# Viscosity and Density of the Ternary Solution of Magnesium Chloride + Sodium Chloride + Water from (298.15 to 318.15) K

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Viscosities and densities of ternary systems of $MgCl_2$−NaCl−water were measured in the range of (298.15 to 318.15) K at 5 K intervals and up to 6 mol·kg$^{-1}$. The experimental viscosity data were satisfactorily correlated as a function of concentration using the extended Jones−Dole equation. The optimized parameters showed that the presence of $MgCl_2$ had a prevailing effect on the viscosity of the ternary solutions rather than NaCl. The dependency of the optimized parameters of the viscosity correlation on temperature was also investigated. The average absolute deviation between the calculated and the experimental viscosities was below 2.2 %.

## 1. Introduction

Magnesium and sodium chlorides are naturally existing in many natural brines such as seawater and in the brines of the Dead Sea in Jordan. Large potash (KCl) and NaCl industries have been established on the side of the Dead Sea in Jordan to produce both industrial and commercial grades of NaCl and KCl. To increase the KCl and NaCl concentration in the brine coming from the Dead Sea, evaporative pans are usually used. Three to four evaporative pans are used in series. The first evaporative pan, called the salt pan, has the largest area (about 75 km$^2$), and the brine solution consists mainly of magnesium and sodium chlorides. According to the difference in solubility, NaCl begins to precipitate first, forming mushroom-like piles (called mushrooms). These mushrooms occupy a large volume of the evaporative pan and affect highly its capacity for the coming brine from the Dead Sea and the flow of the brine solution to the other evaporative pans, which will have a bad impact on the production of potash and NaCl. The change of the viscosity of the brine, which comes mainly from the presence of magnesium and sodium chlorides, affects the rate of precipitation of NaCl and consequently the rate of growth of the mushrooms in the salt pan. Therefore, the NaCl−$MgCl_2$−water system is considered in this study. It is behind the scope of this paper to analyze the growth rate of NaCl in the presence of other salts and specifically $MgCl_2$. Other work can be consulted regarding these issues.[1]

The temperature of the evaporative pan increases with depth. The temperature of the water on the pan's surface is around 20 °C depending on the wind speed, and it reaches around 50 °C on the bottom.

General speaking, many experimental data have been reported on the viscosity of binary solutions, but few measurements are published on ternary systems and especially at high concentrations.[2,3] It is the objective of this work to report the viscosity of the ternary system of NaCl + $MgCl_2$ + water at different concentrations and different temperatures. It is also the objective of this study to cast this data in a mathematical model to calculate the viscosity of the ternary system as a function of concentration and temperature. The viscosity data are of interest for heat and mass transport in the crystallization process and are tools to provide a scientific criteria for developing the crystallization process at the industrial scale.

## 2. Experimental Section

Solutions were prepared by completely dissolving preweighed amounts of $MgCl_2 \cdot 6H_2O$ and NaCl (Merck products) in double-distilled water. A stock solution of both $MgCl_2$ and NaCl were prepared at room temperature and left for 48 h before they were used. Ratios of $MgCl_2$ and NaCl solutions were prepared from the stock solutions by mass. Then for each ratio, a series of solutions of different concentrations were made by dilution by mass. The balance used is precise to within $\pm\ 1 \cdot 10^{-4}$ g. The three components of the mixed blends obtained were denoted as $i = 1$ for NaCl, $i = 2$ for $MgCl_2$, and $i = 3$ for water.

Kinematic viscosities were measured using a calibrated Ubbelhode viscometer (Schott-Gerät). The viscometer has a capillary diameter of 0.53 mm (capillary type 0a). The kinematic viscosities of the solutions were determined from the transit time of the liquid meniscus through the capillary of the viscometer. The time was measured with a precision of ± 0.01 s. Each measurement was repeated five times with a maximum deviation of less than 0.4 %. The viscosity was measured over the temperature range from (298.15 to 318.15) K in 5 K intervals.

The densities of the solution were measured precisely to 0.01 % by using a calibrated pycnometer of about 10 cm$^3$ capacity. The density was calculated by dividing the mass of the solution by the volume of the pycnometer. The viscosity was calculated from the following equation

$$\frac{\eta}{\rho} = kt \qquad (1)$$

where $k$ is the viscometer constant provided by the manufacturer and $t$ is the flow time in seconds. For viscosity and density

