

VOLUMETRIC AND VISCOMETRIC STUDY OF AQUEOUS SOLUTION OF ETHYLENE GLYCOL, PROPYLENE GLYCOL IN ISO-PROPANOL

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ABSTRACT

Densities, ρ and viscosities, η of 0.5 m, 1.0 m and 1.5 m aqueous ethylene glycol and propylene glycol solutions in *iso*-propanol have been measured over the entire composition range at 308.15 K. From this experimental data, deviation in viscosity, $\Delta\eta$, excess free volume, V_f^E , excess internal pressure, π_i^E , excess enthalpy, H^E and excess Gibbs free energy of activation of viscous flow, ΔG^E have been determined. It has been observed that viscosity increases first and attained a maximum value thereafter decreases. Negative values of V_f^E and positive values of $\Delta\eta$, π_i^E , H^E , ΔG^E are observed over the entire composition range in the mixtures studied. The observed negative and positive values of various excess and deviation parameters are attributed to the existence of strong interactions such as geometrical fitting of smaller molecules into the voids created by larger molecules in the liquid mixtures. The measured values of viscosity for all the investigated solutions have been compared with the theoretically estimated values using empirical relations such as, Grunberg, Hind and Frenkel.

Keywords: Density, Viscosity, Excess free volume, Redlich-Kister polynomial.

1. INTRODUCTION

Aqueous solutions play a vital role for many geological processes in various environments, such as geothermal and magmatic hydrothermal settings. Ultrasonic energy is used in medicine, engineering, agriculture, defence and industry. It is found to be useful in studying the chemical processes and in synthesis of chemical substances in chemical industries. Water and alcohol mixtures show unique maxima and minima in their thermodynamic and acoustic properties at low alcohol concentrations¹⁻⁴. The formation of such maxima/minima in aqueous solutions of electrolytes⁵ and in non-aqueous solutions^{6,7} is also reported in literature.

Thermodynamic and transport studies of aqueous non electrolyte solutions of 0.5 m, 1.0 m and 1.5 m ethylene glycol/propylene glycol (non-electrolytes) in *iso*-propanol have been presented in this work. Masso Sakura⁸ reported the partial molar volumes of ethylene glycol and water solutions at multi temperatures 15, 25, 35 and 45°C. Speeds of sound and viscosities in aqueous poly (ethylene glycol) solutions at 303.15 K and 308.15 K were presented by Pal and Wazir Singh⁹. Kanhekar *et al*¹⁰ studied the thermodynamic properties in aqueous solution of glycine at different temperatures. Molecular interionic interaction studies of divalent transition metal sulphates in aqueous ethylene glycol at different temperatures were studied by Thirumaran and

Sathish¹¹, Peiming *et al*¹² studied the thermodynamic and transport properties of ethylene glycol and its mixtures with water and electrolytes. Zafarani-Moattar *et al*¹³ reported the volumetric and transport properties of glycol+water solutions.

From the experimental results of density (ρ) and viscosity (η) deviation in viscosity, $\Delta\eta$, excess free volume, V_f^E , excess internal pressure, π_i^E , excess enthalpy, H^E and excess Gibbs free energy of activation of viscous flow, ΔG^{*E} have been determined and are discussed in terms of molecular interactions in the present investigated solutions.

2. EXPERIMENTAL

Ethylene glycol (EG), propylene glycol (PG) and *iso*-propanol (IPA) used in the present study were the AR grade products from LOBA Chemicals, India and were purified by standard methods described in the literature^{14,15}. The mass fraction purity of liquids obtained is > 0.995 . Before use, the chemicals were stored over 0.4 μ m molecular sieves approximately for 72 h to remove water content and degassed.

The solutions of aqueous ethylene glycol and aqueous propylene glycol of 0.5 m, 1.0 m and 1.5 m (molality) are prepared using triply distilled deionised water. These solutions, in turn, are used to prepare liquid mixture with *iso*-propanol so that its entire range of composition is covered (0 to 100% of *iso*-propanol). Mixtures are prepared by mass in air tight bottles. The mass measurements are performed with a METTLER TOLEDO (Switzerland make) ABB5-S/FACT digital balance with an accuracy ± 0.01 mg. Densities and viscosities of pure liquids and liquid solutions are determined using 5 cm³ two stem double walled Parker & Parker type pycnometer¹⁶ and Ostwald viscometer which is calibrated as described by Subrahmanyam Naidu and Ravindra Prasad¹⁷ using triply distilled water respectively. The detailed description of measurement of density and viscosity are discussed in our previous papers¹⁸⁻²⁰. The densities and viscosities of pure liquids in this investigation at temperature of 308.15 K are compiled in Table 1 together with the literature data²¹⁻²⁵ available. These results are found to be in good agreement with reported data.

3. RESULTS AND DISCUSSION

The variation of density and viscosity with mole fraction of *iso*-propanol in aqueous ethylene glycol and propylene glycol is presented in Table 2. The

variation of viscosity in the mixtures of *iso*-propanol and aqueous ethylene/propylene glycol is presented in figures 1a and 1b. The viscosity of the systems rises with increasing concentration of *iso*-propanol and attained a maximum afterwards viscosity decreased with increase in concentration of *iso*-propanol. Water and ethylene glycol/propylene glycol are both associated liquids, associated through hydrogen bonding. When these glycols are added to water association between glycols and water molecules takes place through hydrogen bonding. This leads to the increase of open structures in the solution as diol acts as a structure maker. Generally, the viscosity of a system decreases with increasing number of smaller entities and decreasing number of bulk or less mobile entities in the system²⁶. Viscosity increases with decreasing number of small entities and increasing number of bulk entities or less mobile entities. A peak in the viscosity is an indication of strong interactions involving dipole-dipole associations, acceptor-donor type interactions and other interactions that favour complex formation between component molecules. It is well known that alcohol molecules are highly polar and in addition they can accept as well donate protons. Hence, the dipole-dipole interactions and acceptor-donor type interactions are also possible in addition to the already explained hydrogen bonding interaction. The viscosity of the systems is decreasing with increase of *iso*-propanol concentration in the *iso*-propanol region. This may primarily be due to the domination of dissociation of hydrogen bonded clusters present in the solution over associative interaction operating between the component molecules.

Study of deviation/excess properties plays an important role in the study of molecular interactions. The deviation/excess properties of $\Delta\eta$, V_f^E , π_i^E , H^E and ΔG^{*E} of aqueous ethylene glycol and propylene glycol are presented in Tables 3 and 4 respectively. The variation of deviation in viscosity is presented in figures 2a and 2b. The positive values of deviation in viscosity suggest that specific interactions are operative in the system^{27,28} where as negative values of deviation in viscosity indicate that dispersive forces arising from weak molecular interactions are operative in the system. The deviation in viscosity values are positive in the present investigated systems suggests that specific interactions such as formation of new hydrogen bonds, formation of charge transfer

complexes, dipole-dipole interactions and other complex forming interactions are dominant in the systems investigated as the alcohols are highly polar and water is also polar.

