The International Association for the Properties of Water and Steam

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Guideline on the Thermal Conductivity of Seawater

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Summary

The seawater thermal conductivity formulation provided in this Guideline is based on a revised general model for the thermal conductivity of aqueous solutions of electrolytes as a function of temperature, pressure, and ionic concentration [1] and on the 2011 IAPWS formulation for the thermal conductivity of pure water [2]. A simplified version of this model, which replaces individual ion concentrations with salinity, is used here. Details can be found in the article by Wang and Anderko [1]. This equation is designed for the computation of the thermal conductivity of seawater for salinities ranging from 0 to 0.17 $kg \cdot kg^{-1}$, pressures up to 140 MPa, and temperatures from 273.15 K to 523.15 K.

This Guideline contains 6 pages, including this cover page.

Further information about this Guideline and other documents issued by IAPWS can be obtained from the Executive Secretary of IAPWS (Dr. R.B. Dooley, bdooley@structint.com) or from http://www.iapws.org.

Contents

1 Nomenclature

Symbol	Physical quantity	Unit
P	Pressure	MPa
S	Reference-Composition Salinity[1]	$\mathrm{kg\cdot kg^{-1}}$
T	Absolute temperature (ITS-90 [5])	K
λ	Thermal conductivity	$\mathrm{W\cdot m^{-1}\cdot K^{-1}}$
λ_w	Thermal conductivity of pure water	$\mathrm{W\cdot m^{-1}\cdot K^{-1}}$

[1] For seawater of Reference Composition [3], the Salinity S used in this work is related to the commonly measured Practical Salinity [4] S_P by $S = (0.035\,165\,04/35)\,S_\mathrm{P}$

2 Introductory Remarks

The "Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater" [6] provides a recommended formulation for predicting the thermodynamic properties of seawater. It describes the specific Gibbs energy of seawater relative to that of pure water in the liquid state [7]. This Guideline is intended to provide a method for calculating the thermal conductivity of seawater to supplement the thermodynamic formulation that is already available. The method presented here describes the thermal conductivity of seawater relative to that of pure liquid water as calculated from the 2011 IAPWS formulation [2]. A discussion of the background, development, and validation of this formulation is presented in Ref. [1].

3 Summary of the Formulation

The thermal conductivity λ of seawater is calculated as a function of temperature (T), pressure (P), and salinity (S), relative to that of the solvent (i.e., pure water) at the same temperature and pressure (thermal conductivity of pure water – λ_{w}). The increment due to the presence of salts in seawater is given by:

$$(\lambda - \lambda_{\mathrm{w}}) / \lambda_0 = a \cdot (1000S)^{1+b} \qquad (1)$$

where λ_0 = 1 W·m^{-1}·K^{-1} and a and b are parameters with the following temperature and pressure dependence:

$$a = a_1 \exp\left[a_2 \left((T - T_0) / 1\,\mathrm{K} \right) \right] \qquad (2)$$

$$b = b_1 \exp\left[b_2 \left((T - T_0) / 1\,\mathrm{K} \right) \right] \qquad (3)$$

where T_0 = 273.15 K and

$$a_n = a_n^{(1)} + a_n^{(2)} (P / 1\,\mathrm{MPa}) \qquad (n = 1, 2) \qquad (4)$$

$$b_n = b_n^{(1)} + b_n^{(2)} (P / 1\,\mathrm{MPa}) \qquad (n = 1, 2) \qquad (5)$$

The values of the parameters in Eqs. (2)-(5) are given in Table 1.

Table 1 Parameters for calculating the thermal conductivity of seawater

	$a_1^{(1)}$	$a_1^{(2)}$	$a_2^{(1)}$	$a_2^{(2)}$
a	$-7.180\,891\times10^{-5}$	$1.831\,971\times10^{-7}$	$1.048\,077\times10^{-3}$	$-4.494\,722\times10^{-6}$
	$b_1^{(1)}$	$b_1^{(2)}$	$b_2^{(1)}$	$b_2^{(2)}$
b	$1.463\,375\times10^{-1}$	$9.208\,586\times10^{-4}$	$-3.086\,908\times10^{-3}$	$1.798\,489\times10^{-5}$

4 Range of Validity and Estimates of Uncertainty

With the parameters listed in Table 1 and the 2011 IAPWS formulation for pure water [2], the model for the thermal conductivity of seawater is valid for the following conditions, provided that the seawater is in the liquid phase:

$$273.15\ \mathrm{K} \le T \le 523.15\ \mathrm{K}$$
$$P \le 140\ \mathrm{MPa}$$
$$0 \le S \le 0.17\ \mathrm{kg\cdot kg^{-1}}$$

In cases when pure water is in the vapor phase at a given temperature and pressure, the thermal conductivity of metastable liquid water may be used for λ_w. These ranges represent the conditions for which the coefficients listed in Table 1 have been determined to match the results obtained from a comprehensive formulation for electrolyte solutions that include major seawater components [1]. A short extrapolation of the correlation is expected to be reasonable to temperatures below 273.15 K. Precipitation is not considered in this Guideline; at many conditions some components of seawater will precipitate well before the upper salinity limit given above is reached [8].

