

Measurement and modeling of viscosity for binary mixtures of diisopropyl ether with n-alkanes (C₇-C₁₀)

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Abstract—The kinematic viscosity (ν) of binary mixture of diisopropyl ether+n-heptane or n-octane or n-nonane or n-decane was measured at 298.15 K, 308.15 and 318.15 K. Using experimental data, the deviation in kinematic viscosity ($\Delta\nu$) was calculated. The $\Delta\nu$ follows the sequence: n-heptane<n-octane<n-nonane<n-decane. The kinematic viscosity data were correlated by using various empirical equations suggested by Heric-Brewer, Krishnan-Ladda, Lulian et al. Predicted data using these empirical equations agree well with the experimental data. Kinematic viscosity data was also analyzed by applying the McAllister equation. Dynamic viscosity (η) for binary mixture of diisopropyl ether (DIPE)+n-heptane or n-octane was calculated using density data reported in earlier papers. Deviation in dynamic viscosity ($\Delta\eta$) was also calculated. Bloomfield and Dewan model was used to predict dynamic viscosity, and the predicted values agree well with experimental data for the present binary systems. The $\Delta\nu$ and $\Delta\eta$ values were fitted to Redlich-Kister polynomial equation. The effect of temperature on kinematic viscosity was also studied.

Keywords: Viscosity, Deviation In Kinematic Viscosity, Diisopropyl Ether, Alkanes, Intermolecular Interactions

INTRODUCTION

Environmental pollutants emitted from vehicles and various industries into air consist of CO₂ and CO cause various adverse effects on living beings. Researchers are, therefore, focused on the measurements of experimental data of various thermodynamic properties of possible mixtures containing oxygenates as octane booster and components of gasoline such as alkanes, cycloalkanes and aromatics over a wide temperature range, the knowledge of which is very helpful for designing and developing environmental friendly fuel [1-3]. Viscosity is an important physical property to get significant knowledge about the various types of molecular interactions taking place in the binary mixtures, which is very essential for the solutions of many engineering problems. Viscosity data for various liquids and liquid mixtures have been reported from time to time [4-11]. In the present work, kinematic viscosity (ν) of the binary mixture of diisopropyl ether (DIPE)+n-heptane or n-octane or n-nonane or n-decane was measured at 298.15 K, 308.15 and 318.15 K. Very few data are available for the viscosity of binary mixture of DIPE and n-alkanes [1-3]. As far as we know, ν for the present systems, except DIPE+n-heptane at 298.15 K, are not available in the literature.

Using experimental data, the deviation in kinematic viscosity ($\Delta\nu$) was calculated. The ν data were correlated by using various empirical equations suggested by Heric-Brewer, Krishnan-Ladda

and Lulian et al. The viscosity data was also analyzed by applying McAllister equation. The dynamic viscosity (η) for binary mixture of DIPE+n-heptane or n-octane was calculated using density data reported in earlier papers [12,13]. The deviation in dynamic viscosity ($\Delta\eta$) was also calculated. Bloomfield and Dewan model [14-16] was used to predict dynamic viscosity, and the predicted values agree well with experimental data for binary mixtures of DIPE+n-heptane or n-octane. The $\Delta\nu$ and $\Delta\eta$ values were fitted to Redlich-Kister polynomial equation. Effect of temperature on ν was also studied.

EXPERIMENTAL

DIPE (Sigma Aldrich) and n-alkanes (Junsei Chemical Co.) of analytical grade were preserved in amber colored bottles over molecular sieves (4A) for more than 72 hours. All chemicals were analyzed by gas chromatography for their purity and have purity greater than >99.6%. The ν of the pure compounds and binary mixture of DIPE+n-heptane or n-octane or n-nonane or n-decane was measured at 298.15 K-318.15 K using Ubbelohde viscometer. The viscometer was calibrated at working temperatures beforehand. Freshly distilled water was filled in the water thermostat up to the appropriate level. The viscometer was placed in specially designed stand so that it could be immersed in the water thermostat vertically. The samples were injected in the viscometer, and then viscometer was kept submerged in a thermostat bath (accuracy 0.01 K) for approximately 30 min to attain thermal equilibrium. Samples were pumped through the capillary of the viscometer until the upper part

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Table 1. Kinematic viscosities (ν) of the pure compounds

Compound	ν (mm ² ·s ⁻¹)					
	298.15 K		308.15 K		318.15 K	
	Exptl.	Lit.	Exptl.	Lit.	Exptl.	Lit.
Diisopropyl ether	0.4358	0.4355[2] 0.4356[17]	0.4073	0.3996[2] 0.3998[17]	0.3719	-
n-Heptane	0.5705	0.5711[18] 0.5712[7] 0.5768[19]	0.5241	0.5204[18] 0.5219[7] 0.5276[19]	0.4789	0.4790[7]
n-Octane	0.7266	0.7226[18] 0.7245[7] 0.7273[19]	0.6601	0.6516[18] 0.6520[7] 0.6564[19]	0.6019	0.591[7]
n-Nonane	0.9207	0.9132[18] 0.9167[8] 0.9246[19]	0.8227	0.8129[18] 0.8164[8] 0.8218[19]	0.7404	0.7224[8]
n-Decane	1.1566	1.1619[18] 1.1438[8] 1.1677[19]	1.0144	1.0200[18] 0.9974[8] 1.029[19]	0.9040	0.87011[8]

^aStandard uncertainties u are $u(\nu)=0.001 \text{ mm}^2\text{s}^{-1}$, $u(T)=0.01 \text{ K}$. The range of Ubbelohde viscometer utilized in this experiment was approximately 0.5 to 3 mm²·s⁻¹

of the measuring cell filled with the fixed volume of the sample (approximately 6 cm³). Then the sample flowed down and the time of flow through the capillary was noted carefully. It was repeated for 3-4 times for each sample and the average value was considered as the flow time. Accuracy of flow measurement time was 0.01 s. The characteristic constants A and B of viscometer were then determined from the measured time of flow of two liquids of known viscosities at desired temperatures by using following equation.

