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 cryogens 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We have included the most accurate available formulation for each fluid, realizing that some of those included will be superseded in the future.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.

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It is with sincere appreciation that we acknowledge the assistance of Dr. Richard B. Stewart for his critical evaluation of this work. Dr. Stewart was the founder of the Center for Applied Thermodynamic Studies at the University of Idaho and the director from 1975 to 1986. Much of the information in this book is a direct consequence of his work at the Center and at the National Institute of Standards and Technology (formerly the National Bureau of Standards). We also acknowledge the critical review of Dr. Klaus Timmerhaus of the Chemical Engineering Department at the University of Colorado, who encouraged us to initiate this work in 1991. We thank Dr. Steven W. Beyerlein for his editorial comments and Dr. Anthony R. H. Goodwin for his assistance with the experimental uncertainties. We are indebted to Mr. Mark D. Panasiti for his assistance in developing the programs and for creating the P–H and T–S diagrams shown for the cryogenic fluids in this book.

Contents

List of Symbols

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

W	Speed of sound	m/s
Y	Statistical weight	
Z	Compressibility factor	
α	Dimensionless Helmholtz energy, $\alpha = A/RT$	
β	Volume expansivity	1/K
β_s	Adiabatic compressibility	1/MPa
δ	Reduced density ($\delta = \rho/\rho_c$)	
ϕ	Fugacity coefficient	
κ	Isothermal compressibility	1/MPa
γ	Multiplier for δ in exponential terms of the fundamental equation	
μ_J	Joule–Thomson coefficient	K/MPa
ρ	Density ($\rho = 1/v$)	mol/dm^3
τ	Reciprocal reduced temperature ($\tau = T_c/T$)	
ω	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