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Theoretical Predictions of Viscosity of Binary and Ternary Liquid Mixtures at 298.15 K

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Viscosities of five binary [cyclohexane (1) + carbon tetrachloride (2), benzene (1) + toluene (2), benzene (1) + cyclohexane (2), toluene (1) + carbon tetrachloride (2) and toluene (1) + cyclohexane (2)] and three ternary liquid mixtures [carbon tetrachloride (1) + cyclohexane (2) + benzene (3), toluene (1) + cyclohexane (2) + carbon tetrachloride (3) and benzene (1) + cyclohexane (2) + toluene (3)] at 298.15 K have been calculated using Frenkel relation, Kendall-Munroe relation, Bingham relation, Arrhenius-Eyring relation, Wassiljewa relation, Sutherland-Wassiljewa relation and Croenauer-Rothfus-Kermore relation. Validity of these relations has been checked by calculating average percentage deviations between calculated values and experimental values obtained from literature. Sutherland-Wassiljewa relation gives maximum deviations for all the systems in comparison to other methods employed. Other relations give comparatively good results.

Key Words: Viscosity, Binary, Ternary, Liquid mixture, Transport properties.

INTRODUCTION

Thermodynamic and transport properties[1] of binary and ternary liquid mixtures provide a lot of knowledge about molecular interactions occurring in liquid mixtures. However, viscosity is an important transport property[2] for process design in petroleum, petrochemical, chemical and other industries involving fluid transportation, mixing, agitation, filtration, heat exchange and concentration. Therefore, viscosities of binary and multicomponent liquid mixtures have been determined using experimental methods[3-10] and theoretical methods[11-13] by several workers. Various liquid viscosity models (Frenkel, Kendall-Munroe, additive, Bingham, Hind-Ubbelhode, *etc.*), proposed for binary non-electrolytic solutions, have been extended[14] for predicting the viscosity of multicomponent liquid solutions. Although a number of predictive equations are available for estimating viscosity of

multicomponent systems, few workers[11-14] have used these relations for the prediction of viscosity of liquid mixtures. Moreover, for computing the viscosities of mixture only the experimental values of viscosity and molecular weight of pure components along with the density of the mixture are required. For the first time, as far as our knowledge is concerned, we are doing comparative study of these relations for the prediction of viscosity of binary and ternary liquid mixtures. In this paper, we are reporting the calculated values of viscosity of five binary [cyclohexane (1) + carbon tetrachloride (2), benzene (1) + toluene (2), benzene (1) + cyclohexane (2), toluene (1) + carbon tetrachloride (2) and toluene (1) + cyclohexane (2)] and three ternary liquid mixtures [carbon tetrachloride (1) + cyclohexane (2) + benzene (3), toluene (1) + cyclohexane (2) + carbon tetrachloride (3) and benzene (1) + cyclohexane (2) + toluene (3)] at 298.15 K using Frenkel[12] relation, Kendall-Munroe[12] relation, Bingham[12] relation, Arrhenius-Eyring[12] relation, Wassiljewa[11] relation, Sutherland-Wassiljewa[3] relation and Croenauer-Rothfus-Kermore[3] relation. Validity of these relations has been checked by calculating average percentage deviations (APD) between calculated and experimental values obtained from literature[15].

THEORETICAL

The viscosity of the binary and ternary liquid mixtures, undertaken for the present study, has been calculated using Frenkel relation, Kendall-Munroe relation, Bingham relation, Arrhenius-Eyring relation, Wassiljewa relation, Sutherland-Wassiljewa relation and Croenauer-Rothfus-Kermore relation which are outlined below.

Frenkel relation:

$$\ln \eta_m = \sum_{i=1}^{3} x_i \eta_i + 2(x_1x_2 \ln \eta_{12} + x_2x_3 \ln \eta_{23} + x_3x_1 \ln \eta_{31}) + 3x_1x_2x_3 \ln \eta_{123} \quad (1)$$

Kendall-Munroe relation:

$$\ln \eta_m = \sum_{i=1}^{3} x_i \ln \eta_i \quad (2)$$

Bingham relation:

$$\eta_m = \sum_{i=1}^{3} x_i \eta_i \quad (3)$$

Arrhenius-Eyring relation:

$$\ln (\eta_m V_m) = \sum_{i=1}^{3} x_i \ln (\eta_i V_i) \quad (4)$$

Wassiljewa relation:

$$\eta_m = \sum_i \left(\frac{\eta_i}{1 + A_{ij}\left(\frac{x_j}{x_i}\right)} \right) \tag{5}$$