$$\nu_i = A t_i - \frac{B}{t_i} \quad (1)$$

where ν , t_i are the kinematic viscosity and time of flow in seconds of pure liquids, respectively. For the viscometer, the values of constants at 298.15 K are $A=3.2642 \times 10^{-3} \text{ mm}^2\text{s}^{-2}$, $B=2.5755 \text{ mm}^2$ and at 308.15 K are $A=3.2616 \times 10^{-3} \text{ mm}^2\text{s}^{-2}$, $B=1.4772 \text{ mm}^2$ and at 318.15 K

are $A=3.2958 \times 10^{-3} \text{ mm}^2\text{s}^{-2}$, $B=2.5179 \text{ mm}^2$. The ν values of the pure compounds were calculated using Eq. (1) and agree well with their respective literature [2,7,8,17-19] values as shown in Table 1. The estimated averaged standard uncertainty ($u(\nu)$) was calculated in the manner described elsewhere [4] and found to be less than 0.001 mm²·s⁻¹. The binary mixture samples (approximately 15 ml) were prepared using weight balance (OHAUS Co. DV215CD) having the precision of $1 \times 10^{-5} \text{ g}$. The error in the sample preparation is estimated to be less than 1×10^{-4} in mole fraction. Viscosity deviations ($\Delta \nu$) were calculated from the experimental viscosities of the pure and mixture samples.

RESULTS AND DISCUSSION

The experimental ν values of binary mixture of DIPE and n-

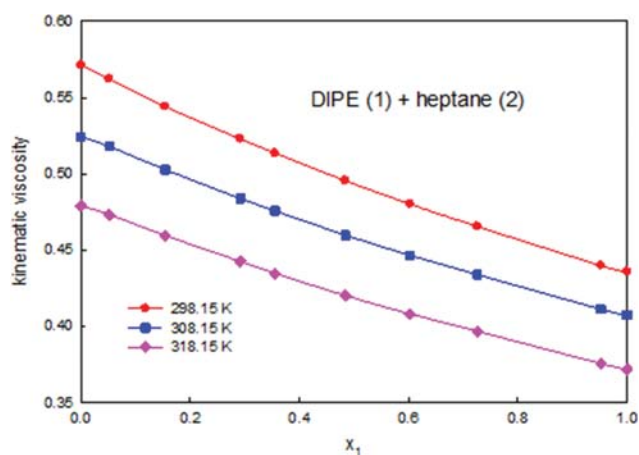


Fig. 1. Kinematic viscosity, ν (mm²·s⁻¹) of binary mixture of DIPE (1)+n-heptane (2) at 298.15 K, 308.15 K and 318.15 K.

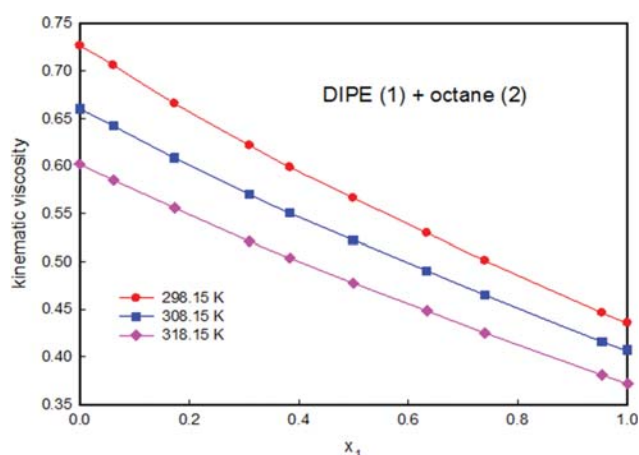


Fig. 2. Kinematic viscosity, ν (mm²·s⁻¹) of binary mixture of DIPE (1)+n-octane (2) at 298.15 K, 308.15 K and 318.15 K.

Table 2. Experimental kinematic viscosity (ν) and deviation in kinematic viscosity ($\Delta \nu$) of binary mixtures at 298.15 K, 308.15 K and 318.15 K

