



Original Research Article

Correlations for Liquid and Vapour Dynamic Viscosities for Ammonia-Water Solution

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ABSTRACT

Dynamic viscosity is a key thermodynamic property needed for the design and simulation of ammonia-water refrigeration systems. It is there important to generate correlations that accurately produce empirical or/and experimental values. In this paper, dynamics viscosity correlations were derived for pure ammonia and water for both the liquid and vapour solution for ammonia-water solutions and then applied in generating dynamic viscosity data. They were then compared with values generated from the procedure presented in the literature. For the liquid solution, the average percentage errors between correlation values and generated data are significantly low ($\pm 0.199\%$ and $\pm 0.129\%$) for the two temperature ranges considered in this paper. When the data generated by the correlation was compared with literature values, the average percentage error was determined to be $\pm 2.457\%$ for the liquid solution. For the vapour phase, comparing the generated data had an average percentage deviation of $\pm 1.39\%$, while the percentage error of fit is $\pm 0.00497\%$. Therefore, the correlations derived in this paper can be used to calculate the dynamic viscosity of ammonia-water solution for both the liquid and vapour solutions.

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1. INTRODUCTION

Viscosity is one of the thermodynamic properties necessary in the design and simulation of flow equipment and systems. Viscosity can be considered the energy that makes a fluid flow as the molecules interact. Generally, viscosity decreases with increasing temperature in liquids, while it increases with increasing temperature in gases. Because of the role this property plays in the design and simulation of flow systems, various correlations have been developed to express the relationship between it and temperature. For gases, pressure also becomes a factor. One of the areas where accurate viscosity values play an important

factor is the design and simulation of ammonia-water absorption refrigeration. Poor design, verification or simulation emanating from wrong or inaccurate viscosity values result in inefficient processes or products that do not meet specifications.

It is known that mixing water and ammonia does not result in an ideal mixture. It is, therefore, necessary to consider the non-ideality of the mixture if correlations are to be developed empirically. However, results generated from theoretical studies should be validated with results from experiments to determine the percentage error of the fit before such correlations can be applied for design and simulation purposes. Scanning through literature, it can be determined that experimental data for viscosity of ammonia-water solution are scarce. In addition, where it could be found, the data ranges in respect to temperature or pressure are negligible. The experimental data presented by Pinevic (1948) can be considered one of the few that covered a wide data range. The correlation for calculating viscosity of liquid ammonia-water solution developed by Pinevic (1948) was modified by El-Sayed (1988). However, the deviation from experimental data was significant and therefore can only be applied for estimations purposes. Various other researchers, such as Stokar (1986) and Frank *et al.* (1996), developed equations for estimating viscosity of liquid ammonia-water solution but have also been considered to deviate significantly from experimental results.

Two methods can be used to estimate the viscosity of a gas mixture. The first is the method that uses the viscosity of the pure components. The methods presented by Hering and Zipperers (1936), Brokaw (1969), Reichenberg (1973), Wilke (1950) and Gillen *et al.* (1990) fall into this category. The second category, such as the procedures presented by Chung *et al.* (1984) and Stiel and Thodos (1961), uses the mixing rule. Deviations from experimental values are in the region of 8-9% (Latini, 2017). Reichenberg (1973)'s method considers properties such as temperature, critical pressure, critical temperature composition, the viscosity of the pure component, molecular weight, and components' dipole moment. The Reichenberg (1973) Equation is rather complex because of the number of parameters involved. Gillén *et al.* (1990) presented equations for the calculation of the viscosity of ammonia-water liquid solutions. However, these equations are limited because they do not cover all temperature and mass fractions ranges that apply to ammonia-water refrigeration systems. The equation by Wilke (1950) is recommended for low-pressure system calculation of viscosity, and the ammonia-water refrigeration system can be considered to be in this range. Though the results generated by Reichenberg (1973) procedure are considered more accurate than other procedures, it is rather very complex to apply (Heikkilä, 2014). Wilke (1950) method is a well-tested one for calculating vapour viscosity of mixtures and produces acceptable levels of errors and will be applied in this paper. In addition, it is relatively easy to use.

