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Thermophysical Properties of NH₃/IL+ Carbon Nanomaterial Solutions

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Abstract: This study proposes the use of new working fluids, refrigerant/IL+ carbon nanomaterials (CNMs), in absorption systems as an alternative to conventional working fluids. In this regard, the thermophysical properties of ammonia and carbon nanomaterials (graphene and single-wall carbon nanotubes) dispersed into [Bmim]BF₄ ionic liquid are theoretically investigated. The thermophysical properties of NH₃/IL+ CNMs solutions are computed for weight fractions of NH₃ in the range of 0.018–0.404 and temperatures between 293 and 388 K. In addition, two weight fractions of CNMs are considered: 0.005 and 0.01, respectively. Our results indicate that by adding a small amount of nanomaterial to the ionic liquid, the solution’s thermal conductivity is enhanced, while its viscosity and specific heat are reduced. Correlations of the thermal conductivity, viscosity, specific heat, and density of the NH₃/IL+ CNMs solutions are proposed.

Keywords: ammonia; ionic liquid; carbon nanomaterials

1. Introduction

Ionic liquids (ILs) are considered a novel type of green working fluid used in various fields, such as absorption refrigeration, solar applications, chemistry (gas capture, storage), and electrochemistry (batteries, sensors). In recent years, ionic liquids have been considered a promising alternative to the conventional working fluids (NH₃/H₂O and H₂O/LiBr) used as absorbents in absorption refrigeration systems due to their good thermal stability, high absorption capacity, and very low vapor pressure [1–3].

The thermophysical properties of solutions containing ionic liquids may influence their application in absorption refrigeration systems. Refrigerant/ionic liquid solutions are studied in the literature by way of thermodynamic models, mainly equations of state or activity models [4–15]. In addition, two studies on the use of ionic liquids as absorbents have been published by Shiflett and Yokozeki [16,17].

In one paper, Yokozeki and Shiflett [7] carried out a study on the performance of an absorption refrigeration system using NH₃ as the refrigerant and various ionic liquids as absorbents ([Bmim][PF₆], [Hmim]Cl, [Bmim][BF₄], [Emim][SCN], [DMEA][Ac]). The results indicated that the COPs of all the studied solutions were lower than those of the NH₃/H₂O solution.

The thermophysical properties (vapor pressures and heat capacities) of the H₂O + ([Dmim]dmp) system were investigated by Dong et al. [8]. The results revealed that the coefficient of the performance of the H₂O + [Dmim]dmp system is close to that of the conventional working pair H₂O + LiBr system.

Kim et al. [9] theoretically investigated the thermodynamic performance of a miniature absorption system using various refrigerant mixtures (R125, R152a, R32, R134a, R143a) /ILs ([Emim][Tf₂N], [Emim][BF₄], [Bmim][BF₄], [Bmim][PF₆], [Hmim][Tf₂N], [Hmim][BF₄], [Hmim][PF₆]) as the working fluids. They found that refrigerant/IL solu-
tions were promising materials for absorption refrigeration systems that utilize low-grade waste heat, such as those of electronic systems.

Kim and Kohl [10] carried out an analysis of the performance of R134a/[Bmim][PF₆] and R134a/[Hmim][TeF₆] using the Redlich–Kwong equation of state and a two-phase pressure drop model. They noticed that R134a/[Hmim][TeF₆] exhibited a higher system efficiency compared to R134a [Hmim][PF₆], except in the case where the solubility difference between the absorber and desorber converged to zero.

In another paper, Kim and Kohl [11] investigated the cooling capability of the R134/[Bmim][PF₆] used in an absorption refrigeration system. They compared the performance of R134/[Bmim][PF₆] with R134a/[Bmim][PF₆] and found that R134/[Bmim][PF₆] had a 1.9 times higher cooling capability than R134a/[Bmim][PF₆] at a desorber temperature as low as 63 °C. In addition, R134/[Bmim][PF₆] had a coefficient of performance up to three times higher than that of R134a/[Bmim][PF₆]. Chen and Bay [18] investigated the thermal performance of an absorption refrigeration system using [Emim]CuCl₃/NH₃ and found that the thermal performance of the [Emim]CuCl₃/NH₃ solution was better than that of a NH₃/H₂O solution, but slightly lower than that of a LiBr/H₂O solution. In another study, Chen et al. [19] numerically investigated the thermodynamic performance of an absorption system using [Bmim]ZnCl₂/NH₃. The results revealed that the [Bmim]ZnCl₂/NH₃ absorption system exhibited higher thermal performance compared to a NaSCN/NH₃ absorption system.