Figures 3a and 3b represent respectively the variation of excess free volume for the mixtures of *iso*-propanol + aqueous ethylene glycol/propylene glycol. These excess values are negative over the entire composition range of mixtures. This suggests that the component molecules are more close together in the liquid mixture than in the pure liquids forming the mixture, indicating that strong attractive interactions between component molecules such as hydrogen bonding, dipole-dipole interactions. The geometrical fitting/interstitial accommodation of smaller molecules in the voids created by bigger molecules also favourable for the observed negative free volume^{27,29-31}.

The variation of excess internal pressure, excess enthalpy and excess Gibbs free energy is presented in figures 4a, 4b, 5a, 5b, 6a and 6b for *iso*-propanol + aqueous ethylene glycol solution and *iso*-propanol + aqueous propylene glycol solution respectively. From these figures it is observed that all the excess properties are positive over the entire composition range of *iso*-propanol. These positive values indicate that strong specific interactions are operative in the systems investigated.

Some of the deviation/excess properties have been fitted to Redlich-Kister³² type polynomial equation. The values of coefficients A_i in the R-K polynomial have been determined using the least square method and standard deviations $\sigma(Y^E)$ calculated using the standard equations are compiled in Table 5. From the above discussion it is observed that strength of interaction is more in *iso*-propanol + 0.5 m aqueous ethylene/propylene glycol compared to *iso*-propanol + 1.0 m aqueous ethylene/propylene glycol and *iso*-propanol + 1.5 m aqueous ethylene/propylene/glycol. When compared to glycols strength of interaction is predominant in case of propylene glycol than ethylene glycol.

The dynamic viscosities of the binary liquid mixtures have been calculated using Grunberg and Nissan, Hind and Ubbelohde and Frenkel empirical relations (detailed discussion on these theories was explained in our previous papers). These theoretical values and viscosity and percentage error are presented in Tables 6 and 7 for *iso*-propanol + aqueous ethylene glycol and for *iso*-propanol + aqueous propylene glycol solutions respectively. The interaction terms in the

empirical relations are adjustable parameters representing the binary interactions in the empirical relations presented in Table 8 along with the standard deviations, σ . These results are in good agreement with the results derived from the excess properties. Prolongo *et al*³³ reported positive values of interaction parameter corresponding to systems with negative excess molar volumes. This is in good agreement with our results. The estimated values of σ are smaller indicating that experimental values of viscosities are well correlated by all the four viscosity models.

4. CONCLUSIONS

The mixtures of *iso*-propanol with aqueous ethylene glycol and aqueous propylene glycol with three different molalities 0.5 m, 1.0 m and 1.5 m have been prepared at 308.15 K.

- (i) From the experimental results deviation/excess properties like deviation in viscosity, excess free volume, excess enthalpy, excess internal pressure and excess Gibbs free energy of activation viscous flow are evaluated and some of these properties have been fitted to Redlich-Kister type polynomial.
- (ii) The positive and negative deviation/excess properties are attributed to strong specific interactions such as formation hydrogen bond, dipole-dipole interactions and geometrical fitting of smaller entities in to larger entities.
- (iii) The strength of interaction is predominant in case of propylene glycol compared to ethylene glycol in *iso*-propanol solution. On comparison of molalities, interaction is more in 0.5 m aqueous glycol with *iso*-propanol compared other two molalities.
- (iv) The experimental viscosity values are compared with the viscosity values obtained from different empirical relations and these are in good agreement with the experimental values.

Table 1: Comparison of densities (ρ) and viscosities (η) of pure liquids with literature data at 308.15 K

Compound	$\rho/\text{kg}\cdot\text{m}^{-3}$		$\eta/10^{-3}\text{N}\cdot\text{s}\cdot\text{m}^{-2}$	
	present work	Literature	present work	literature
Water	994.06	994.10[21]	0.719	0.721[21]
Ethylene glycol	1102.60	1102.90[22]	10.968	10.590[22]
<i>Iso</i> -propanol	771.66	772.20[23]	1.494	1.546[24]
		772.88[24]		1.494[25]

Table 2: Experimental values of densities (ρ) and viscosities (η) with mole fraction of *iso*-propanol, x in aqueous ethylene glycol/propylene glycol solutions at 308.15 K

x	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta/10^{-3}\text{N}\cdot\text{s}\cdot\text{m}^{-2}$	x	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta/10^{-3}\text{N}\cdot\text{s}\cdot\text{m}^{-2}$
0.5 m aqueous ethylene glycol			0.5 m aqueous propylene glycol		
0.0000	999.00	0.752	0.0000	997.63	0.762
0.0560	985.41	1.003	0.0635	984.64	0.879
0.1186	970.14	1.324	0.1314	972.83	1.131
0.1811	954.87	1.625	0.2092	962.44	2.066
0.2606	933.86	1.826	0.2996	940.22	2.053
0.3402	912.82	1.954	0.3904	934.58	2.034
0.4604	876.64	2.104	0.4948	898.24	2.012
0.5399	866.78	2.052	0.5966	868.20	1.924
0.6793	838.82	1.726	0.7442	823.62	1.664
0.8212	811.58	1.543	0.8345	808.22	1.585
1.0000	771.66	1.494	1.0000	771.66	1.494
1.0 m aqueous ethylene glycol			1.0 m aqueous propylene glycol		
0.0000	1003.32	0.773	0.0000	999.63	0.793
0.0477	993.08	1.091	0.0677	985.83	1.002
0.1148	976.34	1.455	0.1287	973.12	1.448
0.1816	959.37	1.819	0.2078	953.89	1.757
0.2634	934.25	2.005	0.2986	932.65	1.954
0.3433	913.13	2.053	0.3762	914.30	2.243
0.4416	888.44	1.965	0.4822	887.42	2.192
0.5404	865.84	1.878	0.5860	862.81	2.038
0.6746	836.80	1.704	0.7268	827.65	1.786
0.8198	807.67	1.558	0.8477	805.41	1.537
1.0000	771.66	1.494	1.0000	771.66	1.494
1.5 m aqueous ethylene glycol			1.5 m aqueous propylene glycol		
0.0000	1005.00	0.859	0.0000	1001.26	0.847
0.0540	993.58	1.104	0.0643	988.59	1.062
0.1186	976.34	1.432	0.1310	975.58	1.567
0.1828	959.98	1.654	0.2049	957.91	1.775
0.2486	940.62	1.842	0.2934	932.56	1.845
0.3162	920.05	1.906	0.3811	910.06	1.969
0.4468	877.86	1.964	0.4862	884.64	1.873
0.5401	862.96	1.868	0.5802	862.09	1.793
0.6723	835.34	1.717	0.7104	836.46	1.732
0.8222	804.52	1.607	0.8402	802.87	1.611
1.0000	771.66	1.494	1.0000	771.66	1.494

