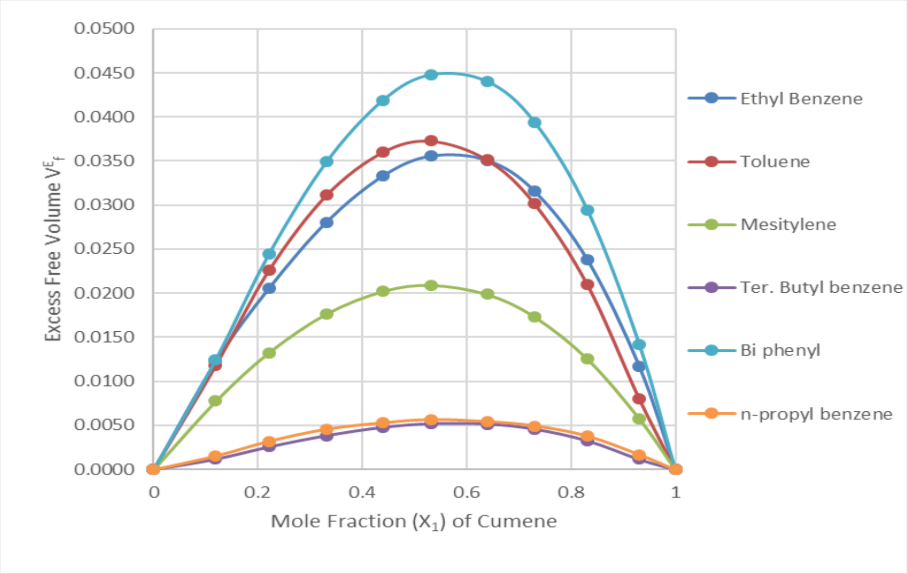


**Figure 2: Curves of excess free volume $(V_f^E)$ against the mole fraction of isopropyl benzene (cumene) $x_1$, for the binary mixture (isopropyl benzene (cumene) (1) + Aromatic Hydrocarbons (2)) at 298.15K. The solid lines represent the values calculated from the Redlich–Kister equation.**

The excess free volume $(V_f^E)$ is positive for all the studied binary mixtures of isopropyl benzene (cumene) with ethyl benzene, toluene, mesitylene, n-propyl benzene, tert-butyl benzene, and biphenyl. Positive $(V_f^E)$ indicates that the interactions between molecules of the mixed components are weaker than those in the pure components. This behavior is typically observed when one component contains non-polar groups and the other is non-polar or weakly polar. In the present systems, isopropyl benzene is weakly polar, while the aromatic hydrocarbons are nearly non-polar. Upon mixing, the non-polar hydrocarbon molecules intersperse among the isopropyl benzene molecules, reducing interactions among the hydrocarbon molecules and disrupting dispersive interactions between benzene rings. As a result, interactions between unlike molecules are weaker, leading to an overall expansion in volume.

The enthalpy for the pure liquids isopropyl benzene (cumene), Ethyl Benzene, Toluene, mesitylene, *n*-propyl benzene, *tert*-butyl benzene and biphenyl have been calculated using vide eq. 7. The calculated volumes for all the liquid are enlisted in Table 3. The excess enthalpy ($H^E$) have been calculated through free volume of the mixture and ideal free volume vide eq. 8 the value of excess enthalpy ($H^E$) for these system are also enlisted in Table 4. The variation of excess enthalpy ($H^E$) with mole fraction ($x_1$) of isopropyl benzene (cumene) at 298.15 K for the binary mixture of isopropyl benzene (cumene) with Ethyl Benzene, Toluene, mesitylene, *n*-propyl benzene, *tert*-butyl benzene and biphenyl are displayed in Figure 3.

Figure 3 shows the variation of excess enthalpy ($H^E$) with mole fraction of isopropyl benzene (cumene) at the temperature 298.15K For the binary system isopropyl benzene (cumene) with aromatic hydrocarbons (Ethyl Benzene, Toluene, mesitylene, *n*-propyl benzene, *tert*-butyl benzene and biphenyl) , the excess enthalpy ($H^E$) values are positive and decreasing with the increase in mole fraction of isopropyl benzene (cumene) up to the mole fraction (0.5) and the increase with increase in mole fraction. Excess enthalpy ($H^E$) is an important parameter for understanding molecular interactions in liquid mixtures. In the present study, for all six binary systems, ($H^E$) decreases as the mole fraction of isopropyl benzene (cumene) increases, as illustrated in Figure 4.

