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EXPERIMENTAL AND CORRELATION ANALYSIS OF TEMPERATURE-DEPENDENT DYNAMIC VISCOSITY IN IONIC LIQUID-ALCOHOL BINARY SYSTEMS

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Abstract- This study reports an experimental investigation of the dynamic viscosity of binary systems composed of the ionic liquid 1-ethyl-3-methylimidazolium methane sulfonate ([EMIM][$MeSO_3$]) and methanol over a range of temperatures, under both atmospheric pressure and conditions corresponding to the saturated vapor pressure. The measurements were performed using a vibrating-tube viscometer (Anton Paar SVM 3000) in conjunction with a controlled-stress rotational rheometer (Anton Paar MCR 302). The structural components, operational principles, and measurement capabilities of these instruments were examined and briefly analyzed in order to ensure the reliability of the experimental procedure. The dynamic viscosity of binary mixtures comprising methanol and an imidazolium-derived ionic liquid was experimentally evaluated over an extended temperature range (T = 263.15-413.15 K), encompassing both atmospheric pressure and pressures corresponding to vapor-liquid equilibrium (saturation) conditions of the systems. The measurements were performed in both low- and high-temperature regions, enabling the formation of a reliable experimental database for the thermophysical properties of the studied system. The experimental viscosity data obtained using the two measurement techniques were analyzed and compared to evaluate their consistency. In order to describe the viscosity behavior at elevated temperatures, the experimental results were extrapolated up to T = 413.15 K under saturated vapor pressure conditions. The temperature dependence of both the measured and extrapolated viscosity values was correlated using a polynomial empirical equation. Furthermore, the variation of the dynamic viscosity, $\eta(p,T)$ (mPa×s), as a function of the methanol mole fraction (x) in binary systems comprising methanol and an imidazolium-based ionic liquid is illustrated graphically over the temperature range 263.15-413.15 K, under both atmospheric pressure and conditions corresponding to vapor-liquid equilibrium (saturation). Based on the proposed correlation equation, the mean absolute deviation between the calculated and experimental viscosity values was evaluated, demonstrating good agreement. The obtained results provide valuable thermophysical data for ionic liquid-alcohol systems and may be useful for the design and optimization of absorption refrigeration systems, heat pumps, and solar thermal installations, where accurate knowledge of dynamic viscosity is essential for engineering calculations and process modeling.

Keywords: Renewable Energy Sources, Ionic Liquid, Dynamic Viscosity, Binary Mixture, Methanol, Temperature Dependence.

1. INTRODUCTION

The widespread use of renewable energy sources has become one of the key directions of global energy policy in recent decades. Ensuring energy security, reducing the effects of climate change, and limiting carbon emissions have encouraged many countries to intensively develop alternative and environmentally friendly energy technologies. In Azerbaijan, the sustainable development of the energy sector and the comprehensive modernization of the national energy system have been established as central pillars of state policy. Notably, under the "Socio-Economic Development Strategy of the Republic of Azerbaijan for 2022-2026", strategic emphasis is placed on the transition to green energy, the improvement of energy efficiency, and the advancement of a low-carbon economy as core national priorities. Within this framework, the rapid evolution of contemporary science and technology, coupled with the ongoing pursuit of innovative functional materials and next-generation working fluids, constitutes a critical factor in improving the operational efficiency and performance of energy and thermal systems. In recent years, increasing attention has been devoted to the investigation of novel functional fluids that can be applied in alternative energy technologies and heat-transfer systems. Ionic liquids, as a class of emerging functional materials, have attracted significant attention owing to their distinctive physicochemical characteristics [1]. Consequently, they have been extensively investigated by both academic and industrial researchers in recent years [2].

These substances are essentially salts composed entirely of ions and are characterized by their ability to remain in the liquid state at temperatures below their decomposition temperature [3]. In comparison with

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conventional molecular solvents, ionic liquids exhibit a distinctive set of physicochemical properties, including high thermal stability, negligible vapor pressure, elevated ionic conductivity, and the ability to tailor their physicochemical characteristics over a wide temperature range. Due to these advantageous properties, ionic liquids have found potential applications in various technological and industrial fields, including energy systems, heat pumps, absorption refrigeration cycles, and solar energy technologies [4]. Consequently, the experimental investigation of their thermophysical properties, particularly their dependence on temperature and pressure, is of considerable scientific and practical importance [5].