As discussed in Ref. [1], it is preferable to construct a seawater formulation based on the available data for major seawater components (i.e., binary, ternary and quaternary combinations of NaCl, KCl, $MgCl_2$, $CaCl_2$, Na_2SO_4, K_2SO_4, $MgSO_4$, Na_2CO_3, $NaHCO_3$, K_2CO_3, $KHCO_3$, and NaBr) rather than to rely on the available direct measurements for seawater. This is due to the fact that the available data for major seawater components are more accurate, consistent, and cover a wider range of conditions. The average deviation between the comprehensive model for electrolyte solutions and this simplified model for seawater (Eqs. 1-5) is 0.03 % over the range of conditions described above, and the maximum deviation is 0.2 %.

A detailed comparison of this correlation with experimental data for both seawater and solutions containing the main components of seawater is available in Ref. [1]. The overall standard uncertainty is estimated at 0.44 % based on comparisons with the experimental data that were deemed reliable in Ref. [1].

5 Computer-Program Verification

To assist the user in computer-program verification, Table 2 gives check values at several specified conditions.

Table 2 Numerical check values for calculating the thermal conductivity of seawater

S (kg·kg^{-1})	T (K)	P (MPa)	λ_W (W·m^{-1}·K^{-1})	λ (W·m^{-1}·K^{-1})	$\lambda - \lambda_W$ (W·m^{-1}·K^{-1})
0.035	293.15	0.1	0.598 011 575	0.593 825 535	–0.004 186 040
0.035	293.15	120	0.656 010 299	0.651 692 949	–0.004 317 350
0.035	333.15	0.1	0.650 999 590	0.646 875 533	–0.004 124 057
0.035	333.15	120	0.706 748 952	0.702 484 548	–0.004 264 405
0.100	293.15	0.1	0.598 011 575	0.584 191 754	–0.013 819 821
0.100	373.15	1.0	0.677 721 421	0.664 627 314	–0.013 094 107
0.120	293.15	0.1	0.598 011 575	0.581 006 273	–0.017 005 302
0.120	293.15	120	0.656 010 299	0.635 815 483	–0.020 194 816
0.120	333.15	120	0.706 748 952	0.687 026 483	–0.019 722 469

6 Recommendation for Industrial Use

For industrial calculations where greater computing speed is needed, and/or where thermodynamic properties in the application are being calculated from the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (IAPWS-IF97) [9], it is recommended to use IAPWS-IF97 in the calculation of the pure-water thermal conductivity λ_W, as described in Section 3 of [2]. The additional uncertainty due to the use of IAPWS-IF97 is small and negligible for most purposes, as described in Section 3.3 of [2].

The range of validity of this industrial calculation is the same as that given in Section 4 of this Guideline, except that the upper pressure limit is reduced to 100 MPa (which is the upper pressure limit of validity for IAPWS-IF97).

7 Recommendation for Oceanographic Use

For use in oceanographic calculations where the pure-water part of the thermodynamic properties of seawater as described in [6] are being calculated from the IAPWS Supplementary Release on a Computationally Efficient Thermodynamic Formulation for Liquid Water for Oceanographic Use [10], it is recommended to use the formulation documented in Ref. [10] also to calculate the density from input variables of temperature and pressure when calculating the pure-water thermal conductivity λ_W. Furthermore, it is recommended that, for this use, the critical enhancement $\overline{\lambda}_2$ as documented in Section 2.6 of [2] (which is negligible in the range of validity of [10]) be set to zero. The additional uncertainty due to these simplifications is less than 0.001 % over the entire range of validity described below.

The temperature and pressure range of validity of this oceanographic calculation of the thermal conductivity of seawater is the same as that given in Ref. [10], where the pressure range extends from 100 Pa to 100 MPa with a temperature range that extends from a pressure-dependent lower limit to an upper limit of 313.15 K.

8 References

[1] Wang, P., and Anderko, A., Revised Model for the Thermal Conductivity of Multicomponent Electrolyte Solutions and Seawater. *Int. J. Thermophys.* **36**, 5-24 (2015).

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[7] Wagner, W., and Pruß, A., The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use. *J. Phys. Chem. Ref. Data* **31**, 387-535 (2002); see also IAPWS, *Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use*, available from http://www.iapws.org (2014).

[8] Marion, G.M., Millero, F.J., and Feistel, R., Precipitation of solid phase calcium carbonates and their effect on application of seawater S_A-T-P models. *Ocean Science* **5**, 285-291 (2009).

[9] IAPWS, *Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam*, available from http://www.iapws.org (2007).

[10] IAPWS, *Supplementary Release on a Computationally Efficient Thermodynamic Formulation for Liquid Water for Oceanographic Use*, available from http://www.iapws.org (2009).