International Journal of Natural and Engineering Sciences
E-ISSN: 2146-0086 12 (1): 26-36, 2018

An Experimental Study of the Viscometric and Volumetric Properties of 1-Alkanol (C3 – C11) Ternary Systems at Different Temperature Levels.

Nidal M. Hussein [1],* Abdul-Fattah A. Asfour [2]
[1]Department of Civil Engineering, University of Petra, Amman – Jordan
[2]Environmental Engineering, University of Windsor, Windsor, Ontario, Canada

***Corresponding Author**
E-mail: nidal.hussein@uop.edu.jo

Received: January 7, 2018
Accepted: March 28, 2018

Abstract

Kinematic viscosity-composition and density-composition data of ten ternary systems containing 1-propanol, 1-pentanol, 1-heptanol, 1-nonanol, and 1-undecanol have been experimentally measured and reported in this study. Seven intermediate composition points and pure components densities and kinematic viscosities were measured at 293.15 and 298.15 K temperature levels. The measured values of kinematic viscosity were compared to viscosity values predicted by various viscosity models. The investigated models are: the generalized McAllister three-body interaction model, the GC-UNIMOD model, the generalized corresponding states principle (GCSP) model, and the Allan and Teja correlation. The analysis of the models testing results shows that the generalized McAllister three-body interaction model gave the best prediction results.

Keywords: Viscosity, Density, l-Alkanol, Ternary systems, McAllister model

1 INTRODUCTION

Most of the industrial and engineering applications require the design of a pumping system to transport fluids from one point to another to overcome the fluids resistance to flow. The physical property that describes this kind of resistance is the fluid's viscosity. In many of these applications the transported fluids are multi-component liquid mixtures. For liquid mixtures, the composition of a mixture significantly affects the molecular interaction within the fluid that leads to changing the fluid's resistance to flow. In addition, temperature change is widely believed to affect the different types of molecular bonds within the fluid and result in changes in fluid's viscosity. This has motivated many researchers to investigate the dependence of viscosity of liquid mixtures on composition and temperature. It is assumed that the knowledge of the dependence of viscosity on temperature and composition may ultimately provide a better insight into liquid's structure. As a result various viscosity models were developed. Those models can be classified into two categories; *viz.*, correlative and predictive models.

The correlative models contain adjustable parameters that can be calculated using experimentally measured values of viscosity. Predictive models can predict the viscosity of a liquid mixture with the knowledge of composition and/or some molecular parameters and/or properties of the pure components constituting the mixture being investigated.

The objective of this work is to obtain and report the kinematic viscosities and densities of ten ternary systems of (1-propanol, 1-pentanol, 1-heptanol, 1-nonanol, and 1-undecanol) over the entire composition range and at two different temperature levels of 293.15 and 298.15 K. Moreover, the data reported in this work are to be used for testing the predictive capability of four widely accepted and used viscosity models.. The models selected are: the generalized McAllister three-body interaction model (model 1) reported by Nhaesi and Asfour [1], the GC-UNIMOD model (model 2) reported by Cao *et al.* [2], the Generalized Corresponding States Principle (GCSP) model (model 3) reported by Teja and Rice [3], and the Allan and Teja correlation (model 4) reported by Allan and Teja [4]. The first three models are predictive whereas the Allan Teja model is correlative.

2 EXPERIMENTAL SECTION

2.1 Material

chemicals used during calibration of both the viscometers and the density meter and for constituting the liquid systems investigated in this study were purchased from Sigma-Aldrich and from Fluka with stated purities of 99.0+%. Their purities were tested by gas chromatography analysis using a Hewlett-Packard 5890A Gas Chromatograph with a flame ionization detector (FID) and an HP 1 [cross linked methyl silicone gum] 30m (long) x 0.53 mm (diameter) and 2.65 µm (film thickness) column was used. The chemicals' stated purities and the results of the GC analysis are reported in Table 1. Table 1 confirms that the purities of the chemicals were better than their stated values.

Table 1: Gas Chromatographic Analysis Results of the Pure Chemicals Used in the Present Study

Compound	Supplier	Stated Purity, mole %	GC Analysis, mass %
1-Propanol	Sigma-Aldrich	99.5+%	99.9%
1-Pentanol	Sigma-Aldrich	99+%	99.8%
1-Heptanol	Fluka	99.0+%	99.7%
1-Nonanol	Fluka	98.0+%	99.2%
1-Undecanol	Sigma-Aldrich	99+%	99.6%
Octane	Sigma-Aldrich	99+%	99.5%
Toluene	Sigma-Aldrich	99.8+%	99.9%
Eythl Benzene	Sigma-Aldrich	99.8+%	99.9%
Undecane	Sigma-Aldrich	99.0+%	99.9%
Tridecane	Sigma-Aldrich	99.0+%	99.5%

2.2 Preparation of Solution

The procedure that was suggested by Asfour [5] was followed in preparing the liquid samples. For every system, the pure components were injected into glass vials sealed with Tuf-Bond discs and aluminum seals to prevent evaporation and moisture absorption that affect the composition of it. The liquid mixture samples were prepared using a Mettler HK 160 electronic balance with a precision of ± 1 X 10^{-4} g.