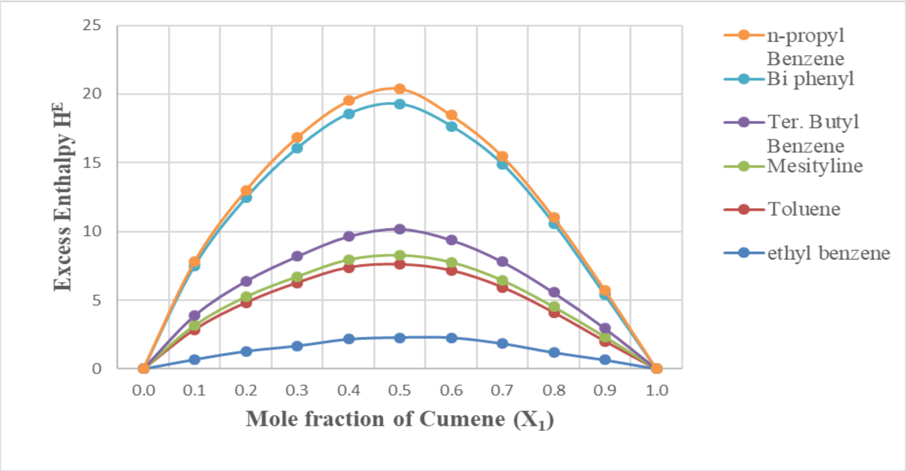


**Figure 3: Curves of excess enthalpy ($H^E$) against the mole fraction of isopropyl benzene (cumene) $x_1$, for the binary mixture (isopropyl benzene (cumene) (1) + Aromatic Hydrocarbons (2)) at 298.15K. The solid lines represent the values calculated from the Redlich–Kister equation.**

According to Nakayama and Shinoda [49], the observed behavior of excess enthalpy ($H^E$) can be interpreted as the result of a balance between positive contributions, arising from hydrogen-bond rupture or dispersive interactions between unlike molecules, and negative contributions, resulting from intermolecular dipolar interactions or geometrical fitting of the molecules. The variation of excess enthalpy ($H^E$) with the mole fraction ($x_1$) of isopropyl benzene (cumene) in binary mixtures with aromatic hydrocarbons (ethylbenzene, toluene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl) is shown in Figure 4 at 298.15 K. The excess enthalpy ($H^E$) values are positive for all six binary systems studied. Positive excess enthalpy indicates that the interactions between molecules of the mixed components are weaker than those present in the pure components. This behavior typically occurs when both components are non-polar or weakly polar. In the present systems, isopropyl benzene is weakly polar, while the aromatic hydrocarbons are nearly non-polar. Upon mixing, the non-polar hydrocarbon molecules intersperse among the cumene molecules, reducing the strength of dispersive interactions among the benzene rings. The newly formed interactions between unlike molecules are weaker, resulting in an overall expansion of the mixture [50].

Internal pressure ($P_i$) is a measure of the cohesive forces in a liquid, resulting from the balance between attractive and repulsive interactions. The attractive forces primarily include hydrogen bonding, dipole–dipole, and dispersion interactions, while repulsive forces, which act at very short intermolecular distances, generally play a minor role under normal conditions. Figure 4 shows the variation of excess internal pressure ($p_\mathrm{i}^\mathrm{E}$) with the mole fraction of isopropyl benzene (cumene) at 298.15 K. The internal pressures of the pure liquids cumene, ethylbenzene, toluene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl were calculated using Eq. 6, and the values are listed in Table 3. Excess internal pressures ($p_\mathrm{i}^\mathrm{E}$) (were subsequently obtained from the difference between the internal pressure of the mixture and the ideal internal pressure (Eq. 8), and these values are also presented in Table 4. The variation of ($p_\mathrm{i}^\mathrm{E}$) with the mole fraction of cumene for all six binary mixtures is displayed in Figure 4. The excess internal pressure is negative across the entire composition range for all mixtures, indicating predominantly weak intermolecular interactions. In each system, the absolute magnitude of ($p_\mathrm{i}^\mathrm{E}$) decreases as the concentration of cumene increases. The magnitude of ($p_\mathrm{i}^\mathrm{E}$) follows the sequence: ethylbenzene > toluene > mesitylene > n-propylbenzene > tert-butylbenzene > biphenyl. This trend reflects the relative strengths of interactions between cumene and the aromatic hydrocarbons, suggesting that intermolecular interactions are strongest in the cumene + ethylbenzene system and weakest in the cumene + biphenyl system.

