The International Association for the Properties of Water and Steam

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Advisory Note No. 6

Relationship between Various IAPWS Documents and the International Thermodynamic Equation of Seawater – 2010 (TEOS-10)

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Summary

The international oceanographic standard TEOS-10 [1] was adopted by UNESCO-IOC for all member states in 2009, and by IUGG in 2011. TEOS-10 makes reference to several IAPWS documents whose roles are described in this Advisory Note.

This Advisory Note contains 5 pages, including this cover page.

Further information about this Advisory Note 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.

Introduction

In the context of global climate change, the need for accurate, consistent, and comprehensive descriptions of the thermodynamic properties of seawater and its equilibria in contact with ice and humid air led to the development of the new oceanographic standard TEOS-10, the Thermodynamic Equation of Seawater 2010 [1]. The formulation and successful international adoption of TEOS-10 was the result of close cooperation between the SCOR[1]/IAPSO[2] Working Group 127 and IAPWS in the years 2006-2011. TEOS-10 was adopted by UNESCO-IOC[3] for all member states in 2009 for oceanography with respect to thermodynamic properties of seawater and ice, and by IUGG[4] in 2011 for marine sciences by a resolution that also recommends the use of the TEOS-10 equation for humid air.

TEOS-10 includes a systematic development of the thermodynamic properties of seawater, ice, and humid air, the definition of a new salinity scale to describe the salt content of seawater, and a procedure to account for variations in the chemical composition of sea salt. At the core of TEOS-10 are four empirical thermodynamic formulations:

(i) the specific Helmholtz energy of pure fluid water, $f^{\mathrm{F}}(T,\rho)$, as a function of ITS-90 temperature, T, and mass density, ρ, generally known as the IAPWS-95 formulation;
(ii) the specific Gibbs energy of hexagonal ice I, $g^{\mathrm{Ih}}(T,p)$, as a function of temperature and pressure, p;
(iii) the specific Gibbs energy of IAPSO Standard Seawater, $g^{\mathrm{SW}}(S_{\mathrm{A}},T,p)$, as a function of Absolute Salinity, S_{A}, temperature, and pressure, and;
(iv) the specific Helmholtz energy of humid air, $f^{\mathrm{AV}}(A,T,\rho)$, as a function of dry-air mass fraction, A, temperature, and mass density.

By design, the identity $f^{\mathrm{AV}}(0,T,\rho)\equiv f^{\mathrm{F}}(T,\rho)$ holds for humid air in the limiting case of air-free water vapor, and similarly $g^{\mathrm{SW}}(0,T,p)\equiv f^{\mathrm{F}}(T,\rho)+p/\rho$ is obeyed in the zero-salinity limit of pure liquid water. The reference states for energy and entropy in the formulations are carefully matched so that the formulations can be combined to perform phase-equilibrium calculations [2].

The four thermodynamic potentials of TEOS-10 satisfy axiomatic conditions of *completeness*, *consistency*, and *independence*. Here, completeness means that all thermodynamic properties of the pure phases, their phase equilibria and composites can be computed from algebraic combinations of partial derivatives of the potentials [1,3,4]; for example, computing equilibria between ice and seawater involves the formulations (ii) and (iii) above. Consistency means the impossibility of deriving from the potentials two numerically different results for the same

[1] SCOR: Scientific Committee on Oceanic Research, http://www.scor-int.org/
[2] IAPSO: International Association for the Physical Sciences of the Oceans, http://iapso.iugg.org/
[3] IOC: Intergovernmental Oceanographic Commission of UNESCO, http://ioc-unesco.org/
[4] IUGG: International Union of Geodesy and Geophysics, http://www.iugg.org/

thermodynamic property. Finally, independence means that none of these potentials, nor any thermodynamic properties derived from them, can be derived from any of the others.

TEOS-10 is partly based on or makes reference to a number of IAPWS documents whose roles are described in this Advisory Note. Citation practice should carefully distinguish between IAPWS documents which have utility independent of TEOS-10 and marine sciences, and the TEOS-10 document [1] which specializes to oceanic applications.

IAPWS documents included in or directly related to TEOS-10:

1. IAPWS R6-95(2016): Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use (generally referred to as IAPWS-95) (September 2016).