x1	298.15 K		308.15 K		318.15 K	
	$\nu/\text{mm}^2\cdot\text{s}^{-1}$	$\Delta \nu/\text{mm}^2\cdot\text{s}^{-1}$	$\nu/\text{mm}^2\cdot\text{s}^{-1}$	$\Delta \nu/\text{mm}^2\cdot\text{s}^{-1}$	$\nu/\text{mm}^2\cdot\text{s}^{-1}$	$\Delta \nu/\text{mm}^2\cdot\text{s}^{-1}$
DIPE (1)+n-heptane (2)						
0.0000	0.5712	0.0000	0.5241	0.0000	0.4789	0.0000
0.0521	0.5620	-0.0021	0.5178	-0.0002	0.4732	-0.0002
0.1541	0.5440	-0.0063	0.5027	-0.0034	0.4596	-0.0029
0.2916	0.5229	-0.0088	0.4838	-0.0063	0.4426	-0.0052
0.3551	0.5135	-0.0096	0.4757	-0.0070	0.4348	-0.0062
0.4842	0.4954	-0.0102	0.4598	-0.0078	0.4202	-0.0070
0.6026	0.4801	-0.0094	0.4466	-0.0072	0.4082	-0.0063
0.7259	0.4654	-0.0074	0.4339	-0.0055	0.3968	-0.0045
0.9520	0.4398	-0.0024	0.4112	-0.0017	0.3756	-0.0015
1.0000	0.4358	0.0000	0.4073	0.0000	0.3719	0.0000
DIPE (1)+n-octane (2)						
0.0000	0.7266	0.0000	0.6601	0.0000	0.6019	0.0000
0.0610	0.7061	-0.0028	0.6423	-0.0024	0.5854	-0.0024
0.1729	0.6659	-0.0104	0.6087	-0.0077	0.5562	-0.0060
0.3098	0.6219	-0.0146	0.5702	-0.0116	0.5212	-0.0095
0.3835	0.5988	-0.0163	0.5507	-0.0125	0.5037	-0.0100
0.4993	0.5666	-0.0149	0.5226	-0.0113	0.4776	-0.0095
0.6338	0.5299	-0.0124	0.4905	-0.0094	0.4485	-0.0077
0.7398	0.5011	-0.0104	0.4651	-0.0080	0.4253	-0.0065
0.9535	0.4466	-0.0028	0.4160	-0.0030	0.3811	-0.0015
1.0000	0.4359	0.0000	0.4073	0.0000	0.3719	0.0000
DIPE (1)+n-nonane (2)						
0.0000	0.9207	0.0000	0.8227	0.0000	0.7404	0.0000
0.0833	0.8750	-0.0053	0.7857	-0.0024	0.7096	-0.0001
0.1643	0.8257	-0.0154	0.7431	-0.0113	0.6750	-0.0049
0.2348	0.7859	-0.0210	0.7099	-0.0153	0.6459	-0.0080
0.3655	0.7129	-0.0306	0.6476	-0.0232	0.5899	-0.0158
0.4960	0.6459	-0.0344	0.5888	-0.0278	0.5370	-0.0206
0.6203	0.5900	-0.0300	0.5418	-0.0232	0.4946	-0.0172
0.7305	0.5412	-0.0253	0.5010	-0.0182	0.4593	-0.0120
0.8331	0.4986	-0.0182	0.4636	-0.0131	0.4249	-0.0085
0.9505	0.4531	-0.0068	0.4256	-0.0023	0.3896	-0.0006
1.0000	0.4359	0.0000	0.4073	0.0000	0.3719	0.0000
DIPE (1)+n-decane (2)						
0.0000	1.1566	0.0000	1.0144	0.0000	0.9040	0.0000
0.0912	1.0755	-0.0155	0.9476	-0.0115	0.8477	-0.0078
0.2512	0.9299	-0.0457	0.8287	-0.0332	0.7496	-0.0207
0.3861	0.8206	-0.0577	0.7326	-0.0474	0.6657	-0.0328
0.4822	0.7425	-0.0666	0.6690	-0.0527	0.6099	-0.0375
0.5793	0.6800	-0.0591	0.6166	-0.0461	0.5620	-0.0337
0.6399	0.6411	-0.0543	0.5850	-0.0409	0.5328	-0.0307
0.7468	0.5721	-0.0463	0.5253	-0.0358	0.4788	-0.0279
0.8557	0.5113	-0.0285	0.4721	-0.0228	0.4312	-0.0175
0.9553	0.4566	-0.0115	0.4245	-0.0100	0.3873	-0.0084
1.0000	0.4358	0.0000	0.4073	0.0000	0.3719	0.0000

^aStandard uncertainties u are $u(\nu)=0.001 \text{ mm}^2\text{s}^{-1}$, $u(T)=0.01 \text{ K}$. The range of Ubbelohde viscometer utilized in this experiment was approximately 0.5 to 3 $\text{mm}^2\cdot\text{s}^{-1}$

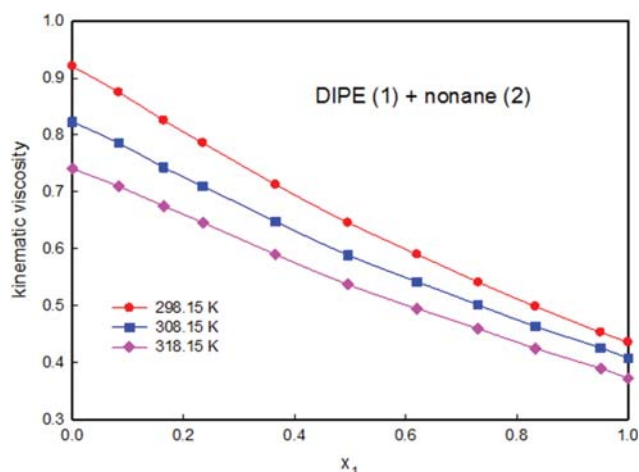


Fig. 3. Kinematic viscosity, ν ($\text{mm}^2 \cdot \text{s}^{-1}$) of binary mixture of DIPE (1)+n-nonane (2) at 298.15 K, 308.15 K and 318.15 K.

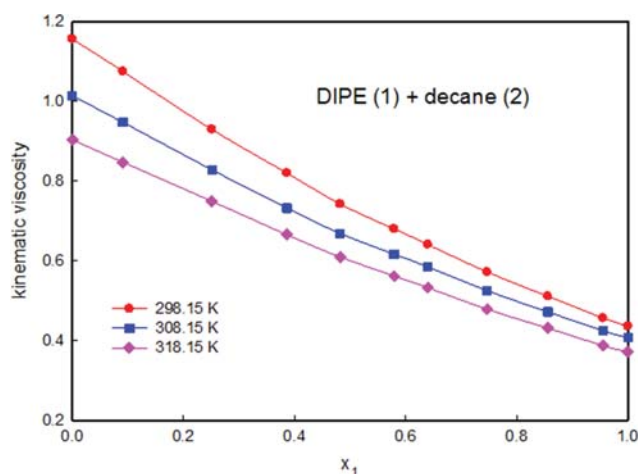


Fig. 4. Kinematic viscosity, ν ($\text{mm}^2 \cdot \text{s}^{-1}$) of binary mixture of DIPE (1)+n-decane (2) at 298.15 K, 308.15 K and 318.15 K.