Density does not change significantly with an increase in pressure for ammonia-water vapour solution, and therefore viscosity is only majorly sensitive to pressure. At higher pressure, however, this is not the case as the density increases significantly. Thus, the effect of pressure should be taken into account in the calculation of viscosity.

With varying accuracies of inconsistencies for viscosity correlations from literature compared to experimental values, it is necessary to investigate other methods to be used to calculate these properties. Therefore, the purpose of this paper is to develop empirical correlations supported by confirmatory data irrespective of their theoretical basis for the calculation of viscosity of ammonia-water solution for liquid and vapour phases. The new correlations for the calculation of this property for ammonia-water solution shall be generated from experimental data of pure components and the accuracy of these correlations determined based on experimental data from literature.

2. METHODOLOGY

2.1. Data Sources

To develop correlations for density and thermal conductivities, there is a need to use authentic experimental data. Many experimental data exist in literature, but these sources must be verified before use. For ammonia and water, experimental data has been authenticated by International Association for the Properties of Water

and Steam (IAPWS). The data for liquid and vapour ammonia are extracted from data provided by Engineering toolbox (2015) and that of water from Engineering toolbox (2004). Validation was done by comparing the liquid, and vapour viscosity values for pure water are generated using the method recommended by IAPWS R12-08 (2008). The viscosity values of pure ammonia gas are extracted from Shimotake and Thodos (1963). Calculated liquid and gas viscosity values of ammonia were validated with values obtained from Fenghour (1995), while data generated from the procedure presented here are compared with data generated by Conde-Petit (2006). The accuracy of an empirical correlation depends on the authenticity of the data, be it experimental or generated, and on the method followed to arrive at the correlation. All correlations for pure components were developed using Microsoft Excel Correlation development procedure, while those of ammonia-water solution correlations were developed using the Proportional Node Three-Parameters Plot Procedure.

2.2. Dynamic Viscosity for the Liquid Ammonia-Water Solution

Conde-Petit (2006) presented an equation that is considered to represent accurately experimental data. The model proposed used pure ammonia and water viscosity values at reduced temperature. Conde-Petit (2006) used the International Association for the Properties of Water and Steam (IAPWS) procedure to calculate the dynamic viscosity of water. The procedure presented by Fenghour *et al.* (1995) was used to calculate the dynamic viscosity of Ammonia. In the procedure presented in this paper, the equation for dynamic viscosity were generated directly from experimental data. The viscosity of water is ammonia, and water were calculated as follows.

$$\eta_{NH_3} = 1.0 \times 10^{+03} \left(10^{(-8.591 + 867.4/T + 2.681 \times 10^{-02}T - 36.12 \times 10^{-06}T^2)} \right) \quad (1)$$

$$\eta_{H_2O} = aT^6 + bT^5 + cT^4 + dT^3 + eT^2 + fT + g \quad (2)$$

Where:

$$\begin{aligned} a &= 4.524 \times 10^{-17} \\ b &= -1.2692894 \times 10^{-13} \\ c &= 1.4709554085 \times 10^{-10} \\ d &= -9.014393368784 \times 10^{-8} \\ e &= 3.082715014561580 \times 10^{-5} \\ f &= -0.00558379692056264 \\ g &= 0.419428700262259 \end{aligned}$$

The procedure presented above generates dynamic viscosity values for various mass fractions and temperatures for the liquid solution. A single equation can be generated to fit the data by combining Equations (2) and (3) and applying the proportional node three-parameters plot procedure.