To assess the applicability of such mixtures, it is necessary to accurately study their thermophysical and rheological properties, especially dynamic viscosity. Dynamic viscosity directly affects such important indicators as fluidity, hydraulic resistance and intensity of heat-mass transfer processes in liquid systems. Therefore, experimental studies of the viscosity behavior of ionic liquid-alcohol systems depending on temperature, pressure and composition provide important information for engineering calculations and optimization of technological processes.

Among the key thermophysical properties of liquids, viscosity plays a fundamental role in determining their transport behavior and flow characteristics. Viscosity characterizes the internal resistance of a fluid to flow and represents the magnitude of the internal friction forces arising between adjacent fluid layers during motion. In other words, viscosity reflects the resistance generated when layers of a liquid slide relative to each other. Liquid viscosity is generally classified into dynamic viscosity and kinematic viscosity. Dynamic viscosity represents the resistance of a fluid to flow and is expressed in SI units of Pa×s.

Various experimental methods are used to determine dynamic viscosity, including rotational viscometry, the falling-body method, and rheometric measurement techniques. State-of-the-art viscometric and rheometric techniques are extensively employed in the characterization of fluid transport properties due to their high accuracy and reproducibility. In this work, the dynamic viscosity of an imidazolium-derived ionic liquid was systematically investigated across a broad temperature interval (T = 263.15-413.15 K) at ambient pressure. Experimental data were obtained using a precision oscillating-tube viscometer coupled with a controlled-stress rotational rheometric method. It should be noted that the MCR series rheometers produced by Anton-Paar are among the leading instruments worldwide due to their high measurement accuracy and wide application capabilities [6]. The results obtained in this study contribute to a deeper understanding of the thermophysical properties of ionic liquids and provide valuable data for evaluating their potential applications in modern energy systems.

In this study, the dynamic viscosity of binary mixtures comprising an imidazolium-based ionic liquid and methanol was experimentally investigated over a broad temperature range and under varying pressure conditions. The obtained data were subsequently correlated using empirical models, and the rheological behavior of the system was systematically analyzed. This work is of great importance both from a fundamental and applied point of view.

2. RESEARCH OBJECTIVE AND PROBLEM STATEMENT

2.1. Chemical Substances and Sample Preparation

The principal compound employed in this study was an imidazolium-based ionic liquid, specifically 1-ethyl-3-methylimidazolium methane sulfonate ([EMIM][$MeSO_3$]). The substance was procured as a high-purity industrial product from a reputable German supplier (Merck). It possesses a molecular weight of 0.26024 kg·mol^{-1}, CAS number 145022-44-2, chemical formula $C_7H_{11}N_2F_3O_3S$, production batch number 4900610100, and a stated purity of ≥ 99%. Structurally, [EMIM][$MeSO_3$] comprises a $C_7H_{11}N_2^+$ cation and a $MeSO_3^-$ anion, forming an organic salt-type ionic compound. The molecular structure of this ionic liquid is depicted in Figure 1.

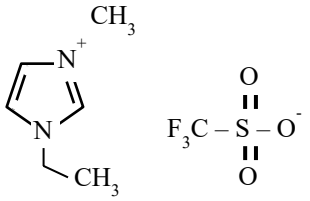

Figure 1. Molecular structure of the imidazolium-based ionic liquid [EMIM][$MeSO_3$]

To guarantee the precision of the experimental measurements, the ionic liquid sample was subjected to a preliminary purification protocol. It is well known that ionic liquids generally possess very high boiling temperatures and often decompose thermally before reaching their boiling point. To eliminate potential volatile components and trace impurities, the ionic liquid was subjected to vacuum drying at 423.15 K for 4 hours. This treatment effectively removed residual volatiles and minor contaminants from the sample. Following the drying procedure, the water content of the ionic liquid was quantified using the Karl Fischer titration method and was confirmed to be below 100 ppm, a level considered essential for obtaining reliable and reproducible viscosity measurements.

Experimental procedure and measurement methodology: The primary aim of this study is the experimental determination of the dynamic viscosity of binary mixtures composed of an imidazolium-based ionic liquid and methanol, as a function of both temperature and mixture composition. To this end, the dynamic viscosity, η (p_0, T), of the binary system {$x$$CH_3OH$ + (1−x) [EMIM][$MeSO_3$]} was measured using two complementary high-precision techniques: an oscillating-tube viscometer and a controlled-stress rotational rheometer. The SVM 3000 Stabinger viscometer (Figure 2) is a modern instrument designed for highly accurate

viscosity measurements of liquids within the temperature range T = 273.15-373.15 K. One of the main advantages of this instrument is its wide measurement range and high temperature stability [7].

