Density and viscosity correlations of aqueous solvents for amine-based CO_2 capture

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Abstract

Density and viscosity data are essential in designing process equipment and process simulations in the amine-based CO_2 capture process. In literature, semi-empirical and empirical correlations for density and viscosity were fitted to measured data available in the literature and the goodness of fit by calculating Average Absolute Relative Deviations (AARDs %) were examined. The correlations based on excess properties give insights on intermolecular interactions and packing efficiency in multicomponent liquid mixtures.

In this study, correlations for density, excess density (ρ^E, $ln(\rho^E)$) viscosity and excess viscosity (η^E, $ln(\eta^E)$) were examined for binary aqueous mixtures (Monoethylethanolamine) EMEA (1) + H_2O (2) and (Monoethylethanolamine) EMEA (1) + (Diethylethanol amine) DEEA (2) to represent the measured density and viscosity. The Redlich and Kister type polynomials were used to fit the excess properties and the goodness of fit was determined by calculating AARD%. The fitted experimental data at different mole fractions and temperatures were able to acquire a good accuracy. Highest deviation for density correlations of EMEA + DEEA mixtures was observed with AARD 0.135 % and AMD 2.98 kg·m^{-3}. For the EMEA + H_2O mixtures, the highest deviation was observed with AARD 0.23 % and AMD 8.38 kg·m^{-3}. Viscosity correlations showed a highest deviation for the EMEA + DEEA mixtures in which AARD was 5.2 % and AMD was 1.2 mPa·s. For the EMEA + H_2O mixtures, the highest deviation observed with AARD was 1.1% and AMD was 0.75 mPa·s.

McAllister's kinematic viscosity model is a semi-empirical model based on Eyring's theory for viscosity. The kinematic viscosity data were fitted to McAllister's three-body model to investigate whether the suggested intermolecular interactions in the model are capable of describing the nature of the binary mixtures. The results indicated a good agreement between data and model with accuracies $R^2 = 0.99$ and AARD 2% for EMEA + DEEA mixtures and AARD 6% for EMEA + H_2O mixtures.

Keywords: *correlations, density, viscosity*

1. Introduction

Amine-based CO_2 capture is a matured technology that has been adopted to remove CO_2 and H_2S from natural gas. The aqueous solvents of MEA (Monoethanolamine), MDEA (Methyldiethanolamine), and DEA (Diethanolamine) are proven solvents for gas purification. There are advantages and disadvantages of using these amines, and none of them are perfect to use in post-combustion CO_2 capture. Solvents with characteristics such as higher CO_2 loading capacity and lower heat of reaction enable the applicability of using this technology for post-combustion CO_2 capture. As a result, new amines and blends of existing amines are continuously examined to find a solvent that can give higher CO_2 capture efficiency at a low rate of use of energy. The physicochemical properties are measured to support further research in CO_2 capture.

2. Literature

Density and viscosity data are essential in designing process equipment and performing process simulations in the amine-based CO_2 capture process. Semi-empirical and empirical correlations for density and viscosity were fitted to measured data that are available in literature and the goodness of the fit was examined by calculating relative deviation. The correlations based on excess properties give insights into intermolecular interactions and packing efficiency in multicomponent liquid mixtures. In a binary liquid mixture, excess molar volume V^E rises mainly due to the difference in intermolecular interaction between unlike molecules compared to the intermolecular interaction present in pure components, and differences in size and shapes of molecules that affect the packing efficiency in the mixture (Mahajan and Mirgane 2013). The positive deviation for V^E are responsible for having weak dipole-dipole interactions among the unlike molecules while negative deviations are responsible for charge transfer, H-bonds and other complex forming interactions. The negative V^E can also be a result of the fitting of component molecules of the mixture due to the structural differences of size and shape. The viscosity deviation or excess viscosity η^E calculated using [measured] mixture and pure liquid viscosities can provide similar information as V^E for the intermolecular interactions (Fort and Moore 1966). There, positive η^E indicates stronger intermolecular interactions like H-bonds while negative η^E indicates weak dipolar interactions.