2.3. Dynamic Viscosity for the Vapour Ammonia-Water Solution

For the vapour solution, the correlation by Wilke (1950) is applied. This can be represented by Equations (4) and (5).

$$\eta_m = \sum_i^n \frac{y_i \eta_i}{\sum_{j=1}^n y_j \phi_{ij}} \quad (3)$$

Where:

$$\phi_{ij} = \frac{\left[1 + \sqrt{\frac{\eta_j}{\eta_i} \left(\frac{M_j}{M_i} \right)^{\frac{1}{4}}} \right]^2}{\sqrt{8 \left(1 + \frac{M_j}{M_i} \right)}} \quad (4)$$

Where η_i is the pure component viscosity, Pa.s, y_i is the vapour mole fraction, and ϕ is an interaction parameter. For the two components, Equation (4) can be reduced to:

$$\eta_m = \frac{y\eta_{NH_3}}{y+(1-y)\varphi_{12}} + \frac{(1-y)\eta_{H_2O}}{(1-y)+y\varphi_{12}} \quad (5)$$

with the following auxiliary equations:

$$\varphi_{12} = \frac{\left[1 + \left(\frac{\eta_{NH_3}}{\eta_{H_2O}}\right)^{0.5} \left(\frac{M_{H_2O}}{M_{NH_3}}\right)^{0.25}\right]^2}{\left[8 \left(1 + \frac{M_{NH_3}}{M_{H_2O}}\right)\right]^{0.5}} \quad \varphi_{12} = \varphi_{12} \frac{\eta_{H_2O}}{\eta_{NH_3}} \frac{M_{NH_3}}{M_{H_2O}}$$

Where M_{H_2O} is 18.015268 and M_{NH_3} is 17.03026

The viscosity of ammonia-water vapour varies appreciably with pressure. To take care of this effect, the temperature for a set pressure is calculated for each of the pure components from Equation (6) (Patek and Klomfar (1995).

$$T(P, y) = T_0 \sum_i a_i (1-y)^{\frac{m_i}{4}} \left[\ln \left(\frac{p_0}{p} \right) \right]^{n_i} \quad (6)$$

Where the parameters are given in Table 1.

Table 1: parameters for ammonia-water vapour correlation			
<i>i</i>	Parameters		
	<i>m_i</i>	<i>n_i</i>	<i>a_i</i>
1	0	0	+0.324 004 × 10 ¹
2	0	1	-0.395 920 × 10 ²
3	0	2	+0.43 5624 × 10 ⁻¹
4	0	3	-0.218 943 × 10 ⁻²
5	1	0	-0.143 526 × 10 ¹
6	1	1	+0.105 256 × 10 ¹
7	1	2	-0.719 281 × 10 ⁻¹
8	2	0	+0.122 362 × 10 ²
9	2	1	-0.224 368 × 10 ¹
10	3	0	-0.201 780 × 10 ²
11	3	1	+0.110 834 × 10 ¹
12	4	0	+0.145 399 × 10 ²
13	4	2	+0.644 312 × 10 ⁰
14	5	0	-0.221 246 × 10 ¹
15	5	2	-0.756 266 × 10 ⁰
16	6	0	-0.135 529 × 10 ¹
17	7	2	+0.183 541 × 10 ⁰

With the value of the temperature known at each pressure for the components, their viscosities can be calculated. Pressure variations affect ammonia significantly, and so pressure variation as it affects viscosity is considered. This condition is applied to ammonia only as the effect of pressure does not significantly affect calculated values for water vapour. For ammonia-water absorption refrigeration systems, the pressure ranges are relatively low (3 - 18 bar), so a single equation will be used to calculate the viscosity of water. As was done in the case of the liquid solution, a single equation will be generated to fit the data by combining Equations (3) to (6) and applying the proportional node three-parameters plot procedure.