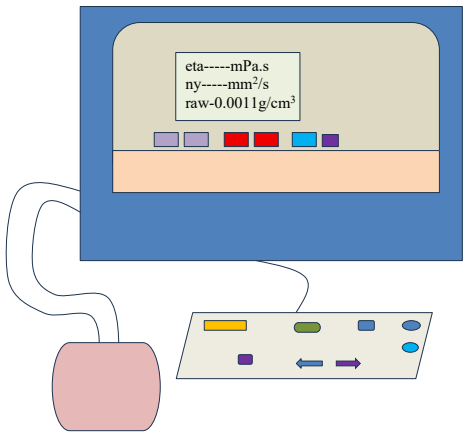

Figure 2. General schematic of the oscillating-tube viscometer used for dynamic viscosity measurements [7]

To broaden the experimental temperature range and enable measurements at both lower and higher temperatures, a controlled-stress rotational rheometer was additionally utilized (Figure 3) [8]. The use of two different instruments also allowed a comparative analysis of the experimental results obtained by different measurement techniques. Measurements using the oscillating-tube viscometer: The oscillating-tube viscometer is equipped with a Peltier-based temperature control system and operates according to the Stabinger measurement principle. This device enables highly accurate measurements of viscosity and temperature over a wide measurement range. The viscosity determination is based on the rotational measurement principle, in which the braking torque generated by the rotating system is measured. The vortex currents generated within the measuring system are directly related to the torque changes associated with the rotation speed, allowing the viscosity of the fluid to be determined.

The operating principle of the apparatus and the experimental procedure have been described in detail in previous studies [9], [10], [11], [12]. Before starting the measurements, the instrument was thoroughly cleaned and dried. A small portion of the liquid sample was first introduced into the measuring cell using a syringe. After approximately 5 minutes, the remaining portion of the sample was added to the measuring chamber. Subsequently, the measurement mode was selected and the system was allowed to reach thermal equilibrium. Once the temperature stabilized, the viscosity and temperature readings were recorded. Dynamic viscosity measurements were conducted in a stepwise manner across the temperature range of 273.15-373.15 K to ensure precise characterization of the system's thermal response. After each measurement, the measuring cell was cleaned by flushing it with distilled water, followed by acetone, and then dried using a stream of air to prepare the device for the next experiment.

Measurements using the MCR 302 rheometer: The MCR 302 rheometer operates based on rheological measurement principles and is widely used for studying the flow behavior of liquids and complex fluids over a wide temperature range. During the experiments, the liquid sample was placed on the stationary lower plate of the rheometer [8]. The upper rotating plate was then lowered to compress the sample to a specific thickness. At this stage, the thickness of the compressed sample h (mm) was measured with high precision. The device can operate automatically under different temperature conditions or within a specified temperature range. All experimental data obtained during the measurements are automatically processed by the computer software system of the instrument. The processed results are presented in the form of tables and graphs representing the dynamic viscosity values $\eta(p_0, T)$.

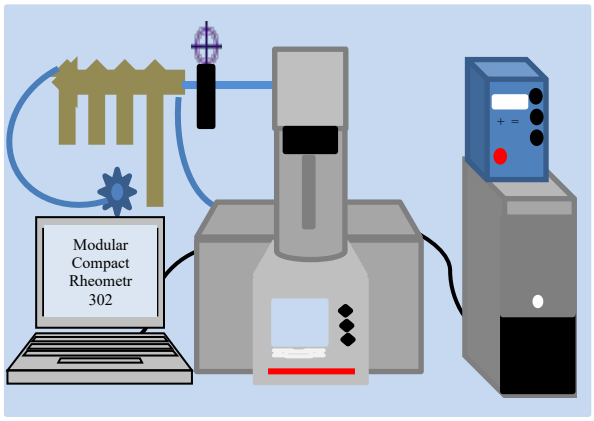

Figure 3. General view of the MCR 302 rheometer [8]

3. PROBLEM SOLUTION

Methanol was selected as a component of the mixture primarily because its thermophysical properties have been extensively investigated in the literature [13], [14]. The experimental dynamic viscosity data, $\eta(p_{0,s}, T,w)$, for binary mixtures of an imidazolium-based ionic liquid and methanol {(1−x)[EMIM][MeSO$_3$] + xCH$_3$OH}, obtained using two independent measurement techniques over the temperature range T = 263.15-413.15 K at both atmospheric pressure (p = 0.101 MPa) and corresponding saturation pressures, are summarized in Table 1. Notably, the dynamic viscosity of these binary mixtures has been investigated experimentally in this work for the first time.