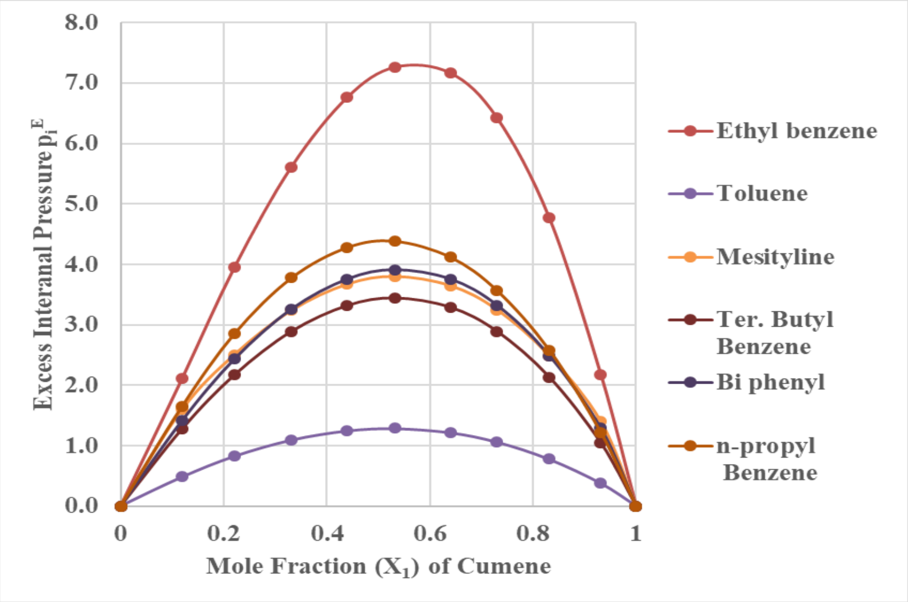


**Figure 4: Curves of excess internal pressure ($p_\mathrm{i}^\mathrm{E}$) against the mole fraction of isopropyl benzene (cumene) $x_1$, for the binary mixture (isopropyl benzene (cumene) (1) + Aromatic Hydrocarbons (2)) at 298.15K. The solid lines represent the values calculated from the Redlich–Kister equation.**

The predominant interaction in isopropyl benzene (cumene) + aromatic hydrocarbon mixtures is likely of the electron donor–acceptor (charge-transfer) type [51], involving the π-electrons of the cumene aromatic ring (acting as donor) and the π-electrons of the aromatic hydrocarbon rings (acting as acceptor). Notably, the excess internal pressure($p_{\mathrm{i}}^{\mathrm{E}}$) decreases as the number of –$CH_3$ substituents on the aromatic ring increases, from benzene (no –$CH_3$) to mesitylene (three –$CH_3$ groups). This behavior can be attributed to the electron-releasing nature of the methyl groups, which enhances the electron density of the aromatic ring but simultaneously reduces its electron-accepting ability. Consequently, the donor–acceptor interactions between unlike molecules weaken as the number of methyl groups increases, leading to lower ($p_{\mathrm{i}}^{\mathrm{E}}$) values. Similar trends in ($p_{\mathrm{i}}^{\mathrm{E}}$) and excess free volume ( $V_f^E$) have been observed in tetrahydrofuran + aromatic hydrocarbon binary mixtures [52]. This interpretation of molecular interactions satisfactorily explains the compositional trends observed in the ($p_{\mathrm{i}}^{\mathrm{E}}$) values for the present systems.