3. RESULTS AND DISCUSSION

To calculate the dynamic viscosity of ammonia-water liquid solution, a single equation (Equation 7) was generated to simplify the approach to fit the data by combining Equations (3) and (4). For ammonia-water liquid solution and temperature range $273.15\text{ K} \leq T < 435.15\text{ K}$, the correlation derived is represented by Equation (3).

$$\eta_l = H - JS \quad (7)$$

Where:

$$H = a_1x_m^6 + a_2x_m^5 + a_3x_m^4 + a_4x_m^3 + a_5x_m^2 + a_6x_m + a_7 \quad (8)$$

$$J = b_1x_m^6 + b_2x_m^5 + b_3x_m^4 + b_4x_m^3 + b_5x_m^2 + b_6x_m + b_7 \quad (9)$$

$$S = c_1T^3 + c_2T^2 + c_3T + c_4 \quad (10)$$

For $273.15\text{ K} \leq T < 343.15\text{ K}$, the parameter for Equation (7) are given in Table 2 while for the temperature range $343.15\text{ K} \leq T \leq 423.15\text{ K}$, the parameters for Equation (7) are given in Table 3.

As was done in the case of the liquid solution, a single equation (Equation 11) was generated to fit the data by combining Equations (3) to (6). However, variations are in terms of pressure as it affects vapour viscosity significantly. For ammonia-water vapour and temperature range $1\text{ bar} \leq P < 25\text{ bar}$, the correlation derived is represented by Equation (11). Equation 11 generates dynamic viscosity values for various mass fractions and temperatures for the vapour phase with parameters shown in Table 4.

$$\eta_v = H + JS \quad (11)$$

Where:

$$H = a_1y_m^2 + a_2y_m + a_3 \quad (12)$$

$$J = b_1y_m^6 + b_2y_m^5 + b_3y_m^4 + b_4y_m^3 + b_5y_m^2 + b_6y_m + b_7 \quad (13)$$

$$S = c_1T^3 + c_2T^2 + c_3T + c_4 \quad (14)$$

Table 2: Density parameter values for $273.15\text{ K} \leq T < 343.15\text{ K}$

Parameter	Value
a_1	4.32056×10^{-02}
a_2	-0.1607810
a_3	0.2198870
a_4	-0.1245730
a_5	1.7618×10^{-02}
a_6	3.0434×10^{-03}
a_7	$1.7630000 \times 10^{-03}$
b_1	$4.4096000 \times 10^{-02}$
b_2	-0.1592070
b_3	0.2116710
b_4	-0.1168600
b_5	$1.6257001 \times 10^{-02}$
b_6	$2.7609998 \times 10^{-03}$
b_7	$1.3680001 \times 10^{-03}$
c_1	2.156×10^{-06}
c_2	$-2.214932 \times 10^{-03}$
c_3	0.7615065
c_4	-86.75783713
Percentage error: $\pm 0.199\%$	

Table 3: Density parameter values for $343.15 \text{ K} \leq T < 423.15 \text{ K}$

Parameter	Value
a_1	$-8.9x10^{-04}$
a_2	$-1.574x10^{-03}$
a_3	$8.216xTx10^{-03}$
a_4	$-7.713x10^{-03}$
a_5	$1.361x10^{-03}$
a_6	$2.83x10^{-04}$
a_7	$3.95x10^{-04}$
b_1	$1.171x10^{-03}$
b_2	$-8.492x10^{-03}$
b_3	$1.6549x10^{-02}$
b_4	$-1.1795x10^{-02}$
b_5	$1.947x10^{-03}$
b_6	$4.75x10^{-04}$
b_7	$2.01x10^{-04}$
c_1	$9.72x10^{-07}$
c_2	$-1.1784760x10^{-03}$
c_3	0.486130874
c_4	-67.297813633
Percentage error: $\pm 0.129\%$	

Table 4: Viscosity parameter values for $1 \text{ bar} \leq P < 25 \text{ bar}$

Parameter	Value
a_1	$1.212x10^{-06}$
a_2	$-5.397x10^{-06}$
a_3	$1.2051x10^{-05}$
b_1	$1.857x10^{-06}$
b_2	$-5.247x10^{-06}$
b_3	$4.65x10^{-06}$
c_1	$-6.217x10^{-06}$
c_2	$4.7856901x10^{-04}$
c_3	$-1.3747011x10^{-02}$
c_4	0.1885810
Percentage error: $\pm 0.00497\%$	