Sutherland-Wassiljewa relation:

$$\eta_m = \sum_i \frac{x_i \eta_i}{\sum_j A_{ji} x_j} \tag{6}$$

Croenauer-Rothfus-Kermore relation:

$$\ln \nu_m = \sum_i x_i \ln \nu_i \tag{7}$$

In eqns. 1-7, η_m, V_m, ν_m, x_i, η_i, V_i and ν_i are respectively the viscosity, molar volume and kinematic viscosity of mixture and mole fraction, viscosity, molar volume and kinematic viscosity of ith component of liquid mixture. A_{ij} and A_{ji} are adjustable parameters called Wassiljewa coefficients interpreted by Grey *et al.*[16] and Pandey *et al.*[17] as the ratio of the efficiencies with which molecules 'j' and 'i' impede the transport of momentum by molecules 'i'. A_{ij} can be expressed as

$$A_{ij} = \frac{1}{4}\left\{1 + \left(\frac{\eta_i}{\eta_j}\right)^{1/2}\left(\frac{M_j}{M_i}\right)^{3/8}\right\}^2 \tag{8}$$

RESULTS AND DISCUSSION

The values of density and viscosity of pure component taken from literature[15] are recorded in Table-1. The values of viscosity of five binary [cyclohexane (1) + carbon tetrachloride (2), benzene (1) + toluene (2), benzene (1) + cyclohexane (2), toluene (1) + carbon tetrachloride (2) and toluene (1) + cyclohexane (2)] and three ternary liquid mixtures [carbon

TABLE-1
VALUES OF DENSITY AND VISCOSITY OF PURE LIQUIDS AT 298.15 K

Pure liquid	ρ (10^3 kg m^{-3})	η (mPa s)
Benzene	0.8736	0.5985
Toluene	0.8628	0.6033
Cyclohexane	0.7734	0.8799
Carbon tetrachloride	1.5851	0.8992

TABLE-2
CALCULATED VALUES OF VISCOSITY OF BINARY LIQUID MIXTURES AT 298.15 K USING FRENKEL RELATION, KENDALL-MUNROE RELATION, BINGHAM RELATION, ARRHENIUS-EYRING RELATION, WASSILJEWA RELATION, SUTHERLAND-WASSILJEWA RELATION AND CROENAUER-ROTHFUS-KERMORE RELATION AND THEIR PERCENTAGE DEVIATIONS FROM EXPERIMENTAL VALUES

x_1	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
Cyclohexane (1) + Carbon tetrachloride (2)														
0.0903	0.8974	0.8974	0.8975	0.8969	0.8964	0.7386	0.9083	0.15	0.15	0.15	0.21	0.27	17.82	-1.06
0.1291	0.8967	0.8967	0.8967	0.9000	0.8952	0.7485	0.9160	0.18	0.18	0.18	-0.19	0.35	16.67	-1.97
0.1666	0.8960	0.8960	0.8960	0.8950	0.8941	0.7583	0.9149	0.20	0.21	0.20	0.32	0.42	15.53	-1.90
0.2288	0.8948	0.8947	0.8948	0.8951	0.8923	0.7752	0.9210	0.24	0.24	0.24	0.20	0.52	13.57	-2.69
0.2775	0.8938	0.8938	0.8938	0.8929	0.8909	0.7890	0.9229	0.28	0.28	0.27	0.38	0.60	11.97	-2.97
0.3162	0.8931	0.8931	0.8931	0.8940	0.8899	0.8004	0.9269	0.29	0.30	0.29	0.19	0.65	10.64	-3.48
0.3561	0.8923	0.8923	0.8923	0.8945	0.8889	0.8124	0.9300	0.32	0.33	0.32	0.08	0.71	9.25	-3.88
0.3937	0.8916	0.8916	0.8916	0.8948	0.8879	0.8242	0.9323	0.35	0.35	0.35	-0.01	0.76	7.88	-4.20
0.4340	0.8908	0.8908	0.8908	0.8855	0.8870	0.8371	0.9243	0.37	0.37	0.37	0.96	0.80	6.37	-3.38
0.4788	0.8899	0.8899	0.8900	0.8808	0.8860	0.8521	0.9207	0.40	0.40	0.40	1.42	0.84	4.64	-3.05
0.5134	0.8893	0.8892	0.8893	0.8796	0.8852	0.8640	0.9200	0.42	0.42	0.42	1.50	0.87	3.25	-3.03
05590	0.8884	0.8884	0.8884	0.9006	0.8843	0.8803	0.9423	0.45	0.45	0.45	-0.92	0.91	1.36	-5.59
0.5938	0.8877	0.8877	0.8877	0.8792	0.8836	0.8931	0.9196	0.47	0.47	0.47	1.42	0.93	-0.13	-3.10
0.6332	0.8870	0.8869	0.8870	0.8756	0.8830	0.9081	0.9149	0.50	0.50	0.50	1.78	0.95	-1.88	-2.64
Benzene (1) + Toluene (2)														
0.1263	0.6027	0.6027	0.6027	0.6041	0.6026	0.5762	0.6050	-0.07	-0.07	-0.07	-0.31	-0.05	4.33	-0.45
0.1417	0.6026	0.6026	0.6026	0.6032	0.6025	0.5772	0.6042	3.75	3.75	3.75	3.66	3.76	7.82	3.50
0.1664	0.6025	0.6025	0.6025	0.6025	0.6024	0.5786	0.6036	3.06	3.06	3.06	3.05	3.07	6.90	2.88