Eyring's viscosity model, which is based on Eyring's theory of absolute reaction rate provides a mechanism to explain the viscosity of liquids (Eyring 1936). The excess free energy of activation for viscous flow ΔG^{E*} defined for mixtures provides information of the nature of intermolecular interactions similar to V^E and η^E (Meyer *et al.*, 1971) in which positive ΔG^{E*} indicates stronger intermolecular interactions like H-bonds while negative ΔG^{E*} indicates weak dipolar interactions. McAllister (1960) developed a model to predict kinematic viscosity using Eyring's approach for binary mixtures. There different types of molecular interactions were considered in the model development. The relevant parameters in model can be estimated by regression.

Correlations based on Redlich-Kister type polynomial (Redlich and Kister 1948) is a commonly used approach to represent measured density and viscosity for binary mixtures. The calculated excess properties such as excess molar volume V^E and excess viscosity η^E are fitted to a Redlich-Kister type polynomial and relevant parameters are found by minimizing the deviation between predictions and data. Karunarathne *et al.* (2020) reviewed the developed correlations for MEA (Monoethanolamine) + H_2O + CO_2 mixture and discussed the accuracies of predictions by comparing different data sets.

This study discusses several approaches to develop correlations for density and viscosity of Monoethylethanolamine EMEA (1) + Diethylethanol amine DEEA (2) and Monoethylethanolamine EMEA (1) + H_2O (2) mixtures. The correlations were evaluated for the accuracy of data fit by calculating different statistical quantities such as average absolute relative deviation AARD and absolute maximum deviation AMD. Measured densities and viscosities for EMEA + DEEA and EMEA + H_2O mixtures for this study were taken from published data by Chen *et al.* (2016).

3. Methodology

Several approaches have been considered for the fitting of measured data to density and viscosity correlations. For the density, [four corrections] were considered as shown from (1) to (6). Equation (1) is an analogous correlation proposed for density based on the viscosity correlation proposed by Heric and Brewer (1967). The parameter A_i is further correlated to the temperature of the mixture through a linear relation of $A_i = a_{i1} + a_{i2}T$. Equation (2) was proposed by Aronu *et al.* (2012) to represent the density of aqueous amino acid salt and amine amino acid salt solutions. Equations (3) and (4) were based on the excess density ρ^E in which excess properties are represented by Redlich and Kister type polynomials with temperature dependent parameters. Equations (5) and (6) considered natural logarithm of excess density $ln(\rho^E)$ and Redlich and Kister type polynomials with temperature dependent parameters were adopted to fit the calculated $ln(\rho^E)$ as described in (6).

$$\begin{aligned} ln(\rho) = x_1 ln(\rho_1) + x_2 ln(\rho_2) + x_1 ln(M_1) \\ + x_2 ln(M_2) \\ - ln(x_1 M_1 + x_2 M_2) \\ + x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \end{aligned} \tag{1}$$

$$\rho = \left(A_0 + \frac{A_1 x_2}{T}\right) exp\left(\frac{A_2}{T^2} + \frac{A_3 x_1}{T} + A_4\left(\frac{x_1}{T}\right)^2\right) \tag{2}$$

$$\rho^E = \rho - \sum_{i=1}^{n} x_i \rho_i \tag{3}$$

$$\rho^E = x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \tag{4}$$

$$ln(\rho^E) = ln(\rho) - \sum_{i=1}^{n} x_i ln(\rho_i) \tag{5}$$

$$ln(\rho^E) = x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \tag{6}$$

Four correlations for dynamic viscosity have been considered as illustrated from (7) to (12). Equation (7) is proposed for viscosity by Heric and Brewer (1967). A correlation developed by Aronu *et al.* (2012) in (8) was adopted as it does not require any pure component viscosities to calculate mixture viscosity. For (9) and (10), excess viscosity or viscosity deviation η^E was calculated from pure component viscosities and Redlich and Kister type polynomials with temperature dependent parameters were proposed to represent η^E. The natural logarithm of excess viscosity $ln(\eta^E)$ and Redlich and Kister type polynomials with temperature dependent parameters were adopted to fit the calculated $ln(\eta^E)$ as described in (11) and (12).