## CONCLUSIONS

Excess thermodynamic properties represent the difference between the real and ideal mixing behavior of liquid systems. In this study, we report a combined experimental investigation of density, sound velocity, viscosity, and refractive index, along with the derived thermodynamic excess and deviation properties, $V_m^E, V_f^E$, $p_{\mathrm{i}}^{\mathrm{E}}$ and $H^E$) for the pure liquids isopropyl benzene (cumene), ethylbenzene, toluene, mesitylene, n-propylbenzene, tert-butylbenzene, and biphenyl and their binary mixtures. These properties are essential for understanding molecular interactions and for designing various chemical and industrial processes. The Redlich–Kister polynomial provided a statistically significant representation of the ($V_m^E$ , $V_f^E$, $p_{\mathrm{i}}^{\mathrm{E}}$ and $H^E$), with an optimal number of coefficients yielding accuracy comparable to or better than the experimental uncertainties. The observed composition dependence of these excess and deviation properties has been successfully interpreted in terms of intermolecular interactions and structural effects in the mixtures.

### Nomenclature

- ρ- Density of the mixture ($g.cm^{-3}$)
- u -Sound speed of the mixture ($m.s^{-1}$)
- $\eta$ –Viscosity (mPa)
- M- Molar mass
- T-Temperature
- P-Pressure
- V-Volume
- T- Temperature (Kelvin)
- $V_m$-molar volume
- ($V_m^E$)- Excess molar volume
- (H)- Enthalpy ($J.mol^{-1}$)
- ($H^E$)- Excess enthalpy ($J.mol^{-1}$)
- ($V_f$)- Free volume ($M^3mol^{-1}$)
- ($V_f^E$)-Excess free volume, ($M^3mol^{-1}$)
- ($P_i$)- Internal pressure ($N\ m^{-2}$)

- ($p_i^E$)- Excess internal pressure (N $m^{-2}$)
- $Y^E$, Thermodynamic excess function
- $X_1$ -Mole Fraction of isopropyl benzene (Cumene)

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data Availability Statement

Data will be made available on request.

## Author Contributions

**Chandra Pal Prajapati:** Data curation, Investigation, Formal Analysis, Software
**Dhirendra Kumar Sharma:** Methodology, Supervision, Writing – original draft
**Suneel Kumar:** Software, Validation, methodology

## References

[1] Das, N.; Praharaj, M. K.; Panda, S. Exploring ultrasonic wave transmission in liquids and liquid mixtures: A comprehensive overview. J. Mol. Liq. 2024, 403, No. 124841.

[2] Rathnam, M. V.; Ambavadekar, D. R.; Nandini, M. Densities, viscosities, and sound speed of binary mixtures of hexyl acetates with tetrahydofuran, 1, 4-dioxane, anisole, and butyl vinyl ether. J. Chem. Eng. Data 2013, 58, 3370–3377.

[3] Vanathi, V.; Mullainathan, S.; Nithiyanantham, S. PhysioChemical Studies on the Ternary Mixture of Chlorobenzene +Chloroform+Cyclohexane Liquid Mixtures at 303.15, 308.15 and 313.15 K. J. Comput. Theor. Nanosci. 2013, 10, 1952–1955.

[4] Varma, R. P.; Kumar, S. Ultrasonic velocity and density measurements of ammonium soaps in 2-propanol. Indian J. Pure Appl. Phys. 2000, 2, 96–100.

[5] Tironi, I. G.; Wilfred, F. V. G. A molecular dynamics simulation study of chloroform. Mol. Phys. 1994, 83, 381–403.

[6] Bertagnolli, H.; Leicht, D. O.; Zeidler, M. D. X-ray diffraction study of liquid chloroform. Mol. Phys. 1978, 35, 193−197. (6) Ali, A.; Tiwari, K.; Nain, A. K.; Chakravarty, V. Ultrasonic study of molecular interactions in ternary mixtures of dimethyl sulfoxide (1) + carbon tetrachloride (2) + aromatic hydrocarbons (3) at 308.15 K. Ind. J. Phys. 2000, 74B, 351–355.

[7] Upadhyay, S. K. Ultrasonic study of molecular interactions and compressibility behaviour of lithium soaps in 50:50% (v/v) benzenemethanol mixture. Indian J. Chem. 2000, 39A, 537–540.

[8] Ali, A.; Tiwari, K.; Nain, A. K.; Chakravarty, V. Ultrasonic study of molecular interactions in ternary mixtures of dimethyl sulfoxide (1) + carbon tetrachloride (2) + aromatic hydrocarbons (3) at 308.15 K. Ind. J. Phys. 2000, 74B, 351–355.

[9] J. George, N.V. Sastry, J. Chem. Eng. Data 48 (2003) 1529–1539.

[10] E. Zorebski, M. Dzida, M. Piotrowska, J. Chem. Eng. Data 53 (2008) 136–144.