x_1	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
0.1881	0.6024	0.6024	0.6024	0.6020	0.6023	0.5799	0.6032	2.84	2.84	2.84	2.91	2.86	6.46	2.71
0.2131	0.6023	0.6023	0.6023	0.6029	0.6022	0.5814	0.6043	2.95	2.95	2.95	2.85	2.97	6.31	2.63
0.2314	0.6022	0.6022	0.6022	0.6028	0.6021	0.5826	0.6043	3.11	3.11	3.11	3.00	3.13	6.27	2.77
0.3195	0.6018	0.6018	0.6018	0.6003	0.6016	.05880	0.6020	3.32	3.32	3.32	3.55	3.34	5.53	3.27
0.3578	0.6016	0.6016	0.6016	0.6002	0.6014	0.5904	0.6021	3.44	3.44	3.44	3.65	3.46	5.24	3.36
0.4029	0.6014	0.6014	0.6014	0.5995	0.6012	0.5932	0.6015	3.86	3.86	3.86	4.15	3.89	5.17	3.84
0.4403	0.6012	0.6012	0.6012	0.5990	0.6010	0.5956	0.6011	4.65	4.65	4.65	4.99	4.68	5.54	4.67
0.4846	0.6010	0.6010	0.6010	0.6004	0.6008	0.5984	0.6025	4.95	4.96	4.95	5.04	4.98	5.36	4.72
0.5031	0.6009	0.6009	0.6009	0.5983	0.6007	0.5996	0.6003	4.97	4.97	4.97	5.38	5.00	5.17	5.06
0.5408	0.6007	0.6007	0.6007	0.5992	0.6005	0.6020	0.6013	5.24	5.24	5.24	5.47	5.27	5.03	5.15
0.5670	0.6006	0.6006	0.6006	0.5990	0.6004	0.6038	0.6010	5.39	5.39	5.39	5.65	5.42	4.89	5.33
0.6016	0.6004	0.6004	0.6004	0.5991	0.6002	0.6060	0.6011	5.74	5.74	5.74	5.95	5.77	4.86	5.64
0.6405	0.6002	0.6002	0.6002	0.5993	0.6001	0.6086	0.6012	6.10	6.10	6.10	6.24	6.12	4.78	5.94
0.7185	0.5998	0.5998	0.5999	0.5989	0.5997	0.6139	0.6005	6.46	6.46	6.46	6.62	6.49	4.28	6.35
0.7536	0.5997	0.5997	0.5997	0.5995	0.5995	0.6163	0.6011	10.83	10.83	10.83	10.86	10.85	8.36	10.62
0.7892	0.5995	0.5995	0.5995	0.5994	0.5994	0.6187	0.6008	8.78	8.78	8.78	8.80	8.80	5.86	8.58
0.8280	0.5993	0.5993	0.5993	0.5993	0.5992	0.6214	0.6005	9.01	9.01	9.01	9.01	9.03	5.66	8.83
0.8639	0.5992	0.5992	0.5992	0.5995	0.5994	0.6239	0.6005	9.26	9.26	9.26	9.20	9.27	5.51	9.05
0.8941	0.5990	0.5990	0.5990	0.5996	0.5989	0.6261	0.6004	9.58	9.58	9.58	9.50	9.59	5.50	9.38
Benzene (1) + Cyclohexane (2)														
0.1323	0.8397	0.8362	0.8427	0.8354	0.8357	0.9384	0.8357	10.12	10.50	9.81	10.58	10.55	-0.44	10.55
0.1898	0.8225	0.8178	0.8265	0.8166	0.8173	0.9012	0.8170	6.20	6.74	5.75	6.87	6.80	-2.77	6.83
0.2577	0.8024	0.7967	0.8074	0.7941	0.7961	0.8591	0.7945	1.09	1.79	0.47	2.11	1.86	-5.91	2.06
0.3241	0.7829	0.7766	0.7887	0.7717	0.7760	0.8200	0.7721	-4.82	-3.97	-5.60	-3.32	-3.89	-9.78	-3.38
0.3375	0.7790	0.7726	0.7849	0.7710	0.7720	0.8123	0.7715	-2.50	-1.66	-3.28	-1.45	-1.57	-6.88	-1.51