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**Table 1. Density $\rho$, Viscosity $\eta$, and Calculated Viscosity $\eta_c$ at 298.15 K for the NaCl−$MgCl_2$−Water System**

| $m_1$ / mol·kg$^{-1}$ | $m_2$ / mol·kg$^{-1}$ | $\rho$ / g·cm$^{-3}$ | $\eta$ / mPa·s | $\eta_c$ / mPa·s |
|---|---|---|---|---|
| mole ratio = 0.46 | | | | |
| 1.2439 | 2.7076 | 1.2065 | 2.8470 | 2.7769 |
| 1.0855 | 2.3591 | 1.1836 | 2.4120 | 2.4074 |
| 0.9592 | 2.0894 | 1.1636 | 2.1319 | 2.1206 |
| 0.8628 | 1.8766 | 1.1503 | 1.9459 | 1.9490 |
| 0.7837 | 1.7014 | 1.1374 | 1.7970 | 1.7966 |
| 0.7155 | 1.5576 | 1.1262 | 1.6943 | 1.6764 |
| 0.6588 | 1.4368 | 1.1182 | 1.6099 | 1.5964 |
| 0.4262 | 0.9273 | 1.0775 | 1.3023 | 1.2725 |
| 0.3273 | 0.7110 | 1.0662 | 1.2341 | 1.2069 |
| 0.0982 | 0.2157 | 1.0154 | 0.9819 | 1.0392 |
| mole ratio = 0.69 | | | | |
| 1.5722 | 2.2839 | 1.1933 | 2.4808 | 2.4328 |
| 1.3261 | 1.9252 | 1.1670 | 2.1016 | 2.0888 |
| 1.1449 | 1.6629 | 1.1470 | 1.8570 | 1.8583 |
| 1.0098 | 1.4650 | 1.1304 | 1.6909 | 1.6862 |
| 0.9030 | 1.3066 | 1.1181 | 1.5787 | 1.5708 |
| 0.8146 | 1.1827 | 1.1066 | 1.4892 | 1.4718 |
| 0.7430 | 1.0797 | 1.0980 | 1.4210 | 1.4038 |
| 0.4628 | 0.6679 | 1.0611 | 1.1879 | 1.1649 |
| 0.3468 | 0.5052 | 1.0466 | 1.1073 | 1.0951 |
| 0.0995 | 0.1452 | 1.0114 | 0.9508 | 0.9806 |
| mole ratio = 1.38 | | | | |
| 2.4667 | 1.7834 | 1.1936 | 2.2885 | 2.2487 |
| 2.1411 | 1.5528 | 1.1684 | 1.9835 | 1.9674 |
| 1.9011 | 1.3806 | 1.1525 | 1.7940 | 1.8077 |
| 1.7076 | 1.2400 | 1.1387 | 1.6622 | 1.6799 |
| 1.5511 | 1.1253 | 1.1171 | 1.5500 | 1.4997 |
| 1.4222 | 1.0292 | 1.1152 | 1.4814 | 1.4846 |
| 1.3132 | 0.9559 | 1.1057 | 1.4274 | 1.4142 |
| 0.8463 | 0.6187 | 1.0701 | 1.2024 | 1.1911 |
| 0.6538 | 0.4788 | 1.0544 | 1.1259 | 1.1135 |
| 0.1958 | 0.1439 | 1.0147 | 0.9587 | 0.9732 |
| mole ratio = 2.75 | | | | |
| 3.0925 | 1.1282 | 1.1718 | 1.8701 | 1.8401 |
| 2.6200 | 0.9478 | 1.1491 | 1.6454 | 1.6458 |
| 2.2763 | 0.8193 | 1.1312 | 1.5216 | 1.5085 |
| 1.9969 | 0.7252 | 1.1152 | 1.4047 | 1.3973 |
| 1.7829 | 0.6484 | 1.1068 | 1.3505 | 1.3433 |
| 1.6122 | 0.5878 | 1.0953 | 1.2792 | 1.2745 |
| 1.4736 | 0.5359 | 1.0869 | 1.2374 | 1.2281 |
| 0.9251 | 0.3304 | 1.0560 | 1.0914 | 1.0820 |
| 0.7011 | 0.2560 | 1.0412 | 1.0504 | 1.0265 |
| 0.1990 | 0.0740 | 1.0097 | 0.9343 | 0.9385 |
| mole ratio = 4.1 | | | | |
| 3.6311 | 0.8859 | 1.1745 | 1.8145 | 1.7807 |
| 3.1806 | 0.7685 | 1.1557 | 1.6436 | 1.6284 |
| 2.8215 | 0.6868 | 1.1397 | 1.5310 | 1.5108 |
| 2.5405 | 0.6166 | 1.1262 | 1.4298 | 1.4202 |
| 2.3070 | 0.5584 | 1.1257 | 1.3745 | 1.4166 |
| 2.1146 | 0.5133 | 1.1079 | 1.3117 | 1.3087 |
| 1.9523 | 0.4757 | 1.0979 | 1.2567 | 1.2545 |
| 1.2729 | 0.3087 | 1.0661 | 1.1156 | 1.1080 |
| 0.9727 | 0.2353 | 1.0503 | 1.0578 | 1.0508 |
| 0.2952 | 0.0717 | 1.0136 | 0.9481 | 0.9574 |
| AAD % 1.173 | | | | |