The kinematic viscosities of EMEA (1) + DEEA (2) and EMEA (1) + H_2O (2) mixtures were calculated using measured dynamic viscosities and densities. McAllister (1960) model was fitted to the range of mole fractions of x_1 from 0 to 1 and temperatures from 293.15 K to 333.15 K. Equations from (13) to (17) described the McAllister model in which the enthalpies and entropies were found using regression.

$$\begin{aligned} ln(\eta) = x_1 ln(\eta_1) + x_2 ln(\eta_2) + x_1 ln(M_1) \\ + x_2 ln(M_2) \\ - ln(x_1 M_1 + x_2 M_2) \\ + x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \end{aligned} \quad (7)$$

$$\begin{aligned} \eta = \left(1 + \frac{A_0 x_1}{T} + \frac{A_1 x_1 x_2^2}{T^2}\right) exp\left(A_2 + \frac{A_4}{T} \right. \\ \left. + \frac{A_5}{T^3} + \frac{A_6 x_1 x_2}{T^4}\right) \end{aligned} \quad (8)$$

$$\eta^E = \eta - \sum_{i=1}^{n} x_i \eta_i \quad (9)$$

$$\eta^E = x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \quad (10)$$

$$ln(\eta^E) = ln(\eta) - \sum_{i=1}^{n} x_i ln(\eta_i) \quad (11)$$

$$ln(\eta^E) = x_1 x_2 \left[\sum_{i=0}^{n} A_i (x_1 - x_2)^i\right] \quad (12)$$

$$\begin{aligned} ln(\nu) = x_1^3 ln(\nu_1) + 3x_1^2 x_2 ln(\nu_{12}) \\ + 3x_1 x_2^2 ln(\nu_{21}) \\ + x_2^3 ln(\nu_2) \\ - ln\left(x_1 + x_2 \frac{M_2}{M_1}\right) \\ + 3x_1^2 x_2 ln\left[\frac{\left(2 + \frac{M_2}{M_1}\right)}{3}\right] \\ + 3x_1 x_2^2 ln\left[\frac{\left(1 + \frac{2M_2}{M_1}\right)}{3}\right] \\ + x_2^3 ln\left(\frac{M_2}{M_1}\right) \end{aligned} \quad (13)$$

$$\nu_1 = \frac{hN}{M_1} e^{-\Delta S_1^*/R} e^{\Delta H_1^*/RT} \quad (14)$$

$$\nu_{12} = \frac{hN}{M_{12}} e^{-\Delta S_{12}^*/R} e^{\Delta H_{12}^*/RT} \quad (15)$$

$$\nu_{21} = \frac{hN}{M_{21}} e^{-\Delta S_{21}^*/R} e^{\Delta H_{21}^*/RT} \quad (16)$$

$$\nu_2 = \frac{hN}{M_2} e^{-\Delta S_2^*/R} e^{\Delta H_2^*/RT} \quad (17)$$

$$AARD = \frac{100\%}{D} \sum_{i=1}^{D} \left|\frac{A_i^m - A_i^c}{A_i^m}\right| \quad (18)$$

$$AMD = MAX|A_i^m - A_i^c| \quad (19)$$

4. Results and Discussion

4.1. Density correlations

The density correlations from (1) to (6) have been fitted for the measured densities for EMEA+DEEA and EMEA + H_2O binary mixtures. Tab. 1 summarized the calculated AARD (%) and AMD ($kg \cdot m^{-3}$) for the different correlations. Fig. 1 and 2 illustrate the accuracy of fitting (1) and (2) into the measured densities and both correlations showed acceptable accuracies of EMEA + DEEA and EMEA + H_2O mixtures. For EMEA + H_2O, the deviations are relatively higher compared to EMEA + DEEA mixtures. The density correlation from Aronu *et al.* (2012) showed a highest AMD of 2.98 $kg \cdot m^{-3}$ at $x_1 = 0$ and temperature 333.15 K for EMEA + DEEA and AMD of 8.38 $kg \cdot m^{-3}$ at $x_1 = 0$ and temperature 293.15 K for EMEA + H_2O mixtures respectively. The correlations (3,4) and (5,6) were fitted and parameters were found at each temperature level. This led to higher fitting accuracies as listed in Tab. 1. The estimated parameters for the correlations are given in Tab. 2 and 3.