The thermodynamic performance of an absorption chiller using [Emim][dmp]/H₂O was simulated by Zhang and Hu [20]. Their results showed that the coefficient of performance was lower than that of a H₂O/LiBr solution, concluding that [Emim][dmp] may be a good absorbent for refrigeration systems. Martin et al. [21] carried out a study on the use of ILs with supercritical CO₂ using a group contribution equation of state and found that the coefficient of performance was lower compared to a conventional NH₃/H₂O system.

Table 1 presents the values of the coefficients of performance for absorption refrigeration systems using ammonia/ionic liquids as working fluids.

| NH₃ Ionic Liquid               | Ariyadi [22] | Yokozeki, M.B. Shiflett [6,7] | Ferro et al. [23] | Chen and Bay [18] |
|-------------------------------|--------------|-------------------------------|-------------------|-------------------|
| NH₃/[Bmim][BF₄]               | 0.715        | 0.557                         |                   |
| NH₃/[Bmim][PF₆]               | 0.588        | 0.575                         |                   |
| NH₃/[Emim][TeF₆]              | 0.657        | 0.589                         |                   |
| NH₃/[Emim][EtOSO₃]            | 0.612        | 0.485                         | 0.540             |
| NH₃/[Emim][SCN]               | 0.648        | 0.557                         | 0.592             |
| NH₃/[DMEA][Ac]                | 0.612        |                               |                   |
| NH₃/[Emim][Ac]                | 0.573        | 0.644                         |                   |
| NH₃/[Emim]CuCl₂               |              |                               | 0.781             |
| NH₃/[Choline][NTf₂]           |              |                               | 0.668             |
| NH₃/Water                     |              |                               | 0.646             |

Investigations into the application of ammonia/ionic liquids as working fluids in absorption refrigeration systems are limited in the open literature. Moreover, studies on absorption refrigeration systems using ammonia/ionic liquid+nanomaterials as working fluids are not reported in the literature. In order to improve the performance of absorption systems, new working fluids are herein proposed. The thermophysical properties of working fluids are the main data in this evaluation of the performance of absorption refrigeration systems. In this regard, the thermophysical properties of ammonia with graphene (GE) and single-wall carbon nanotubes (SWCNTs), respectively, dispersed into [Bmim]BF₄ ionic liquid, are analyzed and discussed. Correlations for the studied proper-
ties, required for the modeling and simulation of the performance of various absorption refrigeration systems, are also proposed.

2. Thermophysical Properties of the Solutions

The thermophysical properties of the working fluids used in absorption refrigeration systems must be determined as an essential step in the evaluation of the thermodynamic performance of these fluids. In this study, ammonia and two types of carbon nanomaterials (CNMs—graphene (GE) and single-wall carbon nanotubes (SWCNTs)) with two weight fractions (0.005 and 0.01), dispersed into a [B\textsubscript{min}][BF\textsubscript{4}]+ionic liquid, will be analyzed and discussed. The thermophysical properties of ammonia and CMNs/[B\textsubscript{min}][BF\textsubscript{4}] were taken from the NIST database [24] and Fang et al. [25], respectively.

Since there are no data on the thermo-properties of IL+CNMs mixed with NH\textsubscript{3} solutions, the properties (thermal conductivity, specific heat, and density) were calculated using a general equation, based on the weighted average of the properties of both components of the mixture [26,27]:

$$M_{\text{sol}} = w_{\text{NH}_3}M_{\text{NH}_3} + w_{\text{IL}}M_{\text{IL+CNMs}}$$ (1)

in which the mass fraction of NH\textsubscript{3} is calculated as:

$$w_{\text{NH}_3} = \frac{x_AM_A}{x_AM_A + x_BM_B}$$ (2)

The solution dynamic viscosity is calculated as:

$$\ln \mu_{\text{sol}} = w_{\text{NH}_3} \ln \mu_{\text{NH}_3} + (1 - w_{\text{NH}_3}) \ln \mu_{\text{IL+CNMs}}$$ (3)