**Table 2. Density $\rho$, Viscosity $\eta$, and Calculated Viscosity $\eta_c$ at 303.15 K for the NaCl−$MgCl_2$−Water System**

| $m_1$ / mol·kg$^{-1}$ | $m_2$ / mol·kg$^{-1}$ | $\rho$ / g·cm$^{-3}$ | $\eta$ / mPa·s | $\eta_c$ / mPa·s |
|---|---|---|---|---|
| mole ratio = 0.46 | | | | |
| 1.2439 | 2.7076 | 1.2046 | 2.5276 | 2.4758 |
| 1.0855 | 2.3591 | 1.1814 | 2.1452 | 2.1557 |
| 0.9592 | 2.0894 | 1.1616 | 1.9081 | 1.9102 |
| 0.8628 | 1.8766 | 1.1482 | 1.7397 | 1.7609 |
| 0.7837 | 1.7014 | 1.1351 | 1.6134 | 1.6248 |
| 0.7155 | 1.5576 | 1.1240 | 1.5134 | 1.5200 |
| 0.6588 | 1.4368 | 1.1158 | 1.4419 | 1.4474 |
| 0.4262 | 0.9273 | 1.0757 | 1.1656 | 1.1571 |
| 0.3273 | 0.7110 | 1.0630 | 1.0878 | 1.0872 |
| 0.0982 | 0.2157 | 1.0154 | 0.8821 | 0.9204 |
| mole ratio = 0.69 | | | | |
| 1.5722 | 2.2839 | 1.1909 | 2.2034 | 2.1770 |
| 1.3261 | 1.9252 | 1.1650 | 1.8832 | 1.8830 |
| 1.1449 | 1.6629 | 1.1450 | 1.6619 | 1.6804 |
| 1.0098 | 1.4650 | 1.1284 | 1.5212 | 1.5298 |
| 0.9030 | 1.3066 | 1.1160 | 1.4115 | 1.4263 |
| 0.8146 | 1.1827 | 1.1046 | 1.3399 | 1.3386 |
| 0.7430 | 1.0797 | 1.0958 | 1.2725 | 1.2751 |
| 0.4628 | 0.6679 | 1.0596 | 1.0687 | 1.0595 |
| 0.3468 | 0.5052 | 1.0447 | 0.9972 | 0.9907 |
| 0.0995 | 0.1452 | 1.0100 | 0.8799 | 0.8753 |
| mole ratio = 1.38 | | | | |
| 2.4667 | 1.7834 | 1.1915 | 2.0460 | 2.0171 |
| 2.1411 | 1.5528 | 1.1661 | 1.7787 | 1.7723 |
| 1.9011 | 1.3806 | 1.1502 | 1.6054 | 1.6324 |
| 1.7076 | 1.2400 | 1.1364 | 1.4912 | 1.5206 |
| 1.5511 | 1.1253 | 1.1151 | 1.3900 | 1.3634 |
| 1.4222 | 1.0292 | 1.1135 | 1.3352 | 1.3523 |
| 1.3132 | 0.9559 | 1.1038 | 1.2819 | 1.2875 |
| 0.8463 | 0.6187 | 1.0684 | 1.1000 | 1.0853 |
| 0.6538 | 0.4788 | 1.0528 | 1.0136 | 1.0127 |
| 0.1958 | 0.1439 | 1.0132 | 0.8625 | 0.8740 |
| mole ratio = 2.75 | | | | |
| 3.0925 | 1.1282 | 1.1695 | 1.6824 | 1.6603 |
| 2.6200 | 0.9478 | 1.1470 | 1.4785 | 1.4907 |
| 2.2763 | 0.8193 | 1.1289 | 1.3555 | 1.3682 |
| 1.9969 | 0.7252 | 1.1130 | 1.2725 | 1.2700 |
| 1.7829 | 0.6484 | 1.1051 | 1.2181 | 1.2246 |
| 1.6122 | 0.5878 | 1.0930 | 1.1509 | 1.1595 |
| 1.4736 | 0.5359 | 1.0847 | 1.1129 | 1.1178 |
| 0.9251 | 0.3304 | 1.0538 | 0.9803 | 0.9840 |
| 0.7011 | 0.2560 | 1.0397 | 0.9312 | 0.9341 |
| 0.1990 | 0.0740 | 1.0084 | 0.8411 | 0.8478 |
| mole ratio = 4.10 | | | | |
| 3.6311 | 0.8859 | 1.1723 | 1.6208 | 1.5910 |
| 3.1806 | 0.7685 | 1.1534 | 1.4868 | 1.4601 |
| 2.8215 | 0.6868 | 1.1379 | 1.3718 | 1.3612 |
| 2.5405 | 0.6166 | 1.1241 | 1.2835 | 1.2801 |
| 2.3070 | 0.5584 | 1.1139 | 1.2323 | 1.2240 |
| 2.1146 | 0.5133 | 1.1058 | 1.1821 | 1.1820 |
| 1.9523 | 0.4757 | 1.0956 | 1.1450 | 1.1324 |
| 1.2729 | 0.3087 | 1.0644 | 1.0052 | 1.0012 |
| 0.9727 | 0.2353 | 1.0486 | 0.9502 | 0.9470 |
| 0.2952 | 0.0717 | 1.0119 | 0.8471 | 0.8517 |
| AAD % 0.856 | | | | |

measurements, the temperature was controlled with a thermostatted water bath. The precision of the temperature control was ± 0.1 K.