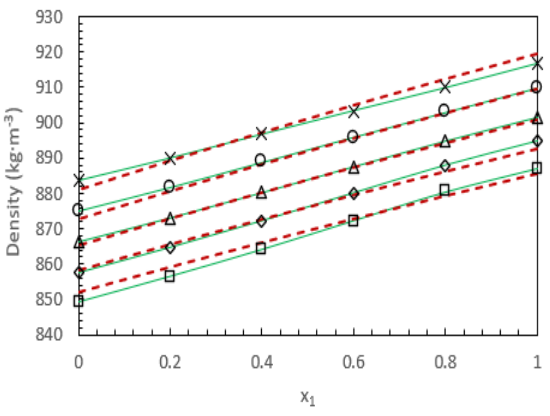

Figure 1: Density of EMEA + DEEA mixtures. Measured: 293.15 K, ‘x’; 303.15 K, ‘○’; 313.15 K, ‘Δ’; 323.15 K, ‘◊’; 333.15 K, ‘□’. Correlation: Equation (1) ‘___’, Equation (2) ‘_ _ _’.

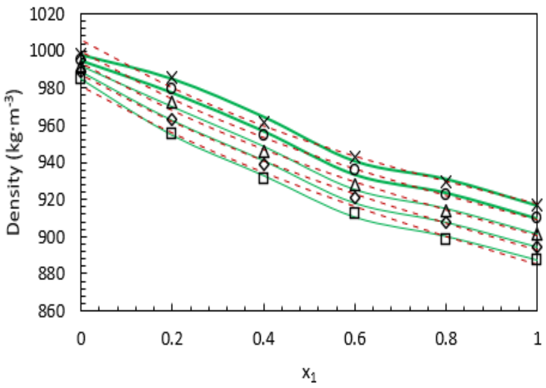

Figure 2: Density of EMEA + H_2O mixtures. Measured: 293.15 K, 'x'; 303.15 K, '○'; 313.15 K, 'Δ'; 323.15 K, '◊'; 333.15 K, '□'. Correlation: Equation (1) '___', Equation (2) '_ _ _'.

4.2. Viscosity correlations

Viscosity correlations showed from (7) to (12) were fitted into the measured viscosities of EMEA + DEEA and EMEA + H_2O mixtures. The accuracy of the fit was examined using calculated AARD (%) and AMD (mPa·s) as listed in Tab. 4. A comparison between correlation (7) and (8) for the viscosities of EMEA + DEEA mixtures is illustrated in Fig. 3. Correlation (7) was able to represent measured data with acceptable fitting accuracies as given in Tab. 4. Correlation (8) showed a relatively high AARD (%) of 5.2. The deviation between measured data and (8) is high as demonstrated in Fig. 4 and AMD is 1.2 mPa·s at $x_1 = 1$ and temperature 293.15 K. For the EMEA + H_2O mixtures, (7) gives an acceptable accuracy for the data fit as shown in Tab. 4. The correlation (8) was not appropriate for EMEA + H_2O mixtures as it gave a higher AARD (%). For the correlations (9,10) and (11,12), measured viscosities were fitted and parameters were found at each temperature level. As a result, higher accuracies were obtained as given in Tab. 4. This is a result of the simplification of the complexity of the correlations and at the same time correlation had to be fitted into a relatively small data set compared to the previous scenarios.

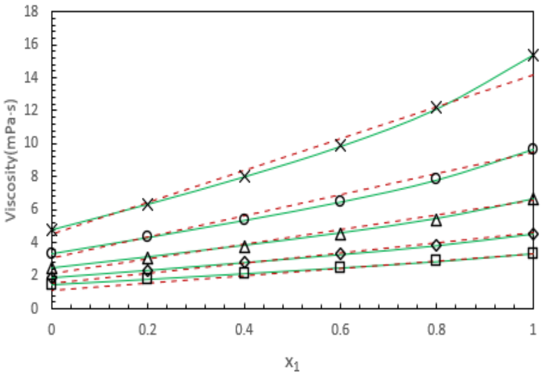

Figure 3: Viscosity of EMEA + DEEA mixtures. Measured: 293.15 K, 'x'; 303.15 K, '○'; 313.15 K, 'Δ'; 323.15 K, '◊'; 333.15 K, '□'. Correlation: Equation (7) '___', Equation (8) '_ _ _'.