2.3 Density Measurements

The density of the liquid samples was measured using an Anton-Paar density meter. The density meter consists of a DMA 60 processing unit and a DMA 602 measuring cell. The sample is injected directly to the measuring cell. The processing unit gives the reading of the oscillation period. In order to calculate the density of the injected samples, the oscillation period reading is substituted into an equation suggested by the instrument supplier. The stated uncertainty in the density meter measurements was estimated to be ± 1.5 x 10^{-6} kg/L. The density meter equation has the following form:

$$\rho = \frac{AT^2}{1-BT^2} - C \qquad (1)$$

where ρ is the density of the sample in kg/L and T is the oscillation period in seconds. A, B, and C are the calibration constants and they are temperature dependant. The values of the calibration constants were determined using known density values of certain chemicals at the temperature levels investigated in this study. The density values of those chemicals were fitted to Eq. (1) using the least-squares technique and the values of the calibration constant were obtained at the desired temperature. The chemicals that were used for calibration are: octane, toluene, ethylbenzene, tridecane, and undecane. The temperature of the measuring cell was maintained within ± 0.01 K of the desired level using a Haake N4 circulator. An Omega electronic thermometer fitted with a calibrated platinum temperature sensor (ITS-90) with a precision of ± 0.005 K was used to monitor the circulator water temperature. The measuring cell and the processing unit were kept inside a wooden chamber. The temperature inside the chamber is controlled by an arrangement described in details earlier by Asfour [6] and is kept within ±0.5 K of the desired temperature.

2.4 Viscosity Measurements

The kinematic viscosity of the pure components and the different ternary mixture were measured with the help of 100 and 150 Cannon Ubbelohde glass viscometers. Those sizes are used to measure the kinematic viscosities that range between 3-15 and 7-35 X 10-6 m2/s, respectively. The efflux time of each sample was measured three times with electronic stopwatches with a stated accuracy of ± 0.01 s. The average value of efflux time was substituted into viscosity equation suggested by the viscometer manufacturer. For the Cannon-Ubbelohde viscometer used in the present study, the viscosity equation has the following form:

$$v = Ct - \frac{E}{t^2} \qquad (2)$$

where v is the kinematic viscosity of the sample in m^2/s and t is the efflux time in seconds. C, and E are the calibration constants at each temperature level that were determined using calibration fluids supplied by Cannon Instrument Company with viscosity range of 4.62-22.7 X 10^{-6} m^2/s. The calibration fluids that were used in this study are: S3, S6, and N10. The values of the calibration constants were determined by fitting the viscosities of the calibration fluids and their corresponding efflux times using the least-squares technique and Eq. (2). The viscometer was placed in a Cannon CT-1000, constant temperature bath where temperature can be controlled to within ± 0.01K.

3 RESULTS AND DISCUSSION

The experimentally measured density, kinematic viscosity, and calculated absolute viscosity, μ, at the desired temperature levels and the corresponding literature values for the pure components used in this study are listed in Table 2. The comparison between the experimental and literature values provided by Table 2 shows that both values are in a good agreement with each other. Table 3 lists the experimental values of the densities, kinematic viscosities, and the calculated absolute viscosities of the investigated ternary systems. The measured kinematic viscosity values reported in Table 3 were used to test the predictive capabilities of selected viscosity models.

The first model that was tested is the generalized McAllister three-body interaction model for multi-component n-alkane and for regular solutions was developed and reported by Nhaesi and Asfour [1]. They suggested the following equation for calculating the kinematic viscosity of any multi-component liquid system:

Table 2: Pure Components Properties and their Comparison with their Corresponding Literature Values at Different Temperatures