Figures 1 and 2 show a plot comparing liquid dynamic viscosity data generated by the procedure presented and with data generated by Conde-Petit (2006) for various temperatures. The average percentage deviation for generated data is $\pm 2.457\%$ when generated data are compared with those generated by Conde-Petit (2006) for the liquid phase. To determine the accuracy of the fit, the data generated by Equation (1) was compared to the data generated by the procedure presented by Conde-Petit (2006). The results are depicted in Figures 3 and 4. The calculated average percentage deviations are $\pm 0.199\%$ and $\pm 0.129\%$ for the two temperature ranges considered. Figure 5 shows the variation of dynamic viscosity with mass fractions for various pressures for ammonia-water vapour while Figure 6 compares calculated values of dynamic viscosity with those generated from the correlation for various pressures. The calculated average percentage deviation is found to be $\pm 0.00497\%$. For the liquid phase, an average percentage deviation for generated data of $\pm 2.457\%$ is arrived at when this data is compared with those generated by Conde-Petit (2006), meaning the new equations for calculating pure components dynamic viscosity can be applied with the procedure presented by Conde-Petit (2006). New correlations have been formulated to fit the generated data. Compared with the data generated by Conde-Petit (2006), the data generated by the new correlations are significantly low (percentage error of fit are $\pm 0.199\%$ and $\pm 0.129\%$ for the two temperature ranges considered) two temperature ranges considered. This is depicted in Figures 3 and 4. Therefore Equation (3)

can be used to calculate the dynamic viscosity of the ammonia-water liquid solution. For the vapour phase, comparing the generated data with those generated by Conde-Petit (2006) gives an average percentage deviation of $\pm 1.39\%$, while the percentage error of fit is $\pm 0.00497\%$. Therefore Equation (8) can be considered a satisfactory representation of the ammonia-water vapour dynamic viscosity data.

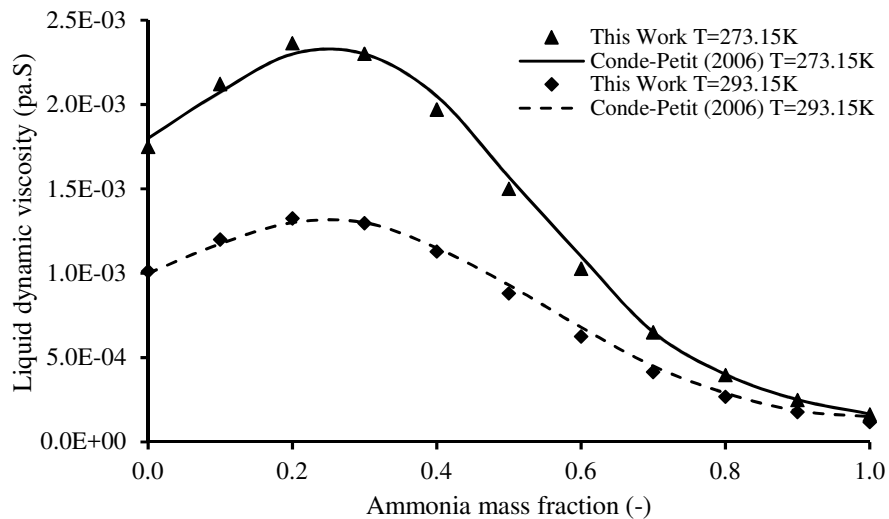


Figure 1: Comparing dynamic viscosity data generated by the procedure presented with data generated by Conde-Petit (2006) for 273.15 K and 293.15 K