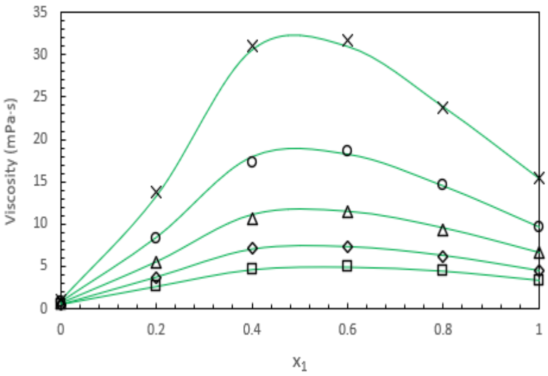

Figure 4: Viscosity of EMEA + H_2O mixtures. Measured: 293.15 K, 'x'; 303.15 K, '○'; 313.15 K, 'Δ'; 323.15 K, '◊'; 333.15 K, '□'. Correlation: Equation (7) '___'.

Table 1: Calculated AARD (%) and AMD ($kg·m^{-3}$) for different density correlations and mixtures.

Correlation	**AARD (%)**		**AMD ($kg·m^{-3}$)**	
	EMEA + DEEA	*EMEA + H_2O*	*EMEA + DEEA*	*EMEA + H_2O*
Equation (1)	0.012	0.127	0.37	3.03
Equation (2)	0.135	0.23	2.98	8.38
Equation (3) & (4)	1.85×10^{-6}	1.04×10^{-11}	$1.2x10^{-6}$	$8.2x10^{-11}$
Equation (5) & (6)	0.09	8.3×10^{-15}	$9.1x10^{-5}$	$1.3x10^{-16}$

4.3. McAllister model for kinematic viscosity

McAllister model was fitted to calculated kinematic viscosities from measured dynamic viscosity and density data for EMEA + DEEA and EMEA + H_2O mixtures for the mole fraction range from 0 to 1 and temperature from 293.15 K to 333.15 K. Fig. 5 compares the fitted McAllister model with kinematic viscosity data for EMEA + DEEA mixtures. The accuracy of the fitting is acceptable as it showed AARD (%) of 1.9 and AMD of 4.3×10^{-7} $m^2·s^{-1}$ at $x_1 = 1$ and temperature of 293.15 K. For the EMEA + H_2O mixtures, the deviations are higher as AARD (%) of 5.9 and AMD of 2.8×10^{-6} m^2·s^{-1} at $x_1 = 0.8$ and temperature of 293.15 K. Fig. 6 compares the fitted McAllister model with kinematic viscosity data for EMEA + H_2O mixtures and local maximums for kinematic viscosities at different temperature levels were observed around mole fraction $x_1 = 0.5$.

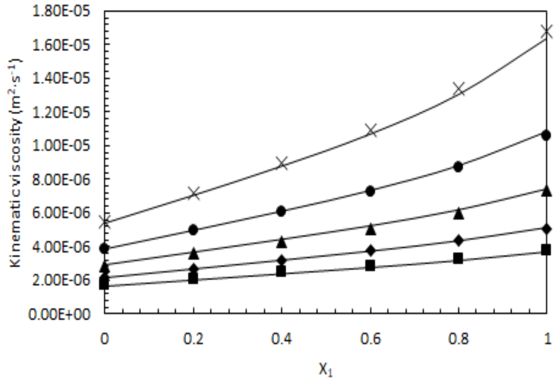

Figure 5: Kinematic viscosity of EMEA + DEEA mixtures. Measured: 293.15 K, ‘x’; 303.15 K, ‘○’; 313.15 K, ‘Δ’; 323.15 K, ‘◊’; 333.15 K, ‘□’. Correlation: Equation (13) ‘___’.