Double-distilled water was used to calibrate the viscometer and the pycnometer. The measured viscosity of the water used in the experiments was within 0.008 %, 0.8 %, and 0.4 % at (298.15, 303.15, and 313.15) K, respectively, of the published values.[4] Meanwhile, the measured density of water was less than 0.3 % at all (298.15, 303.15, 313.15, 313.15, and 318.15) K of the published values.[5]

## 3. Results and Discussion

Densities and viscosities for the ternary solutions over a temperature range from (298.15 to 318.15) K in 5 K intervals and at different NaCl/$MgCl_2$ mole ratios are presented in Tables 1 to 5. The studied mole ratios were 0.46, 0.69, 1.38, 2.75, and 4.10. The viscosity of the solutions is correlated as a function of the molarities of both NaCl and $MgCl_2$ in the mixture as the following

$$\frac{\eta}{\eta_o} = 1 + A_1(c_1^{1/2} + c_2^{1/2}) + A_2(c_1 + c_2) + A_3(c_1^{2} + c_2^{2}) \quad (2)$$

**Table 3. Density $\rho$, Viscosity $\eta$, and Calculated Viscosity $\eta_c$ at 308.15 K for the NaCl−$MgCl_2$−Water System**

| $m_1$ / mol·kg$^{-1}$ | $m_2$ / mol·kg$^{-1}$ | $\rho$ / g·cm$^{-3}$ | $\eta$ / mPa·s | $\eta_c$ / mPa·s |
|---|---|---|---|---|
| mole ratio = 0.46 | | | | |
| 1.2439 | 2.7076 | 1.2026 | 2.2485 | 2.2021 |
| 1.0855 | 2.3591 | 1.1796 | 1.9223 | 1.9301 |
| 0.9592 | 2.0894 | 1.1596 | 1.7079 | 1.7171 |
| 0.8628 | 1.8766 | 1.1465 | 1.5638 | 1.5886 |
| 0.7837 | 1.7014 | 1.1333 | 1.4517 | 1.4689 |
| 0.7155 | 1.5576 | 1.1222 | 1.3691 | 1.3761 |
| 0.6588 | 1.4368 | 1.1136 | 1.3030 | 1.3081 |
| 0.4262 | 0.9273 | 1.0740 | 1.0551 | 1.0476 |
| 0.3273 | 0.7110 | 1.0617 | 1.0021 | 0.9832 |
| 0.0982 | 0.2157 | 1.0136 | 0.8021 | 0.8084 |
| mole ratio = 0.69 | | | | |
| 1.5722 | 2.2839 | 1.1888 | 1.9801 | 1.9458 |
| 1.3261 | 1.9252 | 1.1625 | 1.6846 | 1.6874 |
| 1.1449 | 1.6629 | 1.1432 | 1.4961 | 1.5166 |
| 1.0098 | 1.4650 | 1.1267 | 1.3696 | 1.3841 |
| 0.9030 | 1.3066 | 1.1140 | 1.2773 | 1.2906 |
| 0.8146 | 1.1827 | 1.1024 | 1.2016 | 1.2109 |
| 0.7430 | 1.0797 | 1.0920 | 1.1447 | 1.1443 |
| 0.4628 | 0.6679 | 1.0575 | 0.9628 | 0.9566 |
| 0.3468 | 0.5052 | 1.0429 | 0.8982 | 0.8924 |
| 0.0995 | 0.1452 | 1.0083 | 0.7691 | 0.7767 |
| mole ratio = 1.38 | | | | |
| 2.4667 | 1.7834 | 1.1892 | 1.8333 | 1.8034 |
| 2.1411 | 1.5528 | 1.1641 | 1.5887 | 1.5937 |
| 1.9011 | 1.3806 | 1.1482 | 1.4462 | 1.4722 |
| 1.7076 | 1.2400 | 1.1343 | 1.3452 | 1.3735 |
| 1.5511 | 1.1253 | 1.1132 | 1.2600 | 1.2352 |
| 1.4222 | 1.0292 | 1.1115 | 1.2087 | 1.2251 |
| 1.3132 | 0.9559 | 1.1013 | 1.1597 | 1.1642 |
| 0.8463 | 0.6187 | 1.0663 | 0.9813 | 0.9829 |
| 0.6538 | 0.4788 | 1.0508 | 0.9203 | 0.9153 |
| 0.1958 | 0.1439 | 1.0114 | 0.7782 | 0.7803 |
| mole ratio = 2.75 | | | | |
| 3.0925 | 1.1282 | 1.1672 | 1.5106 | 1.4931 |
| 2.6200 | 0.9478 | 1.1444 | 1.3291 | 1.3430 |
| 2.2763 | 0.8193 | 1.1267 | 1.2251 | 1.2368 |
| 1.9969 | 0.7252 | 1.1099 | 1.1506 | 1.1450 |
| 1.7829 | 0.6484 | 1.1025 | 1.0978 | 1.1072 |
| 1.6122 | 0.5878 | 1.0905 | 1.0445 | 1.0491 |
| 1.4736 | 0.5359 | 1.0817 | 1.0087 | 1.0095 |
| 0.9251 | 0.3304 | 1.0521 | 0.8905 | 0.8924 |
| 0.7011 | 0.2560 | 1.0377 | 0.8426 | 0.8444 |
| 0.1990 | 0.0740 | 1.0064 | 0.7578 | 0.7612 |
| mole ratio = 4.10 | | | | |
| 3.6311 | 0.8859 | 1.1700 | 1.4623 | 1.4179 |
| 3.1806 | 0.7685 | 1.1511 | 1.3312 | 1.3058 |
| 2.8215 | 0.6868 | 1.1354 | 1.2349 | 1.2194 |
| 2.5405 | 0.6166 | 1.1214 | 1.1591 | 1.1478 |
| 2.3070 | 0.5584 | 1.1118 | 1.1081 | 1.1014 |
| 2.1146 | 0.5133 | 1.1038 | 1.0689 | 1.0645 |
| 1.9523 | 0.4757 | 1.0935 | 1.0331 | 1.0199 |
| 1.2729 | 0.3087 | 1.0621 | 0.9107 | 0.8992 |
| 0.9727 | 0.2353 | 1.0468 | 0.8645 | 0.8495 |
| 0.2952 | 0.0717 | 1.0101 | 0.7691 | 0.7539 |
| AAD % 0.988 | | | | |

