THERMAL CONDUCTIVITY OF AQUEOUS NaCl SOLUTIONS
FROM 20°C TO 330°C

By

Huseyin Ozbek and
Sidney L. Phillips

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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Supported by the U.S. Department of Energy, Office of Basic Energy Science,
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Abstract

An evaluation of published data on the thermal conductivity of aqueous NaCl solutions is presented. The literature was screened from 1929 through 1979, and the evaluated data were tabulated. The data were converted where necessary to a set of internally consistent units of °C, watts/m-°C and molal concentrations. An empirical correlation equation with an average deviation of $\pm 2\%$ is given for the thermal conductivity of aqueous NaCl solutions from 20°C to 330°C at saturation pressures. A table of smoothed values generated using this correlation equation is provided for NaCl concentrations between 0 and 5 molal over this temperature range.

A. Introduction

Thermal conductivity data on aqueous electrolyte solutions are required in the development and utilization of geothermal energy, petroleum recovery, desalination of sea water, and other energy systems involving water containing dissolved salts. Both sea water and geothermal brines contain a large variety of dissolved electrolytes with NaCl the main salt constituent. Consequently, modeling and other studies which require the thermal conductivity of naturally occurring aqueous solutions, such as geothermal fluids, are often based on NaCl solutions (Ref. 1, 2).

This report covers a critical evaluation of the available literature on the thermal conductivity of aqueous NaCl solutions for regions of geothermal interest: temperatures to 350°C, pressures to 500 bars (50 MPa), and concentrations up to saturation. The literature screened in compiling the numerical values covers the time period from 1929 to 1979; earlier data are contained in the International Critical Tables (Ref. 3). The results of this literature survey showed that published numerical data are at atmospheric or vapor saturation pressure, with the highest temperature being 150°C. By far, the most extensive data are contained in graphical form in the report by Yusufova, et al., with over 50 data points between 100°C and 330°C (Ref. 4).

Units

1 MPa = 10 bars = 145.04 psi

1 watts/m-°C = 0.578175 Btu/hr-ft-°F = 0.860422 Kcal/hr-m-°C

Density data needed to convert molar to molal concentrations are obtained from the report "Density of NaCl Solutions to 800°C, 200 MPa and Saturation Concentrations" (Ref. 5). Data on the thermal conductivity of water and the corresponding correlation equation are contained in the reports from International Conference on the Properties of Steam (Ref. 6, 7). For a detailed discussion on thermal conductivity and methods for measuring this property, the reader is referred to Touloukian, et al., (Ref. 8).

B. Analytical Expressions and Correlations

This section covers selected analytical expressions and empirical correlations which have been used to describe the variation in thermal conductivity for NaCl solutions as a function of concentration and temperature.

Based on theoretical considerations, Predvoditelev (Ref. 9) developed the following equation for predicting the thermal conductivity of aqueous solutions:

$$\frac{\lambda}{\lambda_w} = \frac{C_p}{C_{pw}} \left(\frac{\rho}{\rho_w} \right)^{4/3} \left(\frac{M_w}{M} \right)^{1/3} \quad (1)$$

where

λ : thermal conductivity of aqueous solution

λ_w : thermal conductivity of water

C_p : heat capacity of aqueous solution

C_{pw} : heat capacity of water

ρ : density of aqueous solution

ρ_w : density of water

M : molecular weight for aqueous solution, determined by additivity rule

M_w : molecular weight of water

Vargaftik and Os'minin (Ref.10) measured the thermal conductivity of various aqueous solutions including aqueous NaCl solutions at 30°C and found that the deviation between the measured and the predicted values by Equation 1 were no more than 5%. The only exception was aqueous HNO₃ solutions, deviation for which showed an increase as the acid concentration increased, reaching a maximum deviation of 12%.