Table 1. Experimental dynamic viscosity, η (p_0, s, T, w), of binary mixtures {(1−x) [EMIM][MeSO$_3$] + xCH$_3$OH} measured over the temperature range T = 263.15-413.15 K at atmospheric pressure (p = 0.101 MPa) and corresponding saturation pressures

T, K	w	η
263.15	0.0000	3246.0669
303.15	0.0000	114.9621
343.15	0.0000	21.7494
383.15	0.0000	8.2135
413.15	0.0000	4.9313
263.15	0.8503	2126.6309
303.15	0.8503	93.5955
343.15	0.8503	18.8848
383.15	0.8503	7.4749

413.15	0.8503	4.7120
263.15	1.9024	1331.0439
303.15	1.9024	73.9097
343.15	1.9024	16.2494
383.15	1.9024	6.7707
413.15	1.9024	4.4485
263.15	4.2894	548.3678
303.15	4.2894	46.9202
343.15	4.2894	12.2821
383.15	4.2894	5.6297
413.15	4.2894	3.8973
263.15	8.5756	167.9821
303.15	8.5756	24.7135
343.15	8.5756	8.2328
383.15	8.5756	4.2521
413.15	8.5756	3.0665
263.15	12.4535	76.2955
303.15	12.4535	15.5477
343.15	12.4535	6.0395
383.15	12.4535	3.3482
413.15	12.4535	2.4662
263.15	16.9854	37.4343
303.15	16.9854	9.9123
343.15	16.9854	4.3671

T, K	*w*	*η*
383.15	16.9854	2.5582
413.15	16.9854	1.9186
263.15	19.6252	26.6150
303.15	19.6252	7.8935
343.15	19.6252	3.6724
383.15	19.6252	2.2008
413.15	19.6252	1.6641
263.15	22.5051	19.2233
303.15	22.5051	6.3033
343.15	22.5051	3.0763
383.15	22.5051	1.8795
413.15	22.5051	1.4313
263.15	28.6195	10.8949
303.15	28.6195	4.1773
343.15	28.6195	2.1927
383.15	28.6195	1.3769
413.15	28.6195	1.0588
263.15	40.0251	5.0813
303.15	40.0251	2.3130
343.15	40.0251	1.3077
383.15	40.0251	0.8404
413.15	40.0251	0.6487
263.15	52.2538	2.8977
303.15	52.2538	1.4548
343.15	52.2538	0.8527
383.15	52.2538	0.5515
413.15	52.2538	0.4224
263.15	55.7919	2.5438
303.15	55.7919	1.3020
343.15	55.7919	0.7678
383.15	55.7919	0.4966
413.15	55.7919	0.3790
263.15	63.9978	1.9581

T, K	*w*	*η*
303.15	63.9978	1.0378
343.15	63.9978	0.6179
383.15	63.9978	0.3990
413.15	63.9978	0.3018
263.15	76.6302	1.4226
303.15	76.6302	0.7815
343.15	76.6302	0.4684
383.15	76.6302	0.3011
413.15	76.6302	0.2243
263.15	85.1880	1.1948
303.15	85.1880	0.6672
343.15	85.1880	0.4005
383.15	85.1880	0.2564
413.15	85.1880	0.1890
263.15	90.8015	1.0807
303.15	90.8015	0.6086
343.15	90.8015	0.3653
383.15	90.8015	0.2333
413.15	90.8015	0.1708
263.15	94.5235	1.0164
303.15	94.5235	0.5751
343.15	94.5235	0.3452
383.15	94.5235	0.2200
413.15	94.5235	0.1604
263.15	97.6428	0.8471
303.15	97.6428	0.5470
343.15	97.6428	0.2868
383.15	97.6428	0.1475
413.15	97.6428	0.0919
263.15	100.000	0.9174
303.15	100.000	0.5195
343.15	100.000	0.3193
383.15	100.000	0.2029
413.15	100.000	0.1470

Table 1 presents *w*, as the mass fraction of methanol in the investigated binary mixture. The obtained results for the dynamic viscosity, $\eta(p_0, T)$, of the investigated binary mixture $\{x\mathrm{CH_3OH} + (1-x)[\mathrm{EMIM}][\mathrm{MeSO_3}]\}$ are represented by the following polynomial equation:

$$\ln \eta\left(p_0, T\right) = \sum_{i=0}^{4}\left(\frac{1}{T}\right)^{i} \sum_{j=0}^{3} a_{ij}\,(x/mole \times fr)^{j} \tag{1}$$

where, a_{ij} are the coefficients of Equation (1), determined via the least-squares method, with their corresponding values listed in Table 2; x denotes the mole fraction of methanol in the binary mixture. Equation (1) allows us to calculate the experimental results with an average relative error of $\Delta\eta/\eta = \pm 0{,}56\%$.

