

The Effect of Co-Saturated Salts on the Kinematic Viscosity of Water

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Abstract

It is well documented in the literature how individual salts such as sodium chloride (NaCl) and potassium chloride (KCl) effect the kinematic viscosity of a water solution. However, there exists little to no information on how the presence of both NaCl and KCl in a co-saturated state affect the kinematic viscosity of the solution. This paper reviews experimental measurements of co-saturated aqueous NaCl:KCl solutions across the temperature range of 20-65 oC at three different concentration ratios. These data are compared to the known kinematic viscosity curves of saturated NaCl solution and pure water from literature.

Keywords: NaCl, KCl, co-saturation, kinematic viscosity, water, brine

Introduction

The effect of KCl or NaCl salts on the kinematic viscosity of water has been extensively measured and reported in literature by Kestin, Khalifa, and Correia (1981a, 1981b). In their works, they tabulated the kinematic viscosity of aqueous NaCl or KCl solutions as a function of temperature over the temperature range of 25-250 oC and pressure range of 0.1-35 MPa . Unfortunately single-salt saturated solutions are not always used in practice and in the industry. A locally important example of this is in the mining sector where potash (mostly KCl and NaCl) is extracted for agriculture, pharmaceuticals, food processeses and manufacturing textiles (Canpotex 2018). One method for reaching deep underground potash ore deposits is to use solution mining.

In solution mining, hot water is pumped underground into the ore body where the NaCl and KCl salt dissolve together into the water. The saturated brine mixture is then pumped back up to the surface for processing and distribution (Kay 2018). The benefits of solution mining over conventional mining is lower initial project costs, shorter construction phases, educed engineering risk, more extraction opportunities and higher operating efficiencies to name a few (Gensource Potash Corp n.d).

To properly model the salt brine in solution mining, the combined effects of both NaCl and KCl on the kinematic viscosity of water should be known. Indeed there exist some information on this matter in the literature. Correia, Kestin,

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Table 1: Summary of analysis of NaCl:KCl mixtures by Correia, Kestin, and Khalifa (1979).

Solution #	Ratio of NaCl:KCL	Total Molality	Molality of NaCl	Molality of KCL	NaCl concentration g/ml
			mol/kg H ₂ O		
1	1:1	2.0096	1.0044	1.0052	0.059
2	3:1	4.0037	3.0029	1.0008	0.175
3	2:2	3.9951	1.9993	1.9958	0.116
4	1:3	4.0518	1.0297	3.0221	0.060

and Khalifa measured the dynamic viscosity of four aqueous NaCl:KCl mixtures at 25, 80, 150 °C in the pressure range 0.1-35 MPa (1979). The mixture details are provided in Table 1. However the aqueous solutions they measured are not in a state of co-saturation but rather in a state of only partial saturation. This paper attempts to investigate how both NaCl and KCl in a co-saturated state affect the kinematic viscosity of water.

Effect of Individual Salts

To provide a benchmark for how multiple salts affect the kinematic viscosity of water, one should first look at the effect of single-salted solutions. Using tabulated data acquired by Kestin, Khalifa, and Correia (1981a), one is able to see how the kinematic viscosity of an aqueous NaCl solution changes with both temperature and concentration. In Figure 1 one can see that as the temperature of the NaCl solution increases, there is a decrease in the kinematic viscosity of the solution. Alternatively, if one increases the concentration of NaCl then there is an increase in the viscosity. Each NaCl curve in Figure 1 is distinct and independent from the rest; no overlap occurs between any of the curves.

However, it can be observed from Figure 2 that the effects of the presence of KCl salt exhibits less consistency and independence. Although an increase in temperature still led to decreased kinematic viscosity, it appears that the addition of KCl can either increase or decrease the viscosity of water depending on the temperature. At lower temperatures the KCl addition seems to decrease the viscosity of water while at higher temperatures one can see the reverse effect. It is notable to point out that there is considerable magnitude difference between the NaCl and KCl viscosity curves. NaCl appears to have an effect on viscosity that is 10 times greater than that of KCl. One cannot help but speculate that when the salts are in a co-saturated state the dominating chloride compound will be that of sodium as it induces a greater change in viscosity.