Compound	$\rho/\mathrm{kgL^{-1}}$		$10^6\,\nu/\mathrm{m^2s^{-1}}$	Absolute Viscosity, mPa.s	
	Exptl	Literature	Exptl	Exptl	Literature
T= 293.15 K					
1-Propanol	0.8035	0.80375 [6]	2.828	2.272	2.196 [6]
1-Pentanol	0.8146	0.8151 [6]	4.946	4.029	4.0608 [6]
1-Heptanol	0.8222	0.8225 [6]	8.64	7.104	7.058 [7]
1-Nonanol	0.8278	0.828 [6]	14.11	11.683	11.635 [8]
1-Undecanol	0.8324	0.8335 [6]	20.64	17.182	17.284 [8]
T= 298.15 K					
1-Propanol	0.7996	0.79975 [6]	2.459	1.966	1.943 [6]
1-Pentanol	0.811	0.8115 [6]	4.308	3.494	3.5128 [6]
1-Heptanol	0.8187	0.8186 [6]	7.32	5.993	5.898 [6]
1-Nonanol	0.8244	0.8247 [6]	11.73	9.671	9.6921 [9]
1-Undecanol	0.829	0.8297 [6]	16.92	14.025	14 [6]

Table 3: Density, Kinematic Viscosity, and Calculated Absolute Viscosity of Ten Ternary Subsystems of the Quinary System: 1-Propanol, 1-Pentanol, 1-Heptanol, 1-Nonanol, and 1-Undecanol

Mole Fraction			$\rho/\mathrm{kgL^{-1}}$	$10^6\,\nu/\mathrm{m^2s^{-1}}$	$\mu/\mathrm{mPa.s}$	$\rho/\mathrm{kgL^{-1}}$	$10^6\,\nu/\mathrm{m^2s^{-1}}$	$\mu/\mathrm{mPa.s}$
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Heptanol (3)			298.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Heptanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	0.0000	1.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.1234	0.1582	0.7184	0.8197	7.1806	5.8858	0.8162	6.1719	5.0373
0.2308	0.6182	0.1509	0.8142	4.8745	3.9686	0.8105	4.2451	3.4409
0.3383	0.3276	0.3341	0.8151	5.2337	4.2659	0.8115	4.5431	3.6866
0.4088	0.2011	0.3900	0.8151	5.2113	4.2477	0.8115	4.5298	3.6759
0.4987	0.3887	0.1126	0.8113	4.1218	3.3441	0.8076	3.6212	2.9247
0.5971	0.2500	0.1528	0.8109	4.0325	3.2698	0.8072	3.5482	2.8639
0.6933	0.1014	0.2053	0.8105	4.0192	3.2577	0.8068	3.5241	2.8564
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Heptanol (2) + 1-Nonanol (3)			298.15 K 1-Propanol (1) + 1-Heptanol (2) + 1-Nonanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.0000	0.0000	1.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.1367	0.1619	0.7014	0.8250	11.1516	9.2005	0.8216	9.4148	7.7353
0.237	0.6115	0.1516	0.8205	7.6818	6.3032	0.8170	6.5544	5.3553
0.3419	0.3266	0.3314	0.8206	7.8239	6.4202	0.8171	6.6649	5.4459
0.4188	0.195	0.3861	0.8200	7.5301	6.1749	0.8165	6.4275	5.2481
0.5079	0.3894	0.1027	0.8163	5.6702	4.6288	0.8128	4.9431	4.0175
0.6018	0.2429	0.1553	0.8152	5.3351	4.3493	0.8116	4.6385	3.7647
0.6999	0.0979	0.2022	0.8139	4.9642	4.0405	0.8103	4.3437	3.5355

Table 3: Density, Kinematic Viscosity, and Calculated Absolute Viscosity of Ten Ternary Subsystems of the Quinary System: 1-Propanol, 1-Pentanol, 1-Heptanol, 1-Nonanol, and 1-Undecanol (cont'd)

Mole Fraction			ρ/kgL^{-1}	$10^6\,\nu$/m^{2}s^{-1}	μ/mPa.s	ρ/kgL^{-1}	$10^6\,\nu$/m^{2}s^{-1}	μ/mPa.s
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Nonanol (3)			298.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Nonanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	0.0000	1.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.1279	0.1661	0.7061	0.8242	10.5693	8.7117	0.8208	8.8666	7.2777
0.2223	0.6276	0.1501	0.8157	5.4401	4.4377	0.8122	4.7268	3.8389
0.3545	0.3174	0.3281	0.8180	6.1504	5.0309	0.8144	5.2312	4.2605
0.4095	0.2033	0.3872	0.8187	6.7124	5.4952	0.8151	5.7514	4.6880
0.5025	0.3927	0.1048	0.8125	4.4423	3.6094	0.8088	3.8909	3.1470
0.6116	0.2379	0.1505	0.8126	4.5377	3.6874	0.8089	3.9682	3.2100
0.6874	0.1211	0.1915	0.8128	4.6711	3.7968	0.8092	4.0776	3.3143
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Heptanol (2) + 1-Undecanol (3)			298.15 K 1-Propanol (1) + 1-Heptanol (2) + 1-Undecanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1414	0.1658	0.6928	0.8284	15.9346	13.2003	0.8250	13.1998	10.8897
0.2308	0.6218	0.1473	0.8217	8.3658	6.8740	0.8182	7.0884	5.7997
0.3561	0.3176	0.3263	0.8227	9.4448	7.7704	0.8192	7.9944	6.5492
0.4191	0.1995	0.3813	0.8228	9.6369	7.9294	0.8193	8.1134	6.6475
0.5078	0.3871	0.1050	0.8174	5.8764	4.8033	0.8138	4.9958	4.0656
0.6052	0.2444	0.1504	0.8167	6.0347	4.9285	0.8131	5.2422	4.2625
0.7146	0.0901	0.1953	0.8157	5.7652	4.7027	0.8121	5.0009	4.0793