Tab. 7 lists the estimated enthalpies and entropies for the viscous flow from the McAllister model from (13) to (17). This approach enables to fit the model to the complete temperature interval rather than fitting the model and estimating parameters at different temperature levels. Then this model can easily be implemented in a computer program to estimate kinematic viscosities for unmeasured mole fractions and temperatures.

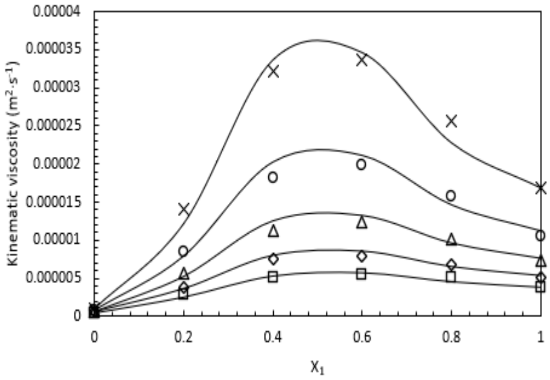

Figure 6: Kinematic viscosity of EMEA + H_2O mixtures. Measured: 293.15 K, ‘x’; 303.15 K, ‘○’; 313.15 K, ‘Δ’; 323.15 K, ‘◊’; 333.15 K, ‘□’. Correlation: Equation (13) ‘___’.

Table 2**:** Estimated parameters for (1) and (2) for EMEA + DEEA and EMEA + H_2O mixtures.

Parameters	**Equation (1)**	
	EMEA + DEEA	*EMEA + H_2O*
A_0	$a_{0,1} = 0.0323$	$a_{0,1} = 1.433$
	$a_{0,2} = 1.80 \times 10^{-5}$	$a_{0,2} = -9.982 \times 10^{-4}$
A_1	$a_{1,1} = -0.0472$	$a_{1,1} = -0.9877$
	$a_{1,2} = 1.734 \times 10^{-4}$	$a_{1,2} = 12.1 \times 10^{-4}$
A_2	$a_{2,1} = -0.0741$	$a_{2,1} = 0.8215$
	$a_{2,2} = 2.41 \times 10^{-4}$	$a_{2,2} = -14.45 \times 10^{-4}$
Parameters	**Equation (2)**	
	EMEA + DEEA	*EMEA + H_2O*
A_0	756.4	712.5
A_1	2334	1.08×10^5
A_2	1.22×10^4	-6221
A_3	17.04	58.13
A_4	-413.2	1.10×10^4

Table 3: Estimated parameters for (3-4) and (5-6) for EMEA + DEEA and EMEA + H_2O mixtures.

T/K	**EMEA + DEEA for Equation (3-4)**					
	A_0	A_1	A_2	A_3	A_4	A_5
293.15	-0.4543	0.9649	-4.3077	-220.741	1.0024	618.5851
303.15	-0.6092	-5.3242	-0.4388	23.6887	1.0971	0.9997
313.15	0.5983	3.9766	0.6330	-0.4727	0.8590	0.3681
323.15	-0.0575	3.6604	1.3813	2.1979	1.4297	1.0157
333.15	-0.1798	1.4632	4.3446	15.4171	3.7869	2.1474

$\mathrm{T/K}$	EMEA + H_2O Equation (3-4)					
	A_0	A_1	A_2	A_3	A_4	A_5
293.15	-23.478	-21.8423	59.9364	-41.852	24.3164	-15.812
303.15	-31.131	-15.3706	53.4441	-37.049	21.8259	-13.9841
313.15	-43.1324	2.0342	51.4202	-55.204	21.1892	-21.4963
323.15	-52.0017	9.7800	23.5946	-9.9850	10.1867	-3.5205
333.15	-61.211	4.3467	14.7591	10.9855	-2.7181	3.4607
$\mathrm{T/K}$	EMEA + DEEA for Equation (5-6)					
	A_0	A_1	A_2	A_3	A_4	A_5
293.15	0.01534	0.0020	-0.4258	-0.2184	1.0525	0.6052
303.15	0.0154	0.0020	-0.4236	-02155	1.0584	0.6132
313.15	0.0163	0.0020	-0.4106	-0.2134	1.0289	0.6116
323.15	0.0158	0.0021	-0.4152	-0.2110	1.0435	0.6116
333.15	0.01581	0.0021	-0.4130	-0.2067	1.0486	0.6236
$\mathrm{T/K}$	EMEA + H_2O Equation (5-6)					
	A_0	A_1	A_2	A_3	A_4	A_5
293.15	-0.0210	-0.0163	0.0611	-0.2523	0.0247	0.5137
303.15	-0.0288	-0.0100	0.0550	-0.2478	0.0224	0.5154
313.15	-0.0412	0.0077	0.0054	-0.2674	0.0216	0.5107
323.15	-0.0505	0.0152	0.0253	-0.2121	0.01213	0.5031
333.15	-0.1783	-0.0094	3.2896	0.3112	-8.1848	-0.7458