**Table 4. Density $\rho$, Viscosity $\eta$, and Calculated Viscosity $\eta_c$ at 313.15 K for the NaCl−$MgCl_2$−Water System**

| $m_1$ / mol·kg$^{-1}$ | $m_2$ / mol·kg$^{-1}$ | $\rho$ / g·cm$^{-3}$ | $\eta$ / mPa·s | $\eta_c$ / mPa·s |
|---|---|---|---|---|
| mole ratio = 0.46 | | | | |
| 1.2439 | 2.7076 | 1.2001 | 2.0216 | 1.9758 |
| 1.0855 | 2.3591 | 1.1772 | 1.7319 | 1.7410 |
| 0.9592 | 2.0894 | 1.1577 | 1.5372 | 1.5598 |
| 0.8628 | 1.8766 | 1.1446 | 1.4215 | 1.4472 |
| 0.7837 | 1.7014 | 1.1310 | 1.3252 | 1.3376 |
| 0.7155 | 1.5576 | 1.1200 | 1.2389 | 1.2551 |
| 0.6588 | 1.4368 | 1.1122 | 1.1804 | 1.1996 |
| 0.4262 | 0.9273 | 1.0720 | 0.9570 | 0.9549 |
| 0.3273 | 0.7110 | 1.0596 | 0.9084 | 0.8931 |
| 0.0982 | 0.2157 | 1.0113 | 0.7224 | 0.7138 |
| mole ratio = 0.69 | | | | |
| 1.5722 | 2.2839 | 1.1862 | 1.7917 | 1.7533 |
| 1.3261 | 1.9252 | 1.1613 | 1.5255 | 1.5383 |
| 1.1449 | 1.6629 | 1.1410 | 1.3530 | 1.3800 |
| 1.0098 | 1.4650 | 1.1247 | 1.2398 | 1.2634 |
| 0.9030 | 1.3066 | 1.1118 | 1.1572 | 1.1775 |
| 0.8146 | 1.1827 | 1.0999 | 1.0931 | 1.1035 |
| 0.7430 | 1.0797 | 1.0908 | 1.0441 | 1.0505 |
| 0.4628 | 0.6679 | 1.0553 | 0.8775 | 0.8707 |
| 0.3468 | 0.5052 | 1.0409 | 0.8148 | 0.8104 |
| 0.0995 | 0.1452 | 1.0067 | 0.6987 | 0.6953 |
| mole ratio = 1.38 | | | | |
| 2.4667 | 1.7834 | 1.1853 | 1.6488 | 1.6179 |
| 2.1411 | 1.5528 | 1.1616 | 1.4365 | 1.4447 |
| 1.9011 | 1.3806 | 1.1461 | 1.3102 | 1.3405 |
| 1.7076 | 1.2400 | 1.1325 | 1.2223 | 1.2543 |
| 1.5511 | 1.1253 | 1.1117 | 1.1400 | 1.1325 |
| 1.4222 | 1.0292 | 1.1093 | 1.1007 | 1.1187 |
| 1.3132 | 0.9559 | 1.1000 | 1.0555 | 1.0690 |
| 0.8463 | 0.6187 | 1.0642 | 0.8904 | 0.8977 |
| 0.6538 | 0.4788 | 1.0487 | 0.8359 | 0.8342 |
| 0.1958 | 0.1439 | 1.0094 | 0.7103 | 0.7021 |
| mole ratio = 2.75 | | | | |
| 3.0925 | 1.1282 | 1.1647 | 1.3944 | 1.3560 |
| 2.6200 | 0.9478 | 1.1423 | 1.2087 | 1.2245 |
| 2.2763 | 0.8193 | 1.1240 | 1.1099 | 1.1268 |
| 1.9969 | 0.7252 | 1.1086 | 1.0421 | 1.0511 |
| 1.7829 | 0.6484 | 1.1003 | 0.9999 | 1.0126 |
| 1.6122 | 0.5878 | 1.0877 | 0.9526 | 0.9572 |
| 1.4736 | 0.5359 | 1.0780 | 0.9176 | 0.9175 |
| 0.9251 | 0.3304 | 1.0497 | 0.8108 | 0.8143 |
| 0.7011 | 0.2560 | 1.0357 | 0.7749 | 0.7705 |
| 0.1990 | 0.0740 | 1.0037 | 0.6891 | 0.6878 |
| mole ratio = 4.10 | | | | |
| 3.6311 | 0.8859 | 1.1653 | 1.2044 | 1.2643 |
| 3.1806 | 0.7685 | 1.1462 | 1.1027 | 1.1670 |
| 2.8215 | 0.6868 | 1.1302 | 1.0288 | 1.0911 |
| 2.5405 | 0.6166 | 1.1169 | 0.9674 | 1.0313 |
| 2.3070 | 0.5584 | 1.1074 | 0.9242 | 0.9912 |
| 2.1146 | 0.5133 | 1.0988 | 0.8913 | 0.9562 |
| 1.9523 | 0.4757 | 1.0886 | 0.8635 | 0.9165 |
| 1.2729 | 0.3087 | 1.0572 | 0.7623 | 0.8066 |
| 0.9727 | 0.2353 | 1.0430 | 0.7212 | 0.7631 |
| 0.2952 | 0.0717 | 1.0060 | 0.6387 | 0.6678 |
| AAD % 2.158 | | | | |