Riedel (Ref. 11) developed an equation which has been widely used to describe the variation in thermal conductivity with temperature and concentration of salt solutions such as NaCl:

$$\lambda = \lambda_w + \sum_i a_i C_i \quad (2)$$

a_i = experimentally determined coefficient characteristic for each ion, (-0.0047 for Cl⁻, referred to Na⁺ as 0)

C_i = concentration of each electrolyte

Korosi and Fabuss (Ref. 12) measured the thermal conductivity for 0.7069m NaCl and 3.5345m NaCl, over the temperature range 25°C-150°C. The authors obtained 12 data points and developed the following polynomial fits for these two concentrations:

$$\begin{aligned} 0.7069\text{m NaCl: } \lambda &= 0.540 + 0.001567T - 0.00001397T^2 \\ 3.5345\text{m NaCl: } \lambda &= 0.553 + 0.000821T - 0.00000986T^2 \end{aligned} \quad (3)$$

where

λ : thermal conductivity, watts/m-°C

T: temperature, °C

The six values for each concentration were reproduced with better than 1% deviation by Equation (3).

Yusufova, et al., (Ref. 4) measured the thermal conductivity of aqueous sodium chloride solutions for temperatures ranging from 20°C to 330°C and concentrations of 5, 10, 15, 20 and 25 weight percent NaCl and developed the following correlation equation which reproduces their experimental data for over 50 values with a deviation of 2%:

$$\frac{\lambda}{\lambda_w} = 1.0 - (2.3434 \times 10^{-3} - 7.924 \times 10^{-6} T + 3.924 \times 10^{-8} T^2) S + (1.06 \times 10^{-5} - 2 \times 10^{-8} T + 1.2 \times 10^{-10} T^2) S^2 \quad (4)$$

where

$$S = \frac{5844.3 \times m}{1000 + 58.443 \times m}$$

λ : thermal conductivity of aqueous NaCl solution

λ_w : thermal conductivity of water

m : concentration, molality

T : temperature, °C

Numerical data are not available for measurements by Yusufova, et al., and accurate values cannot be obtained from the figures in the publication. For this reason, data by Yusufova, et al., could not be included in Table 1.

Unterberg developed a family of curves which depict the change in thermal conductivity of NaCl solution with temperatures to 149°C for zero to saturation concentrations (Ref. 13). Unterberg assumed that the

variation of thermal conductivity with temperature followed the same trend for different concentrations as for pure water.

In summary, correlations are available which reproduce data on the thermal conductivity of NaCl solution in the temperature and concentration regions of interest for the utilization of geothermal energy. However, most of the numerical values are not available, and accurate values cannot be obtained from published graphs.

C. Methods for Measuring Thermal Conductivity

The methods commonly used for measurements of thermal conductivity of aqueous solutions include the following: coaxial cylinders, flat plate, and continuous line source. The first two are steady state methods; the third is a transient method.

Chernen'kaya and Vernigora measured the thermal conductivity of NaCl and other solutions at 25°C and 50°C using a cell comprised of two coaxial thin-walled glass cylinders (Ref. 14). The NaCl solution was placed between the cylinders, and the inner cell was thermostated to 25°C or 50°C for 30 minutes. The difference in temperature across the NaCl solution was measured by a differential thermocouple. The instrument was calibrated with doubly distilled gas-free water, methyl alcohol and benzene. Tufeu, et al., (Ref. 15) also used coaxial cylinder method in their measurements.

Yusufova, et al., used a flat plate method for measuring the thermal conductivity of NaCl from 25°C to 330°C (Ref. 3). The solution was placed between an upper and a lower circular metal plate; the upper plate was maintained at a high temperature to provide downward heat flow to prevent natural convection. A guard heater was located on the periphery both to assure linear heat flow, and to minimize convection. The main difficulties with this method center on maintaining linear heat flow and eliminating convection around the edges of the heated plates.

The non-steady state method such as the continuous line source method has been widely used. In this case, heat is generated at a constant rate

in a long, thin wire which is inserted in a large volume of test liquid. The system is initially at a constant temperature; heat is then applied, and the thermal conductivity of NaCl is determined from the measurements of temperature vs. time at a fixed distance from the wire. Vargaftik and Os'minin (Ref.10), Chiquillo (Ref. 16) and Korosi and Fabuss (Ref. 12) used this method in their thermal conductivity measurements.

D. Evaluation and Correlation

The literature scanned for this work covered the time span from 1929 to 1979. The data were converted where necessary to the ^{12}C scale of atomic weights, to units of g/cm^3 for density, to $\text{watts/m-}^\circ\text{C}$ for thermal conductivity, from molar to molal concentrations, and from relative values of thermal conductivity to absolute values for NaCl solutions. The required data and interpolating equation for the thermal conductivity of water were taken from the report on the results of the Sixth International Conference on the Properties of Steam (Ref. 6).