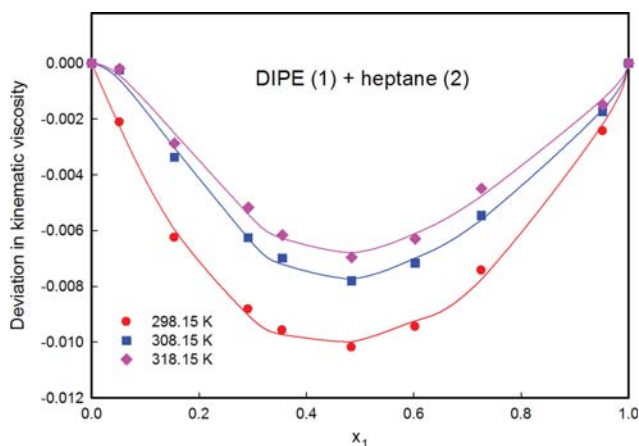


Fig. 5. $\Delta\nu$ ($\text{mm}^2 \cdot \text{s}^{-1}$) of binary mixture of DIPE (1)+n-heptane (2) at 298.15 K, 308.15 K and 318.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

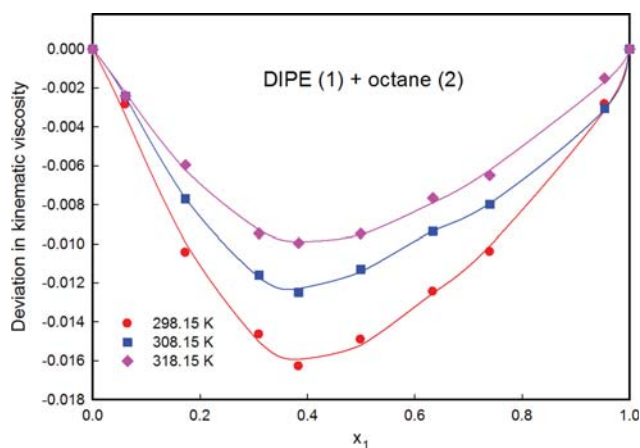


Fig. 6. $\Delta\nu$ ($\text{mm}^2 \cdot \text{s}^{-1}$) of binary mixture of DIPE (1)+n-octane (2) at 298.15 K, 308.15 K and 318.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

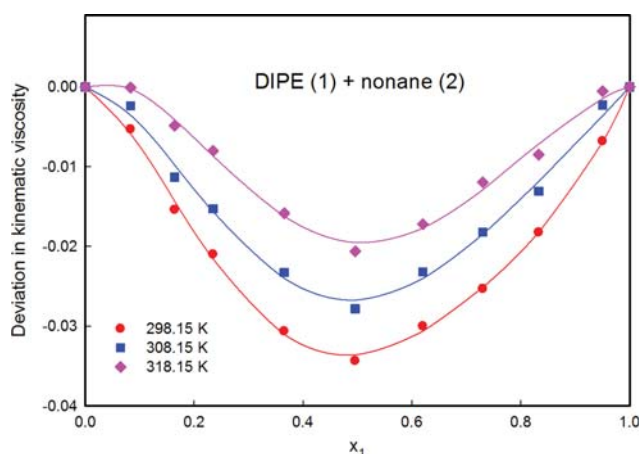


Fig. 7. $\Delta\nu$ ($\text{mm}^2 \cdot \text{s}^{-1}$) of binary mixture of DIPE (1)+n-nonane (2) at 298.15 K, 308.15 K and 318.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

alkanes (C_7 – C_{10}) measured at 298.15 K–318.15 K are listed in Table 2 and shown in Figs. 1–4. From this experimental data, $\Delta\nu$ was calculated using Eq. (2). The $\Delta\nu$ values are given in Table 2 and shown in Figs. 5–8.

$$\Delta X = X - X_1 x_1 - X_2 x_2 \quad (2)$$

where $X = (\nu, \eta)$, x_1 and x_2 are the mole fractions of pure components in binary mixture. The $\Delta\nu$ values were fitted to Redlich-Kister Eq. (3).

$$\Delta X = x_1(1-x_1) \left[\sum_{n=1}^4 X_n (2x_1-1)^n \right] \quad (3)$$

where $X = (\nu, \eta)$ and X_n are Redlich-Kister equation parameters. The Redlich-Kister equation parameters for $\Delta\nu$ along with standard deviation, $\sigma(\Delta X)$, calculated using Eq. (4) are listed in Table 3.

$$\sigma(\Delta X) = \left\{ \frac{\sum (\Delta X_{\text{exptl.}} - \Delta X_{\text{calcd. (Eq. (2))}})^2}{(m-n)} \right\}^{1/2} \quad (4)$$

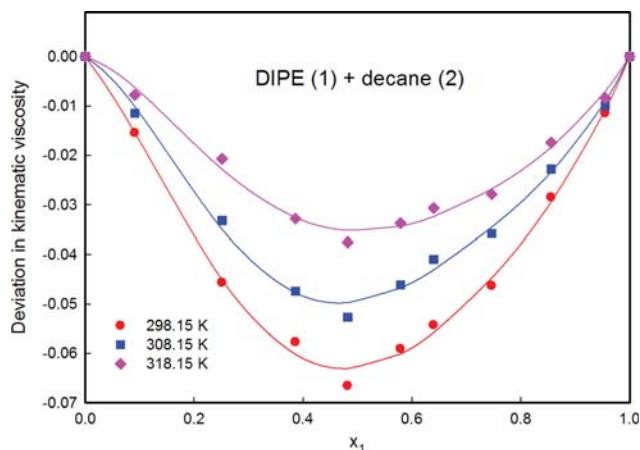


Fig. 8. $\Delta\nu$ ($\text{mm}^2\cdot\text{s}^{-1}$) of binary mixture of DIPE (1)+n-decane (2) at 298.15 K, 308.15 K and 318.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