Table 3: Density, Kinematic Viscosity, and Calculated Absolute Viscosity of Ten Ternary Subsystems of the Quinary System: 1-Propanol, 1-Pentanol, 1-Heptanol, 1-Nonanol, and 1-Undecanol (cont'd)

Mole Fraction			ρ/kgL^{-1}	10^6 ν/m^{2}s^{-1}	μ/mPa.s	ρ/kgL^{-1}	10^6 ν/m^{2}s^{-1}	μ/mPa.s
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Nonanol (2) + 1-Undecanol (3)			298.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Heptanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1462	0.1543	0.6995	0.8292	16.9688	14.0701	0.8257	14.0211	11.5779
0.2317	0.6147	0.1536	0.8255	11.7746	9.7196	0.8220	9.8924	8.1319
0.3582	0.3207	0.3211	0.8247	11.0640	9.1242	0.8212	9.3163	7.6506
0.4273	0.1926	0.3800	0.8240	10.7122	8.8263	0.8205	9.0055	7.3887
0.5092	0.3872	0.1037	0.8206	7.8875	6.4723	0.8171	6.6855	5.4624
0.6121	0.2373	0.1507	0.8188	7.0575	5.7790	0.8153	6.0906	4.9655
0.7058	0.0944	0.1998	0.8170	6.3227	5.1653	0.8134	5.4417	4.4456
X_1	X_2	X_3	293.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Undecanol (3)			298.15 K 1-Propanol (1) + 1-Pentanol (2) + 1-Undecanol (3)		
1.0000	0.0000	0.0000	0.8035	2.8281	2.2724	0.7996	2.4591	1.9663
0.0000	1.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1524	0.1597	0.6879	0.8277	14.8818	12.3176	0.8243	12.3625	10.1901
0.2209	0.6322	0.1468	0.8171	6.0809	4.9686	0.8135	5.2657	4.2837
0.3419	0.3279	0.3301	0.8208	8.0731	6.6264	0.8173	6.8539	5.6017
0.4192	0.1998	0.3810	0.8215	8.7097	7.1550	0.8180	7.4067	6.0586
0.5153	0.3803	0.1044	0.8136	4.8733	3.9651	0.8100	4.2304	3.4267
0.6069	0.2425	0.1506	0.8144	5.1958	4.2313	0.8107	4.5214	3.6656
0.7104	0.0932	0.1964	0.8150	5.5502	4.5232	0.8113	4.8395	3.9440

Table 3: Density, Kinematic Viscosity, and Calculated Absolute Viscosity of Ten Ternary Subsystems of the Quinary System: 1-Propanol, 1-Pentanol, 1-Heptanol, 1-Nonanol, and 1-Undecanol (cont'd)