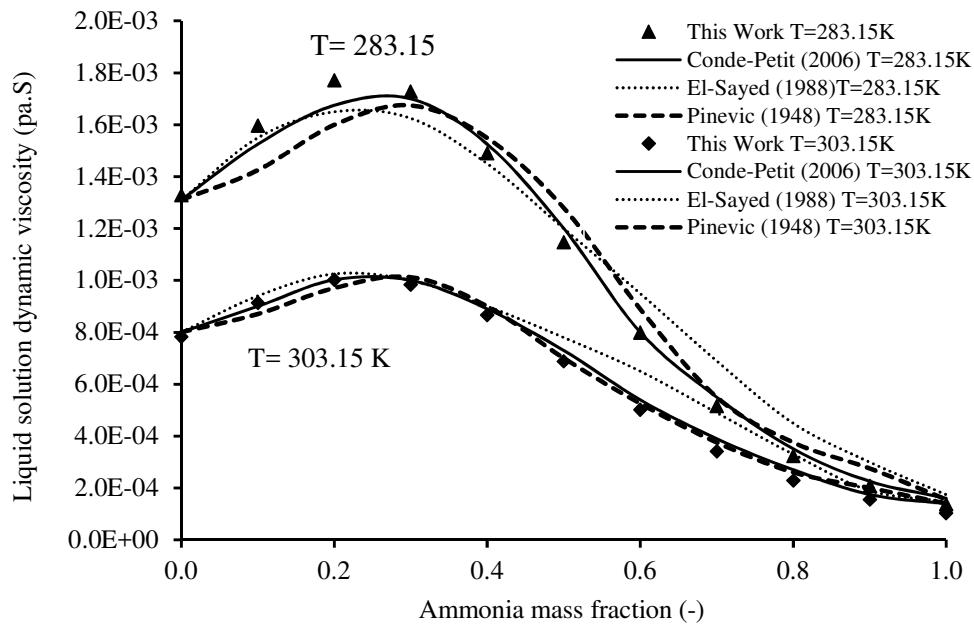


Figure 2: Comparing dynamic viscosity data generated by the procedure presented with data generated by Conde-Petit (2006) for 283.15 K and 303.15 K

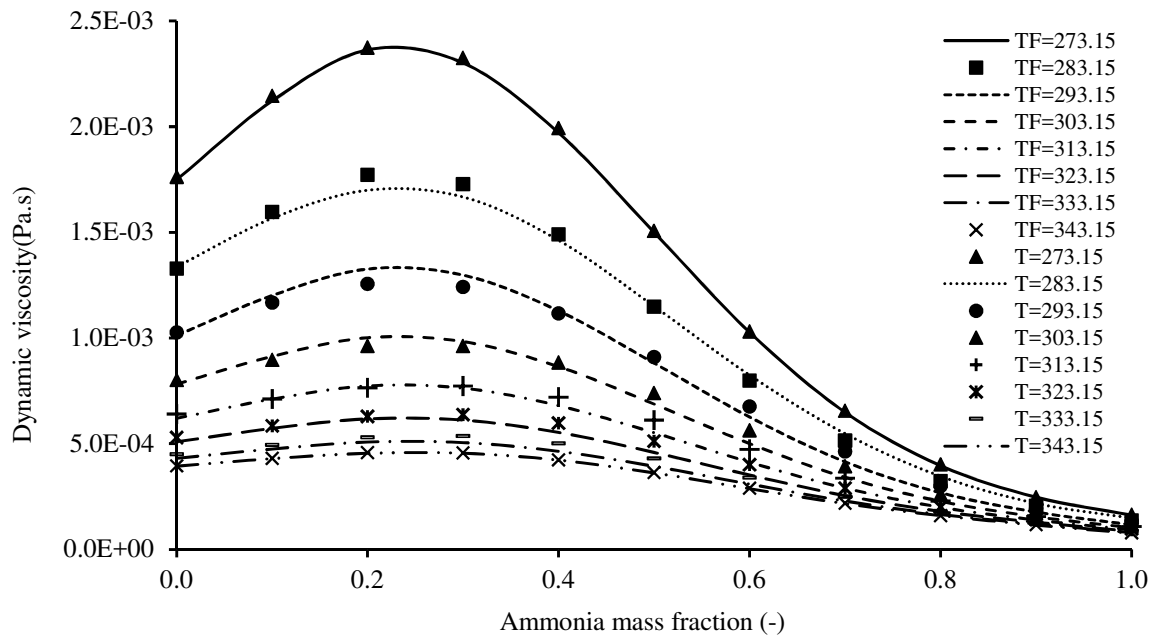


Figure 3: Dynamic viscosity against mass fraction for various Temperature for ammonia-water liquid solution for 273.15 K < T < 343.15 K