x_1	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
0.4498	0.7466	0.7399	0.7533	0.7362	0.7393	0.7505	0.7367	-0.59	0.33	-1.49	0.82	0.41	-1.11	0.75
0.4700	0.7409	0.7341	0.7476	0.7363	0.7336	0.7399	0.7368	-1.83	-0.90	-2.75	-1.19	-0.82	-1.69	-1.26
0.5095	0.7297	0.7230	0.7365	0.7247	0.7225	0.7195	0.7252	-1.83	-0.90	-2.78	-1.13	-0.82	-0.41	-1.20
0.5280	0.7245	0.7179	0.7313	0.7216	0.7174	0.7101	0.7221	-5.74	-4.77	-6.73	-5.31	-4.70	-3.64	-5.39
0.6938	0.6788	0.6735	0.6847	0.6693	0.6732	0.6310	0.6697	0.04	0.82	-0.83	1.43	0.86	7.07	1.37
0.7406	0.6661	0.6614	0.6715	0.6583	0.6612	0.6101	0.6587	0.29	1.00	-0.51	1.47	1.04	8.68	1.41
0.7952	0.6516	0.6477	0.6561	0.6446	0.6475	0.5864	0.6449	1.74	2.33	1.05	2.80	2.36	11.56	2.75
0.8464	0.6381	0.6350	0.6417	0.6322	0.6349	0.5649	0.6325	2.54	3.01	1.98	3.43	3.03	13.71	3.40
0.8984	0.6245	0.6224	0.6271	0.6201	0.6223	0.5438	0.6202	4.74	5.06	4.35	5.42	5.07	17.06	5.40
0.8519	0.6366	0.6337	0.6402	0.6384	0.6335	0.5627	0.6387	3.04	3.49	2.50	2.77	3.51	14.30	2.73
Toluene (1) + Carbon tetrachloride (2)														
0.0932	0.8693	0.8664	0.8716	0.9424	0.8714	0.8768	0.9516	0.14	0.47	-0.13	-8.26	-0.11	-0.73	-9.32
0.1294	0.8578	0.8539	0.8609	0.9321	0.8607	0.8656	0.9443	0.13	0.58	-0.23	-8.52	-0.21	-0.78	-9.95
0.1770	0.8427	0.8379	0.8468	0.8005	0.8465	0.8508	0.8143	0.13	0.70	-0.36	5.13	-0.32	-0.83	3.49
0.2067	0.8334	0.8280	0.8380	0.9022	0.8377	0.8416	0.9199	0.13	0.78	-0.42	-8.12	-0.38	-0.86	-10.23
0.2405	0.8228	0.8169	0.8280	0.8172	0.8276	0.8312	0.8352	0.09	0.81	-0.54	0.78	-0.49	-0.92	-1.41
0.3024	0.8037	0.7970	0.8097	0.8689	0.8093	0.8121	0.8915	0.04	0.87	-0.71	-8.07	-0.65	-1.00	-10.88
0.3209	0.7980	0.7911	0.8042	0.7948	0.8038	0.8063	0.8163	0.01	0.86	-0.78	0.40	-0.72	-1.05	-2.30
0.3602	0.7859	0.7788	0.7926	0.8514	0.7921	0.7942	0.8762	-0.05	0.85	-0.91	-8.40	-0.84	-1.11	-11.54
0.4001	0.7738	0.7665	0.7808	0.7685	0.7803	0.7819	0.7921	-0.13	0.82	-1.04	0.55	-0.97	-1.18	-2.50
0.4418	0.7612	0.7538	0.7685	0.8249	0.7679	0.7691	0.8512	-0.22	0.76	-1.17	-8.60	-1.10	-1.25	-12.06
0.4797	0.7499	0.7425	0.7573	0.7412	0.7567	0.7575	0.7654	-0.32	0.67	-1.31	0.85	-1.23	-1.33	-2.40
0.5189	0.7383	0.7311	0.7457	0.8012	0.7452	0.7455	0.8278	-0.44	0.55	-1.45	-8.99	-1.37	-1.42	-12.61