Table 2. Coefficients a_{ij} of the polynomial equation (1) for the binary mixture $\{x\mathrm{CH_3OH} + (1-x)\,[\mathrm{EMIM}][\mathrm{MeSO_3}]\}$

a_{00} = 263.8733606	a_{13} = 3.950243941	a_{32} = -6.708825×10^{-5}
a_{01} = -652.4907497	a_{20} = 0.01007410717	a_{33} = 3.362442×10^{-5}
a_{02} = 709.2690889	a_{21} = -0.02889513729	a_{40} = 1.156057582×10^{-8}
a_{03} = -330.0303279	a_{22} = 0.03547650696	a_{41} = -3.591390×10^{-8}
a_{10} = -2.619747428	a_{23} = -0.01745213606	a_{42} = 4.708259×10^{-8}
a_{11} = 7.061861531	a_{30} = -1.753090311·10^{-5}	a_{43} = -2.396074×10^{-8}
a_{12} = -8.238604449	a_{31} = 5.263691623·10^{-5}	

The average absolute deviation (AAD) is calculated as:

$$AAD = \left(100/n\right) \times \left(\eta_{\exp} - \eta_{cal}\right) / \eta_{\exp} = \pm 0.56\% \tag{2}$$

This correlation provides an accurate representation of the experimental data, yielding a mean relative deviation of $\triangle\eta/\eta = \pm 0.56\%$, which confirms the high precision of the viscosity measurements. The polynomial model allows for reliable interpolation of viscosity values across the studied temperature range and composition, facilitating the prediction of $\eta(p_0,T)$ for other mixture ratios within the examined conditions.

A structured modeling methodology was employed to characterize the variation of dynamic viscosity as a function of both temperature and composition in the investigated binary mixture $\{x\mathrm{CH_3OH} + (1-x)$

[EMIM][MeSO₃]}. The modeling framework includes the stages of analytical expression of experimental data, parameter estimation, and model adequacy verification. In the first stage, it was assumed that the dynamic viscosity of the mixture is a function of temperature and the mole fraction of the components:

$$\eta = f(T, x) \tag{3}$$

where, η is the dynamic viscosity, T is the temperature, x denotes the mole fraction of methanol in the binary mixture. To characterize the temperature dependence of dynamic viscosity, an Arrhenius-type exponential model and its logarithmic form were employed:

$$\eta(T) = A\exp\left(\frac{B}{T}\right) \tag{4}$$

where,

$$\ln\eta = \ln A + \frac{B}{T} \tag{5}$$

where A and B are empirical constants and are determined based on experimental data. However, in order to achieve higher accuracy over a wider temperature range, a polynomial approximation method was used:

$$\eta(T, x) = a_0 + a_1T + a_2T^2 + a_3x + a_4x^2 + a_5Tx \tag{6}$$

This model allows for simultaneous consideration of both temperature and composition effects. The model parameters were estimated using the least-squares method, whereby the sum of the squared differences between the experimental and calculated values was minimized. With increasing temperature, the following changes occur in the system:

- The kinetic energy of molecules increases;
- Ion clusters weaken and disperse;
- The duration of interactions decreases;

As a result of this process, the viscosity changes according to the law given in equation (2). This expression shows that the viscosity is related to the activation energy required for fluidity. As the temperature increases:

- The activation barrier effectively decreases;
- The free movement of molecules becomes easier;

The fact that this effect is more pronounced in the high-temperature region indicates the temperature sensitivity of the ionic liquid structure. The observed viscosity changes in the binary mixtures {xCH₃OH + (1−x)[EMIM][MeSO₃]} deviate significantly from the ideal mixing laws. This non-ideal behavior should be considered as a result of the complex intermolecular interactions and structural changes present in the system.

The non-ideal behavior of the mixture has already been evaluated through the viscosity:

The obtained results show that negative η^E→ structural weakening prevails. This is due to the disruption of the ionic liquid structure by methanol. This result reveals the following important physical consequences:

The interactions in the system do not obey the law of linear superposition;

There is a synergistic effect between the components of the mixture;

At the same time, the extremum points of excess viscosity indicate the areas of maximum interaction in the system. One of the widely used semi-empirical models for describing the dynamic viscosity of binary fluid mixtures is the Grunberg-Nissan model. This model allows for a more realistic representation of the viscosity of the mixture by taking into account the interactions between components. The Grunberg-Nissan model is written as follows:

$$\ln\eta = x_1\ln\eta_1 + x_2\ln\eta_2 + x_1x_2\ln G_{12} \tag{6}$$

where, η is dynamic viscosity of the mixture, η_1, η_2 is viscosity of pure components, x_1, x_2 is mole fractions, G_{12} is interaction parameter.