Table 3: Calculated properties of deviation in viscosity, $\Delta\eta$, excess free volume, V_f^E , excess internal pressure, π_i^E , excess enthalpy, H^E and excess Gibbs free energy of activation of viscous flow, ΔG^{*E} with mole fraction, x of *iso*-propanol (x) in aqueous ethylene glycol solution at $T = 308.15$ K

x	$\Delta\eta/10^{-3}\text{N}\cdot\text{s}\cdot\text{m}^{-2}$	$V_f^E/10^{-7}\text{m}^3\cdot\text{mol}^{-1}$	$\pi_i^E/10^6\text{Pa}$	$H^E/\text{J}\cdot\text{mol}^{-1}$	$\Delta G^{*E}/\text{kJ}\cdot\text{mol}^{-1}$
0.5 m aqueous ethylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0560	0.209	-0.2168	103.47	3960.4	0.6500
0.1186	0.484	-0.3589	207.90	8578.7	1.2617
0.1811	0.739	-0.4319	295.89	12905.5	1.6856
0.2606	0.881	-0.4414	328.74	15285.7	1.8582
0.3402	0.950	-0.4286	335.55	16622.4	1.9035
0.4604	1.010	-0.3976	336.28	18167.8	1.8878
0.5399	0.899	-0.3476	284.00	16066.6	1.6804
0.6793	0.470	-0.2092	134.65	7950.5	0.9760
0.8212	0.182	-0.1089	63.74	3760.0	0.4147
1.0000	0.000	0.0000	0.00	0.0	0.0000
1.0 m aqueous ethylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0477	0.284	-0.2648	140.02	5588.4	0.8074
0.1148	0.599	-0.3964	260.30	10940.4	1.4428
0.1816	0.915	-0.4613	363.48	16100.5	1.9126
0.2634	1.042	-0.4566	380.99	18150.4	2.0454
0.3433	1.032	-0.4302	363.74	18420.6	1.9828
0.4416	0.874	-0.3719	296.39	16102.8	1.7122
0.5404	0.715	-0.3070	227.50	13158.2	1.4276
0.6746	0.445	-0.1999	124.28	7768.7	0.9416
0.8198	0.194	-0.1088	61.69	4127.3	0.4447
1.0000	0.000	0.0000	0.00	0.0	0.0000
1.5 m aqueous ethylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0540	0.211	-0.1567	90.23	3581.6	0.5712
0.1186	0.498	-0.2812	197.42	8410.4	1.1593
0.1828	0.679	-0.3277	257.88	11556.1	1.4474
0.2486	0.825	-0.3500	298.60	14264.9	1.6464
0.3162	0.846	-0.3475	305.91	15577.9	1.6535
0.4468	0.821	-0.3131	274.80	15658.6	1.5622
0.5401	0.666	-0.2565	203.13	12458.9	1.3009
0.6723	0.431	-0.1690	112.34	7598.6	0.8841
0.8222	0.226	-0.1048	67.90	5097.4	0.4808
1.0000	0.000	0.0000	0.00	0.0	0.0000

Table 4: Calculated properties of deviation in viscosity, $\Delta\eta$, excess free volume, V_f^E , excess internal pressure, π_i^E , excess enthalpy, H^E and excess Gibbs free energy of activation of viscous flow, ΔG^{*E} with mole fraction, x of *iso*-propanol (x) in aqueous propylene glycol solution at $T = 308.15$ K

X	$\Delta\eta/10^{-3}\text{N}\cdot\text{s}\cdot\text{m}^{-2}$	$V_f^E/10^{-7}\text{m}^3\cdot\text{mol}^{-1}$	$\pi_i^E/10^6\text{Pa}$	$H^E/\text{J}\cdot\text{mol}^{-1}$	$\Delta G^{*E}/\text{kJ}\cdot\text{mol}^{-1}$
0.5 m aqueous propylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0635	0.071	-0.0936	20.27	508.4	0.2531
0.1314	0.273	-0.2999	97.35	3847.5	0.7725
0.2092	1.151	-0.6369	400.41	18946.3	2.1622
0.2996	1.072	-0.5821	385.96	17873.4	1.9562
0.3904	0.986	-0.5175	347.39	16253.0	1.7709
0.4948	0.888	-0.4508	306.71	15390.9	1.5889
0.5966	0.725	-0.3687	242.33	13026.4	1.3254
0.7442	0.357	-0.2152	121.13	6700.7	0.7149

0.8345	0.212	-0.1316	68.48	3784.9	0.4373
1.0000	0.000	0.0000	0.00	0.0	0.0000
1.0 m aqueous propylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0677	0.162	-0.1990	60.51	2442.8	0.4854
0.1287	0.565	-0.4662	209.10	9568.9	1.3264
0.2078	0.818	-0.5322	288.49	13810.1	1.6964
0.2986	0.952	-0.5298	325.97	16130.9	1.8179
0.3762	1.186	-0.5356	385.41	20151.2	2.0508
0.4822	1.061	-0.4666	341.03	18722.3	1.8261
0.5860	0.834	-0.3790	265.94	15177.6	1.4742
0.7268	0.484	-0.2436	154.54	9105.5	0.9062
0.8477	0.150	-0.1015	48.90	2527.3	0.3205
1.0000	0.000	0.0000	0.00	0.0	0.0000
1.5 m aqueous propylene glycol					
0.0000	0.000	0.0000	0.00	0.0	0.0000
0.0643	0.173	-0.1823	63.46	2607.8	0.4808
0.1310	0.635	-0.4425	229.66	10555.0	1.3741
0.2049	0.795	-0.4745	278.60	13229.9	1.5873
0.2934	0.808	-0.4544	280.07	13930.6	1.5690
0.3811	0.875	-0.4386	293.10	15358.6	1.6159
0.4862	0.711	-0.3660	237.30	12814.6	1.3357
0.5802	0.571	-0.2999	187.47	10521.5	1.0924
0.7104	0.425	-0.2145	131.16	7819.3	0.8164
0.8402	0.220	-0.1156	65.21	4111.6	0.4403
1.0000	0.000	0.0000	0.00	0.0	0.0000