The correlation given by Yusufova, et al., (Ref. 4) is the only data available which represents a large number of data points in the temperature and pressure range of geothermal interest. As seen, Equation (5) is the ratio of the thermal conductivity of NaCl solutions to that of pure water. Yusufova used the following equation for liquid water which was contained in the 1968 IFC Formulation, Sixth International Conference on the Properties of Steam (Ref. 6).

$$\lambda_w = -0.92247 + 2.8395 \left(\frac{T + 273.15}{273.15} \right) - 1.8007 \left(\frac{T + 273.15}{273.15} \right)^2 + 0.52577 \left(\frac{T + 273.15}{273.15} \right)^3 - 0.07344 \left(\frac{T + 273.15}{273.15} \right)^4 \quad (5)$$

where

T : temperature, $^\circ\text{C}$

λ_w : thermal conductivity of water, $\text{watts/m-}^\circ\text{C}$

Equation (5) is valid for temperatures ranging from 0°C to 350°C at saturation pressures.

Equations (4) and (5) were used in this work to reproduce and interpolate data on the thermal conductivity of NaCl solutions. Figure 1 shows the variation in thermal conductivity for concentrations from 0 to 5m NaCl and temperatures between 50°C and 300°C. As shown, thermal conductivity decreases almost linearly at each temperature as the concentration increases. Figure 2 is a plot of thermal conductivity versus temperature with concentration as a parameter. Thermal conductivity increases with increasing temperatures up to a broad maximum near 140°C, then decreases as the temperature increases further to 300°C. The thermal conductivity decreases with concentration, by a maximum of 7% for 5m NaCl as compared with pure water. Table 3 contains smoothed values of the thermal conductivity of aqueous NaCl solutions from 20°C to 330°C over the concentration range 0 to 5 molal. Table 2 shows the comparison of the available experimental data with that calculated from Equation (4) and (5). The correlation equation developed by Yusufova, et al., (Ref. 4) reproduces the data by Vargaftik, et al., (Ref. 10), Chernen'kaya, et al., (Ref. 14), Chiquillo (Ref. 16), Riedel (Ref. 11), and Kapustinski (Ref. 17) with smaller deviations than the average deviation (2%) of Equation (4) and (5), with one exception, i.e., the thermal conductivity at 30°C and 3.43m measured by Chiquillo (Ref. 16) deviates 2.8% from that predicted by Equation (4) and (5). The data reported by Korosi and Fabuss (Ref. 12), however, have increasing deviation as temperature increases, reaching 32% at 150°C and 3.53m.

E. Summary and Conclusions

Few experimental data points have been published on the thermal conductivity of NaCl solutions; from 100°C to 150°C there are only the six measurements reported by Korosi and Fabuss (Ref. 12). Data to 330°C reported by Yusufova, et al., (Ref. 4) are not tabulated, but must be calculated from the published correlation. No data are available on the effects of elevated pressures on the thermal conductivity of NaCl solutions. The equation developed by Yusufova, et al., (Ref. 4) was selected for interpolation and used to establish a table of smoothed values for the range 20°C to 330°C and 0 to 5 molal concentration. The available experimental values were compared with these calculated values and the results are shown in Table 2. At a given temperature, thermal conductivity of aqueous NaCl solutions is less than that of pure water, and the maximum difference is about 7% for 5m NaCl concentrations. As the temperature increases, the thermal conductivity initially increases to a broad maximum at about 140°C, then decreases by more than 0.2 watts/m-°C as the temperature is further increased to 330°C.

F. Recommendations

Additional experimental data should be obtained above 50°C to augment those of Korosi and Fabuss (Ref. 12) and Yusufova, et al., (Ref. 4), and to assist in reconciling the difference in their reported values. Dependence of thermal conductivity on pressure should be investigated.

G. Acknowledgment

Thanks are given to Y.S. Touloukian, CINDAS, Purdue University, West Lafayette, IN; R.C. Feber, Los Alamos Scientific Laboratory, Los Alamos, NM; Oleh Weres, Lawrence Berkeley Laboratory, Berkeley, CA; and Ken Trompeter, Bureau of Reclamation, Boulder City, NV for their review.

