FINAL REPORT

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Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice

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(For the documentation of corrections and modifications see the Appendix)

Abstract

This research revised the ASHRAE psychrometric model of moist air as a "real gas" mixture using the virial equation of state. It uses the latest universal gas constant, molar masses of dry air and water, the latest research from IAPWS, CODATA, IUPAC, NIST, NOAA and NASA and builds on the basic ASHRAE algorithm of Goff and Gratch (1945); updated by Hyland and Wexler (1983) and Nelson and Sauer (2001). The new model has a broadened range of validity with pressure from 0.01 kPa to 10 MPa, temperature from –143.15 to 350°C, and humidity ratio from 0 to 10 kg_w/kg_a.

The model was used to produce moist air and H_2O saturation property tables for the psychrometric chapter in the 2009 ASHRAE Handbook of Fundamentals. The new moist air table is close to the 1985 table because moist air at ambient pressure behaves essentially as an ideal gas; also the underlying data used by Hyland and Wexler was quite accurate. Greater deviations to the former models occur at higher pressures and temperatures encountered in the compression stage of gas turbines and in compressed air energy storage applications.

The results of psychrometric research serves (1) ASHRAE and the air-conditioning industry, (2) the World Meteorological Organization and others involved in atmospheric research and meteorology, (3) the Association of Agricultural Engineers who rely on psychrometrics in their modeling and tracking of soil moisture and evaporation and plant transpiration, and (3) the engineering community that deals with (a) air conditioning from deep mines to space capsules, (b) deep vacuum processes, (c) high pressure processes, and (d) the gas and light oil turbine processes that power our airplanes and gas turbine-powered generators.

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Executive Summary

This research updates the ASHRAE model of moist air as a mixture using the virial equation of state. This new model uses the latest data and equations for the universal gas constant, the molar mass of dry air, the molar mass of water, the latest NIST data for the evaluation of the properties of the real gas dry air and the latest IAPWS data for the real gas water vapor. The properties of moist air are calculated from the modified Hyland-Wexler model and consists in the calculation of the:

- Ideal-gas part of the heat capacity, enthalpy, and entropy of dry air from the fundamental equation of Lemmon *et al.*
- Ideal-gas part of the heat capacity, enthalpy, and entropy of water and steam from IAPWS-IF97 for $T \geq 0°C$ and from IAPWS-95 for $T \leq 0°C$
- Vapor-pressure enhancement factor from the equation given by the models of Hyland and Wexler
- Second and third molar virial coefficients for dry air from the fundamental equation of Lemmon *et al.*
- Second and third molar virial coefficients for water and steam from IAPWS-95
- Air-water second molar cross-virial coefficient from Harvey and Huang
- Air-water third molar cross-virial coefficients from Nelson and Sauer
- Saturation pressure of water from IAPWS-IF97 for $T \geq 0°C$ and sublimation pressure from IAPWS-08 for $T \leq 0°C$
- Isothermal compressibility of saturated liquid water from IAPWS-IF97 and that of ice from IAPWS-06 in the determination of the vapor-pressure enhancement factor
- Henry's constant from the IAPWS Guideline 2004 in the determination of the enhancement factor. The mole fractions for the three main components of dry air were taken from Lemmon *et al.* Argon is now considered as the third component of dry air in the calculation of Henry's constant.

For calculating thermodynamic properties of steam, water, and ice the following standards of the International Association for the Properties of Water and Steam (IAPWS) are used:

- "Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use" (IAPWS-95)
- "Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" (IAPWS-IF97)
- "IAPWS Release 2006 on an Equation of State for H_2O Ice Ih" (IAPWS-06)
- "Revised Release 2008 on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance" (IAPWS-08).

The value for the universal molar gas constant is taken from the CODATA standard of Mohr and Taylor, the value for the molar mass of dry air is taken from Gatley *et al.*, and the molar mass of water is taken from IAPWS-95.