Table 5: Coefficients A_i of Redlich-Kister type polynomial equation and the corresponding standard deviations, σ of all the systems under investigation

property	A_0	A_1	A_2	A_3	A_4	σ
iso-propanol with 0.5 m aqueous ethylene glycol						
$\Delta\eta/10^{-3}\text{N.m}^{-2}\text{s}$	3.762	3.267	-3.042	-1.399	2.273	0.041
$V_f^E/10^{-7}\text{m}^3\text{.mol}^{-1}$	-1.4785	-1.3589	-0.0346	-0.7054	-1.7194	0.0090
$\Delta G^E/\text{kJ.mol}^{-1}$	7.0514	5.8959	-1.9406	1.0995	3.2025	0.0595
iso-propanol with 1.0 m aqueous ethylene glycol						
$\Delta\eta/10^{-3}\text{N.m}^{-2}\text{s}$	3.104	3.941	3.065	-0.632	-4.207	0.020
$V_f^E/10^{-7}\text{m}^3\text{.mol}^{-1}$	-1.3564	-1.4072	-0.3006	-1.0788	-2.6764	0.0099
$\Delta G^E/\text{kJ.mol}^{-1}$	6.1891	6.6193	4.5215	2.3932	-1.0381	0.0303
iso-propanol with 1.5 m aqueous ethylene glycol						
$\Delta\eta/10^{-3}\text{N.m}^{-2}\text{s}$	2.929	3.114	0.444	-1.842	-0.386	0.017
$V_f^E/10^{-7}\text{m}^3\text{.mol}^{-1}$	-1.1256	-1.1845	-0.3028	0.0271	-1.2669	0.0046
$\Delta G^E/\text{kJ.mol}^{-1}$	5.6481	5.3285	1.6840	-0.6475	1.0360	0.0285
iso-propanol with 0.5 m aqueous propylene glycol						
$\Delta\eta/10^{-3}\text{N.m}^{-2}\text{s}$	3.362	4.492	6.389	-5.054	-17.402	0.154
$V_f^E/10^{-7}\text{m}^3\text{.mol}^{-1}$	-1.6738	-2.0376	-4.5498	0.4705	8.4537	0.0496
$\Delta G^E/\text{kJ.mol}^{-1}$	5.9228	6.9251	14.2575	-2.8149	-29.7586	0.2195
iso-propanol with 1.0 m aqueous propylene glycol						

$\Delta\eta/10^{-3}\text{N.m}^{-2}.\text{s}$	4.112	3.186	-1.578	-1.506	-1.200	0.063
$V_f^E/10^{-7}\text{m}^3.\text{mol}^{-1}$	-1.7670	-1.4875	-1.8159	-1.0999	2.1154	0.0331
$\Delta G^E/\text{k.J.mol}^{-1}$	7.0129	5.3491	1.8675	0.8515	-6.3945	0.1102
iso-propanol with 1.5 m aqueous propylene glycol						
$\Delta\eta/10^{-3}\text{N.m}^{-2}.\text{s}$	2.713	2.741	3.806	-0.705	-5.754	0.060
$V_f^E/10^{-7}\text{m}^3.\text{mol}^{-1}$	-1.3841	-1.3377	-2.2345	-0.9334	1.8151	0.0319
$\Delta G^E/\text{k.J.mol}^{-1}$	5.0863	4.7944	7.6501	0.9251	-8.8091	0.1118

Table 6: Theoretical values of viscosity from various empirical relations with mole fraction, x of iso-propanol with aqueous ethylene glycol at 308.15 K

x	Grunberg	Hind	Frenkel
0.5 m aqueous ethylene glycol			
0.0000	0.752	0.752	0.752
0.0560	0.925	0.992	0.939
0.1186	1.139	1.232	1.172
0.1811	1.367	1.443	1.424
0.2606	1.664	1.669	1.754
0.3402	1.945	1.847	2.068
0.4604	2.281	2.026	2.441
0.5399	2.409	2.085	2.578
0.6793	2.404	2.074	2.551
0.8212	2.112	1.913	2.199
1.0000	1.494	1.494	1.494
1.0 m aqueous ethylene glycol			
0.0000	0.773	0.773	0.773
0.0477	0.938	0.977	0.977
0.1148	1.198	1.235	1.312
0.1816	1.480	1.459	1.691
0.2634	1.836	1.687	2.185
0.3433	2.165	1.862	2.650
0.4416	2.491	2.012	3.107
0.5404	2.675	2.090	3.342
0.6746	2.637	2.079	3.210
0.8198	2.246	1.916	2.564
1.0000	1.494	1.494	1.494
1.5 m aqueous ethylene glycol			
0.0000	0.859	0.859	0.859
0.0540	1.022	1.080	1.030
0.1186	1.232	1.316	1.251
0.1828	1.449	1.520	1.481
0.2486	1.670	1.698	1.716
0.3162	1.884	1.848	1.945
0.4468	2.211	2.044	2.292
0.5401	2.336	2.108	2.422
0.6723	2.322	2.089	2.397
0.8222	2.046	1.914	2.090
1.0000	1.494	1.494	1.494

Table 7: Theoretical values of viscosity from various empirical relations with mole fraction, x of iso-propanol with aqueous propylene glycol at 308.15 K

x	Grunberg	Hind	Frenkel
0.5 m aqueous propylene glycol			
0.0000	0.762	0.762	0.762
0.0635	0.931	1.031	0.956
0.1314	1.125	1.286	1.184
0.2092	1.358	1.535	1.462
0.2996	1.623	1.767	1.783
0.3904	1.858	1.939	2.067
0.4948	2.058	2.060	2.301
0.5966	2.150	2.100	2.395
0.7442	2.079	2.019	2.264
0.8345	1.925	1.890	2.048
1.0000	1.494	1.494	1.494
1.0 m aqueous propylene glycol			
0.0000	0.793	0.793	0.793
0.0677	0.997	1.075	1.003
0.1287	1.196	1.300	1.211
0.2078	1.468	1.550	1.494
0.2986	1.774	1.780	1.815
0.3762	2.007	1.928	2.058
0.4822	2.243	2.058	2.304
0.5860	2.346	2.105	2.409
0.7268	2.253	2.040	2.302
0.8477	1.983	1.867	2.011
1.0000	1.494	1.494	1.494
1.5 m aqueous propylene glycol			
0.0000	0.847	0.847	0.847
0.0643	1.031	1.109	1.051
0.1310	1.234	1.348	1.281
0.2049	1.466	1.576	1.547
0.2934	1.735	1.795	1.857
0.3811	1.967	1.957	2.125
0.4862	2.167	2.076	2.352
0.5802	2.248	2.114	2.435
0.7104	2.189	2.059	2.342
0.8402	1.949	1.882	2.037
1.0000	1.494	1.494	1.494

Table 8: various interaction parameters calculated from various empirical relations and the corresponding standard deviations ($\sigma/10^{-3} \text{ N.s.m}^{-2}$) of all the systems at 308.15 K