Table 1. Experimental data for thermal conductivity of aqueous NaCl solutions.

Temperature °C	Concentration molal	Thermal Conductivity watts/m-°C	Reference
20	0.901	0.594	Riedel (Ref. 11)
20	1.901	0.589	Riedel (Ref. 11)
20	2.700	0.590	Tufeu, et al. (Ref. 15)
20	3.020	0.583	Riedel (Ref. 11)
20	4.278	0.578	Riedel (Ref. 11)
20	4.180	0.583	Tufeu, et al. (Ref. 15)
20	5.704	0.573	Riedel (Ref. 11)
20	5.770	0.574	Tufeu, et al. (Ref. 15)
25	0.707	0.574	Korosi and Fabuss (Ref. 12)
25	0.741	0.605	Kapustinski and Ruzavin (Ref. 17)
25	0.872	0.606	Kapustinski and Ruzavin (Ref. 17)
25	0.901	0.605	Kapustinski and Ruzavin (Ref. 17)
25	1.573	0.600	Kapustinski and Ruzavin (Ref. 17)
25	1.802	0.600	Kapustinski and Ruzavin (Ref. 17)
25	1.849	0.600	Kapustinski and Ruzavin (Ref. 17)
25	1.944	0.599	Chernen'kaya and Vernigora (Ref. 14)
25	2.534	0.595	Kapustinski and Ruzavin (Ref. 17)
25	2.716	0.595	Kapustinski and Ruzavin (Ref. 17)
25	2.878	0.596	Kapustinski and Ruzavin (Ref. 17)
25	3.535	0.567	Korosi and Fabuss (Ref. 12)
25	3.655	0.589	Kapustinski and Ruzavin (Ref. 17)
25	3.781	0.591	Kapustinski and Ruzavin (Ref. 17)
25	4.494	0.583	Chernen'kaya and Vernigora (Ref. 14)
25	4.521	0.587	Kapustinski and Ruzavin (Ref. 17)
25	4.883	0.587	Kapustinski and Ruzavin (Ref. 17)
25	5.523	0.582	Kapustinski and Ruzavin (Ref. 17)
20-40	1.061	0.608	Chiquillo (Ref. 16)
30	1.901	0.603	Vargaftik and Os'minin (Ref. 10)
20-40	1.936	0.604	Chiquillo (Ref. 16)
20-40	2.857	0.592	Chiquillo (Ref. 16)
20-40	3.434	0.581	Chiquillo (Ref. 16)
30	4.278	0.589	Vargaftik and Os'minin (Ref. 10)
40	2.730	0.615	Tufeu, et al. (Ref. 15)
40	4.220	0.605	Tufeu, et al. (Ref. 15)
40	5.820	0.594	Tufeu, et al. (Ref. 15)
50	0.707	0.577	Korosi and Fabuss (Ref. 12)
50	1.944	0.635	Chernen'kaya and Vernigora (Ref. 14)
50	3.535	0.571	Korosi and Fabuss (Ref. 12)
50	4.494	0.617	Chernen'kaya and Vernigora (Ref. 14)
60	2.760	0.634	Tufeu, et al. (Ref. 15)
60	4.270	0.623	Tufeu, et al. (Ref. 15)
60	5.890	0.611	Tufeu, et al. (Ref. 15)
75	0.707	0.581	Korosi and Fabuss (Ref. 12)
75	3.535	0.557	Korosi and Fabuss (Ref. 12)
80	2.790	0.647	Tufeu, et al. (Ref. 15)
80	4.320	0.635	Tufeu, et al. (Ref. 15)
80	5.960	0.622	Tufeu, et al. (Ref. 15)
100	0.707	0.560	Korosi and Fabuss (Ref. 12)
100	3.535	0.539	Korosi and Fabuss (Ref. 12)
125	0.707	0.518	Korosi and Fabuss (Ref. 12)
125	3.535	0.500	Korosi and Fabuss (Ref. 12)
150	0.707	0.460	Korosi and Fabuss (Ref. 12)
150	3.535	0.455	Korosi and Fabuss (Ref. 12)

Table 2. Comparison of experimental data with those calculated from Equation (4) and (5).