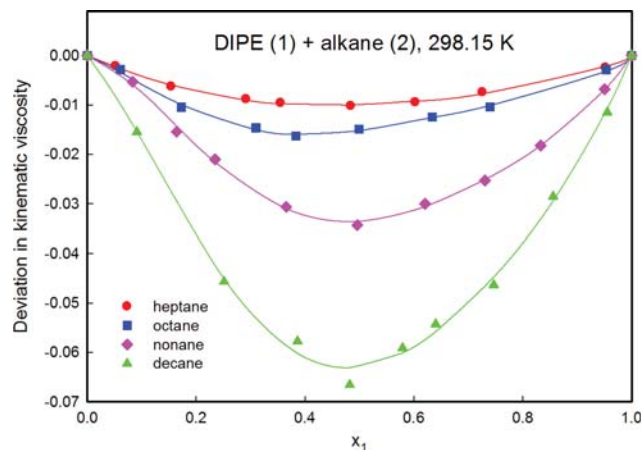


Fig. 9. $\Delta\nu$ ($\text{mm}^2\cdot\text{s}^{-1}$) of binary mixture of DIPE (1)+n-alkanes (2) at 298.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

All binary mixtures have negative value for $\Delta\nu$ and follow the sequence n-heptane < n-octane < n-nonane < n-decane as shown in Figs. 9-11. Negative deviation indicates a weak interaction among unlike molecules. The $\Delta\nu$ values become more negative with the addition of more alkyl group. In DIPE+n-alkane (C₇-C₁₀), there are no specific interactions between the components molecules and $\Delta\nu$ is due to disorder in orientation of hydrocarbon or breaking of cohesion forces between straight chain of hydrocarbons. Viscosity is temperature-dependent. The $\Delta\nu$ values becomes less negative with increase the temperature as shown in Figs. 5-8 because the viscosity of liquids decreases with increase in temperature. At high temperatures, molecules have high energy, overcome strong cohesive forces and move freely. So, the cohesive forces between the molecules of liquids decrease as temperature increases.

McAllister [20] proposed a semi-empirical equation based on Eyring's theory of absolute reaction rates, assuming three body or four body interactions, which has been used for correlating the experimental mixture data by many researchers. The present ν data were also correlated with McAllister model assuming three body interaction using following equation:

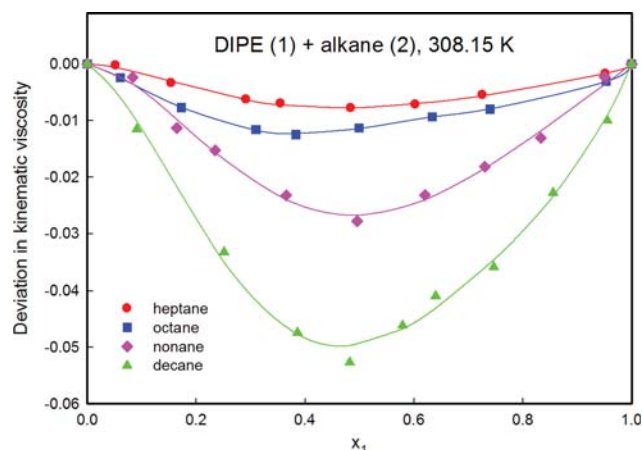


Fig. 10. $\Delta\nu$ ($\text{mm}^2\cdot\text{s}^{-1}$) of binary mixture of DIPE (1)+n-alkanes (2) at 308.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

$$\ln \nu = x_1^3 \ln \nu_1 + 3x_1^2 x_2 \ln \nu_{12} + 3x_1 x_2^2 \ln \nu_{21} + x_2^3 \ln \nu_2 - \ln [x_1 + x_2 M_2 / M_1] + 3x_1^2 x_2 \ln [(1 + 2M_2 / M_1) / 3] + 3x_1 x_2^2 \ln [(1 + 2M_2 / M_1) / 3] + x_2^3 \ln [M_2 / M_1] \quad (5)$$

Table 3. Redlich-Kister equation parameters for deviation in kinematic viscosity ($\Delta\nu$) and standard deviation $\sigma(\Delta\nu)$

System	Temp	ν_1	ν_2	ν_3	ν_4	$\sigma(\Delta\nu)$
DIPE (1)+n-heptane (2)	298.15	-0.0397	0.0079	-0.0087	-0.0110	0.0003
	308.15	-0.0308	0.0071	0.0084	-0.0253	0.0002
	318.15	-0.0270	0.0062	0.0108	-0.0208	0.0003
DIPE (1)+n-octane (2)	298.15	-0.0397	0.0079	-0.0087	-0.0110	0.0003
	308.15	-0.0308	0.0071	0.0084	-0.0253	0.0002
	318.15	-0.0270	0.0062	0.0108	-0.0208	0.0003
DIPE (1)+n-nonane (2)	298.15	-0.1343	0.0131	0.0367	-0.0731	0.0007
	308.15	-0.1069	0.0071	0.0637	-0.0382	0.0012
	318.15	-0.0781	-0.0067	0.0833	-0.02	0.0009
DIPE (1)+n-decane (2)	298.15	-0.2518	0.0262	0.0546	-0.0923	0.0019
	308.15	-0.1980	0.0328	0.0556	-0.1195	0.0018
	318.15	-0.1410	-0.0038	0.0381	-0.0675	0.0017

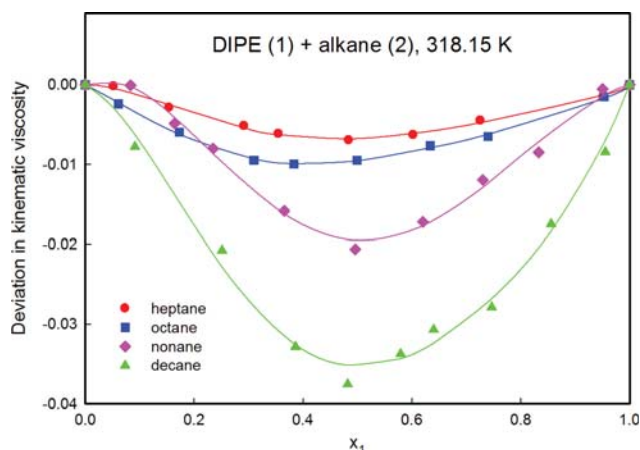


Fig. 11. $\Delta\nu$ ($\text{mm}^2\cdot\text{s}^{-1}$) of binary mixture of DIPE (1)+n-alkanes (2) at 318.15 K. Symbol represent experimental values and line represent values calculated from Redlich Kister parameters.