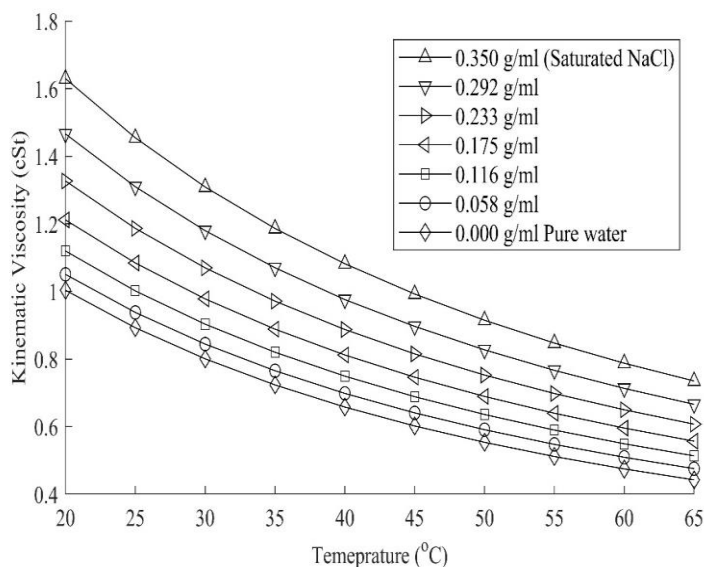


Figure 1: Kinematic viscosity of aqueous NaCl solution vs temperature. Each line represents a different concentration of NaCl. Data collected from (Kestin, Khalifa, and Correia, 1981a).

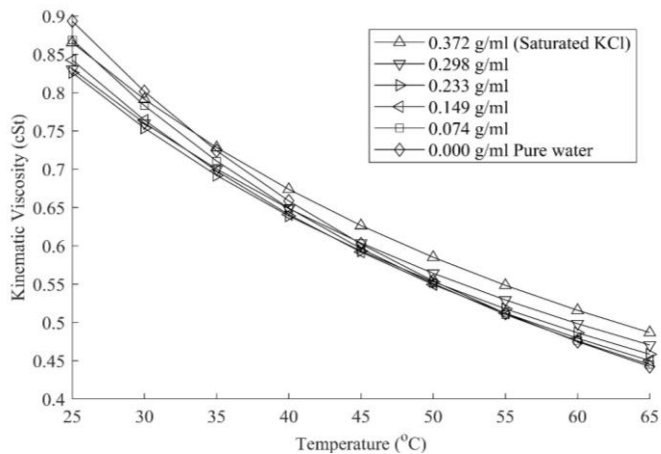


Figure 2: Kinematic viscosity of aqueous KCl solution vs temperature. Each curve represents a different concentration of KCl. Data was collected from Kestin, Khalifa, and Correia (1981b).