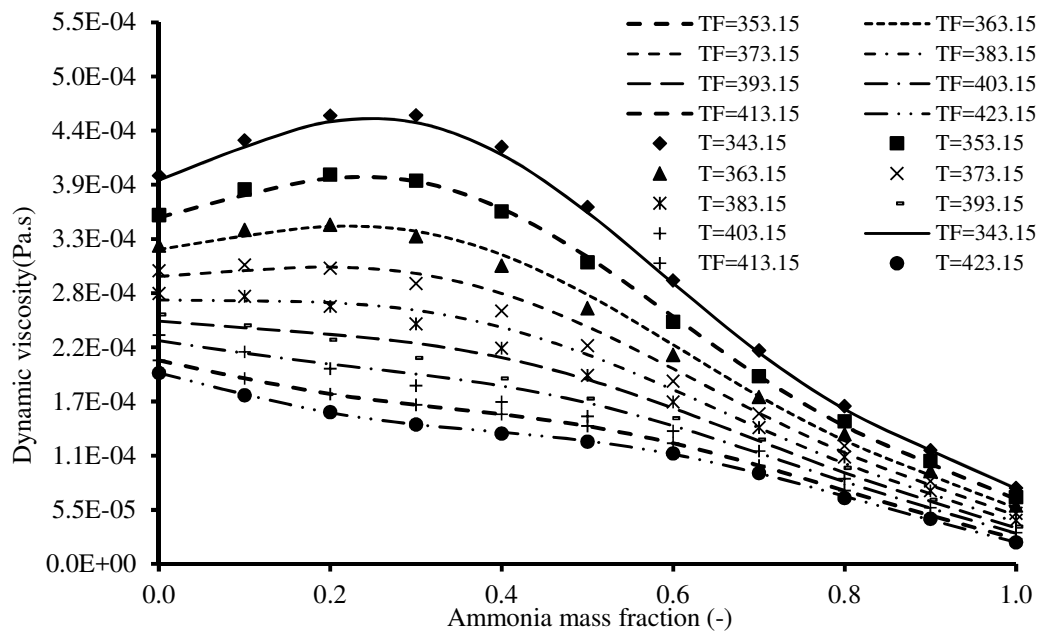


Figure 4: Dynamic viscosity against mass fraction for various temperature for ammonia-water liquid solution for 343.15 K < T < 423.15 K