3. Results and Discussions

In this study, the thermo-properties of the NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}, NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+ GE and NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+ SWCNTs with the temperature at various NH\textsubscript{3} fractions. With increasing temperatures can be seen that the thermal conductivities of all solutions have an upward trend up to $w_{\text{NH}_3} = 0.048$, then with increasing NH\textsubscript{3} fractions (≥0.102), the thermal conductivities decrease with increasing temperatures, but increasing with increasing NH\textsubscript{3} fractions. The addition of carbon nanomaterials to the ionic liquid leads to an enhancement in the solution’s thermal conductivity compared to the base solution. The enhancements in the thermal conductivity of the studied solutions—calculated as $[(k_{\text{NH}_3/\text{IL+CNMs}} - k_{\text{NH}_3/\text{IL}})/k_{\text{NH}_3/\text{IL}}] \cdot 100$—at minimum and maximum NH\textsubscript{3} fractions—$w_{\text{NH}_3} = 0.018$ and $w_{\text{NH}_3} = 0.404$, respectively—are shown in Table 2:

| Temp. [K] | NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+0.005 GE | NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+0.01 GE | NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+0.005 SWCNTs | NH\textsubscript{3}/[B\textsubscript{min}][BF\textsubscript{4}]+0.01 SWCNTs |
|-----------|---------------------------------|-----------------|-----------------|-----------------|
| $w_{\text{NH}_3}$ = 0.018 | w\textsubscript{NH}_3 = 0.404 | w\textsubscript{NH}_3 = 0.018 | w\textsubscript{NH}_3 = 0.404 | w\textsubscript{NH}_3 = 0.018 |
| 293       | 12.28                           | 4.33            | 14.61           | 5.33            |
| 388       | 14.44                           | 7.28            | 15.55           | 7.76            |
It can be seen from Table 2 that the maximum enhancement in thermal conductivity was achieved by $NH_3/[B_{mim}]BF_4 + 0.01 GE$, while the minimum enhancement in thermal conductivity was recorded for $NH_3/[B_{mim}]BF_4 + 0.005 SWCNTs$ for both NH$_3$ fractions. In addition, a descending trend in the thermal conductivity of solutions with higher NH$_3$ fractions may be seen. These results may be explained by the thermal conductivities of carbon nanomaterials dispersed into the ionic liquid. Graphene (GE) exhibits a thermal conductivity of $\sim 4000 \text{ W/mK}$ [28–30], while the thermal conductivity of SWCNTs is usually reported to be in the range of 2000–6000 $\text{ W/mK}$ at a standard temperature (25 $^\circ$C) [31]. Yu et al. [32] measured the thermal conductivity of SWCNTs using a chemical vapor deposition method and found a value higher than 2000 $\text{ W/mK}$. The experimental results related to the thermal conductivity of ionic liquids revealed the increase in thermal conductivity achieved by adding nanoparticles into the ionic liquid and the minor influence of temperature on several ionic liquids containing nanoparticles. The main arguments for these trends are thermal boundary resistance, layering phenomena, and clustering [33].

(a)
Figure 1. Solution thermal conductivity.

The thermal conductivity values are correlated by means of a linear equation as a function of temperature:

\[ k = aT + b \]  

(4)

The coefficient values \( a \), \( b \), and \( R^2 \) are given in Table 3.
3.2. Dynamic Viscosity

Figure 2a–e depict the variation in the viscosity of the solutions, with various NH₃ fractions, at rising temperatures. As shown in Figure 2, the viscosities of the solutions decrease exponentially with higher temperatures. By adding the carbon nanomaterials into the ionic liquid, a reduction in viscosity may be seen compared to the base solution. Higher fractions of carbon nanomaterials lead to an increase in the viscosity of the studied solutions, but these viscosity values do not exceed those of the base solution. With higher NH₃ fractions, a decrease in viscosity may also be seen. The diminution in viscosity is more obvious at the lower mass fractions of NH₃ in the solutions. The viscosities of the NH₃/IL+CNMs solutions are lower than that of the base solution, indicating that these solutions are suitable for NH₃ absorption. The reduction in the viscosity of the studied solutions—calculated as [(μₙH₃/IL − μₙH₃/IL+CNMs)/(μₙH₃/IL)] ∙ 100—at minimum and maximum NH₃ fractions—$w_{NH₃} = 0.018$ and $w_{NH₃} = 0.404$, respectively—is shown in Table 4:

Table 4. Reduction in dynamic viscosity.

| Temp. [K] | $NH₃/[B_{min}]BF₄$ + 0.005 GE | $NH₃/[B_{min}]BF₄$ + 0.01 GE | $NH₃/[B_{min}]BF₄$ + 0.005 SWCNTs | $NH₃/[B_{min}]BF₄$ + 0.01 SWCNTs |
|----------|-------------------------------|-------------------------------|----------------------------------|----------------------------------|
| 293      | 24.0                          | 3.35                          | 36.0                             | 5.65                             |
|          |                               |                               | 28.0                             | 4.44                             |
|          |                               |                               | 8.00                             | 1.24                             |
| 388      | 7.31                          | 0.95                          | 14.64                            | 1.99                             |
|          |                               |                               | 14.86                            | 1.98                             |
|          |                               |                               | 0.026                            | 0.36                             |

From Table 4, it may be seen that at a temperature of 293 K the maximum reduction in viscosity is achieved by $NH₃/[B_{min}]BF₄ + 0.01$ GE, while the minimum is seen in the case of $NH₃/[B_{min}]BF₄ + 0.01$ SWCNTs for both NH₃ fractions. With increasing temperature, $NH₃/[B_{min}]BF₄ + 0.01$ GE and $NH₃/[B_{min}]BF₄ + 0.005$ SWCNTs show similar values of viscosity reduction. In addition, a descending trend in viscosity may be seen at higher NH₃ fractions in the solutions, with the viscosity values of the NH₃/IL+CNMs being similar to the values of the base solution.

The data related to the dynamic viscosity of ionic liquids are still contradictory. Most experimental studies indicate an increase in viscosity with the addition of nanoparticles...
to the ionic liquid, while on the other hand there are studies that have found a decrease in viscosity. The reduction in viscosity can be explained by the interaction between the molecules of the ionic liquid and the nanoparticles, as well as by the lubricating properties of the nanoparticles.
Figure 2. Solution dynamic viscosity.

The dynamic viscosity values are correlated by means of an exponential equation as a function of temperature:

$$\mu = a \cdot e^{b \cdot T}$$  \hspace{1cm} (5)

The coefficient values $a$, $b$, and $R^2$ are given in Table 5.

| Solution | $NH_3/[B_{min}]BF_4$ | $NH_3/[B_{min}]BF_4 + 0.005$ GE | $NH_3/[B_{min}]BF_4 + 0.01$ GE |
|----------|----------------------|----------------------------------|----------------------------------|
| Coefficients | $a$ | $b$ | $R^2$ | $a$ | $b$ | $R^2$ | $a$ | $b$ | $R^2$ |
| $w_{NH_3} = 0.018$ | 3.207 | 0.993 | 6.836 | -0.017 | 0.988 | 1.002 | -0.017 | 0.989 |
| $w_{NH_3} = 0.031$ | 1.2694 | 0.994 | 2.5225 | -0.017 | 0.988 | 1.002 | -0.017 | 0.989 |
| $w_{NH_3} = 0.048$ | 0.5266 | 0.994 | 0.9613 | -0.016 | 0.987 | 1.0015 | -0.016 | 0.989 |
| $w_{NH_3} = 0.070$ | 0.2184 | 0.995 | 0.3606 | -0.015 | 0.986 | 1.001 | -0.016 | 0.989 |
| $w_{NH_3} = 0.102$ | 0.0905 | 0.995 | 0.1352 | -0.014 | 0.985 | 1.0015 | -0.016 | 0.989 |
| $w_{NH_3} = 0.150$ | 0.0375 | 0.996 | 0.0507 | -0.013 | 0.985 | 1.0015 | -0.016 | 0.989 |
| $w_{NH_3} = 0.232$ | 0.0156 | 0.997 | 0.0190 | -0.012 | 0.984 | 1.0015 | -0.016 | 0.989 |
| $w_{NH_3} = 0.404$ | 0.0065 | 0.997 | 0.0071 | -0.011 | 0.984 | 1.0015 | -0.016 | 0.989 |
3.3. Specific Heat

Figure 3a–e illustrate the variation in the specific heat of the solutions, with various NH₃ fractions, at rising temperatures. As shown in Figure 3, the specific heat of the solutions increases with both higher temperatures and higher fractions of NH₃. In addition, by adding nanoparticles to the ionic liquid, a reduction in specific heat may be seen compared to the base solution. Higher CNMs fractions led to a decrease in the specific heat of all the solutions. The presented results are according to an equation proposed by Raud et al. [34], which indicates the increase in a solution’s specific heat with rising temperatures, and also the reduction in specific heat by the addition of nanomaterials into the base solution.