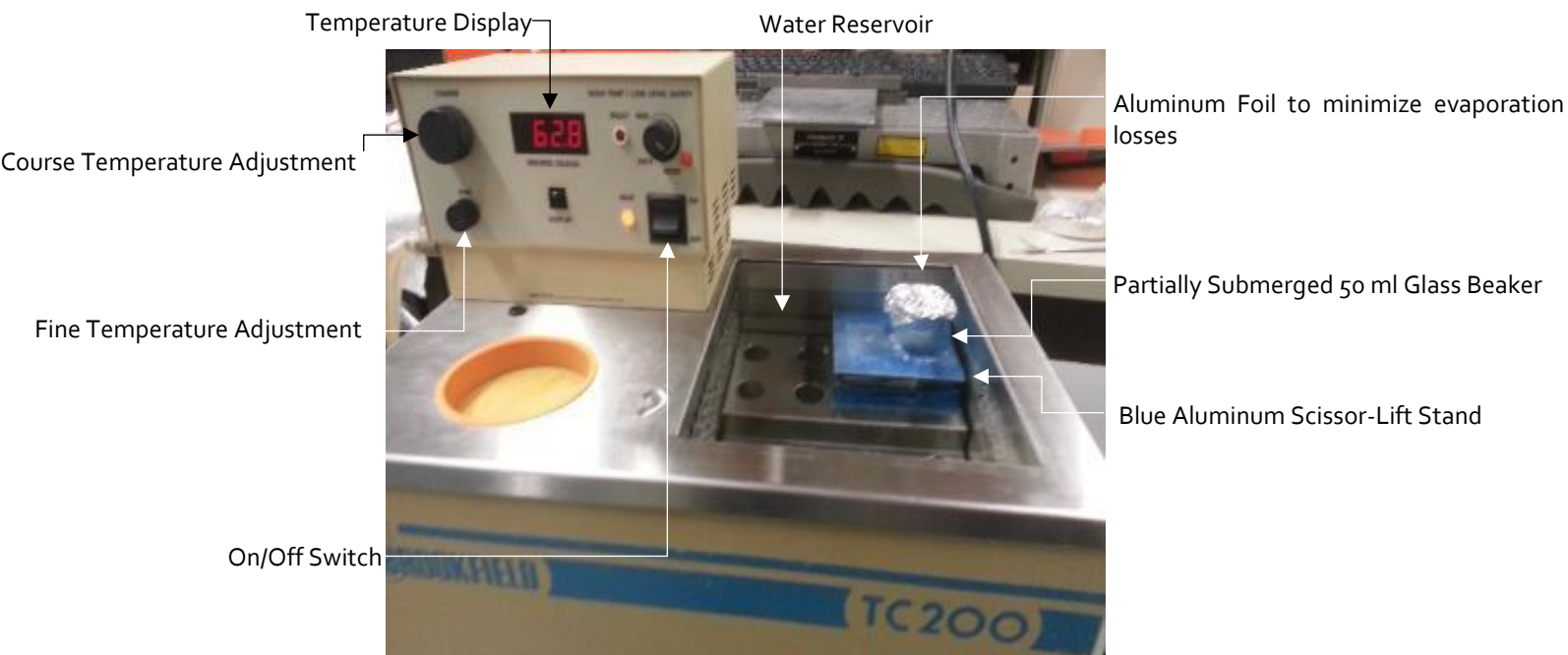


Figure 3: Temperature bath used to heat beaker samples of co-saturated salt solutions.

Procedure

To measure the kinematic viscosity of co-saturated NaCl and KCl solutions directly over the temperature range of 20-65 °C, a Koehler KV3000 kinematic viscosity instrument was used. Note that readings were taken in order of decreasing temperature starting at 65°C. Three solutions were prepared containing both KCl and NaCl in NaCl:KCl ratios of 1:1, 1.5:1 and 2:1. The experimental results, whose estimated uncertainty is $\pm 1\%$, were collected and the kinematic viscosity was plotted against both temperature and concentration ratio. The experiment was performed at room temperature under atmospheric pressure (101.3 KPa).

To ensure that both NaCl and KCl would dissolve relatively uniformly in water, care was taken to pre-mix the salts in solid form before they were poured into a water-filled test beaker. Once the necessary amounts of NaCl and KCl were measured and mixed in the proper proportions they were then poured slowly into a 50ml glass beaker containing 30ml of distilled water at 65 °C until saturation occurred. To keep the beaker at a constant temperature a Brookfield TC200 circulating temperature bath was used (see Figure 3). An aluminum scissor-lift stand helped to keep the beaker rim just above the reservoir water level. To prevent evaporative water loss during heating an aluminum foil cover was placed on the top of the beaker. Once fully saturated and heated, an automatic pipette was used to suction the right amount of fluid into an opaque Cannon-Fenske reverse-flow viscometer tube (see Figure 4). The Cannon-Fenske tube was inverted so as to draw the beaker fluid up to the fill line. The tube was then placed inside the temperature-controlled oil vat of a Koehler KV3000 instrument (see Figure 5).