where $c$ is the molar concentration, $\eta_o$ is the water viscosity, and $A_1$, $A_2$, and $A_3$ are adjustable parameters. Equation 2 can be considered as an extension to the well-known semiempirical Jones−Dole equation for binary systems.[6] The Jones−Dole equation was modified by including the molarities of the two solutes NaCl ($c_1$) and $MgCl_2$ ($c_2$) and by adding a fourth squared term on the right-hand side of eq 2. Analysis of the Jones−Dole equation is to be found elsewhere.[7] The adjustable parameters $A_1$, $A_2$, and $A_3$ were optimized by fitting eq 2 to the experimental data given in Tables 1 to 5. The optimized values of the parameters of eq 2 are given in Table 6.

Furthermore, the experimental and calculated viscosities were compared. The standard deviation (SD) and the average absolute deviation (AAD) are calculated according to eqs 3 and 4, respectively:

$$\mathrm{SD} = \left[\frac{\sum_{i=1}^{n}(\eta_{\exp,i} - \eta_{\mathrm{cal},i})^2}{(n-p)}\right]^{1/2} \tag{3}$$

$$\mathrm{AAD} = \left[\sum_{i=1}^{n} \frac{|\eta_{\exp,i} - \eta_{\mathrm{cal},i}|}{\eta_{\exp,i}}\right] \cdot \frac{100}{n} \tag{4}$$

where $n$ is the number of data points and $p$ is the number of adjusted parameters. The values of AAD and SD are also listed in Table 6. The deviations are not more than 1.7 % at all temperatures. The highest standard deviation was found to be 0.0461 mPa·s for only one set of measurements (mole ratio = 0.46 at 298.15 K); otherwise, the SD was less than 0.03 mPa·s. Examination of both the standard deviation and the AAD of the fit indicates that eq 2 fits the experimental data very well. It can be seen in Table 6 that the three parameters have the same trend at the different temperatures investigated in this study; $A_2$ always has a negative value, and $A_1$ is larger than $A_3$. The change of the values of the three parameters ($A_1$, $A_2$, and $A_3$) with mole ratio is higher at smaller mole ratios, then the change becomes almost constant at larger mole ratios. This shows that the presence of $MgCl_2$ (smaller mole ratio) in the ternary mixtures has a more pronounced effect on the viscosity of the ternary solution than NaCl.

**Table 5. Density $\rho$, Viscosity $\eta$, and Calculated Viscosity $\eta_c$ at 318.15 K for the NaCl−$MgCl_2$−Water System**