G_{12}	σ	H_{12}	σ	η_{12}	σ
0.5 m aqueous ethylene glycol					
3.194	0.423	0.003	0.239	0.006	0.514
1.0 m aqueous ethylene glycol					
3.565	0.646	0.003	0.328	0.010	1.093
1.5 m aqueous ethylene glycol					
2.824	0.399	0.003	0.242	0.006	0.446
0.5 m aqueous propylene glycol					
2.641	0.420	0.003	0.335	0.005	0.470
1.0 m aqueous propylene glycol					
2.941	0.353	0.003	0.258	0.005	0.370
1.5 m aqueous propylene glycol					
2.655	0.373	0.003	0.264	0.005	0.475

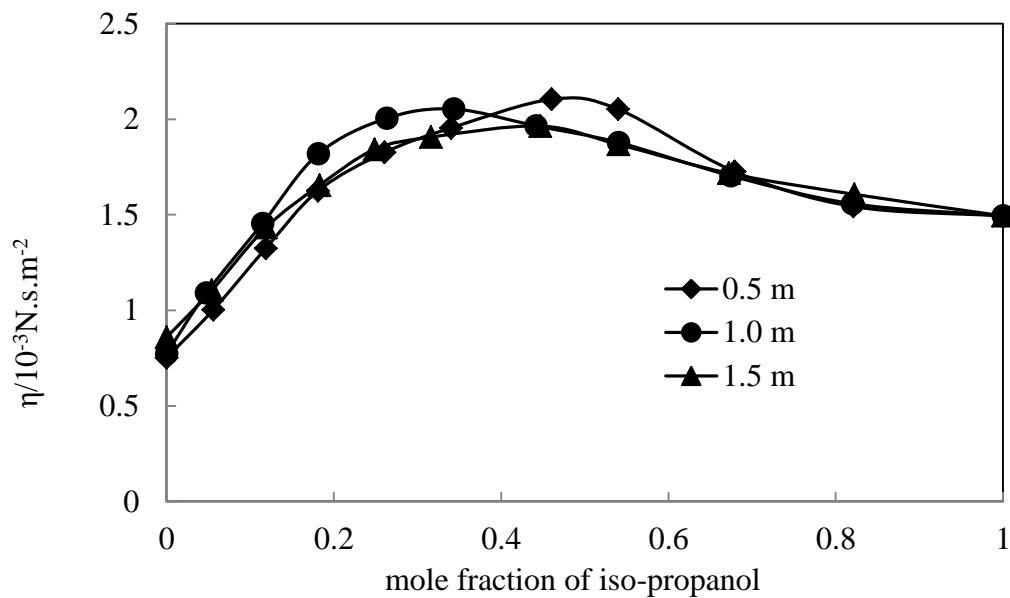


Figure 1a. Variation of viscosity (η) in the mixtures of iso-propanol with aqueous ethylene glycol

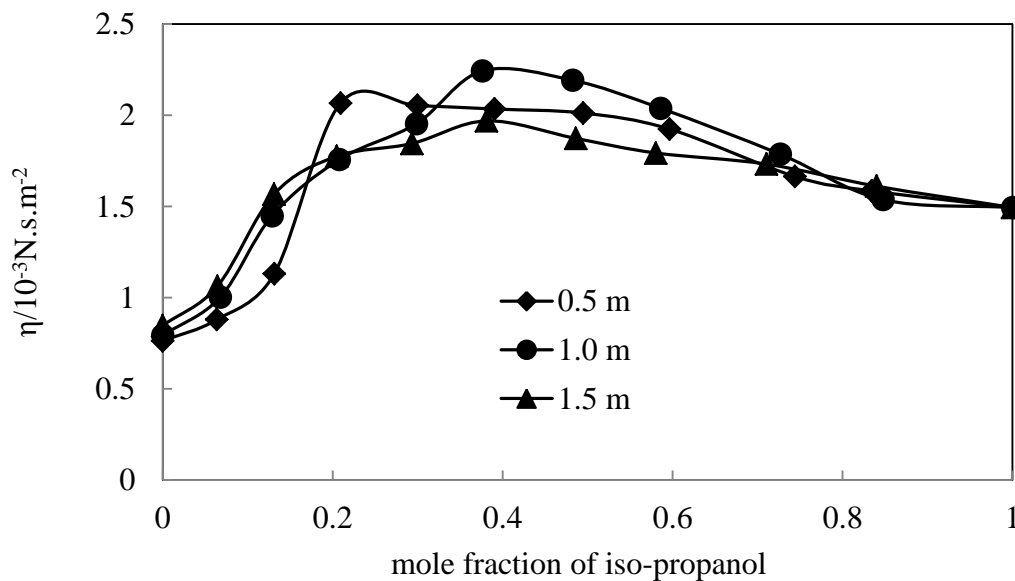


Figure 1b. Variation of viscosity (η) in the mixtures of iso-propanol with aqueous propylene glycol

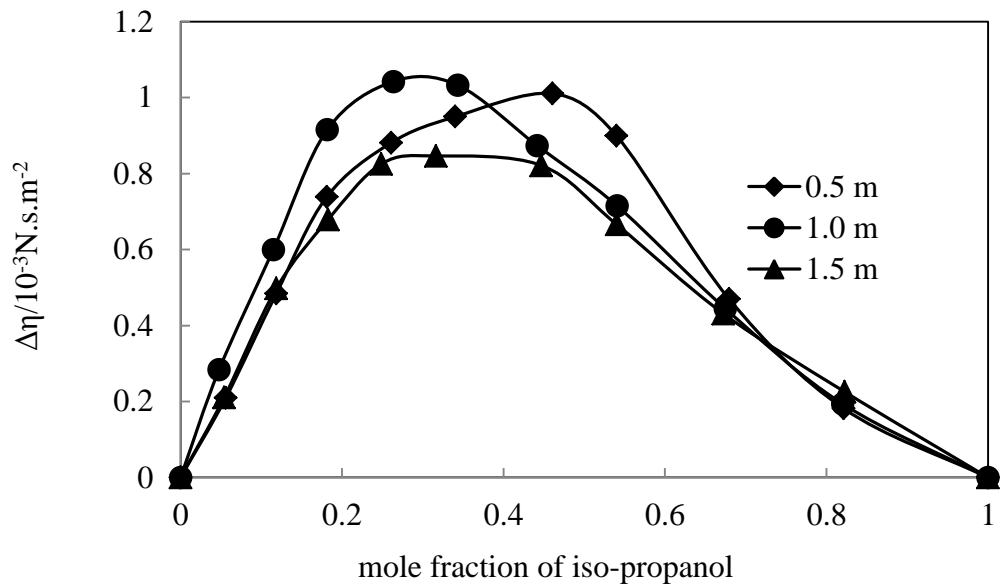


Figure 2a. Variation of deviation in viscosity ($\Delta\eta$) in the mixtures of iso-propanol with aqueous ethylene glycol