Temperature, Deg. Celsius (°C)	Concentration, Molality (m)	Thermal Conductivity Calculated From Equation (4) and (5), watts/m-°C (λ)	Reference	Measured Thermal Conductivity watts/m-°C (λ_m)	% Deviation $\frac{\lambda - \lambda_m}{\lambda} \times 100$
30	1.901	0.606	Vargaftik and Os'minin (Ref. 10)	0.603	0.5
30	4.278	0.594	Vargaftik and Os'minin (Ref. 10)	0.589	0.8
25	1.944	0.598	Chernen'kaya and Vernigora (Ref. 14)	0.599	-0.2
25	4.494	0.586	Chernen'kaya and Vernigora (Ref. 14)	0.583	0.5
50	1.944	0.631	Chernen'kaya and Vernigora (Ref. 14)	0.635	-0.6
50	4.494	0.619	Chernen'kaya and Vernigora (Ref. 14)	0.617	0.3
30	1.061	0.611	Chiquillo (Ref. 16)	0.608	0.5
30	1.944	0.605	Chiquillo (Ref. 16)	0.604	0.2
30	2.857	0.601	Chiquillo (Ref. 16)	0.592	1.5
30	3.434	0.598	Chiquillo (Ref. 16)	0.581	2.8
20	0.901	0.597	Riedel (Ref. 11)	0.594	0.5
20	1.901	0.591	Riedel (Ref. 11)	0.589	0.3
20	3.020	0.585	Riedel (Ref. 11)	0.583	0.3
20	4.278	0.579	Riedel (Ref. 11)	0.578	0.2
20	5.704	0.574	Riedel (Ref. 11)	0.573	0.2
25	0.741	0.606	Kapustinski and Ruzavin (Ref. 17)	0.605	0.2
25	0.872	0.605	Kapustinski and Ruzavin (Ref. 17)	0.606	-0.2
25	0.901	0.605	Kapustinski and Ruzavin (Ref. 17)	0.605	0.0
25	1.573	0.600	Kapustinski and Ruzavin (Ref. 17)	0.600	0.0
25	1.802	0.599	Kapustinski and Ruzavin (Ref. 17)	0.600	-0.2
25	1.849	0.599	Kapustinski and Ruzavin (Ref. 17)	0.600	-0.2
25	2.534	0.595	Kapustinski and Ruzavin (Ref. 17)	0.595	0.0
25	2.716	0.594	Kapustinski and Ruzavin (Ref. 17)	0.595	-0.2
25	2.878	0.593	Kapustinski and Ruzavin (Ref. 17)	0.596	-0.5
25	3.655	0.590	Kapustinski and Ruzavin (Ref. 17)	0.589	0.2
25	3.781	0.589	Kapustinski and Ruzavin (Ref. 17)	0.591	-0.3
25	4.521	0.586	Kapustinski and Ruzavin (Ref. 17)	0.587	-0.2
25	4.883	0.585	Kapustinski and Ruzavin (Ref. 17)	0.587	-0.3
25	5.523	0.582	Kapustinski and Ruzavin (Ref. 17)	0.582	0.0
20	2.700	0.590	Tufeu, et al. (Ref. 15)	0.586	0.7
20	4.180	0.583	Tufeu, et al. (Ref. 15)	0.580	0.5
20	5.770	0.574	Tufeu, et al. (Ref. 15)	0.574	0.0
40	2.730	0.615	Tufeu, et al. (Ref. 15)	0.615	0.0
40	4.220	0.605	Tufeu, et al. (Ref. 15)	0.608	-0.5
40	5.820	0.594	Tufeu, et al. (Ref. 15)	0.602	-1.3
60	2.760	0.634	Tufeu, et al. (Ref. 15)	0.637	-0.5
60	4.270	0.623	Tufeu, et al. (Ref. 15)	0.630	-1.1
60	5.890	0.611	Tufeu, et al. (Ref. 15)	0.624	-2.1
80	2.790	0.647	Tufeu, et al. (Ref. 15)	0.653	-0.9
80	4.320	0.635	Tufeu, et al. (Ref. 15)	0.646	-1.7
80	5.960	0.622	Tufeu, et al. (Ref. 15)	0.640	-2.9