[11] T. Katrinˇák, L. Hnedkovsky´ , I. Cibulka, J. Chem. Eng. Data 57 (2012) 1152–1159.

[12] C. Lisa, M. Ungureanu, P.C. Cosmat¸chi, G. Bolat, The density, the refractive index and the adjustment of the excess thermodynamic properties by means of the multiple linear regression method for the ternary system ethylbenzene–octane–propylbenzene, Thermo chim. Acta, 617 (2015) 76–82. https://www.sciencedirect.com/journal/thermochimica-acta/vol/617/suppl/C

[13] D. D. Perrin, W. L. F. Armarego, purification of Laboratory Chemicals 3rdEdn. (Pergamon, UK) (1988). https://www.scirp.org/reference/referencespapers?referenceid=1287461

[14] Y. Zhao, J. wang, X. Xuan, J. Lu, “Effect of Temperature on Excess Molar Volumes and Viscosities for Propylene Carbonate + N,N-Dimethylformamide Mixtures” J Chem. Eng. Data, 45(3) (2000) 440-444. https://pubs.acs.org/doi/10.1021/je9902746

[15] E. Hanan, M. El-sayed, A. Abdul-Fattah, Asfour. Density and viscosity of the regular quinary system: Benzene (1) + Toluene (2) + Ethyl benzene (3) + Heptane (4) + Cyclooctane (5) and its quaternary subsystems at 293.15 and 298.15K. J. Solution Chem. 42(2013) 136-150. https://link.springer.com/article/10.1007/s10953-012-9950-0

[16] V. K. Rattan, S. Singh, B.P.S. Sethi, Viscosity, density and Ultrasonic velocities of binary mixtures of Ethylbenzene with ethanol, 1-propanol and 1-butanol at (298.15 and 308.15) K. J. Chem. Engg. Data, 49(4) (2004)1074- 1077. https://pubs.acs.org/doi/10.1021/je049912x

[17] J. A. Riddick, W.B. Bunger, T. K. Sakano, Organic solvents: Physical properties and Methods of Purification, 4th ed.: Willey Interscience. New York, (1986).
https://www.scirp.org/reference/referencespapers?referenceid=2259333
https://www.osti.gov/biblio/6190969

[18] Thermodynamic Research Center, Texas A & M University, College Station, T RC Thermodynamic Tables Hydrocarbons, Suppl. No. 92 (1988).
https://books.google.co.in/books/about/TRC_Thermodynamic_Tables.html?id=vClCAQAAIAAJ&redir_esc=y

[19] A.K. Nain, D. Chand, Correlation between molecular interactions and excess thermodynamic parameters of binary mixtures. J. Pure Appl. Ultrason. 43(2021) 8-16.
https://docs.google.com/gview?url=http://www.ultrasonicsindia.org/USI-43(1-2)2021.pdf&embedded=true

[20] M.I. Aralaguppi, T.M. Aminabhavi, S.B. Harogoppad, R.H. balindgi, J. Chem. Eng. Data, 37(3) (1992) 29-303. https://pubs.acs.org/doi/pdf/10.1021/je00007a006

[21] B.K. Sarkar, A. Choudhury, B. Sinha, Excess molar volume, excess viscosities and ultrasonic speed of sound of binary mixtures of 1,2-Dimethoxyethane with some aromatic liquids at 298.15K. J. Solution Chem., 41(2012) 53-74. https://link.springer.com/article/10.1007/s10953-011-9780-5

[22] A.K. Nain, Ultrasonic and viscometric studies of molecular interactions in binary mixtures of tetrahydrofuran with some aromatic hydrocarbons at temperatures from 288.15 to 318.145K. Physics and Chemistry of Liquids. 45(4) (2007) 371-388. https://doi.org/10.1080/00319100701230405

[23] J. M. Resa, C. Gonzalez, S. Prieto, E. Diez, M. Iglesias, Mixing properties of propyl acetate + aromatic hydrocarbons at 298.15K. Korean J. Chem. Eng. 23(1) (2006) 93-101. https://link.springer.com/article/10.1007/BF02705698

[24] TRC thermodynamic tables, Thermodynamic Research Center, Texas A & M University, College Station, TX (1994). https://link.springer.com/chapter/10.1007/978-3-642-74140-1_6