M_1 and M_2 are the molar mass of pure components, ν_{12} and ν_{21} are the adjustable parameters, which were determined by fitting kinematic viscosity-composition data to Eq. (5). ν_1 , ν_2 and ν are the kinematic viscosities of pure components and the binary liquid mixture, respectively. The estimated parameters of McAllister equation along with their percentage standard deviation calculated using Eq. (9) are given in Table 4. The percentage standard deviation for all binary systems was found to be less than 1.2 percent, which indicates that the McAllister model is able to correlate kinematic viscosity data for present systems well.

The ν data were correlated too by using an empirical equation suggested by Heric and Brewer [21]:

$$\ln(\nu M) = x_1 \ln(\nu_1 M_1) + x_2 \ln(\nu_2 M_2) + x_1 x_2 [A_1 + A_2(x_1 - x_2) + A_3(x_1 - x_2)^2] \quad (6)$$

where M is the average molecular weight of the binary mixture and A_1 , A_2 and A_3 are unknown binary constants.

Krishnan and Ladda [22] suggested the following model for correlating the kinematic viscosity data of binary liquid mixtures.

$$\ln \nu = x_1 \ln(\nu_1 M_1) + x_2 \ln(\nu_2 M_2) - \ln(x_1 M_1 + x_2 M_2) \quad (7)$$

Table 4. Parameters of McAllister equation (ν_{12} , ν_{21}) and the corresponding percentage standard deviation σ (%)

System	T/K	ν_{12}	ν_{21}	σ (%)
DIPE (1)+n-heptane (2)	298.15	0.4657	0.5160	0.16
	308.15	0.4249	0.4871	0.41
	318.15	-0.8092	0.4452	0.39
DIPE (1)+n-octane (2)	298.15	0.5264	0.6103	0.45
	308.15	0.4880	0.5598	0.41
	318.15	0.4524	0.5092	0.31
DIPE (1)+n-nonane (2)	298.15	0.5757	0.7404	0.82
	308.15	0.5323	0.6740	1.05
	318.15	0.4917	0.6161	1.16
DIPE (1)+n-decane (2)	298.15	0.6715	0.8359	0.73
	308.15	0.6096	0.7458	0.68
	318.15	0.5611	0.6745	0.62

$$-2.303x_1x_2[B_1+B_2(x_1-x_2)+B_3(x_1-x_2)^2+B_4(x_1-x_2)^3]$$

where B_1 , B_2 , B_3 and B_4 are unknown binary constants, which may be predicted using vapor-liquid equilibrium data or calculated from experimental data for kinematic viscosity of binary liquid mixtures. Values of unknown binary constants were calculated using experimental data in this work.

Lulian et al. [23,24] suggested also the following empirical equations to predict the ν data.

$$\ln \nu = x_1 \ln(\nu_1 M_1) + x_2 \ln(\nu_2 M_2) - \ln(x_1 M_1 + x_2 M_2) - x_1 x_2 [C_1 + C_2(x_1 - x_2) + C_3(x_1 - x_2)^2 + C_4(x_1 - x_2)^3] \quad (8)$$

where C_1 , C_2 , C_3 and C_4 are unknown binary constants. The unknown binary constants used in above Eqs. (5), (6) and (7) were calculated using experimental data.

The predicted ν data using various empirical equations suggested by Heric and Brewer [21], Krishnan and Ladda [22], Lulian et al. [24] agree well with the experimental data. For numerical comparison of the estimation capability of various correlations, the percentage standard deviation (σ (%)) was calculated using the following equation:

$$\sigma(\%) = 100 \times \left[\frac{\sum \{ (X_{\text{exptl.}} - X_{\text{calcd.}}) / X_{\text{exptl.}} \}^2}{(n-1)} \right]^{1/2} \quad (9)$$

where n is the number of experimental points. Comparison of the above correlation in terms of percentage standard deviation calculated using Eq. (9) is given in Table 5. Predicted data using these empirical equations agree well with the experimental data with percentage standard deviation less than 0.72 for all studied binary systems.

Dynamic viscosity for DIPE (1)+heptane (2) and DIPE (1)+octane (2) was also calculated using experimental ν data and density data reported in our earlier papers [12,13]. The $\Delta\eta$ values were also calculated using Eq. (1) and were fitted to the Redlich-Kister equation. The Redlich-Kister equation parameters for $\Delta\eta$ along with standard deviation, $\sigma(\Delta\eta)$, are listed in Table 6.