Mole Fraction			ρ/kgL^{-1}	$10^6\nu$/m^{2}s^{-1}	μ/mPa.s	ρ/kgL^{-1}	$10^6\nu$/m^{2}s^{-1}	μ/mPa.s
X_1	X_2	X_3	293.15 K 1-Pentanol (1) + 1-Heptanol (2) + 1-Nonanol (3)			298.15 K 1-Pentanol (1) + 1-Heptanol (2) + 1-Nonanol (3)		
1.0000	0.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	1.0000	0.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.0000	0.0000	1.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.1209	0.1604	0.7187	0.8256	11.8967	9.8213	0.8221	9.9352	8.1679
0.2118	0.6322	0.1561	0.8219	8.4057	6.9084	0.8184	7.1062	5.8158
0.3393	0.3257	0.3350	0.8223	8.7167	7.1675	0.8188	7.3807	6.0434
0.4089	0.2009	0.3902	0.8223	8.6120	7.0813	0.8188	7.2654	5.9488
0.4916	0.3955	0.1130	0.8198	6.9519	5.6992	0.8163	5.8910	4.8088
0.5881	0.2540	0.1579	0.8194	7.0045	5.7395	0.8159	6.0300	4.9199
0.6873	0.1101	0.2027	0.8191	6.8058	5.5746	0.8156	5.8330	4.7778
X_1	X_2	X_3	293.15 K 1-Pentanol (1) + 1-Nonanol (2) + 1-Undecanol (3)			298.15 K 1-Pentanol (1) + 1-Nonanol (2) + 1-Undecanol (3)		
1.0000	0.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	1.0000	0.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1283	0.1609	0.7108	0.8297	17.2266	14.2927	0.8263	14.2362	11.7631
0.2161	0.6278	0.1561	0.8264	12.5490	10.3707	0.8230	10.4752	8.6208
0.3382	0.3291	0.3327	0.8261	12.3947	10.2396	0.8227	10.3180	8.4886
0.4086	0.2018	0.3896	0.8257	12.0656	9.9629	0.8223	10.0956	8.3014
0.5013	0.3901	0.1086	0.8231	9.4133	7.7482	0.8196	7.9383	6.5066
0.6038	0.2503	0.1459	0.8221	8.6921	7.1455	0.8186	7.4284	6.0808
0.6918	0.1035	0.2047	0.8214	8.2052	6.7394	0.8179	6.9906	5.7418

Table 3: Density, Kinematic Viscosity, and Calculated Absolute Viscosity of Ten Ternary Subsystems of the Quinary System: 1-Propanol, 1-Pentanol, 1-Heptanol, 1-Nonanol, and 1-Undecanol (cont'd)

Mole Fraction			ρ/kgL^{-1}	$10^6\nu$/m^{2}s^{-1}	μ/mPa.s	ρ/kgL^{-1}	$10^6\nu$/m^{2}s^{-1}	μ/mPa.s
X_1	X_2	X_3	293.15 K 1-Pentanol (1) + 1-Heptanol (2) + 1-Undecanol (3)			298.15 K 1-Pentanol (1) + 1-Heptanol (2) + 1-Undecanol (3)		
1.0000	0.0000	0.0000	0.8146	4.9457	4.0288	0.8110	4.3078	3.4937
0.0000	1.0000	0.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1079	0.1731	0.7190	0.8291	16.8025	13.9314	0.8257	13.8759	11.4575
0.2090	0.6346	0.1564	0.8230	9.2595	7.6203	0.8195	7.8014	6.3934
0.3479	0.3267	0.3253	0.8242	10.3951	8.5678	0.8208	8.7412	7.1744
0.4111	0.1961	0.3928	0.8247	10.8694	8.9636	0.8212	9.1163	7.4866
0.5040	0.3880	0.1079	0.8205	7.6494	6.2761	0.8170	6.5708	5.3681
0.5984	0.2499	0.1517	0.8205	7.6493	6.2760	0.8170	6.5201	5.3267
0.6957	0.1048	0.1995	0.8205	7.7658	6.3718	0.8170	6.6056	5.4198
X_1	X_2	X_3	293.15 K 1-Heptanol (1) + 1-Nonanol (2) + 1-Undecanol (3)			298.15 K 1-Heptanol (1) + 1-Nonanol (2) + 1-Undecanol (3)		
1.0000	0.0000	0.0000	0.8222	8.6400	7.1041	0.8187	7.3198	5.9930
0.0000	1.0000	0.0000	0.8279	14.1129	11.6834	0.8244	11.7308	9.6713
0.0000	0.0000	1.0000	0.8325	20.6395	17.1818	0.8290	16.9172	14.0250
0.1142	0.1661	0.7198	0.8302	18.2024	15.1115	0.8268	14.9427	12.3546
0.2075	0.6381	0.1544	0.8274	13.9910	11.5765	0.8240	11.6182	9.5736
0.3299	0.3344	0.3357	0.8277	14.3662	11.8908	0.8243	11.9272	9.8311
0.3954	0.2061	0.3985	0.8277	14.1665	11.7261	0.8243	11.7487	9.6847
0.5026	0.3899	0.1075	0.8257	11.8941	9.8213	0.8223	9.9293	8.1649
0.5981	0.2499	0.1520	0.8255	11.5567	9.5403	0.8221	9.6772	7.9555
0.6622	0.1072	0.2307	0.8256	11.6002	9.5772	0.8222	9.6831	7.9945

$$\ell n \nu_m = \sum_{i=1}^{n} x_i^3 \ell n(\nu_i M_i) + 3 \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} x_i^2 x_j \ell n(\nu_{ij} M_{ij}) + 6 \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{\substack{k=1 \\ i \neq j \neq k}}^{n} x_i x_j x_k \ell n(\nu_{ijk} M_{ijk}) - \ell n M_m \tag{3}$$