| $m_1$ / mol·kg$^{-1}$ | $m_2$ / mol·kg$^{-1}$ | $\rho$ / g·cm$^{-3}$ | $\eta$ / mPa·s | $\eta_c$ / mPa·s |
|---|---|---|---|---|
| mole ratio = 0.46 | | | | |
| 1.2439 | 2.7076 | 1.1989 | 1.8294 | 1.7902 |
| 1.0855 | 2.3591 | 1.1750 | 1.5775 | 1.5775 |
| 0.9592 | 2.0894 | 1.1553 | 1.4058 | 1.4167 |
| 0.8628 | 1.8766 | 1.1423 | 1.2889 | 1.3175 |
| 0.7837 | 1.7014 | 1.1287 | 1.1996 | 1.2202 |
| 0.7155 | 1.5576 | 1.1182 | 1.1255 | 1.1493 |
| 0.6588 | 1.4368 | 1.1099 | 1.0681 | 1.0957 |
| 0.4262 | 0.9273 | 1.0704 | 0.8764 | 0.8730 |
| 0.3273 | 0.7110 | 1.0579 | 0.8357 | 0.8135 |
| 0.0982 | 0.2157 | 1.0093 | 0.6651 | 0.6299 |
| mole ratio = 0.69 | | | | |
| 1.5722 | 2.2839 | 1.1839 | 1.6253 | 1.5868 |
| 1.3261 | 1.9252 | 1.1584 | 1.3907 | 1.3941 |
| 1.1449 | 1.6629 | 1.1389 | 1.2331 | 1.2590 |
| 1.0098 | 1.4650 | 1.1221 | 1.1321 | 1.1514 |
| 0.9030 | 1.3066 | 1.1096 | 1.0566 | 1.0763 |
| 0.8146 | 1.1827 | 1.0976 | 0.9991 | 1.0085 |
| 0.7430 | 1.0797 | 1.0880 | 0.9479 | 0.9574 |
| 0.4628 | 0.6679 | 1.0533 | 0.7985 | 0.7937 |
| 0.3468 | 0.5052 | 1.0390 | 0.7491 | 0.7364 |
| 0.0995 | 0.1452 | 1.0044 | 0.6451 | 0.6204 |
| mole ratio = 1.38 | | | | |
| 2.4667 | 1.7834 | 1.1838 | 1.5046 | 1.4716 |
| 2.1411 | 1.5528 | 1.1593 | 1.3119 | 1.3147 |
| 1.9011 | 1.3806 | 1.1433 | 1.1929 | 1.2193 |
| 1.7076 | 1.2400 | 1.1299 | 1.1268 | 1.1438 |
| 1.5511 | 1.1253 | 1.1089 | 1.0500 | 1.0332 |
| 1.4222 | 1.0292 | 1.1071 | 1.0077 | 1.0239 |
| 1.3132 | 0.9559 | 1.0971 | 0.9788 | 0.9751 |
| 0.8463 | 0.6187 | 1.0617 | 0.8151 | 0.8191 |
| 0.6538 | 0.4788 | 1.0465 | 0.7673 | 0.7605 |
| 0.1958 | 0.1439 | 1.0072 | 0.6495 | 0.6311 |
| mole ratio = 2.75 | | | | |
| 3.0925 | 1.1282 | 1.1621 | 1.2560 | 1.2333 |
| 2.6200 | 0.9478 | 1.1400 | 1.1053 | 1.1180 |
| 2.2763 | 0.8193 | 1.1214 | 1.0153 | 1.0289 |
| 1.9969 | 0.7252 | 1.1065 | 0.9582 | 0.9628 |
| 1.7829 | 0.6484 | 1.0982 | 0.9133 | 0.9277 |
| 1.6122 | 0.5878 | 1.0857 | 0.8711 | 0.8776 |
| 1.4736 | 0.5359 | 1.0754 | 0.8413 | 0.8388 |
| 0.9251 | 0.3304 | 1.0473 | 0.7423 | 0.7438 |
| 0.7011 | 0.2560 | 1.0332 | 0.7067 | 0.7021 |
| 0.1990 | 0.0740 | 1.0016 | 0.6458 | 0.6229 |
| mole ratio = 4.10 | | | | |
| 3.6311 | 0.8859 | 1.1653 | 1.2044 | 1.1534 |
| 3.1806 | 0.7685 | 1.1462 | 1.1027 | 1.0679 |
| 2.8215 | 0.6868 | 1.1302 | 1.0288 | 1.0005 |
| 2.5405 | 0.6166 | 1.1169 | 0.9674 | 0.9468 |
| 2.3070 | 0.5584 | 1.1074 | 0.9242 | 0.9105 |
| 2.1146 | 0.5133 | 1.0988 | 0.8913 | 0.8786 |
| 1.9523 | 0.4757 | 1.0886 | 0.8635 | 0.8420 |
| 1.2729 | 0.3087 | 1.0572 | 0.7623 | 0.7385 |
| 0.9727 | 0.2353 | 1.0430 | 0.7212 | 0.6963 |
| 0.2952 | 0.0717 | 1.0060 | 0.6387 | 0.5999 |
| AAD % 1.844 | | | | |