Bloomfield and Dewan [14-16] developed a model to predict η

Table 5. Percentage standard deviation of calculated values of dynamic viscosity using various correlations Heric-Brewer (H-B), Krishnan-Ladda (K-L), Lulian et al. (Lu) at 298.15 K, 308.15 K and 318.15 K

System	T/K	H-B	K-L	Lu
DIPE (1)+n-heptane (2)	298.15	0.06	0.05	0.10
	308.15	0.08	0.27	0.20
	318.15	0.11	0.34	0.26
DIPE (1)+n-octane (2)	298.15	0.12	0.05	0.46
	308.15	0.15	0.09	0.40
	318.15	0.18	0.23	0.26
DIPE (1)+n-nonane (2)	298.15	0.15	0.09	0.16
	308.15	0.17	0.28	0.32
	318.15	0.59	0.71	0.61
DIPE (1)+n-decane (2)	298.15	0.28	0.24	0.37
	308.15	0.35	0.37	0.60
	318.15	0.72	0.49	0.30

Table 6. Redlich-Kister equation parameters for $\Delta\eta$ and standard deviation $\sigma(\Delta\eta)$

	T/K	η_1	η_2	η_3	η_4	$\sigma(\Delta\eta)$
DIPE (1)+n-heptane (2)	298.15	-0.0248	0.0055	-0.0062	-0.0089	0.0002
	308.15	-0.0190	0.0047	0.0054	-0.0179	0.0002
	318.15	-0.0164	0.0040	0.0069	-0.0141	0.0002
DIPE (1)+n-octane (2)	298.15	-0.0406	0.0209	-0.0029	-0.0327	0.0003
	308.15	-0.0304	0.0187	-0.0080	-0.0372	0.0001
	318.15	-0.0252	0.0114	0.0005	-0.0143	0.0001

from a combination of theories of free volume and absolute reaction rate. This model was used to predict experimental η data in the present study. The $\Delta\eta$ can also be defined as follows according to Bloomfield and Dewan:

$$\Delta\ln\eta = \ln\eta - (x_1\ln\eta_1 + x_2\ln\eta_2) \quad (10)$$

where η is dynamic viscosity of binary mixture and η_1 and η_2 are the dynamic viscosity of pure components. To calculate, $\Delta\ln\eta$, Bloomfield and Dewan developed the following expression from the combination of the theories of free volume and absolute reaction rate:

$$\Delta\ln\eta = -\frac{\Delta G^R}{RT} + f(\tilde{V}) \quad (11)$$

where ΔG^R is the residual Gibbs free energy of mixing, which is the sum of an enthalpic and an entropic contribution, whereas $f(\tilde{V})$ is a characteristic function of the free volume defined as follows:

$$f(\tilde{V}) = \frac{1}{\tilde{V}-1} - \frac{x_1}{\tilde{V}_1-1} - \frac{x_2}{\tilde{V}_2-1} \quad (12)$$

where \tilde{V} is the reduced volume. The thermodynamic properties can be obtained from the statistical theory of liquid mixtures proposed by Flory and co-workers [25,26]. This theory treats the properties of mixtures in terms of reduced properties of the pure compounds with a single interaction parameter. This procedure has been chosen for the evaluation of the ΔG^R and $f(\tilde{V})$ terms. Thus ΔG^R can be obtained using Eq. (13).

$$\Delta G^R = \Delta G^E + RT \left(x_1 \ln \frac{x_1}{\phi_1} + x_2 \ln \frac{x_2}{\phi_2} \right) \quad (13)$$

where ΔG^E is excess Gibbs free energy, which can be obtained from the statistical theory of liquid mixtures proposed by Flory and Coworkers and calculated using Eq. (14).

$$\begin{aligned} \Delta G^E = & x_1 P_1^* V_1^* \left[\frac{1}{\tilde{V}_1} - \frac{1}{\tilde{V}} + 3\tilde{T}_1 \ln \left(\frac{\tilde{V}_1^{1/3} - 1}{\tilde{V}^{1/3} - 1} \right) \right] \\ & + x_2 P_2^* V_2^* \left[\frac{1}{\tilde{V}_2} - \frac{1}{\tilde{V}} + 3\tilde{T}_2 \ln \left(\frac{\tilde{V}_2^{1/3} - 1}{\tilde{V}^{1/3} - 1} \right) \right] + \frac{x_1 \theta_2 V_1^* \chi_{12}}{\tilde{V}} \end{aligned} \quad (14)$$

The ΔG^E data were calculated from Eq. (14) along with the following set of equations [25,26]:

$$\tilde{T} = \frac{\tilde{V}^{1/3} - 1}{\tilde{V}^{4/3}} \quad (15)$$

$$\tilde{V} = \psi_1 \tilde{V}_1 + \psi_2 \tilde{V}_2 \quad (16)$$

$$\tilde{V}_i = \left(\frac{1 + (4/3)\alpha_i T}{1 + \alpha_i T} \right)^3 \quad (17)$$

$$P^* = \frac{T \tilde{V}_i^2 \alpha_i}{\kappa_i} \quad (18)$$

$$\psi_1 = 1 - \psi_2 = \frac{\phi_1 P_1^*}{\phi_1 P_1^* + \phi_2 P_2^*} \quad (19)$$

$$\phi_1 = 1 - \phi_2 = \frac{x_1 V_1^*}{x_1 V_1^* + x_2 V_2^*} \quad (20)$$

$$\theta_1 = 1 - \theta_2 = \frac{x_1 V_1^* (S_1/S_2)}{x_1 V_1^* + x_2 V_2^*} \quad (21)$$

$$(S_1/S_2) = (V_1^*/V_2^*)^{-1/3} \quad (22)$$

Table 7. Molar volume (V), isobaric expansivity (α), isothermal compressibility (κ_T), characteristic pressure (P^*), characteristic molar volume (V^*) and characteristic temperature (T^*) obtained from Flory theory for the pure liquids at 298.15 K, 308.15 K and 318.15 K