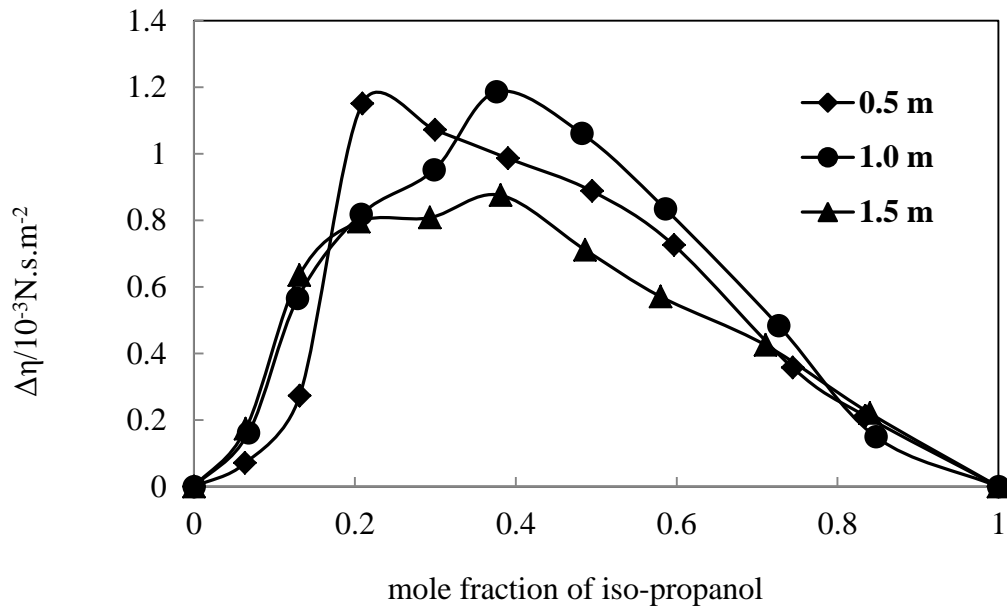


Figure 2b. Variation of deviation in viscosity ($\Delta\eta$) in the mixtures of iso-propanol with aqueous propylene glycol

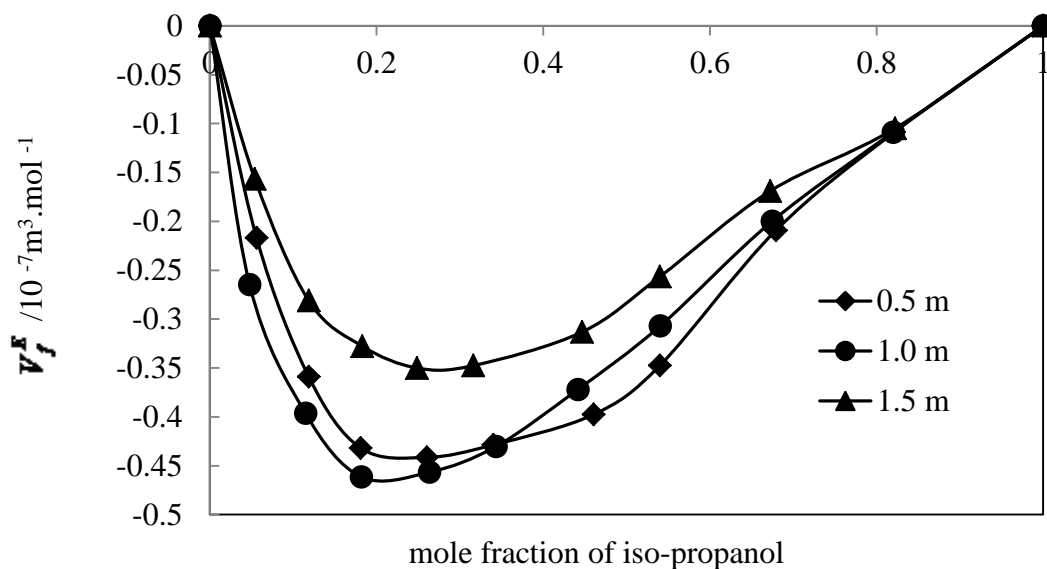


Figure 3a. Variation of excess free volume (V_f^E) in the mixtures of iso-propanol with aqueous ethylene glycol

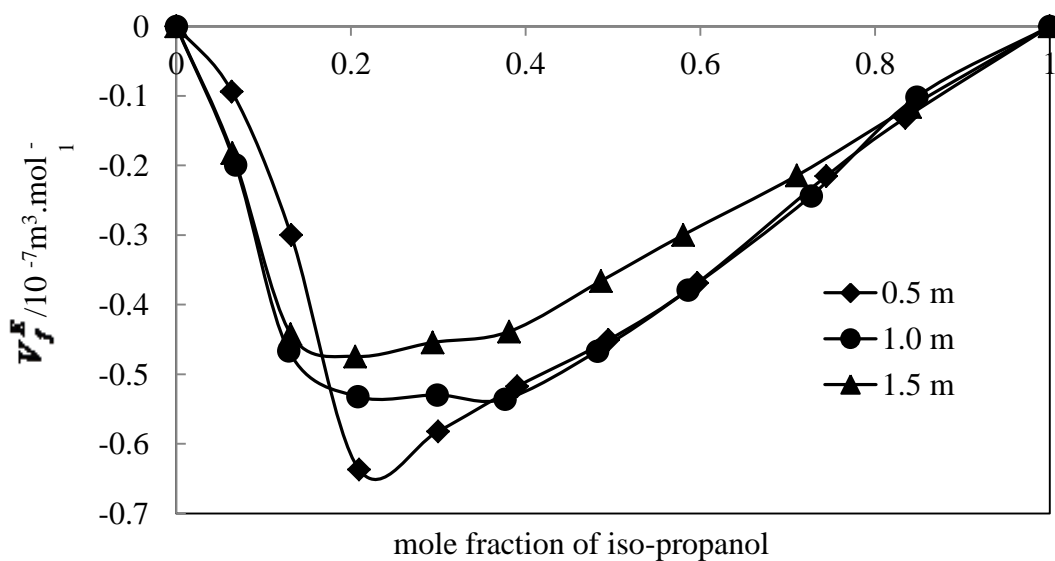


Figure 3b. Variation of excess free volume (V_f^E) in the mixtures of iso-propanol with aqueous propylene glycol

