

# **Thermodynamic Properties of Cryogenic Fluids**

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# **Thermodynamic Properties of Cryogenic Fluids**

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# Preface

This book is intended to provide the practicing engineer and interested scientist with the most accurate information available on the thermodynamic properties of cryogenic fluids. It may also be useful to universities and colleges as a supplementary reference text for elective courses in cryogenic engineering or engineering systems analysis that study systems using cryogenes as the working fluids. Much of the material presented here is the result of a long-term continuing research effort in the Center for Applied Thermodynamic Studies (CATS) at the University of Idaho. While some of the thermodynamic property formulations presented here are the work of CATS staff, many have been developed and published by others. Numerical changes have been made to convert all of the correlations to a single form for ease of computation.

We have included the most accurate available formulation for each fluid, realizing that some of those included will be superseded in the future. We do not apologize for this circumstance, for it is the nature of this rapidly changing, dynamic field that both experimental methods and correlations improve with time. Fortunately most new works extend the ranges of prior research or correct relatively minor errors in numerical models (e.g., near the critical point), and generally tend to verify the values given by models of the quality of those presented here.

In the presentation of correlations of thermodynamic data, it is customary to provide the reader or user with graphical and statistical information that verifies the accuracy of calculated properties. We have referenced the original works that contain these details for the interested user. We have provided sufficient detail on the model for each fluid that the user may program the formulations in any appropriate language or format consistent with a particular application.

In developing this book, we have given a brief review of the fundamentals of thermodynamic property formulations and a summary of current

practices in data analysis and correlation. Although these discussions are intended to be very general, it is likely that the experiences of the authors have influenced the approach. The information included should be sufficient to allow the user to have confidence in the accuracy of calculated properties.

We have included Internet access to both executable and FORTRAN source code for the computer programs used to calculate the fluid properties described in this book. It is our hope that the graphs, tables, and computer programs we have provided will be widely useful to those who need property information for cryogenic fluids. We invite suggestions on the improvement and expansion of these tools by those who use them.

Richard T Jacobsen  
Steven G. Penoncello  
Eric W. Lemmon

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# List of Symbols

<i>Symbol</i>	<i>Physical quantity</i>	<i>Units</i>
<i>A</i>	Helmholtz energy	J/mol
<i>B</i>	Second virial coefficient	dm <sup>3</sup> /mol
<i>B'</i>	Second pressure virial coefficient	1/MPa
<i>B<sub>s</sub></i>	Adiabatic bulk modulus	MPa
<i>C</i>	Third virial coefficient	dm <sup>6</sup> /mol <sup>2</sup>
<i>C'</i>	Third pressure virial coefficient	1/MPa <sup>2</sup>
<i>C<sub>v</sub></i>	Isochoric heat capacity	J/(mol · K)
<i>C<sub>p</sub></i>	Isobaric heat capacity	J/(mol · K)
<i>D</i>	Fourth virial coefficient	dm <sup>9</sup> /mol <sup>3</sup>
<i>D'</i>	Fourth pressure virial coefficient	1/MPa <sup>3</sup>
<i>G</i>	Gibbs energy	J/mol
<i>H</i>	Enthalpy	J/mol
<i>i</i>	Exponent for $\delta$ in the fundamental equation	
<i>j</i>	Exponent for $\tau$ in the fundamental equation	
<i>k</i>	Isentropic expansion coefficient	
<i>k<sub>T</sub></i>	Isothermal expansion coefficient	
<i>K<sub>T</sub></i>	Isothermal bulk modulus	MPa
<i>l</i>	Exponent for $\delta$ in exponential terms of the fundamental equation	
<i>m</i>	Number of terms in the fundamental equation	
<i>N</i>	Coefficient in the fundamental equation	
<i>P</i>	Pressure	MPa
<i>R</i>	Gas constant	J/(mol · K)
<i>S</i>	Entropy	J/(mol · K)
<i>T</i>	Temperature	K
<i>U</i>	Internal energy	J/mol
<i>v</i>	Specific volume ( $v = 1/\rho$ )	dm <sup>3</sup> /mol

$W$	Speed of sound	m/s
$Y$	Statistical weight	
$Z$	Compressibility factor	
$\alpha$	Dimensionless Helmholtz energy, $\alpha = A/RT$	
$\beta$	Volume expansivity	1/K
$\beta_s$	Adiabatic compressibility	1/MPa
$\delta$	Reduced density ( $\delta = \rho/\rho_c$ )	
$\phi$	Fugacity coefficient	
$\kappa$	Isothermal compressibility	1/MPa
$\gamma$	Multiplier for $\delta$ in exponential terms of the fundamental equation	
$\mu_J$	Joule–Thomson coefficient	K/MPa
$\rho$	Density ( $\rho = 1/v$ )	mol/dm <sup>3</sup>
$\tau$	Reciprocal reduced temperature ( $\tau = T_c/T$ )	
$\omega$	Acentric factor	

*Subscript Explanation or meaning*

$c$	Critical point property
$k$	Reference index for terms in the fundamental equation
$o$	Reference state property

*Superscript Explanation or meaning*

$o$	Ideal gas property
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