The reduction in the specific heat of the studied solutions—calculated as $\left[ (c_{p,\text{NH}_3} - c_{p,\text{NH}_3+\text{CNMs}}) / c_{p,\text{NH}_3} \right] \cdot 100$—at minimum and maximum NH₃ fractions—$w_{\text{NH}_3} = 0.018$ and $w_{\text{NH}_3} = 0.404$, respectively—is shown in Table 6:

| Temp. [K] | $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.005\text{ GE}$ | $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.01\text{ GE}$ | $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.005\text{ SWCNTs}$ | $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.01\text{ SWCNTs}$ |
|-----------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|           | $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ | $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ | $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ $w_{\text{NH}_3} = 0.018$ $w_{\text{NH}_3} = 0.404$ |
| 293       | 11.26                                           | 4.25                                            | 14.39                                           | 5.35                                            | 12.32                                           | 4.75                                            | 14.40                                           | 5.45                                            |
| 388       | 11.09                                           | 3.11                                            | 10.89                                           | 2.92                                            | 12.45                                           | 3.65                                            | 10.90                                           | 3.05                                            |

The maximum reduction in specific heat was achieved by both solutions with a 0.01 fraction of nanomaterials, $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.01\text{ GE}$ and $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.01\text{ SWCNTs}$, while the minimum can be seen in the case of $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.005\text{ GE}$, for both NH₃ fractions, at a temperature of 293 K. With higher temperatures, the maximum reduction was recorded for $\text{NH}_3/[B_{\text{min}}]\text{BF}_4 + 0.005\text{ SWCNTs}$. With higher fractions of NH₃, the reduction in specific heat was significant.

The data available in the open literature related to the specific heat of ionic liquids are, as in the case of viscosity, contradictory. The main reasons for this are the interaction between the molecules of the nanomaterials and the ionic liquid and the chemical structure of the ionic liquid.
Figure 3. Solution specific heat.

The specific heat values are correlated by means of a linear equation as a function of temperature:

\[ c_p = aT + b \]  \hspace{2cm} (6)

In Table 7, the coefficient values \( a \), \( b \), and \( R^2 \) are given:
Table 7. Coefficient values $a$, $b$, and $R^2$ obtained by fitting Equation (6).

| Solution                        | $NH_3/[B_{nim}]BF_4$  | $NH_3/[B_{nim}]BF_4 + 0.005 GE$ | $NH_3/[B_{nim}]BF_4 + 0.01 GE$ |
|--------------------------------|------------------------|----------------------------------|----------------------------------|
| $w_{NH_3} = 0.018$            | 6.5091                 | -14.982                          | 0.999                            |
| $w_{NH_3} = 0.031$            | 7.0161                 | -134.92                          | 0.998                            |
| $w_{NH_3} = 0.048$            | 7.6829                 | -293.09                          | 0.992                            |
| $w_{NH_3} = 0.070$            | 8.5537                 | -500.19                          | 0.980                            |
| $w_{NH_3} = 0.102$            | 9.8166                 | -800.83                          | 0.958                            |
| $w_{NH_3} = 0.150$            | 11.706                 | -1249.5                          | 0.927                            |
| $w_{NH_3} = 0.232$            | 14.945                 | -2020.6                          | 0.884                            |
| $w_{NH_3} = 0.404$            | 21.718                 | -3629.6                          | 0.830                            |

Table 8. Enhancement in density.

| Temp. [K] | $NH_3/[B_{nim}]BF_4 + 0.005 GE$ | $NH_3/[B_{nim}]BF_4 + 0.01 GE$ | $NH_3/[B_{nim}]BF_4 + 0.005 SWCNTs$ | $NH_3/[B_{nim}]BF_4 + 0.01 SWCNTs$ |
|-----------|---------------------------------|---------------------------------|-------------------------------------|-------------------------------------|
| $w_{NH_3} = 0.018$ | $0.018$ | $0.018$ | $0.014$ | $0.174$ |
| $w_{NH_3} = 0.232$ | $0.014$ | $0.018$ | $0.014$ | $0.174$ |