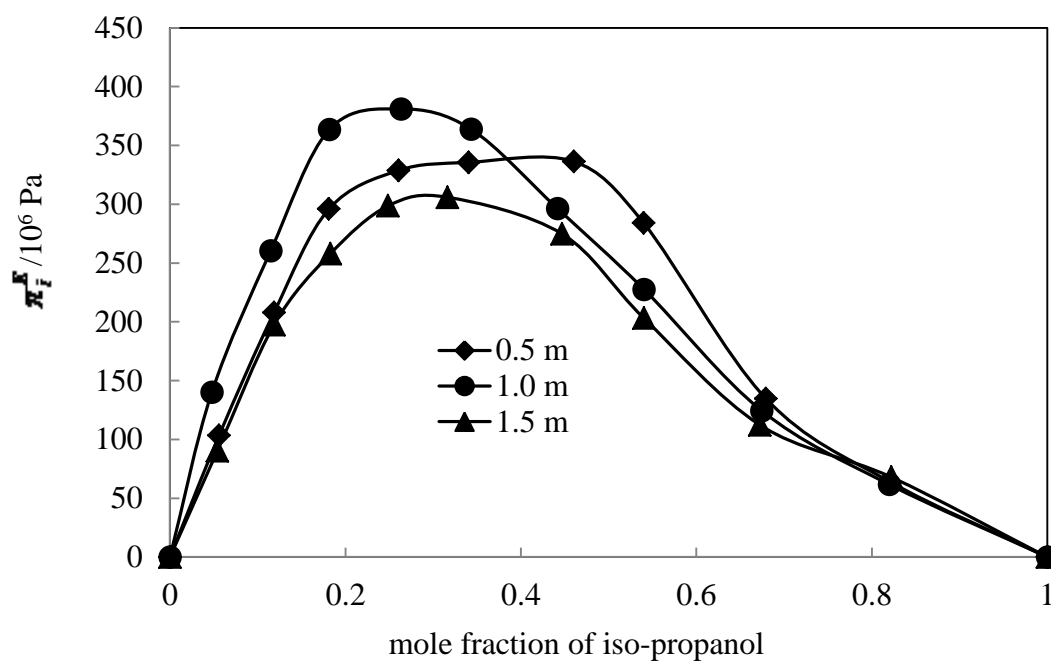


Figure 4a. Variation of excess internal pressure (π_i^E) in the mixtures of iso-propanol with aqueous ethylene glycol

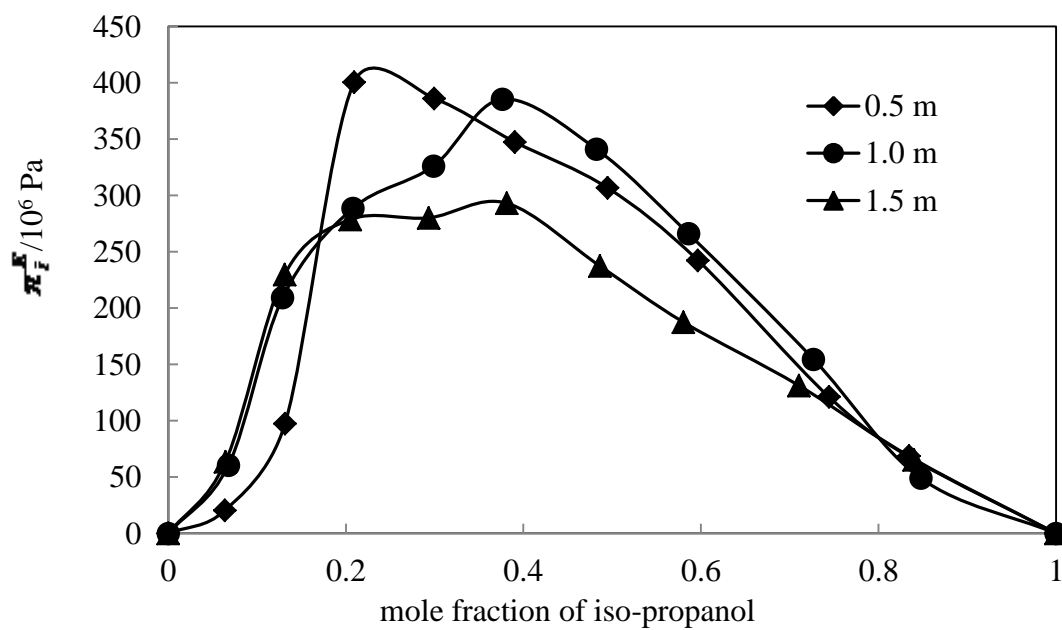


Figure 4b. Variation of excess internal pressure (π_i^E) in the mixtures of iso-propanol with aqueous propylene glycol

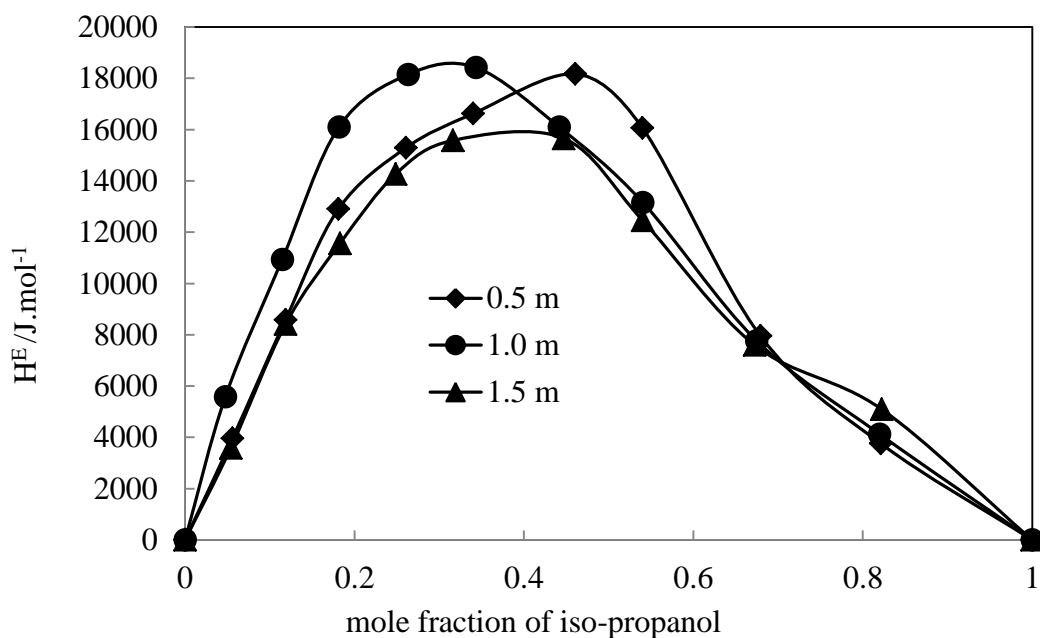


Figure 5a. Variation of excess enthalpy (H^E) in the mixtures of iso-propanol with aqueous ethylene glycol