This model takes into account non-ideal behavior through a correction term added to the ideal logarithmic mixing law. The parameter G_{12}, which plays a key role in the model, characterizes the intensity of interactions between components in the system. The parameter is calculated based on experimental data as follows:

$$G_{12} = \frac{\ln\eta - (x_1\ln\eta_1 + x_2\ln\eta_2)}{x_1x_2} \tag{7}$$

For the studied system, $G_{12} < 0$ values are observed, which is explained by the following physical mechanisms:

- methanol disrupts the ionic liquid structure;
- weakening of ion-ion interactions;
- predominance of ion-dipole interactions;

The temperature dependence of the Grunberg-Nissan parameter was analyzed separately:

$$G_{12} = f(T) \tag{8}$$

Observations show that as temperature increases, the absolute value of G_{12} decreases. This indicates that the interactions are weakening.

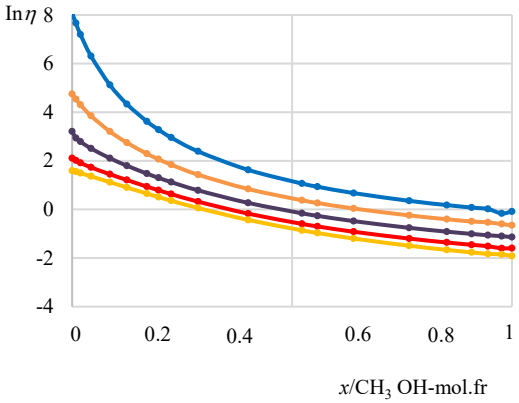

Figure 4. Variation of the dynamic viscosity, $\eta(p_0,T)$ (mPa×s), of the binary system {xCH₃OH + (1−x)[EMIM][MeSO₃]} as a function of the methanol mole fraction (x) across the temperature interval T = 263.15-413.15 K at both atmospheric and vapor-liquid equilibrium pressures. Different symbols represent measurements at specific temperatures: ●- 263.15 K; ●-303.15 K; ●- 343.15 K; ●- 383.15 K; ●-413.15 K

Figure 4 illustrates the variation of dynamic viscosity, $\eta(p_0,T)$ (mPa×s), of the binary mixture {xCH₃OH + (1−x)[EMIM][MeSO₃]} as a function of the methanol mole fraction, x across the temperature range T = 263.15-413.15 K under both atmospheric and saturation pressure conditions.

Figures 5 and 6 present the dependence of the difference between the experimentally measured dynamic viscosity, $\eta_{exp.}(p_0,T)$, and the dynamic viscosity calculated using Equation (4), $\eta_{calc.}(p_0,T)$, of the binary mixture $\{x CH_3OH + (1-x)[EMIM][MeSO_3]\}$ on the methanol mole fraction (x) and temperature (T/K) over the range T = 263.15-413.15 K at atmospheric and saturated vapor pressures.

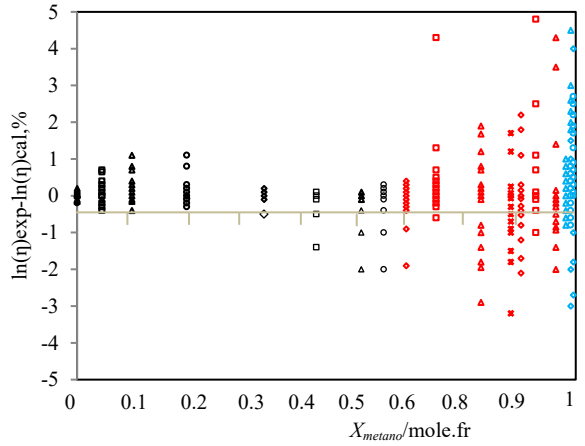

Figure 5. Dependence of the residuals between experimentally determined dynamic viscosity, $\eta_{exp}(p_0,T)$, and the values predicted by Equation (1), $\eta_{calc.}(p_0,T)$, on the methanol mole fraction (x) for the binary system $\{x CH_3OH + (1-x)[EMIM][MeSO_3]\}$ across the temperature interval T=263.15-413.15 K at atmospheric and vapor-liquid equilibrium pressures : ◆- 0.0000; ■-0.0523; ●- 0.1110; ▲- 0.2239; ◇- 0.3765; △- 0.4780; □- 0.5684; ○- 0.6112; ◆- 0.6515; ■- 0.7207; ●- 0.8112; ▲- 0.8757; ◇- 0.8904; △- 0.9196; □- 0.9548; ○- 0.9737; ◇-0.9845; △- 0.9911; □- 0.9963; ○- 1.0000