For n-alkane mixtures, the binary interaction parameters in the previous equation are calculated using the following equation:

$$\frac{\nu_{ij}}{(\nu_i^2 \nu_j)^{1/3}} = 1 + 0.044 \frac{(N_j - N_i)^2}{(N_i^2 N_j)^{1/3}} \tag{4}$$

For the ternary interaction parameters, Nhaesi and Asfour [1] developed the following equation to predict the ternary interaction parameters for n-Alkanes:

$$\frac{\nu_{ijk}}{(\nu_i \nu_j \nu_k)^{1/3}} = 0.9941 + 0.03167 \frac{(N_k - N_i)^2}{N_j} \tag{5}$$

As suggested earlier by Shan [10] and Hussein [11], the generalized version of the predictive model for multi-component n-alkane mixtures were used for the prediction of the viscosities of the 1-alkanol binary mixtures. The second model that was tested is the GC-UNIMOD model was reported by Cao *et al.* [2] that is represented by the following viscosity equation:

$$\ell n(\nu) = \sum_{i=1}^{n} \left[\phi_i \ell n \left(\nu_i \frac{M_i}{M} \right) + 2\phi_i \ell n \left(\frac{x_i}{\phi_i} \right) + \sum_{\text{all groups k}} \nu_k^{(i)} \left[\theta_{ki} - \theta_{ki}^{(i)} \right] \right] \tag{6}$$

where ϕ_i is the average segment fraction of component i, $\theta_{ki}^{(i)}$ is the residual viscosity of group k for component i in a mixture-of-group of pure liquid i in component i. $\nu_k^{(i)}$ is the number of groups k per molecule of component i. The third model considered in this study is the generalized corresponding states principle (GCSP) model reported by Teja and Rice [3] and has the following formula:

$$\ell n(\mu\xi) = \ell n(\mu\xi)^{r1} + \frac{\omega - \omega^{r1}}{\omega^{r2} - \omega^{r1}} \left[\ell n(\mu\xi)^{r2} - \ell n(\mu\xi)^{r1} \right] \tag{7}$$

where r1 and r2 refer to the two fluids, μ is the absolute viscosity, ω is the acentric factor of the non-spherical fluid and ξ is a constant obtained from the critical properties of the fluid and is given by the following equation:

$$\xi = P_c^{-2/3} T_c^{1/6} M^{-1/2} \qquad (8)$$

where P_c and T_c are the critical pressure and temperature, respectively. This model requires the knowledge of the critical properties of the pure components composing the mixture. These data were taken from Reid *et al.* [12]. In order to apply the GCSP equation for liquid mixtures the mixing rules described in details earlier by Wong *et al*. [13] are used.

The last model tested in this study is the Allan and Teja correlation [4]. They proposed the following correlative Antoine-type equation for the estimation of the absolute viscosity:

$$\ell n \mu = A\left[-\frac{1}{B} + \frac{1}{T+C}\right] \qquad (9)$$

where A, B, and C are constants that are correlated to the carbon numbers in the hydrocarbons composing the mixture. For n-alkanes, N is the number of carbon atoms per molecule of the component. For non n-alkane hydrocarbons, viscosity data measured experimentally are needed for the estimation of the effective carbon number.

The kinematic viscosity values calculated by these models were compared with the experimental values. The predictive capabilities of the viscosity models were tested in terms of % average absolute deviation (% AAD), and the maximum percentage deviation of the model from experimental data (% MAX). The % AAD is calculated with the help of the following equation:

$$\%AAD = \frac{1}{n}\left\{\sum_{i=1}^{n} \frac{\left|\nu_i^{exp} - \nu_i^{cal}\right|}{\nu_i^{exp}} \text{ x}100\%\right\} \qquad (10)$$

The % MAX is given by the following equation:

$$\%MAX = MAX\left(\frac{\nu_i^{measured} - \nu_i^{predicted}}{\nu_i^{measured}}\right)\times 100 \qquad (11)$$