3.4. Density

The densities of the solutions, with various NH$_3$ fractions and at rising temperatures, are illustrated in Figure 4a–e. As can be seen, the density decreases with both higher temperature and higher NH$_3$ fractions. The addition of carbon nanomaterials into the ionic liquid increases the solution's density compared to the base solution. In addition, higher CNMs fractions lead to increased density for all solutions. Most experimental studies regarding the density of ionic liquids report an increase in density with the addition of nanoparticles and a decrease with higher temperatures. The presented results show the same trend as the experimental results obtained by other studies [35].

The enhancement in the density of the studied solutions—calculated as $[(\rho_{NH_3,i + CNMs} - \rho_{NH_3,i})/\rho_{NH_3,i}] \cdot 100$ —at minimum and maximum NH$_3$ fractions—$w_{NH_3} = 0.018$ and $w_{NH_3} = 0.404$, respectively—is shown in Table 8:

At a temperature of 293 K, the maximum enhancement in density was achieved by $NH_3/[B_{nim}]BF_4 + 0.01 GE$, while the minimum can be seen in the case of $NH_3/[B_{nim}]BF_4 + 0.005 GE$ for both NH$_3$ fractions. At higher temperatures, the maximum enhancement was recorded for $NH_3/[B_{nim}]BF_4 + 0.005 SWCNTs$. 
Figure 4. Solution density.

The density values are correlated by means of a linear equation as a function of temperature:

$$\rho = aT + b$$  \hspace{1cm} (7)

The coefficient values $a$, $b$, and $R^2$ are given in Table 9.

Table 9. Coefficient values $a$, $b$, and $R^2$ obtained by fitting Equation (7).

| Solution | $NH_3/[B_{mim}]BF_4$ | $NH_3/[B_{mim}]BF_4 + 0.005 GE$ | $NH_3/[B_{mim}]BF_4 + 0.01 GE$ |
|----------|----------------------|----------------------------------|----------------------------------|
| Coefficients | $a$ | $b$ | $R^2$ | $a$ | $b$ | $R^2$ | $a$ | $b$ | $R^2$ |
| $w_{NH_3} = 0.018$ | 0.7283 | 1407.6 | 0.999 | 0.7341 | 1414.2 | 0.999 | 0.75 | 1430.2 | 0.999 |
| $w_{NH_3} = 0.031$ | 0.7558 | 1408.8 | 0.999 | 0.7558 | 1413.8 | 0.999 | 0.77 | 1428.5 | 0.998 |
| $w_{NH_3} = 0.048$ | 0.7678 | 1401.6 | 0.999 | 0.7748 | 1409.1 | 0.999 | 0.7918 | 1425.1 | 0.998 |
| $w_{NH_3} = 0.070$ | 0.7993 | 1398 | 0.999 | 0.7953 | 1401.8 | 0.999 | 0.8233 | 1420.6 | 0.997 |
| $w_{NH_3} = 0.102$ | 0.844 | 1392.2 | 0.998 | 0.844 | 1397.2 | 0.998 | 0.8599 | 1412.3 | 0.996 |
| $w_{NH_3} = 0.150$ | 0.9143 | 1358 | 0.997 | 0.9109 | 1388.5 | 0.998 | 0.9349 | 1405 | 0.995 |
| $w_{NH_3} = 0.232$ | 1.0312 | 1371.6 | 0.996 | 1.0246 | 1373.7 | 0.995 | 1.0429 | 1387.5 | 0.992 |
| $w_{NH_3} = 0.404$ | 1.2654 | 1339.4 | 0.991 | 1.265 | 1341.9 | 0.991 | 1.2802 | 1352.8 | 0.989 |