x_1	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
0.5443	0.7308	0.7236	0.7381	0.7212	0.7376	0.7376	0.7452	-0.52	0.46	-1.53	0.79	-1.46	-1.46	-2.50
0.5988	0.7148	0.7081	0.7220	0.7792	0.7215	0.7209	0.8048	-0.74	0.22	-1.75	-9.81	-1.68	-1.60	-13.42
0.6390	0.7032	0.6968	0.7101	0.6976	0.7096	0.7086	0.7198	-0.92	0.00	-1.91	-0.11	-1.84	-1.70	-3.31
Toluene (1) + Cyclohexane (2)														
0.1067	0.8480	0.8452	0.8504	0.8468	0.8419	0.9901	0.8471	9.32	9.63	9.07	9.45	9.98	-5.88	9.42
0.1608	0.8321	0.8281	0.8354	0.8293	0.8236	0.9456	0.8297	5.38	5.83	5.00	5.70	6.34	-7.53	5.65
0.2260	0.8130	0.8080	0.8174	0.8078	0.8024	0.8952	0.8084	2.18	2.78	1.65	2.80	3.46	-7.71	2.73
0.2838	0.7962	0.7905	0.8014	0.7897	0.7842	0.8531	0.7903	-0.92	-0.19	-1.57	-0.09	0.60	-8.13	-0.17
0.3458	0.7785	0.7722	0.7843	0.7732	0.7655	0.8106	0.7740	-2.86	-2.04	-3.63	-2.17	-1.15	-7.10	-2.27
0.4305	0.7545	0.7480	0.7608	0.7467	0.7410	0.7562	0.7475	-4.60	-3.70	-5.48	-3.53	-2.73	-4.84	-3.63
0.4665	0.7444	0.7379	0.7509	0.7358	0.7309	0.7344	0.7365	-5.26	-4.34	-6.17	-4.04	-3.35	-3.85	-4.14
0.5429	0.7232	0.7169	0.7297	0.7131	0.7102	0.6903	0.7138	-4.83	-3.91	-5.77	-3.36	-2.95	-0.06	-3.47
0.5859	0.7114	0.7053	0.7178	0.7042	0.6990	0.6667	0.7049	-5.74	-4.84	-6.69	-4.67	-3.89	0.91	-4.78
0.6465	0.6950	0.6894	0.7011	0.6916	0.6836	0.6349	0.6922	-3.32	-2.48	-4.22	-2.81	-1.62	5.62	-2.91
0.7835	0.6586	0.6547	0.6632	0.6537	0.6507	0.5685	0.6541	1.42	2.01	0.74	2.16	2.61	14.91	2.09
0.7653	0.6634	0.6592	0.6682	0.6566	0.6549	0.5769	0.6571	-3.14	-2.48	-3.89	-2.09	-1.82	10.31	-2.16
0.8241	0.6480	0.6447	0.6520	0.6424	0.6414	0.5502	0.6428	-2.99	-2.46	-3.62	-2.10	-1.93	12.56	-2.16
0.8834	0.6327	0.6304	0.6356	0.6299	0.6281	0.5244	0.6302	-1.00	-0.63	-1.44	-0.54	-0.26	16.30	-0.59
0.9408	0.6181	0.6169	0.6197	0.6175	0.6157	0.5005	0.6176	0.49	0.69	0.25	0.60	0.88	19.43	0.58

F = Frenkel relation, **KM** = Kendall-Munroe relation, **B** = Bingham relation, **AE** = Arrhenius-Eyring relation, **W** = Wassiljewa relation, **SW** = Sutherland-Wassiljewa relation, **CRK** = Croenauer-Rothfus-Kermore relation.

TABLE-3
CALCULATED VALUES OF VISCOSITY OF TERNARY LIQUID MIXTURES AT 298.15 K USING FRENKEL RELATION, KENDALL-MUNROE RELATION, BINGHAM RELATION, ARRHENIUS-EYRING RELATION, WASSILJEWA RELATION, SUTHERLAND-WASSILJEWA RELATION AND CROENAUER-ROTHFUS-KERMORE RELATION AND THEIR PERCENTAGE DEVIATIONS FROM EXPERIMENTAL VALUES

x_1	x_2	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
Carbon tetrachloride (1) + Cyclohexane (2) + Benzene (3)															
0.1005	0.2646	0.7027	0.6904	0.7032	0.6855	0.6948	0.4870	0.7019	-2.99	-1.99	-3.06	-0.47	-1.83	28.62	-2.87
0.1403	0.2246	0.7044	0.6910	0.7039	0.6865	0.6972	0.4889	0.7080	-3.22	-1.24	-3.13	-0.58	-2.15	28.36	-3.73
0.1751	0.1953	0.7071	0.6930	0.7061	0.6888	0.7008	0.4904	0.7143	-3.55	-1.47	-3.40	-0.86	-2.62	28.19	-4.60
0.2132	0.1544	0.7067	0.6928	0.7061	0.6892	0.7025	0.4852	0.7185	-2.01	0.00	-1.91	0.52	-1.40	29.96	-3.71
0.2525	0.1240	0.7094	0.6958	0.7093	0.6919	0.7072	0.4830	0.7246	-2.19	-0.22	-2.18	0.33	-1.87	30.42	-4.39
0.2911	0.0869	0.7091	0.6967	0.7105	0.6938	0.7100	0.4750	0.7294	-2.02	-0.24	-2.21	0.19	-2.14	31.66	-4.93
0.3284	0.0517	0.7084	0.6979	0.7118	0.6953	0.7129	0.4657	0.7332	1.04	2.52	0.57	2.87	0.42	34.96	-2.41
0.3859	0.1812	0.7703	0.7510	0.7655	0.7500	0.7629	0.5362	0.7907	-3.61	-1.00	-2.96	-0.87	-2.61	27.88	-6.35
0.3461	0.4372	0.8350	0.8155	0.8256	0.8558	0.8192	0.6072	0.8971	-1.54	0.83	-0.40	-4.08	0.38	26.15	-9.10
Toluene (1) + Cyclohexane (2) + Carbon tetrachloride (3)															
0.1131	0.2041	0.8662	0.8557	0.8618	0.8537	0.8579	0.5352	0.8821	-3.69	-2.43	-3.16	-2.19	-2.70	35.94	-5.60
0.1269	0.2244	0.8626	0.8506	0.8573	0.8448	0.8529	0.5459	0.8747	-4.14	-2.70	-3.50	-1.99	-2.98	34.09	-5.61
0.1535	0.3004	0.8557	0.8403	0.8480	0.8367	0.8419	0.5767	0.8706	-4.11	-2.24	-3.17	-1.80	-2.43	29.83	-5.92
0.1734	0.2634	0.8503	0.8343	0.8428	0.8297	0.8370	0.5668	0.8622	-4.29	-2.33	-3.37	-1.77	-2.66	30.48	-5.76
0.1912	0.2818	0.8455	0.8281	0.8372	0.8208	0.8307	0.5743	0.8538	-3.35	-1.22	-2.33	-0.33	-1.54	29.80	-4.37
0.2126	0.3031	0.8395	0.8206	0.8304	0.8150	0.8232	0.5818	0.8483	-4.90	-2.54	-3.77	-1.83	-2.86	27.30	-5.99
0.2318	0.3260	0.8340	0.8140	0.8243	0.7991	0.8162	0.5881	0.8319	-4.93	-2.41	-3.71	-0.54	-2.69	26.00	-4.67