Compound	T/K	V/cm ³ mol ⁻¹	10 ³ α /K ⁻¹	10 ⁶ κ_T /cm ³ J ⁻¹	P [*] /J cm ⁻³	V [*] /cm ³ mol ⁻¹	T [*] /K
DIPE	298.15	141.89	1.435	1817.0	417.00	106.64	4368
	308.15	144.32	1.490	1987.7	420.25	107.00	4378
	318.15	146.55	1.540	2255.0	405.54	107.27	4400
n-Heptane	298.15	147.46	1.253	1459.2	427.43	113.70	4654
	308.15	149.34	1.280	1584.5	430.63	113.97	4686
	318.15	151.30	1.310	1730.7	422.12	114.3	4717
n-Octane	298.15	163.49	1.164	1297.3	438.56	127.70	4827
	308.15	165.41	1.198	1415.2	437.18	127.77	4838
	318.15	167.40	1.204	1526.0	426.39	128.4	4906

Table 8. Experimental dynamic viscosity (η , Exptl.) and dynamic viscosity (η , BFD) calculated using Bloomfield and Dewan Model of binary mixtures at 298.15 K, 308.15 K and 318.15 K

x_1	298.15 K		308.15 K		318.15 K	
	η , Exptl./mPa·s	η , BFD/mPa·s	η , Exptl./mPa·s	η , BFD/mPa·s	η , Exptl./mPa·s	η , BFD/mPa·s
DIPE (1)+n-heptane (2)						
0.0000	0.388	0.388	0.352	0.352	0.317	0.317
0.0521	0.383	0.383	0.348	0.347	0.314	0.314
0.1541	0.373	0.373	0.340	0.339	0.307	0.307
0.2916	0.361	0.361	0.329	0.329	0.297	0.298
0.3551	0.356	0.356	0.325	0.325	0.293	0.294
0.4842	0.346	0.346	0.316	0.316	0.285	0.286
0.6026	0.337	0.338	0.309	0.309	0.279	0.279
0.7259	0.329	0.329	0.302	0.302	0.272	0.273
0.9520	0.316	0.316	0.290	0.291	0.261	0.262
1.0000	0.314	0.314	0.288	0.288	0.259	0.259
DIPE (1)+n-octane (2)						
0.0000	0.508	0.508	0.456	0.456	0.411	0.411
0.0610	0.494	0.493	0.444	0.444	0.400	0.400
0.1729	0.467	0.468	0.422	0.423	0.381	0.382
0.3098	0.438	0.439	0.396	0.397	0.358	0.358
0.3835	0.422	0.423	0.383	0.384	0.347	0.346
0.4993	0.401	0.401	0.365	0.365	0.329	0.329
0.6338	0.376	0.375	0.344	0.343	0.309	0.310
0.7398	0.357	0.356	0.327	0.326	0.294	0.294
0.9535	0.320	0.321	0.294	0.295	0.265	0.265
1.0000	0.313	0.313	0.288	0.288	0.259	0.259

where P_i^* , V_i^* and T_i^* are characteristic pressure, volume and temperature of the pure components and obtained by dividing pressure, volume and temperature by corresponding reduced values (\tilde{P}_i^* , \tilde{V}_i^* , \tilde{T}_i^*) and reported in Table 7.

In these equations ψ_i , ϕ_i , θ_i are the molar contact energy fractions, hard core volume fraction, molecular surface fraction, whereas \tilde{T} , \tilde{V} are the reduced temperature, reduced volume for the mixtures. In this model, properties in terms of reduced properties of pure compounds with single interaction parameter (χ_{12}) have been used to calculate η of binary mixture. Various thermodynamic properties for the pure compounds used in above equations are given in Table 7. The interaction parameter, χ_{12} , used to calculate ΔG^E is usually calculated using excess enthalpy data. Some researchers also used χ_{12} calculated from Prigogine-Flory-Patterson theory for excess molar volume. Initially, we also used χ_{12} calculated from Prigogine-Flory-Patterson theory for excess molar volume given in

our earlier paper [12,13], but agreement of predicted data was not so good. Therefore, we used experimental η data at equimolar composition to calculate χ_{12} . The η data predicted using this χ_{12} agrees well with experimental values. The χ_{12} values along with percentage standard deviation calculated using Eq. (8) are given in Table 9. Thus, the Bloomfield and Dewan model is able to predict experimental η values using physical properties of pure compounds coupled with experimental values of binary mixtures at one composition (here, equimolar mixtures).

CONCLUSION

The kinematic viscosity (ν) of binary mixture of DIPE+n-heptane or n-octane or n-nonane or n-decane was measured at 298.15 K, 308.15 and 318.15 K. Using experimental data, the deviation in kinematic viscosity ($\Delta\nu$) was calculated. The $\Delta\nu$ follows the sequence n-heptane<n-octane<n-nonane<n-decane. The $\Delta\nu$ value becomes less negative with increase in the temperature as viscosity of liquids decreases with increase in temperature. The ν data have been correlated by using various empirical equations suggested by Heric-Brewer, Krishnan-Ladda, Lulian et al. Predicted data using these empirical equations agree well with the experimental data with percentage standard deviation less than 0.72. The ν data was also analyzed by applying the McAllister equation. The η data for binary mixture of DIPE (1)+n-heptane or n-octane were calculated using density data reported in earlier paper. Bloomfield and Dewan model was used to predict the η data, and the pre-

Table 9. Fitting parameter (χ_{12}) and percentage standard deviation ($\sigma(\%)$) of calculated values of dynamic viscosity using Bloomfield and Dewan model of binary mixtures at 298.15 K, 308.15 K and 318.15 K

T/K	DIPE (1)+n-heptane (2)		DIPE (1)+n-octane (2)	
	χ_{12}	$\sigma(\%)$	χ_{12}	$\sigma(\%)$
298.15	0.995	0.09	-0.634	0.19
308.15	0.363	0.12	-1.233	0.19
318.15	0.062	0.17	-2.125	0.29

dicted values agree well with experimental data for the present binary systems of DIPE (1)+n-heptane (2) and DIPE (1)+n-octane (2) with percentage standard deviation less than 0.3.

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