Solution | $NH_3/[B_{mim}]BF_4 + 0.005 SWCNTs$ | $NH_3/[B_{mim}]BF_4 + 0.01 SWCNTs$ |
|----------|----------------------------------|----------------------------------|
| Coefficients | $a$ | $b$ | $R^2$ | $a$ | $b$ | $R^2$ |
| $w_{NH_3} = 0.018$ | 0.7271 | 1407.7 | 0.999 | 0.7261 | 1413.6 | 0.999 |
| $w_{NH_3} = 0.031$ | 0.7421 | 1404.7 | 0.999 | 0.7478 | 1413.3 | 0.999 |
| $w_{NH_3} = 0.048$ | 0.7678 | 1402.6 | 0.999 | 0.7707 | 1409.9 | 0.999 |
| $w_{NH_3} = 0.070$ | 0.801 | 1399.4 | 0.999 | 0.7953 | 1403.8 | 0.999 |
| $w_{NH_3} = 0.102$ | 0.844 | 1393.2 | 0.983 | 0.844 | 1399.2 | 0.983 |
| $w_{NH_3} = 0.150$ | 0.9109 | 1384.5 | 0.998 | 0.9109 | 1390.5 | 0.998 |
| $w_{NH_3} = 0.232$ | 1.0273 | 1370.9 | 0.996 | 1.0281 | 1376.3 | 0.996 |
| $w_{NH_3} = 0.404$ | 1.2632 | 1339.2 | 0.991 | 1.2646 | 1343.1 | 0.991 |
4. Conclusions

In this study, the thermophysical properties of ammonia and carbon nanomaterials (CNMs), dispersed into $[B_{\text{mim}}]BF_4$ ionic liquid, were analyzed and discussed. The results showed that the thermal conductivity of the solutions decreases with higher NH$_3$ fractions. By adding carbon nanomaterials into the ionic liquid, an enhancement in the solution’s thermal conductivity may be seen compared to the base solution, with the maximum enhancement in thermal conductivity having been achieved by NH$_3/[B_{\text{mim}}]BF_4 + 0.01$ GE. The viscosities of the NH$_3$/IL+CMNs solutions were lower than that of the base solution, indicating that these solutions are suitable for NH$_3$ absorption. In this case, the maximum reduction in viscosity was recorded for NH$_3/[B_{\text{mim}}]BF_4 + 0.01$ GE. In addition, by adding CMNs to the ionic liquid, a reduction in the specific heat of the solutions may be seen compared to the base solution. At a temperature of 293 K, the maximum reduction in specific heat was achieved by the solutions with a 0.01 fraction of nanomaterials ($NH_3/[B_{\text{mim}}]BF_4 + 0.01$ GE and $NH_3/[B_{\text{mim}}]BF_4 + 0.01 SWCNTs$). Moreover, the addition of CMNs to the ionic liquid led to an increase in the solution’s density. At a temperature of 293 K, the maximum enhancement in density was achieved by NH$_3/[B_{\text{mim}}]BF_4 + 0.01$ GE. Finally, correlations for all studied properties were proposed.

The results of this study may contribute to the consolidation of the property database of NH3/IL+NMNs for applications in absorption refrigeration. Further investigations concerning the thermophysical characteristics of ammonia with other types of ionic liquids are needed. In addition, for the practical implementation of NH3/ILs+CMNs in absorption refrigeration systems, experimental studies to support the reported theoretical results are needed.

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Nomenclature

- $w$: mass fraction, [kg/kg]
- $x$: molar fraction of components A and B in mixture, [mol/mol]
- $M$: molecular weight, [kg/kmol]
- $c_p$: heat capacity [J/(kgK)]
- $T$: temperature, [K]

Greek letter

- $k$: thermal conductivity [W/(mK)]
- $\mu$: dynamic viscosity [Pa s]
- $\rho$: density [kg/m$^3$]

Subscript

- $A, B$: components A and B
- $NH_3$: species of NH$_3$

Abbreviations

- $[B_{\text{mim}}]BF_4$: 1-butyl-3-methylimidazolium tetrafluoroborate
- $[B_{\text{mim}}][PF_6]$: 1-butyl-3-methylimidazolium hexafluorophosphate
- $[B_{\text{mim}}]Zn_2Cl_5$: 1-Butyl-3-methylimidazolium chloride
- $[B_{\text{mim}}]dmp$: 1-methyl-3-methylimidazolium diethylphosphate
- $[DMEA][Ac]$: dimethylethylamine acetate
- $[Emim][dmp]$: 1-ethyl-3-methylimidazolium dimethyl phosphate
- $[Emim][BF_4]$: 1-ethyl-3-methylimidazolium tetrafluoroborate
- $[Emim][TF_2N]$: 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide
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