x_1	x_2	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
0.2518	0.3444	0.8280	0.8072	0.8180	0.7992	0.8091	0.5919	0.8316	-5.18	-2.54	-3.92	-1.53	-2.78	24.81	-5.64
0.2737	0.3617	0.8213	0.7999	0.8112	0.7889	0.8014	0.5938	0.8201	-5.24	-2.49	-3.95	-1.08	-2.69	23.91	-5.08
0.2970	0.3856	0.8136	0.7920	0.8039	0.7772	0.7929	0.5948	0.8065	-5.09	-2.30	-3.83	-0.39	-2.42	23.17	-4.17
0.3134	0.4080	0.8078	0.7568	0.7986	0.7741	0.7867	0.5946	0.8016	-5.19	-2.42	-4.00	-0.80	-2.45	22.57	-4.39
0.3360	0.4277	0.7997	0.7791	0.7915	0.7680	0.7785	0.5907	0.7929	-5.09	-2.39	-4.02	-0.93	-2.32	22.36	-4.21
0.3573	0.4405	0.7919	0.7723	0.7850	0.7615	0.7711	0.5849	0.7839	-4.09	-1.51	-3.18	-0.09	-1.35	23.12	-3.04
0.3764	0.4496	0.7849	0.7663	0.7791	0.7528	0.7645	0.5782	0.7728	-6.27	-3.75	-5.49	-1.92	-3.50	21.71	-4.63
0.3955	0.4609	0.7775	0.7603	0.7733	0.7470	0.7577	0.5700	0.7643	-7.26	-4.88	-6.67	-3.05	-4.53	21.37	-5.43
0.4172	0.4688	0.7692	0.7536	0.7667	0.7403	0.7503	0.5593	0.7546	-6.14	-3.98	-5.80	-2.15	-3.53	22.82	-4.12
0.4178	0.4536	0.7701	0.7536	0.7668	0.7448	0.7509	0.5612	0.7606	-10.21	-7.85	-9.73	-6.59	-7.45	19.69	-8.84
0.4926	0.3494	0.7505	0.7331	0.7467	0.7206	0.7325	0.5369	0.7377	-8.93	-6.41	-8.37	-4.58	-6.32	22.08	-7.07
0.5386	0.2956	0.7374	0.7206	0.7341	0.7120	0.7212	0.5184	0.7292	-7.39	-4.94	-6.91	-3.69	-5.02	24.51	-6.18
0.6228	0.2279	0.7118	0.6979	0.7105	0.6899	0.6993	0.4808	0.7047	-3.92	-1.88	-3.72	-0.71	-2.09	29.81	-2.88
0.6551	0.1944	0.7023	0.6894	0.7016	0.6816	0.6916	0.4654	0.6961	-2.54	-0.66	-2.44	0.48	-0.98	32.05	-1.64
Benzene (1) + Cyclohexane (2) + Toluene (3)															
0.1331	0.2123	0.6583	0.6529	0.6614	0.6511	0.6495	0.4252	0.6522	-3.65	-2.81	-4.14	-2.51	-2.27	33.05	-2.70
0.1402	0.2115	0.6581	0.6527	0.6611	0.6519	0.6494	0.4269	0.6531	-1.97	-1.13	-2.44	-1.00	-0.61	33.86	-1.19
0.1636	0.2297	0.6631	0.6571	0.6660	0.6557	0.6536	0.4418	0.6570	-3.39	-2.46	-3.86	-2.25	-1.92	31.11	-2.46
0.1854	0.2459	0.6675	0.6610	0.6704	0.6595	0.6575	0.4545	0.6609	-3.77	-2.77	-4.23	-2.53	-2.22	29.35	-2.75
0.2303	0.2829	0.6775	0.6700	0.6804	0.6668	0.6665	0.4794	0.6683	-7.49	-6.31	-7.96	-5.78	-5.74	23.94	-6.02
0.2535	0.3018	0.6826	0.6747	0.6856	0.7123	0.6712	0.4907	0.7139	-4.12	-2.92	-4.57	-8.65	-2.37	25.16	-8.90
0.2763	0.3197	0.6874	0.6792	0.6904	0.6748	0.6757	0.5003	0.6763	-6.90	-5.61	-7.36	-4.92	-5.06	22.20	-5.16