To obtain a reading from the Koehler instrument, LCD display timers would be used to measure the time taken for the co-saturated solution to travel from the lower bulb start line to the lower bulb finish line (see Figure 4). Using the calibration constants found in Table 2 and performing a linear regression one is able to obtain the constants for each measured temperature value within our targeted temperature range of 20-65°C. The elapsed time measured using the display timers would then be multiplied by an appropriate calibration constant to obtain the kinematic viscosity of the solution in terms of centistokes (cSt). Note that each temperature has a unique calibration constant obtained from the manufacturer.

Results

Figure 6 shows the resultant kinematic viscosity of the saturated NaCl:KCl solutions at different ratios against temperature. The raw viscosity data can be found in Appendix A. One can see that it has similarly with the NaCl curves presented in Figure 1. Please note that in the interest of

saving time during the experiment some intermediate data points in Figure 6 were not measured and do not appear in the figure. This curve resemblance between Figure 1 and Figure 6 makes sense as the effect of KCl on the viscosity of water is quite low. Therefore, the expected effect KCl has on a co-saturated sample should also be low, which appears to be the case in this study.

To fully appreciate the relationship between kinematic viscosity, temperature and the ratio of NaCl:KCl it was necessary to plot viscosity against concentration ratio in Figure 7. One can see that there is a clear trend between the different temperature curves. Note that the curve-fits for 20°C, 35°C and 40°C are omitted due to the lack of enough data points. However it is believed they follow a similar trend to the rest. The curve starts in a purely KCl saturated state and as expected the viscosity approaches a maximum value in the form of a horizontal asymptote. This viscosity limit in the graph occurs because of complete NaCl saturation of the solution.

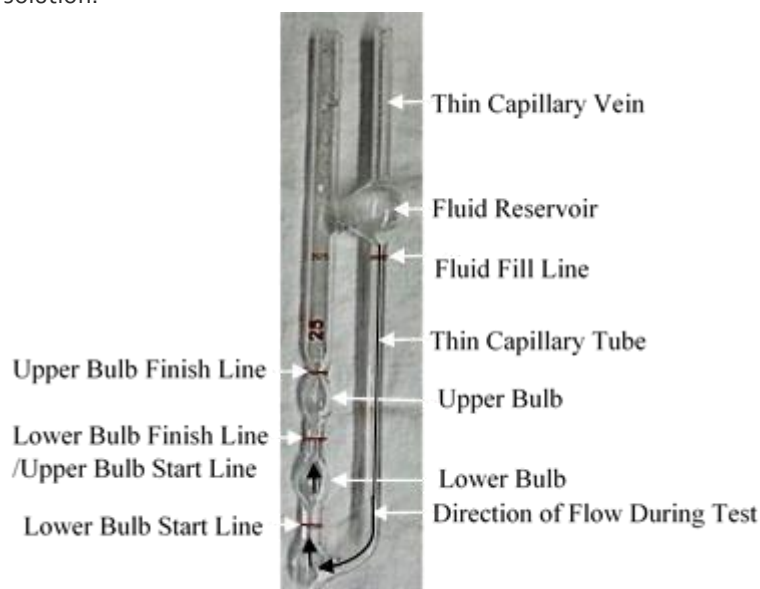


Figure 4: Diagram of Cannon-Fenske reverse-flow viscometer tube. Note the fluid begins in the fluid reservoir where it is pulled down by gravity and up the left glass column.