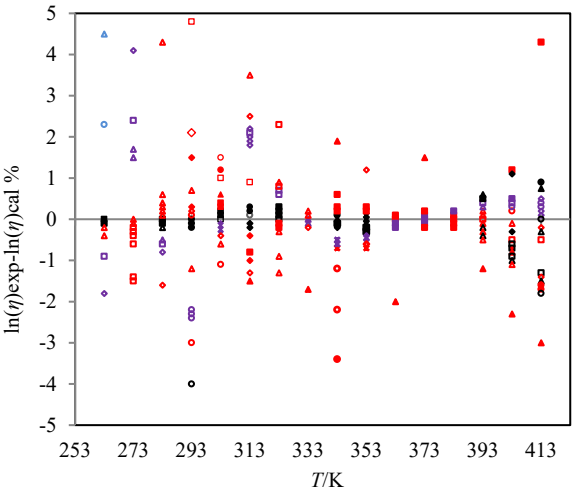

Figure 6. Variation of the residuals between experimentally measured dynamic viscosity, $\eta_{exp}(p_0,T)$, and viscosity calculated from Equation (1), $\eta_{calc.}(p_0,T)$, as a function of temperature (T/K) at different methanol mole fractions for the binary mixture $\{x CH_3OH + (1-x)[EMIM][MeSO_3]\}$ across the temperature interval T = 263.15-413.15 K, under both atmospheric and saturation pressure conditions: ◆-0.0000; ■- 0.0523; ●- 0.1110; ▲- 0.2239; ◇- 0.3765; △- 0.4780; □- 0.5684; ○- 0.6112; ◆- 0.6515; ■- 0.7207; ●- 0.8112; ▲- 0.8757; ◇- 0.8904; △- 0.9196; □- 0.9548; ○- 0.9737; ◇- 0.9845; △- 0.9911; □- 0.9963; ○-1.0000

4. EXAMPLE RESEARCH CASES AND APPLICATION AREAS

Several case studies were considered to more clearly demonstrate the rheological behavior of the investigated binary system $\{x CH_3OH + (1-x)[EMIM][MeSO_3]\}$ and to evaluate its practical application possibilities.

- Case 1: Evaluation of the effect of composition at constant temperature. In this case, the change in dynamic viscosity was analyzed when the temperature of the system was kept constant (e.g., T = 298.15 K) and the mole fraction of methanol varied in the interval $x = 0 \div 1$. The results show that the overall viscosity of the system decreases significantly with an increase in the mole fraction of methanol. This is explained by the low viscosity of methanol. The obtained results also demonstrate the non-ideal behavior of the mixture and the presence of interactions between components.
- Case 2: Analysis of the effect of temperature at constant composition. In this scenario, the change in dynamic viscosity values was investigated when the temperature was changed in the interval T = (263.15-413.15) K, while the composition of the mixture was kept constant (e.g., x = 0.5). The analysis shows that the viscosity decreases exponentially with increasing temperature. This result is explained by the increase in the kinetic energy of the molecules and the decrease in the internal friction forces. This case is of great importance in terms of choosing the thermal regime in industrial processes.
- Case 3: Comparative analysis at atmospheric and saturation pressures. In this study, dynamic viscosity values measured at atmospheric pressure and saturated vapor pressure under the same composition and temperature conditions were compared. The comparison shows that pressure changes, especially in the high temperature range, have a certain effect on viscosity indicators. This requires a deeper study of the phase behavior and molecular interactions of the system.
- Case 4: Application scenario in heating technology. The use of the studied mixtures as working fluids in absorption refrigeration systems and heat pumps was considered. In this scenario, the selection of mixtures with low viscosity leads to a decrease in hydraulic losses in the system and an increase in energy efficiency. Especially at high temperature conditions, a decrease in viscosity has a positive effect on the intensification of heat transfer processes.
- Case 5: Prospects for use in solar energy systems. The thermophysical properties of the mixture for use as a heat carrier in solar energy devices were evaluated. In this case, both stable behavior over a wide temperature range and appropriate viscosity values were taken as the main selection criteria. The analysis conducted shows that the studied system meets these requirements within a certain composition range.