x_1	x_2	η_m **F** mPa s	η_m **KM** mPa s	η_m **B** mPa s	η_m **AE** mPa s	η_m **W** mPa s	η_m **SW** mPa s	η_m **CRK** mPa s	%Δ **F**	%Δ **KM**	%Δ **B**	%Δ **AE**	%Δ **W**	%Δ **SW**	%Δ **CRK**
0.2980	0.3365	0.6919	0.6834	0.6949	0.6779	0.6800	0.5083	0.6795	-7.49	-6.16	-7.96	-5.32	-5.63	21.03	-5.55
0.2973	0.3336	0.6911	0.6826	0.6941	0.6779	0.6792	0.5073	0.6795	-6.59	-5.28	-7.06	-4.55	-4.75	21.76	-4.79
0.3386	0.3739	0.7018	0.6929	0.7051	0.6895	0.6897	0.5219	0.6909	-4.47	-3.13	-4.96	-2.63	-2.67	22.31	-2.85
0.3606	0.3912	0.7063	0.6973	0.7098	0.6933	0.6944	0.5264	0.6947	-4.31	-2.98	-4.83	-2.39	-2.55	22.26	-2.60
0.3821	0.4087	0.7107	0.7018	0.7145	0.6975	0.6991	0.5293	0.6988	-3.40	-2.09	-3.94	-1.47	-1.71	23.00	-1.66
0.4053	0.4176	0.7128	0.7040	0.7169	0.6985	0.7016	0.5290	0.6997	9.55	10.67	9.04	11.37	10.97	32.88	11.21
0.4235	0.4249	0.7145	0.7058	0.7188	0.7012	0.7037	0.5278	0.7024	-3.75	-2.49	-4.37	-1.81	-2.18	23.36	-1.98
0.4443	0.4356	0.7170	0.7086	0.7217	0.7041	0.7067	0.5257	0.7051	-3.36	-2.14	-4.03	-1.49	-1.88	24.22	-1.65
0.4548	0.4311	0.7156	0.7073	0.7204	0.7020	0.7056	0.5232	0.7031	-3.32	-2.12	-4.01	-1.36	-1.87	24.46	-1.51
0.4654	0.4219	0.7130	0.7048	0.7178	0.6996	0.7031	0.5201	0.7007	-3.35	-2.16	-4.04	-1.41	-1.91	24.61	-1.56
0.5072	0.3624	0.6968	0.6889	0.7011	0.6844	0.6873	0.5044	0.6855	-3.09	-1.93	-3.73	-1.25	-1.69	25.37	-1.42
0.5272	0.3428	0.6913	0.6837	0.6956	0.6800	0.6822	0.4974	0.6811	-2.38	-1.25	-3.00	-0.69	-1.03	26.34	-0.86
0.5780	0.2966	0.6786	0.6716	0.6826	0.6681	0.6704	0.4789	0.6692	-2.04	-1.00	-2.64	-0.47	-0.81	27.98	-0.63
0.5665	0.3044	0.6808	0.6737	0.6848	0.6702	0.6724	0.4828	0.6713	-2.14	-1.08	-2.74	-0.55	-0.88	27.56	-0.72
0.5864	0.2855	0.6755	0.6688	0.6795	0.6655	0.6676	0.4751	0.6666	-1.83	-0.81	-2.42	-0.31	-0.63	28.38	-0.48
0.6043	0.2678	0.6707	0.6642	0.6745	0.6606	0.6631	0.4678	0.6617	-1.33	-0.35	-1.90	-0.20	-0.18	29.32	-0.03
0.6235	0.2462	0.6648	0.6588	0.6684	0.6545	0.6577	0.4593	0.6556	-2.68	-1.74	-3.23	-1.08	-1.57	29.07	-1.26
0.6432	0.2297	0.6603	0.6546	0.6637	0.6503	0.6536	0.4513	0.6514	-2.69	-1.80	-3.23	-1.13	-1.65	29.82	-1.30
0.6624	0.2116	0.6554	0.6500	0.6586	0.6466	0.6491	0.4428	0.6477	-1.86	-1.03	-2.37	-0.50	-0.89	31.17	-0.67
0.6797	0.1941	0.6507	0.6456	0.6537	0.6419	0.6448	0.4348	0.6430	-1.66	-0.88	-2.14	-0.30	-0.75	32.06	-0.47
0.6969	0.1759	0.6458	0.6411	0.6486	0.6360	0.6404	0.4264	0.6371	-2.45	-1.72	-2.90	-0.91	-1.60	32.35	-1.08
0.7040	0.1650	0.6429	0.6385	0.6456	0.6342	0.6378	0.4221	0.6352	-1.64	-0.94	-2.06	-0.26	-0.83	33.27	-0.43