Table 2. Comparison of experimental data with those calculated from Equation (4) and (5). (continued)

Temperature, Deg. Celsius (°C)	Concentration, Molality (m)	Thermal Conductivity Calculated From Equation (4) and (5), watts/m-°C (λ)	Reference	Measured Thermal Conductivity watts/m-°C (λ_m)	% Deviation $\frac{\lambda - \lambda_m}{\lambda} \times 100$
25	0.707	0.606	Korosi and Fabuss (Ref. 12)	0.574	5.3
25	3.535	0.590	Korosi and Fabuss (Ref. 12)	0.567	3.9
50	0.707	0.638	Korosi and Fabuss (Ref. 12)	0.577	9.6
50	3.535	0.623	Korosi and Fabuss (Ref. 12)	0.571	8.3
75	0.707	0.661	Korosi and Fabuss (Ref. 12)	0.581	12.1
75	3.535	0.646	Korosi and Fabuss (Ref. 12)	0.557	13.8
100	0.707	0.676	Korosi and Fabuss (Ref. 12)	0.560	17.2
100	3.535	0.660	Korosi and Fabuss (Ref. 12)	0.539	18.3
125	0.707	0.682	Korosi and Fabuss (Ref. 12)	0.518	24.0
125	3.535	0.666	Korosi and Fabuss (Ref. 12)	0.500	24.9
150	0.707	0.681	Korosi and Fabuss (Ref. 12)	0.460	32.5
150	3.535	0.665	Korosi and Fabuss (Ref. 12)	0.455	31.6

Figure 1. Thermal conductivity of aqueous NaCl solutions as a function of NaCl concentration.

Figure 2. Thermal conductivity of aqueous NaCl solutions as a function of temperature.

Table 3. Recommended values for the thermal conductivity of aqueous NaCl solutions, calculated from Equation (4) and (5), watts/m-°C (λ).

Temperature, Deg. Celsius (°C)	Concentration, Molality (m)	0	1	2	3	4	5
20		0.603	0.596	0.590	0.585	0.580	0.577
30		0.618	0.611	0.605	0.600	0.595	0.592
40		0.632	0.624	0.618	0.613	0.609	0.605
50		0.643	0.636	0.630	0.625	0.621	0.617
60		0.653	0.646	0.640	0.635	0.631	0.627
70		0.662	0.655	0.649	0.644	0.640	0.636
80		0.670	0.663	0.657	0.652	0.647	0.643
90		0.676	0.669	0.663	0.658	0.653	0.649
100		0.681	0.674	0.668	0.662	0.658	0.654
110		0.684	0.677	0.671	0.666	0.661	0.658
120		0.687	0.679	0.673	0.668	0.664	0.660
130		0.688	0.680	0.674	0.669	0.664	0.661
140		0.688	0.680	0.674	0.669	0.664	0.660
150		0.687	0.679	0.673	0.667	0.663	0.659
160		0.684	0.677	0.670	0.665	0.660	0.656
170		0.681	0.673	0.667	0.661	0.656	0.652
180		0.677	0.669	0.662	0.656	0.651	0.647
190		0.671	0.663	0.656	0.650	0.645	0.641
200		0.665	0.656	0.649	0.643	0.638	0.633
210		0.657	0.648	0.641	0.635	0.630	0.625
220		0.648	0.640	0.632	0.626	0.620	0.616
230		0.639	0.630	0.622	0.616	0.610	0.605
240		0.628	0.619	0.611	0.604	0.599	0.594
250		0.616	0.607	0.599	0.592	0.586	0.581
260		0.603	0.594	0.586	0.579	0.573	0.567
270		0.589	0.580	0.571	0.564	0.558	0.553
280		0.574	0.565	0.556	0.549	0.543	0.537
290		0.558	0.548	0.540	0.532	0.526	0.520
300		0.541	0.531	0.522	0.515	0.508	0.503
310		0.523	0.512	0.504	0.496	0.489	0.484
320		0.503	0.493	0.484	0.476	0.470	0.464
330		0.482	0.472	0.463	0.455	0.449	0.443

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