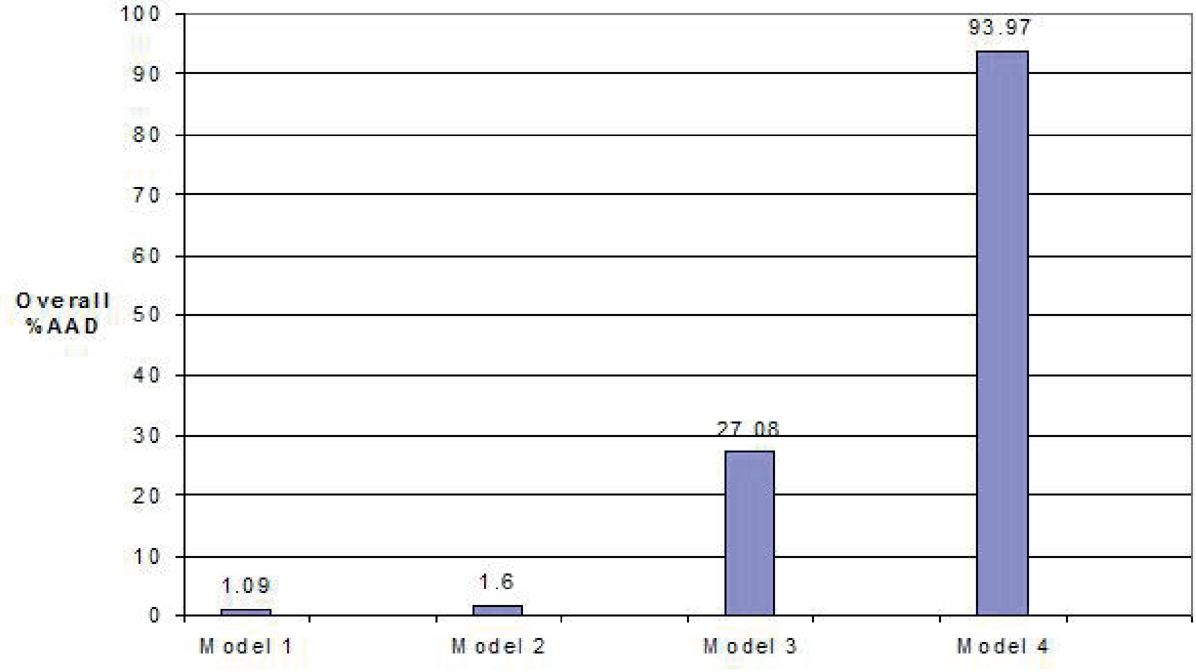
where n is the number of the experimental points and ν is the kinematic viscosity.

The results of testing the different models are shown in Table 4. The four models that were tested in the present study showed a variation in their predictive capabilities. The data reported in Table 4 show that the Generalized McAllister model gave the best overall predictive capability of all the tested models. The overall percentage average absolute deviation values was 1.09 %.

Table 4: Results of Testing Different Models for the Ternary Systems.

		Model 1		Model 2		Model 3		Model 4	
System	T/ K	% AAD	% MAX	% AAD	% MAX	% AAD	% MAX	% AAD	% MAX
1-Propanol + 1-Pentanol + 1-Heptanol	293.15	0.34	-0.85	1.36	-2.04	17.74	39.88	94.42	94.66
	298.15	0.48	1.73	0.39	-0.87	17.96	39.11	93.8	94.08
1-Propanol + 1-Heptanol + 1-Nonanol	293.15	0.59	-2.31	2.87	-3.65	34.36	71.66	94.5	94.84
	298.15	0.58	1.9	1.47	-1.88	34.55	70.94	93.85	94.3
1-Propanol + 1-Pentanol + 1-Nonanol	293.15	1.2	-5.23	3.22	-7.97	38.52	72.35	94.47	94.86
	298.15	1.62	-6.05	2.35	-8.23	38.25	71.36	93.82	94.29
1-Propanol + 1-Heptanol + 1-Undecanol	293.15	1.76	-4.9	2.48	-7.95	49.57	87.53	94.49	95.12
	298.15	2.01	-5.55	1.91	-7.99	49.10	86.84	93.81	94.57
1-Propanol + 1-Nonanol + 1-Undecanol	293.15	1.6	5.35	1.68	-3.49	51.47	-113.78	94.53	95.22
	298.15	1.72	5.9	1.14	2.83	48.63	-107.26	93.84	94.65
1-Propanol + 1-Pentanol + 1-Undecanol	293.15	1.71	5.62	1.28	-2.53	51.02	83.91	94.56	95.17
	298.15	1.91	6.96	1.06	-2.21	50.63	83.18	93.92	94.65
1-Pentanol + 1-Heptanol + 1-Nonanol	293.15	0.67	-2.67	2.22	-4.16	13.52	23.42	94.15	94.3
	298.15	0.91	-3.84	2.46	-5.09	12.62	22.07	93.43	93.65
1-Pentanol + 1-Nonanol + 1-Undecanol	293.15	0.64	1.94	1.47	-2.32	2.84	6.21	94.04	94.4
	298.15	0.52	1.24	1.45	-2.53	2.94	6.08	93.3	93.73
1-Pentanol + 1-Heptanol + 1-Undecanol	293.15	1.05	2.66	1.03	1.74	12.67	-24.04	94.12	94.45
	298.15	0.72	2.2	1.16	1.64	12.09	-23.11	93.4	93.77
1-Heptanol + 1-Nonanol + 1-Undecanol	293.15	1	2.43	0.51	1.13	1.59	-3.41	93.88	94.13
	298.15	0.75	2.16	0.56	0.94	1.44	-3.48	93.09	93.4
Overall % AAD		1.09		1.6		27.08		93.97	