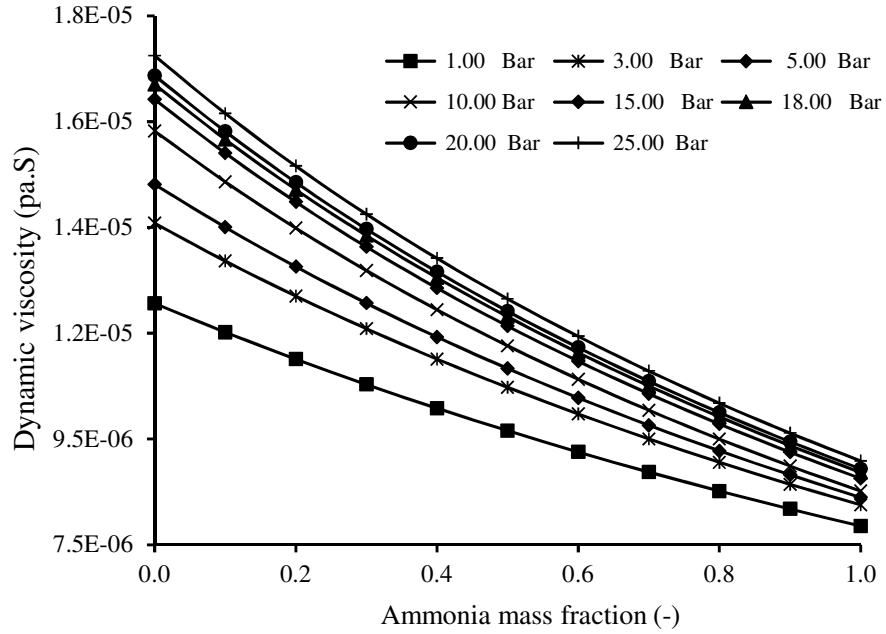


Figure 5: Variation of dynamic viscosity with ammonia mass fraction in ammonia-water Vapour solution for various pressures for $1 \text{ bar} \leq P < 25 \text{ bar}$

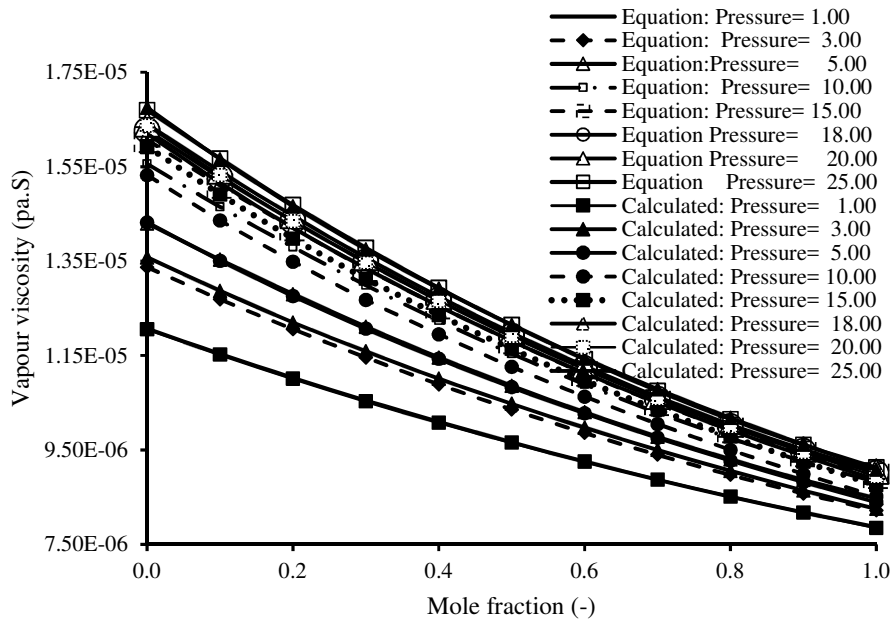


Figure 6: Comparison of generated values of dynamic viscosity values with those generated from the correlation for various pressures for ammonia-water vapour solution

4. CONCLUSION

Dynamics viscosity correlations were derived for pure ammonia and water for the liquid and vapour phases. The correlations developed for the pure components were used to developed models for ammonia-water solution. The data generated by these models were compared with values generated from the procedure presented by Conde-Petit (2006). For the liquid solution, the average percentage errors between model values and generated data are significantly low ($\pm 0.199\%$ and $\pm 0.129\%$ for the two temperature ranges considered in this paper. When the data generated by the correlation is compared with the data generated by Conde-Petit (2006), the average percentage error is determined to be $\pm 2.457\%$ for the liquid solution. For the vapour phase, comparing the generated data with those generated by Conde-Petit (2006) gives an average percentage deviation of $\pm 1.39\%$, while the percentage error of fit is $\pm 0.00497\%$. Therefore, the correlations derived in this paper can be used to calculate the dynamic viscosity of ammonia-water solution for both the liquid and vapour solutions.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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