Table 2: Cannon-Fenske Opaque Viscometer Tube Calibration Constants						
Size #	Tube ID #	Constant @ 40°C Upper Bulb	Constant @ 40°C Lower Bulb	Constant @ 100°C Upper Bulb	Constant @ 100°C Lower Bulb	Range of Viscosities (cSt)
		(cSt/s)				
25	205	0.001419	0.001975	0.001430	0.001986	0.5 to 2

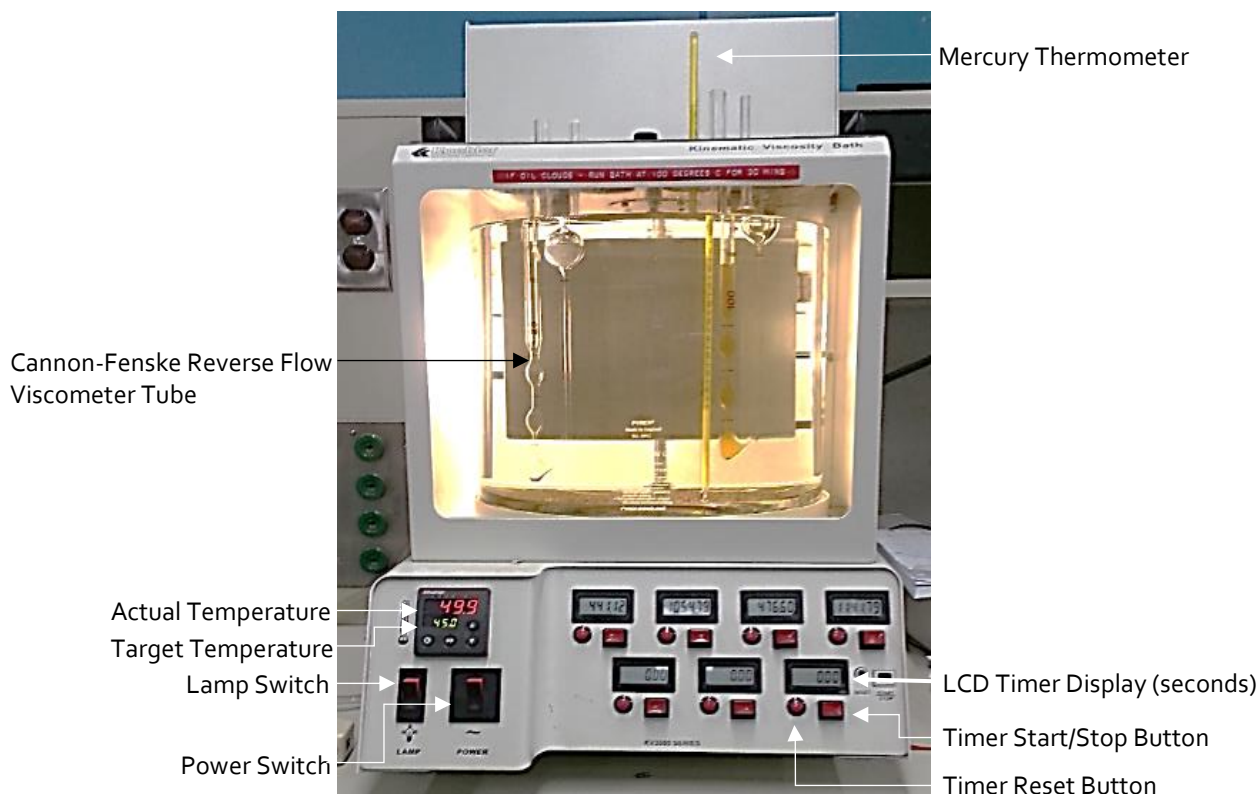


Figure 5: Koehler KV3000 kinematic viscosity instrument

Sources of Error

Although efforts were made to ensure KCl and NaCl would dissolve uniformly into the distilled water by pre-mixing them in solid form, it cannot be certain that they both dissolved at the same rate. If the salts did not dissolve at the same rates as previously assumed, then the ratio of NaCl to KCl in the solution would be skewed and could cause us to see a deviation in the viscosity measurements reported. Another point of concern in the experiment was precipitation of salt particulates in the viscometer tube. Although temperature was kept constant during testing precipitation resulted from

65-25 oC which decreases the solubility of the sample. Any excess solute at high temperatures would then precipitate out of the solvent as temperature is lowered. Due to the small diameter of the capillary vein, the presence of small floating salt particulates would change the behaviour of our ideal aqueous solution to a partial slurry-like fluid. Even though the co-saturated solution was changed half way through the temperature range to minimize precipitation it is believed that suspended salt particles may have had a mild effect on our reported data; the extent of how much is not known.