**Table 6. Parameters for the Fit of Equation 2 at Different Temperatures**

| mole ratio | 0.46 | 0.69 | 1.38 | 2.75 | 4.10 |
|---|---|---|---|---|---|
| $T$ = 298.15 K | | | | | |
| $A_1$ | 51.129 | 36.985 | 27.839 | 23.563 | 24.159 |
| $A_2$ | −61.536 | −45.988 | −33.268 | −27.308 | −26.255 |
| $A_3$ | 12.081 | 10.293 | 6.915 | 4.743 | 3.749 |
| AAD % | 1.553 | 0.938 | 1.166 | 0.636 | 1.215 |
| SD (mPa·s) | 0.046 | 0.024 | 0.027 | 0.014 | 0.026 |
| $T$ = 303.15 K | | | | | |
| $A_1$ | 42.508 | 33.717 | 23.542 | 20.533 | 17.191 |
| $A_2$ | −51.857 | −42.206 | −28.516 | −24.095 | −19.208 |
| $A_3$ | 10.437 | 9.565 | 6.073 | 4.278 | 2.882 |
| AAD % | 0.980 | 0.556 | 1.146 | 0.502 | 0.543 |
| SD (mPa·s) | 0.022 | 0.013 | 0.023 | 0.010 | 0.009 |
| $T$ = 308.15 K | | | | | |
| $A_1$ | 35.461 | 26.714 | 19.315 | 16.001 | 15.300 |
| $A_2$ | −43.719 | −34.044 | −23.780 | −19.158 | −17.254 |
| $A_3$ | 8.979 | 7.968 | 5.214 | 3.525 | 2.633 |
| AAD % | 1.122 | 0.978 | 1.122 | 0.662 | 0.670 |
| SD (mPa·s) | 0.025 | 0.019 | 0.022 | 0.012 | 0.011 |
| $T$ = 313.15 K | | | | | |
| $A_1$ | 30.019 | 23.586 | 17.631 | 16.477 | 10.057 |
| $A_2$ | −37.475 | −30.375 | −21.896 | −19.712 | −11.772 |
| $A_3$ | 7.873 | 7.243 | 4.874 | 3.624 | 1.902 |
| AAD % | 1.389 | 1.268 | 1.167 | 0.999 | 0.681 |
| SD (mPa·s) | 0.026 | 0.023 | 0.021 | 0.017 | 0.010 |
| $T$ = 318.15 K | | | | | |
| $A_1$ | 26.706 | 21.289 | 13.558 | 14.511 | 10.013 |
| $A_2$ | −33.647 | −27.675 | −17.326 | −17.525 | −11.811 |
| $A_3$ | 7.187 | 6.710 | 4.044 | 3.278 | 1.942 |
| AAD % | 1.648 | 1.393 | 1.335 | 0.974 | 0.782 |
| SD (mPa·s) | 0.026 | 0.022 | 0.021 | 0.014 | 0.011 |

The temperature dependence for each viscosity parameter in eq 2 was obtained by

$$A_i = a_i^0 + \frac{a_i^1}{T(\mathrm{K})} \tag{5}$$

The coefficients ($a_i^0$, $a_i^1$) were estimated from the parameter values $A_1$, $A_2$, and $A_3$ previously identified in Table 6 and are given in Table 7. The fitting adequacy was estimated by the least-squares coefficient of determination ($R^2$) and are also shown in Table 7. $R^2$ values are greater than 0.94, which shows that the linear relationship between the parameters and $1/T$ was adequate at all mole ratios. To estimate the viscosity of the ternary solutions at different temperatures, the coefficients of eq 2 were estimated at all temperatures by the coefficients in eq 5, and then the viscosity is calculated ($\eta_c$) from eq 2. The calculated dynamic viscosity $\eta_c$ is presented in Tables 1 to 5 (most right column). For comparison purposes, the AAD % was calculated. Results show that the AAD is not more than 2.2 %, which validates the $1/T$ relationship proposed in eq 5.

## 4. Conclusion

This work led to detailed experimental measurements of density and viscosity of mixed blends of the NaCl−

**Table 7. Regression Coefficients of the Temperature Correlation Equation 5**

| mole ratio | 0.46 | 0.69 | 1.38 | 2.75 | 4.10 |
|---|---|---|---|---|---|
| | | | coefficient $A_1$ | | |
| $a_1^0$ | −341.8 | −227.8 | −192.2 | −118.9 | −203.8 |
| $a_1^1$ | 116703.2 | 78924.8 | 65475.6 | 42248.3 | 67510.9 |
| $R^2$ | 0.989 | 0.985 | 0.993 | 0.944 | 0.960 |
| | | | coefficient $A_2$ | | |
| $a_2^0$ | 387.8 | 263.0 | 212.5 | 126.7 | 207.5 |
| $a_2^1$ | −133498.3 | −92122.6 | −73136.4 | −45661.6 | −69229.8 |
| $R^2$ | 0.990 | 0.985 | 0.993 | 0.944 | 0.960 |
| | | | coefficient $A_3$ | | |
| $a_3^0$ | −66.0 | −50.2 | −37.4 | −18.3 | −25.8 |
| $a_3^1$ | 23496.0 | 18032.4 | 13180.6 | 6828.0 | 8752.5 |
| $R^2$ | 0.991 | 0.985 | 0.993 | 0.944 | 0.958 |

$MgCl_2$−water ternary system. Experimental measurements were reported at five NaCl/$MgCl_2$ mole ratios and at five different temperatures. The present work led to a mathematical correlation to predict the dynamic viscosity accurately as a function of concentration and temperature. The extended Jones−Dole equation with three adjustable parameters was enough to get good predictions for the viscosity of the studied ternary system. The study showed also that the adjustable parameters have a linear relationship with the inverse of the temperature of the system.

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