Table 4: Calculated AARD (%) and AMD (mPa·s) for different viscosity correlations and mixtures.

Correlation	**AARD (%)**		**AMD (mPa·s)**	
	EMEA + DEEA	*EMEA + H_2O*	*EMEA + DEEA*	*EMEA + H_2O*
Equation (7)	0.4	1.1	0.1	0.75
Equation (8)	5.2	-	1.2	-
Equation (9) & (10)	1×10^{-6}	8×10^{-12}	2.5×10^{-6}	1.6×10^{-10}
Equation (11) & (12)	1×10^{-4}	6×10^{-12}	6.6×10^{-7}	1.5×10^{-11}

Table 5: Estimated parameters for (7) and (8) for EMEA + DEEA and EMEA + H_2O mixtures.

Parameters	**Equation (7)**	
	EMEA + DEEA	*EMEA + H_2O*
A_0	$a_{0,1} = -0.03826$	$a_{0,1} = 31.37$
	$a_{0,2} = 7.24 \times 10^{-4}$	$a_{0,2} = -0.0742$
A_1	$a_{1,1} = -1.243$	$a_{1,1} = -21.55$
	$a_{1,2} = 33.23 \times 10^{-4}$	$a_{1,2} = 0.0527$
A_2	$a_{2,1} = 0.2905$	$a_{2,1} = 7.403$
	$a_{2,2} = -10.58 \times 10^{-4}$	$a_{2,2} = -0.0149$

Parameters	**Equation (8)**
	EMEA + DEEA
A_0	633.1
A_1	0.3369
A_2	-16.81
A_3	3343
A_4	0.724
A_5	0.0539

Table 6: Estimated parameters for (9-10) and (11-12) for EMEA + DEEA and EMEA + H_2O mixtures.

T/K	EMEA + DEEA for Equation (9-10)			
	A_0	A_1	A_2	A_3
293.15	-4.7227	-3.0143	-1.2044	0.8790
303.15	-2.2813	-1.5235	-0.7812	0.0651
313.15	-1.6719	-1.1849	-0.9115	-0.5859
323.15	-0.5898	-0.3581	-0.3581	0.0977
333.15	-0.4102	-0.4362	-0.1628	0.4883
T/K	**EMEA + H_2O Equation (9-10)**			
	A_0	A_1	A_2	A_3
293.15	100.3320	-26.2695	-94.2383	92.6758
303.15	54.7930	-7.0247	-44.3034	32.3893
313.15	31.8516	-6.0026	-23.8932	20.3776
323.15	19.8906	-6.8229	-12.8906	20.5729
333.15	12.4609	-2.7344	-5.2734	8.9844
T/K	**EMEA + DEEA for Equation (11-12)**			
	A_0	A_1	A_2	A_3
293.15	0.1449	-0.2919	-0.0011	0.1276
303.15	0.1630	-0.2461	-0.02023	0.04032
313.15	0.0878	-0.2493	-0.0837	-0.0785
323.15	0.1951	-0.1457	-0.0730	0.0682
333.15	0.1650	-0.2096	-0.0276	0.2274
T/K	**EMEA + H_2O Equation (11-12)**			
	A_0	A_1	A_2	A_3
293.15	8.5296	-5.4086	2.8146	-0.7541
303.15	7.6668	-4.4286	2.6108	-1.2722
313.15	6.8749	-4.1453	2.2607	-0.9154
323.15	6.2346	-4.0936	2.0644	0.4892
333.15	5.5350	-3.3344	2.3431	-0.3038

Table 7: Estimated enthalpies and entropies for the viscous flow.