The exemplary research cases presented above serve to more clearly demonstrate the behavior of the system under various conditions and to substantiate the practical application of the experimental results. This approach increases both the scientific value and the engineering significance of the article.

5. RESULTS AND DISCUSSION

The dynamic viscosity, $\eta(p_0,T)$, of the binary mixture $\{x\mathrm{CH_3OH} + (1-x)[\mathrm{EMIM}][\mathrm{MeSO_3}]\}$ was systematically determined over the temperature interval T = 263.15-413.15 K at atmospheric pressure using a high-precision oscillating-tube viscometer and a controlled-stress rotational rheometer. The obtained data were analyzed and correlated with a polynomial model to allow reliable prediction of viscosity values across the studied composition and temperature range. The values of the polynomial coefficients, calculated using the least squares method, are presented in the table. Equation (1) allows the experimental data to be reproduced with a mean relative deviation of $\triangle\eta/\eta = \pm 0.56\%$. The polynomial correlation also enables the interpolation and extrapolation of viscosity values beyond the directly measured data points.

Comparison of dynamic viscosity measurements obtained from the oscillating-tube viscometer and the controlled-stress rotational rheometer demonstrated excellent agreement within the experimental uncertainties. Minor discrepancies at higher temperatures can be attributed to instrument-specific thermal response characteristics and the increasing influence of molecular interactions at elevated temperatures.

Figure 4 presents the variation of dynamic viscosity with methanol mole fraction at selected temperatures. As expected, the viscosity decreases with increasing methanol content due to the lower intrinsic viscosity of methanol compared to $[\mathrm{EMIM}][\mathrm{MeSO_3}]$. The temperature dependence of viscosity exhibits a typical decreasing trend, reflecting reduced intermolecular interactions at higher thermal energy levels.

The analysis showed that with increasing temperature, the dynamic viscosity decreases, and this change is nonlinear, mainly exponential. Simultaneously, an increase in the methanol mole fraction results in a reduction of the mixture's viscosity, which can be attributed to the distinct rheological characteristics of the individual components. The obtained results confirm the non-ideal behavior of the system and the presence of interactions between components.

For the purpose of processing and generalizing the experimental data, an empirical modeling approach was applied and appropriate equations were obtained expressing the dependence of dynamic viscosity on temperature and composition. The proposed models described the experimental results with high accuracy, and the low calculated absolute mean error values confirmed the adequacy of the model. The extrapolation results carried out in the high temperature range created additional opportunities in terms of predicting behavior of system.

The polynomial correlation allows for interpolation and extrapolation of viscosity data beyond the directly measured points. Figure 5.6 illustrates the predicted viscosity values over the entire studied composition and temperature range, highlighting the model's suitability for engineering applications. Such a reliable correlation is particularly valuable for the design and optimization of absorption refrigeration systems, heat exchangers, and solar thermal systems, where accurate viscosity data are critical for fluid flow and heat transfer calculations [15].

Finally, the high accuracy of the correlation, as reflected by the low relative deviations, confirms the suitability of the oscillating-tube viscometer and the controlled-stress rotational rheometer for the precise characterization of ionic liquid-alcohol systems. The results provide a comprehensive dataset that can support both theoretical modeling and practical implementation of $[\mathrm{EMIM}][\mathrm{MeSO_3}]$-methanol mixtures in energy and thermal management technologies.

Comparison of the results obtained with different measurement methods (viscometer and rheometer) revealed that they showed good agreement and confirmed the reliability of the measurement results. This indicates the accuracy and reproducibility of the experimental methodology. The results obtained in this work provide valuable insights into the rheological and thermophysical characteristics of ionic liquid-alcohol mixtures, contributing to the fundamental understanding of their behavior. The acquired data, together with the proposed predictive models, establish a reliable framework for the rational selection and optimization of working fluids in absorption refrigeration systems, heat pumps, and solar energy technologies.

Comparison of the results obtained using the Anton-Paar SVM 3000 Stabinger viscometer and the Anton-Paar MCR 302 rheometer confirmed their mutual agreement and demonstrated the reliability of the measurements. Overall, the conducted research makes a significant contribution to the study of the thermophysical and rheological properties of ionic liquid-alcohol systems. The obtained results and the proposed models create a reliable scientific basis for the selection and optimization of working fluids used in various engineering applications, especially in absorption cooling systems, heat pumps and solar energy devices.

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