[25] J. M. Resa, C. Gonzalez, de L. Ortiz, J. Lanz, Densities, excess molar volume and refractive indices of ethyl acetate and aromatic hydrocarbon binary mixtures. J. Chem. Thermodyn., 34 (7) (2002) 995-1004. https://www.sciencedirect.com/journal/the-journal-of-chemical-thermodynamics/vol/34/issue/7

[26] D. K. Sharma, C. P. Prajapati, S. Kumar, Density, Ultrasonic Velocity, Viscosity and their Excess Parameters of Some Binary Liquid Mixtures of Cumene with Aromatic Hydrocarbons at 298.15 K. Der Pharma Chemica.16(2) (2024) 301-306. https://www.derpharmachemica.com/archive/dpc-volume-16-issue-2-year-2024.html

[27] M. A. Saleh, M. Habibullah, M. Shamsuddin Ahmed, M. Ashraf Uddin, S. M. H. Uddin, M. Afsar Uddin & F. M. Khan, Excess molar volume and viscosities of some alkanols with Cumene. Physics and Chemistry of liquids, 44(1) (2006) 31- 43. https://doi.org/10.1080/00319100500287853 https://www.tandfonline.com/toc/gpch20/44/1?nav=tocList

[28] S. Aktar, M. Abdur Rahman, M. Shahadat Hossian, S. Akhtar, Excess molar volume and deviation in viscosity of the binary liquid mixtures of 1-Pentanol + Aromatic Hydrocarbons at 298.15K. European Scientific Journal. 11(5) (2015) 213-225. https://eujournal.org/index.php/esj.

[29] M. Page, J. Huot, A. Jolicoeur, Comprehensive thermodynamic investigation of water-ethanolamine mixtures at 10, 25 and 40 $^0$C. Can. J. Chem., 45(1993) 1064-1072. https://www.sciencedirect.com/org/journal/canadian-journal-of-chemistry/issues

[30] N. G. Tsierkezos, M. M. Palaiologou, I E. Molinou, Densities and Viscosities of 1-Pentanol binary mixtures at 293.15K. J. Chem. Eng. Data. 45(2000) 272-275. https://pubs.acs.org/doi/10.1021/je9902138

[31] M. Kumar, V.K. Rattan, Thermophysical properties for binary mixture of Di methyl sulfoxide and isopropyl benzene at various temperatures. Journal of Thermodynamics, 23 (2013), https://onlinelibrary.wiley.com/journal/6962

[32] M. K. Hossani, A. Rahman, S. Akhatar, Molar Interactions of Some Aromatic Hydrocarbons in n-Heptane by Viscometric Measurements at 298.15K, The Chittagong Univ. J. Sci. 40 (2018) 97-110. DOI: 10.3329/cujs.v40i1.47918

[33] Sh. Fujii, K. Tamura, S. Murakam, Thermodynamic properties of (an alkylbenzene+ cyclohexane) at the temperature 298.15 K. J Chem. Thermodynamics 27(12)(1995) 1319–28. https://www.sciencedirect.com/science/article/pii/S0021961485701401

[34] D.L. Prak, S.L. Graft, Th.R. Johnson, J.S. Cowart, P. C. Trulove, Binary mixtures of aromatic compounds (n-Propylbenzene, 1, 3, 5-trimethylbenzene, and 1, 2, 4-trimethylbenzene) with 2, 2, 4, 6, 6-pentamethylheptane: densities, viscosities, speeds of sound, bulk moduli, surface tensions, and flash points at 0.1 MPa. J. Chem. Eng. Data, 65(5)(2020) 2625-2641. https://pubs.acs.org/toc/jceaax/65/5

[35] R. Padmanaban, A. Gayathri, S. Kapoor, G. A. Iyengar, Dong-Eun Lee, V. Kannan, V. Karthikeyan, D. S. Assi, A.L. Vellaisamy Roy, Comparative Evaluation of Thermophysical and Acoustical Properties of Binary Mixtures of Cumene + Methyl Acetate and Cumene + Ethyl Acetate over the Range of Molar Compositions and Temperatures from 298.15 to 318.15 K: Experimental Measurements and Application of Deviation Modeling. J. Chem. Eng. Data. 70 (2025) 3491–3508. https://pubs.acs.org/toc/jceaax/70/9