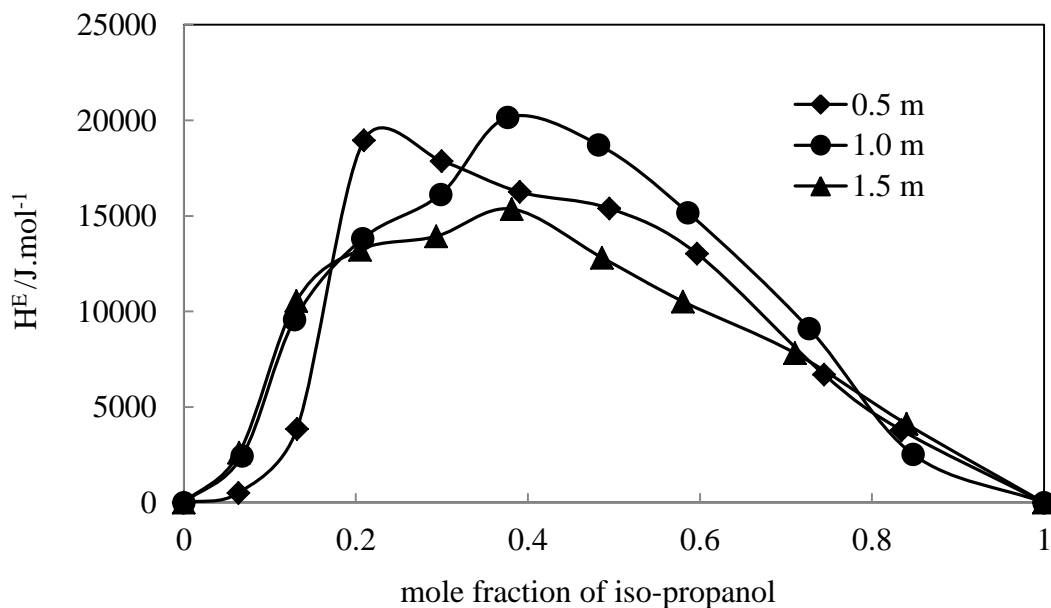


Figure 5b. Variation of excess enthalpy (H^E) in the mixtures of iso-propanol with aqueous propylene glycol

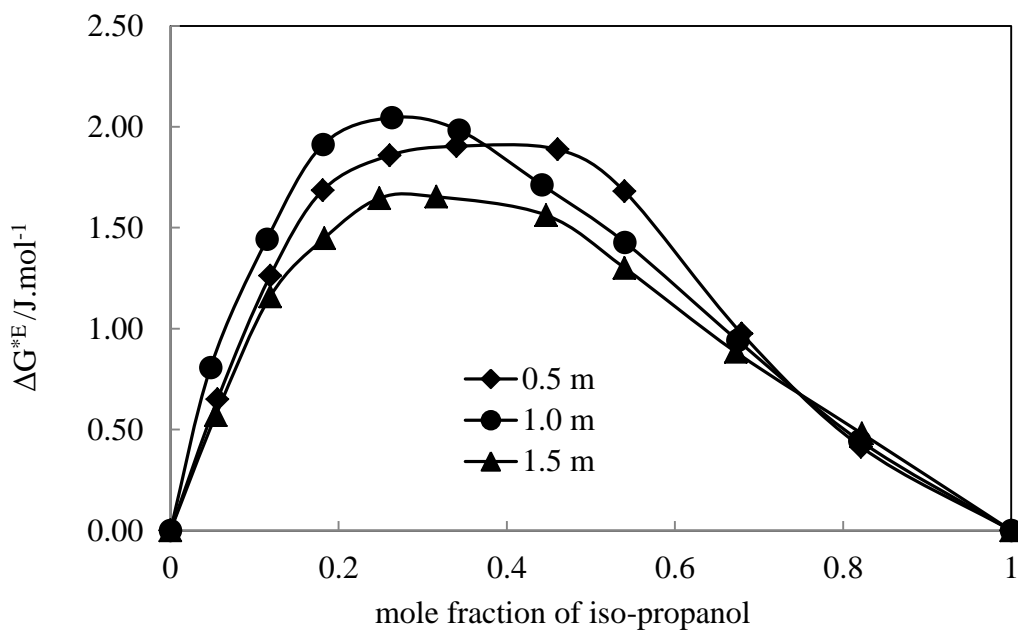


Figure 6a. Variation of excess Gibb's free energy of activation of viscous flow (ΔG^{*E}) in the mixtures of iso-propanol with aqueous ethylene glycol

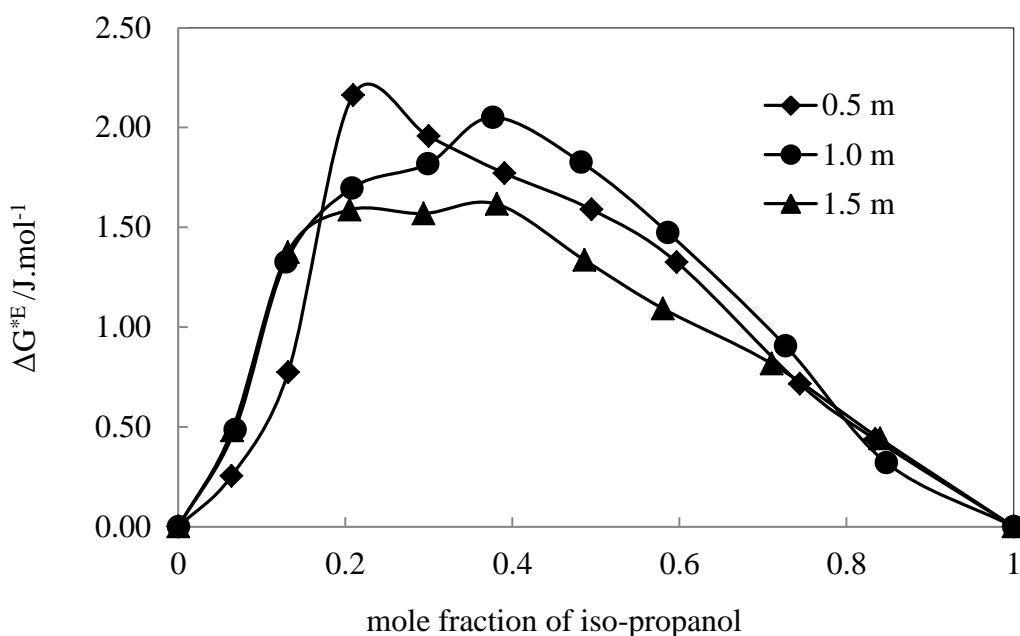


Figure 6b. Variation of excess Gibb's free energy of activation of viscous flow (ΔG^{*E}) in the mixtures of iso-propanol with aqueous propylene glycol

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