Mixture	ΔH^*/ kJ·mol^{-1}	ΔS^*/ J·mol^{-1}·K^{-1}
EMEA + DEEA	$\Delta H_1^* = 30.25$	$\Delta S_1^* = 35.0$
	$\Delta H_{12}^* = 30.0$	$\Delta S_{12}^* = 26.5$
	$\Delta H_{21}^* = 26.4$	$\Delta S_{21}^* = 25.3$
	$\Delta H_2^* = 23.45$	$\Delta S_2^* = 18.8$
EMEA + H_2O	$\Delta H_1^* = 30.35$	$\Delta S_1^* = 35.04$
	$\Delta H_{12}^* = 31.6$	$\Delta S_{12}^* = 40.8$
	$\Delta H_{21}^* = 54.5$	$\Delta S_{21}^* = 97.3$
	$\Delta H_2^* = 15.4$	$\Delta S_2^* = 20.6$

5. Conclusions

This work presents developed correlations to represent measured densities and viscosities of EMEA + DEEA and EMEA + H_2O mixtures. Further, the study discusses the applicability of McAllister's kinematic viscosity model for the kinematic viscosities of EMEA + DEEA and EMEA + H_2O mixtures. Developed correlations showed acceptable accuracies in data fitting in which for the density, correlations from (3) to (6) showed a very low deviation from measured data. This is mainly because the data were fitted into the correlation at different temperature levels and the number of data points for the fitting was small compared to the fitting for (1) and (2). The highest deviation for density correlations for the EMEA + DEEA mixtures was observed for (2) in which AARD (%) was 0.135 and AMD was 2.98 kg·m^{-3}. For the EMEA + H_2O mixtures, the highest deviation was observed for (2) in which AARD (%) was 0.23 and AMD was 8.38 kg·m^{-3}.

Proposed correlations for the viscosity of EMEA + DEEA and EMEA + H_2O mixtures showed acceptable accuracies for the fitting and correlations can be used in engineering applications. Equations (7) and (8) have parameters to correlate the effect of temperature on viscosity of the mixtures that do not have in (9) to (12). Equations from (9) to (12) were fitted at different temperature levels into the correction. Consequently, that led to high accuracies in data fitting. Viscosity correlations indicated the highest deviation for the EMEA + DEEA mixtures for (8), where AARD (%) was 5.2 and AMD was 1.2 mPa·s. The McAllister model was able to represent kinematic viscosities for both EMEA + DEEA and EMEA + H_2O mixtures with acceptable accuracies. The calculated enthalpies and entropies for the viscous flow enable the use of the model at different temperatures and mole fractions.

In future work, suggestions are to develop new semi-empirical and empirical correlations for measured densities and viscosities to reduce the complexity of the corrections and acquire higher accuracies.

Nomenclature

Letters	Description	Units
A_i	Parameters	
A_i^m	Measured property	$kg \cdot m^{-3}$ or $Pa \cdot s$
A_i^c	Calculated property	$kg \cdot m^{-3}$ or $Pa \cdot s$
h	Planck‘s constant	$m^2 \cdot kg \cdot s^{-1}$
H	Enthalpy of viscous flow	$kJ \cdot mol^{-1}$
M	Molecular weight	$kg \cdot mol^{-1}$
N	Avogadro’s number	mol^{-1}
R	Universal gas constant	$J \cdot mol^{-1} \cdot K^{-1}$
S	Entropy of viscous flow	$kJ \cdot mol^{-1} \cdot K^{-1}$
T	Temperature	K
x_i	Mole fraction	-
ρ	Density	$kg \cdot m^{-3}$
ρ^E	Excess density	$kg \cdot m^{-3}$
η	Dynamic viscosity	$Pa \cdot s$
η^E	Excess viscosity	$Pa \cdot s$
ν	Kinematic viscosity	$m^2 \cdot s^{-1}$

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