2. IAPWS G9-12: Guideline on a Low-Temperature Extension of the IAPWS-95 Formulation for Water Vapor (October 2012).

3. IAPWS R10-06(2009): Revised Release on the Equation of State 2006 for H_2O Ice Ih (referred to as IAPWS-06 in the text of TEOS-10) (September 2009).

4. IAPWS R14-08(2011): Revised Release on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance (September 2011).

5. IAPWS R13-08: Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater (referred to as IAPWS-08 in the text of TEOS-10) (September 2008).

6. IAPWS R8-97: Release on the Static Dielectric Constant of Ordinary Water Substance for Temperatures from 238 K to 873 K and Pressures up to 1000 MPa (September 1997).

7. IAPWS SR7-09: Supplementary Release on a Computationally Efficient Thermodynamic Formulation for Liquid Water for Oceanographic Use (referred to as IAPWS-09 in the text of TEOS-10) (September 2009).

8. IAPWS SR1-86(1992): Revised Supplementary Release on Saturation Properties of Ordinary Water Substance (September 1992).

9. IAPWS G8-10: Guideline on an Equation of State for Humid Air in Contact with Seawater and Ice, Consistent with the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater (referred to as IAPWS-10 in the text of TEOS-10) (July 2010).

Notes on the listed documents and their application:

a) The four fundamental documents that form TEOS-10 are the mutually consistent equations of state of pure fluid water (#1 above), of ice Ih (#3 above), of seawater (#5 above), and of humid air (#9 above). In combination, these equations describe the thermodynamic properties of ambient seawater, pure liquid water, ice, and humid air, as well as of their phase transitions such as the freezing-point temperature or the evaporation enthalpy of seawater [1-4].

b) IAPWS-95 (#1 above) is a fundamental equation of Helmholtz free energy as a function of temperature and density, $f = f(T, \rho)$, which yields other thermodynamic properties by differentiation and algebraic manipulation without the use of any other information. IAPWS-95 defines accurately the thermodynamic properties of the fluid phases of ordinary water substance, with complete thermodynamic consistency among these properties, over a wide range of states (pressures up to 1000 MPa and temperatures from the melting and sublimation temperatures to 1273 K). This definition of properties includes those on the liquid–vapor equilibrium line, which is conveniently approximated in #8 above. The equation extrapolates sensibly to higher pressures and temperatures. Thus, IAPWS-95 is recommended as the source of the thermodynamic properties of water and steam, and of the pure water parts of the equations of state of seawater (#5 above) and humid air (#9 above). However, since the independent variables of IAPWS-95 are temperature and density, computing times for some applications may be excessive and alternatives are available as indicated below.

For the gas phase, the low-temperature limit of IAPWS-95 can be reduced from 130 K to 50 K with the low-temperature extension described in (#2 above).

c) The IAPWS Revised Release on an Equation of State for Ice Ih (#3 above) defines the thermodynamic properties of the solid phase, when the ice form Ih is the equilibrium state, at temperatures below the melting and sublimation curves, conveniently numerically available from #4 above.

d) The Release on the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater (#5 above) describes the property changes of water caused by dissolved sea salt. Sea salt is a mixed solute of specified chemical composition [5]. The formulation is constructed such that thermodynamic properties of seawater, including salt-related properties such as osmotic coefficient, may be obtained by differentiation and algebraic manipulation.

e) The Guideline on an Equation of State for Humid Air in Contact with Seawater and Ice, Consistent with the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater (#9 above) describes the property changes of water vapor caused by admixed dry air. Dry air is a gas mixture of specified chemical composition [6]. For application to the atmosphere at high altitudes, the validity of the equation of state of water vapor may be extended to 50 K using document #2.

f) Properties described by the Release on the Static Dielectric Constant of Ordinary Water Substance for Temperatures from 238 K to 873 K and Pressures up to 1000 MPa (#6 above) were exploited for the proper limiting law of dilute electrolytes, included in #5 above.

g) The Supplementary Release on a Computationally Efficient Thermodynamic Formulation for Liquid Water for Oceanographic Use (#7 above) is recommended for fast computation of seawater properties such as for ocean modeling, as a substitute for IAPWS-95 in the oceanic ranges of pressure and temperature.

References

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