[36] D S. Wankhede, Isentropic Compressibility for Binary Mixtures of Propylene Carbonate with Benzene and Substituted Benzene. Journal of the Korean Chemical Society. 56(1) (2012) 7-13. https://www.scimagojr.com/journalsearch.php?q=4700152644&tip=sid&clean=0

[37] S. C. Bhatia, R. Ruman, R. Bhatia, Viscosities, densities, speeds of sound and refractive indices of binary mixtures of o-xylene, m-xylene, p-xylene, ethylbenzene and mesitylene with 1-decanol at 298.15 and 308.15 K. Journal of Molecular Liquids. 159 (3) (2011) 132–141. https://www.sciencedirect.com/journal/journal-of-molecular-liquids/vol/159/issue/3

[38] O. Redlich, A.T. Kister, Algebraic representation of thermodynamic properties and the classification of solutions, Ind. Eng. Chem. 40 (1948) 345–348, https://doi. org/10.1021/ie50458a036

[39] E. C. Bingham, Fluidity and Plasticity, McGraw Hill, New York, (1922).

[40] D.B. Macleod, "On a direct calculation of the viscosity of a liquid, both under ordinary pressures and high pressures, from the viscosity of its vapour, on the basis of a new equation of state", Trans Faraday Soc., 41, 771-777, (1945).

[41] C.V. Suryanarayana and J. Kuppusami, J. Acoust. Soc. Ind. 4, 75 (1976).

[42] C.V. Suryanarayana, Ind. J. Pure Appl. Phys. 27, 751 (1989).

[43] J.H. Hildebrand, R.L. Scott, Regular Solutions (Prentice Hall, Englewood Cliffs, New Jersey, 1962).

[44] Chhikara Y, Yadav JS, Sharma D, Sharma VK. Excess molar volumes, excess molar enthalpies, and excess isentropic compressibilities of binary mixtures containing n-methyl-2-pyrrolidone and isomeric xylenes at 308.15 K. Journal of Solution Chemistry. 2012; 41(10):1696- 1712

[45] A. J. Treszczanowicz, O. Kiyohara, G. C. Benson, *J. Chem.Thermodynamics*, 253 (1981).

[46] T. M. Aminabhavi, M. I. Aralaguppi, S. B. Harpogoppad and R. H. Bulundgi, *J. Chem*. *Eng Data*, 38, 31(1993).

[47] J.M. Resa, C. Gonzalez, J. Lanz, J. A. Mtz. de Ilarduya, “Excess volumes for binary mixtures formed by methyl acetate with aromatic hydrocarbons,” J. of Thermal Anal. and Calorimetry, 52(3) (1998) 895 . https://kchem.org/journal/jkcs.

[48] J. M. Resa, C. Gonzalez, J. Lanz, J. A. Mtz. de Ilarduya, M. Iglesias, “Excess volumes of binary mixtures of vinyl acetate and aromatic hydrocarbons,” J. Chem. Thermodyn., 33(7) (2001) 723-732. https://www.sciencedirect.com/journal/the-journal-of-chemical-thermodynamics/vol/33/issue/7

[49] H. Nakayama, K. Shinoda, Enthalpies of mixing of water with some cyclic and linear ethers. J. Chem. Thermodynamics 3(3) (1971) 401-405. https://www.sciencedirect.com/science/article/abs/pii/S0021961471800575

[50] J.M. Resa, C. Gonzalez, R.G. Concha, M. Iglesias Influence of temperature on excess molar volumes for butyl acetate + aromatic hydrocarbons. Phy. Chem. Liq. 42 (5) (2004) 493-520. https://doi.org/10.1080/00319100410001724557

[51] C. Yang, P. Ma Q. Zhou, Excess molar volumes and viscosities of binary mixtures of sulfolane with benzene, toluene, ethylbenzene, *p*-xylene, *o*-xylene, and *m*-xylene at 303.15 and 323.15 K and atmospheric pressure, J. Chem. Eng. Data, 49(4) (2004) 881-885. https://pubs.acs.org/toc/jceaax/49/4

[52] W. Wang, W. Liu J. Huang, Densities and volumetric properties of a (xylene+ dimethyl sulfoxide) at temperature from (293.15 to 353.15) K, J. Chem. Thermodyn., 36 (9) (2004) 743-752. https://www.sciencedirect.com/journal/the-journal-of-chemical-thermodynamics/vol/36/issue/9