F = Frenkel relation, **KM** = Kendall-Munroe relation, **B** = Bingham relation, **AE** = Arrhenius-Eyring relation, **W** = Wassiljewa relation, **SW** = Sutherland-Wassiljewa relation, **CRK** = Croenauer-Rothfus-Kermore relation.

tetrachloride (1) + cyclohexane (2) + benzene (3), toluene (1) + cyclohexane (2) + carbon tetrachloride (3) and benzene (1) + cyclohexane (2) + toluene (3)] at 298.15 K have been calculated using eqns. 1-8 and are recorded in Tables 2 and 3, respectively. Percentage deviations between calculated and experimental values are also reported in Tables 2 and 3. The values of density of the mixture required for the calculation are taken from literature[15]. Validity of aforementioned relations has been checked by calculating average percentage deviations (ADP) between calculated and experimental values obtained from literature[15] and recorded in Tables 4 and 5.

TABLE-4
AVERAGE PERCENTAGE DEVIATIONS BETWEEN EXPERIMENTAL AND CALCULATED VALUES OF VISCOSITY OF BINARY LIQUID MIXTURES AT 298.15 K USING FRENKEL RELATION, KENDALL-MUNROE RELATION, BINGHAM RELATION, ARRHENIUS-EYRING RELATION, WASSILJEWA RELATION, SUTHERLAND-WASSILJEWA RELATION AND CROENAUER-ROTHFUS-KERMORE RELATION

Binary liquid mixture	**F**	**KM**	**B**	**AE**	**W**	**SW**	**CRK**
Cyclohexane (1) + Carbon tetrachloride (2)	0.33	0.33	0.33	0.69	0.68	8.64	3.07
Benzene (1) + Toluene (2)	5.33	5.33	5.33	5.45	5.35	5.67	5.21
Benzene (1) + Cyclohexane (2)	3.14	3.15	3.33	3.34	3.15	7.00	3.33
Toluene (1) + Carbon tetrachloride (2)	0.27	0.63	0.95	5.16	0.89	1.15	7.19
Toluene (1) + Cyclohexane (2)	3.56	3.20	3.95	3.07	2.91	8.34	3.12

F = Frenkel relation, **KM** = Kendall-Munroe relation, **B** = Bingham relation, **AE** = Arrhenius-Eyring relation, **W** = Wassiljewa relation, **SW** = Sutherland-Wassiljewa relation, **CRK** = Croenauer-Rothfus-Kermore relation.

TABLE-5
AVERAGE PERCENTAGE DEVIATIONS BETWEEN EXPERIMENTAL AND CALCULATED VALUES OF VISCOSITY OF TERNARY LIQUID MIXTURES AT 298.15 K USING FRENKEL RELATION, KENDALL-MUNROE RELATION, BINGHAM RELATION, ARRHENIUS-EYRING RELATION, WASSILJEWA RELATION, SUTHERLAND-WASSILJEWA RELATION AND CROENAUER-ROTHFUS-KERMORE RELATION

Ternary liquid mixture	**F**	**KM**	**B**	**AE**	**W**	**SW**	**CRK**
Carbon tetrachloride (1) + Cyclohexane (2) + Benzene (3)	2.46	0.97	2.20	1.20	1.71	29.58	4.68
Toluene (1) + Cyclohexane (2) + Carbon tetrachloride (3)	5.33	3.04	4.53	1.83	3.11	26.07	5.01
Benzene (1) + Cyclohexane (2) + Toluene (3)	3.68	2.68	4.18	2.38	2.37	27.28	2.55

F = Frenkel relation, **KM** = Kendall-Munroe relation, **B** = Bingham relation, **AE** = Arrhenius-Eyring relation, **W** = Wassiljewa relation, **SW** = Sutherland-Wassiljewa relation, **CRK** = Croenauer-Rothfus-Kermore relation.

A perusal of Table-4 reveals that maximum deviations are obtained by using Sutherland-Wassiljewa relation for the prediction of viscosity of binary liquid mixtures under the present study while other relations give comparatively good results. The best results obtained through utilizing Frenkel's relation are due to the fact that it incorporates all the possible major interactions. Results obtained by using Kendall-Munroe relation and Bingham relation are also good because these relations were developed considering the ideal mixing of solutions.

An inspection of Table-5 suggests that Sutherland-Wassiljewa relation for the prediction of viscosity of ternary liquid mixtures gives maximum deviations for all the systems in comparison to other methods employed for the calculation. Best results are obtained by using Arrhenius-Eyring relation for the computation of viscosity of ternary liquid mixtures followed by Kendall-Munroe relation. The trend of validity of the presently used relations is as follows:

For binary systems: Frenkel relation > Kendall-Munroe relation > Bingham relation > Arrhenius-Eyring relation > Wassiljewa relation > Croenauer-Rothfus-Kermore relation > Sutherland-Wassiljewa relation.

For ternary systems: Arrhenius-Eyring relation > Kendall-Munroe relation > Wassiljewa relation > Bingham relation > Croenauer-Rothfus-Kermore relation > Frenkel relation > Sutherland-Wassiljewa relation.

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