Figure 1: Comparison of the overall predictive capabilities of the tested models



4 CONCLUSIONS

The kinematic viscosities and densities of ten ternary of the quinary system: 1-propanol, 1-pentanol, 1-heptanol, 1-nonanol, and 1-undecanol over the entire composition range were measured at 293.15, 298.15 K. The measured kinematic viscosity values reported in this work were compared to the predicted values of kinematic viscosity of the four selected viscosity models. The predictive capability of each of the viscosity models was determined by calculating the percent average absolute deviation (%AAD). For the investigated ternary systems the generalized McAllister model showed the best overall predictive capability of all models with a % AAD value of 1.09.

Acknowledgment

Financial assistance in form of a discovery grant from the Natural Sciences and Engineering Council of Canada (NSERC) is acknowledged with thanks.

REFERENCES

[1] A. H. Nhaesi, A. A. Asfour "Prediction of the Viscosity of Multicomponent Liquid Mixtures: A generalized McAllister Three-body Interaction Model". Chem. Eng. Sci., Vol. 55, 2000, 2861-2873

[2] W. Cao, K. Knudsen, A. Fredenslund, and P. Rasmussen "Group-Contribution Viscosity Predictions of Liquid Mixtures Using UNIFAC-VLE Parameters". Ind. Eng. Chem. Res., 32, 1993, 2088-2092.

[3] A. S. Teja and P. Rice "Generalized Corresponding States Method For the Viscosities of Liquid Mixtures". I&EC Fundam., 20, 1981, 77-81.

[4] J.M. Allan and A. S. Teja "Correlation and Prediction of Viscosity of Defined and Undefined Hydrocarbon Liquids". Can. J. Chem. Eng., 69, 1991, 986-99l.

[5] A. A. Asfour "Mutual and intra-(self-) diffusion coefficients and viscosities of binary liquid solutions at 25.00 °C". Ph.D. Thesis, University of Waterloo, Waterloo, Canada, 1980.

[6] TRC Thermodynamic Tables - Hydrocarbons; Thermodynamic Research Center, Texas A&M University: College Station, TX, 1988.

[7] M.N.M. Al-Hayan, A. M. Abdul-latif, J. Chem. Thermodynamics. 38, 68 (2006)

[8] M. A. Franca Faria, C. F. de Sa´, G. R. Lima, J. I. B. C. Filho, R. J. Martins, M. J. E. de M. Cardoso; and O. E. Barcia "Measurement of Density and Viscosity of Binary 1-Alkanol Systems (C8-C11) at 101 kPa and Temperatures from (283.15 to 313.15) K". J. Chem. Eng. Data., 50, 2005, 1938-1943.

[9] A. S. Al-Jimaz, J. A. Al-Kandary, and A. M. Abdul-latif "Densities and Viscosities for Binary Mixtures of Phenetole with 1-Pentanol, 1-Hexanol, 1-Heptanol, 1-Octanol, 1-Nonanol, and 1-Decanol at Different Temperatures". Fluid Phase Equilibria, 218, 2004, 247–260.

[10] Z. Shan "An Experimental Study of the Viscometric and Volumetric Properties of 1-Alkanol Multi-Component Liquid Mixtures at Several Temperature Level". Ph.D. Thesis, University of Windsor. Windsor, Canada, 2000.

[14] N. Hussein "A Study of the Viscometric and Volumetric Properties of 1-Alkanol (C3 - CI1) Multi-component Liquid Systems at Different Temperature Levels". M.A.Sc. Thesis, University of Windsor. Windsor, Canada, 2007.

[15] R. C. Reid, J.M. Praunitz, and T. K. Sherwood "The Properties of Gases and Liquids, "McGeaw - Hill, New York, (1987).

[16] D. S. H. Wong, S. I. Sandler, and A. S. Teja, "Vapor-Liquid Equilibrium Calculations by Use of Generalized Corresponding States Principle. I. New Mixing Rules", I&EC Fundam., 23, 1994, 38-44.