Conclusions

The effect that co-saturation has on the kinematic viscosity of water is an important characteristic to understand. It is necessary to properly model the brines that are pumped from underground ore bodies in the process of solution mining. From existing literature, it is known that NaCl changes the viscosity of water by a factor of about 10 times more than KCl. Due to the minimal effect that KCl has on viscosity it is observed that the concentration ratio curves of NaCl:KCl look strikingly similar to the original NaCl curves found in literature. This similarity shows that in a solution where both NaCl and KCl are in a co-saturated state it is NaCl that contributes most to determining the viscosity of a salt brine.

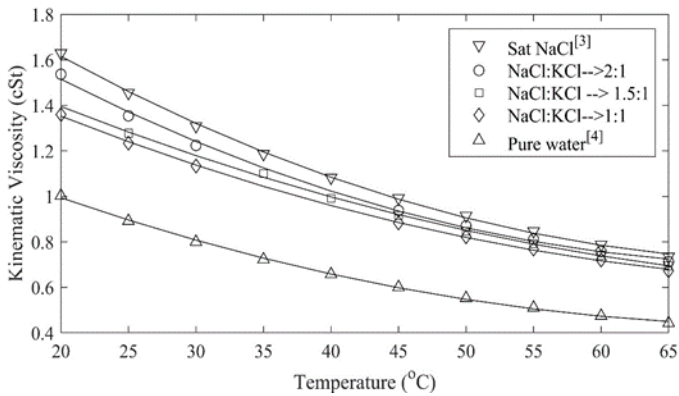


Figure 6: Viscosity of co-saturated aqueous NaCl and KCl solution vs temperature. Saturated NaCl and pure water values obtained from (Kestin, Khalifa, and Correia, 1981a).

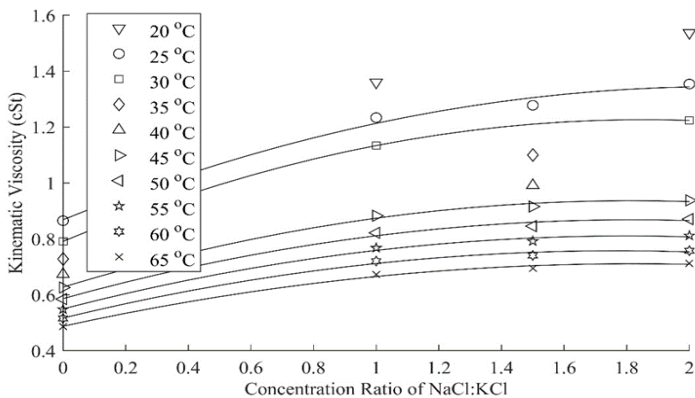


Figure 7: Kinematic viscosity of co-saturated solution of NaCl:KCl vs concentration ratio. Zero point data collected from (Kestin, Khalifa, and Correia, 1981b).

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Appendix – Raw Viscosity data

A summary of the collected viscosity data is shown below in Table 3.

Table 3: Co-saturated NaCl:KCl Kinematic Viscosity Data			
Temperature (°C)	Concentration Ratio NaCl:KCl		
	1:1	1.5:1	2:1
	Kinematic Viscosity (cSt)		
20	1.360	-	1.537
25	1.234	1.278	1.354
30	1.134	-	1.224
35	-	1.100	-
40	-	0.992	-
45	0.883	0.916	0.938
50	0.822	0.846	0.871
55	0.768	0.792	0.812
60	0.721	0.741	0.758
65	0.673	0.695	0.713

