Helium Cryogenics

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To Mary, Travis, and Courtenay

Preface

At least 10 years have elapsed since a comprehensive monograph concerned with the broad subject of cryogenics has been published. During this time a considerable quantity of research and development has been carried out in the field of cryogenics. Furthermore, there has been a certain degree of redirection of effort within the field, mostly driven by the variety of new applications, ranging from superconductive magnet systems to microelectronics. Greater emphasis is now being placed on low-temperature cryogenics, particularly that of liquid helium. Until now cryogenic books have provided a broad survey of materials and fluid properties over the entire cryogenic regime, $T \lesssim 150$ K. This approach does not allow sufficient detail in any particular area to bring the reader to the current level of understanding in the subject. In addition, the behavior of helium has been lumped with that of other cryogenic fluids, although the properties of helium are quite unique. As a result, a clear relationship has not been established between the fundamental understanding of helium fluids and their potential applications.

The present book has been written to fill this void. The approach is to survey the field of cryogenics, specifically as it pertains to helium fluids. This approach is more specialized than that contained in previous cryogenics books. Furthermore, the level of treatment is more advanced and a certain knowledge of fundamental engineering and physics principles has been assumed. Unlike previous books on liquid helium, the present treatment contains both engineering and physical descriptions. The goal throughout the work is to bridge the gap between the physics and engineering aspects of helium fluids to encourage their use and enhance their usefulness in low-temperature systems.

The content of the book is based on a course offered at the University of Wisconsin–Madison. Students who register for this course are almost exclusively at the graduate level. As a result, a reasonable background knowledge of physics and engineering has been assumed. Recommended prerequisites include a working knowledge of thermodynamics and statistical physics, heat transfer, and elementary solid-state physics. Without this background, the reader may find it necessary to review one or more of these subjects. A number of useful references are given at the end of the book.

The material contained in this book is divided into nine chapters. Chapter 1 introduces the basic principles of cryogenics, including a discussion of applications. Chapter 2 describes the thermal properties of materials at low temperatures, concentating on solids. This is not only a useful background review but it also introduces some fundamental physics, which is used in later chapters. Chapter 3 introduces helium as a classical fluid, concentrating on its physical aspects as they can be described using classical models. Chapter 4 then discusses helium as a quantum fluid, emphasizing the theory and experimental evidence associated with superfluidity. Chapter 5 turns to the engineering problem of heat transfer in superfluid helium, and how the fundamental understanding of helium introduced in Chapter 4 can be used to describe its characteristics. Chapter 6 concentrates on the problem of heat transfer in pool boiling normal helium. Chapter 7 extends the discussion of helium to fluid flow, including heat transfer and pressure drop. Chapter 8 discusses the thermodynamic aspects of liquefaction and refrigeration systems, including a discussion of actual refrigeration systems in use today. Finally, Chapter 9 summarizes some special topics of interest to both helium cryogenics and related disciplines. The goal here is to survey a few very specific areas of helium cryogenics and related disciplines which, although slightly outside the main scope of the text, are still important in low-temperature applications.

Throughout the writing of this book, I have received considerable assistance and encouragement from collegues, students, and friends. Their support should not go unrecognized. I would like to give thanks to two of my students, D. Scott Holmes and John G. Weisend II, for their critical review of the partially completed manuscript and for assisting in developing problems. A number of colleagues read sections of the manuscript and made substantive suggestions on improvements to be made. They are Drs. A. F. Clark, F. R. Fickett, and V. Arp, all of the National Bureau of Standards; Dr. L. Dresner, Oak Ridge National Laboratory; Prof. O. E. Vilches, University of Washington; Prof. J. T. Tough, Ohio State University; and Prof. R. F. Barron, Louisiana Tech University. Their help is greatly appreciated. The conversion of my handwritten version to a readable typewritten text was due to the efforts of Ms. Kay Ewers. This task was certainly second only to the actual writing in terms of the amount of effort involved. Production of the graphics must be credited to Ms. Helga Fack and her staff. Finally, I would like to acknowledge the indirect

help that my family has provided in terms of encouragement and willingness to forego some leisure activities so that time could be devoted to the effort of writing this book. In retrospect, it has been worthwhile.

S. W. Van Sciver

Contents

Symbols, SI Units

A — area, m^2
— Gorter–Mellink parameter, m · s/kg
— Schottky specific heat coefficient, J · K/kg · ion

a — absorptivity
— coefficient of turbulence buildup, $W^{3/2}/m^{3/2}$
— van der Waals gas coefficient, N/mole
— vortex core radius, m
— Zeehman ordering parameter

B — Brillouin function
— magnetic flux density, T
— second virial coefficient, m^3/kg
— vortex interaction parameter

b — coefficient of expansion
— impact parameter, m
— van der Waals gas coefficient, $m^3/mole$

C — circulation, m^2/s
— cost, $
— heat capacity, J/K, $J/m^3 \cdot K$, J/mole K
— specific heat, J/kg · K
— third virial coefficient, m^6/kg^2

c — sound velocity, m/s
— surface wave speed, m/s

D — density of states
— diameter, m
— thermal diffusivity, m/s
— fourth virial coefficient, m^9/kg^3

d — diameter, m
— film thickness, m
— number of atomic layers

E — binding energy, J
— energy flux, J/m^2
— electric field, V/m
— internal energy, J
— radiant energy flux, W/m^2
— Young's modulus, N/m^2

e — charge of electron, coul
— specific internal energy, J/kg
— spectral energy density, W/m^3

F — force, N

f — bubble detachment frequency, s^{-1}
— Fermi–Dirac distribution function
— force per unit length, N/m
— friction factor
— heat conductivity function, W^3/m^5
— Maxwell-Boltzmann distribution

G — specific mass flux, $kg/m^2 \cdot s$

Gr — Grashof number

g — degeneracy
— Landé g-factor
— specific Gibbs potential, J/kg

g — gravitational acceleration, m/s^2

H — hamiltonian
— height, m
— magnetic field, A/m

h — heat transfer coefficient, W/m^2K
— hydrostatic head, m
— Planck's constant, J/K
— specific enthalpy, J/kg

J — exchange interaction
— particle collision term
— total angular momentum quantum number

j — momentum flux, kg/m^2s

K — forced convection parameter
— numerical constant

k — expansion parameter
— thermal conductivity, W/m · K
— wave number

k_B — Boltzmann constant, J/K

L — length, m
— Lorenz number
— orbital angular momentum quantum number

l — mean free path, m

M — magnetization, A/m
— molecular weight, kg/mole

m — mass, kg
— electron spin quantum number

N — number of particles

N_0 — Avogadro's number, mole^{-1}

Nu — Nusselt number

n — number density, m^{-3}
— statistical distribution

P — momentum, kg · m/s
— perimeter, m
— polarization
— refrigeration power, W

Pr — Prandtl number

p — pressure, Pa

Q — heat rate, W

q — critical quality
— heat flux, W/m^2
— isosteric heat, K

R — gas constant, J/mole K

Ra — Rayleigh number

Re — Reynolds number

r — radius, m

S — entropy, J/K, J/m^3 · K, J/mole K
— slip ratio
— spin quantum number
— vortex line dimension, m

s — specific entropy, J/kg · K

T — temperature, K

t — reduced temperature
— time, s
— transmission coefficient

U — attractive potential, J

u — velocity component, m/s

V — volume, m^3

v — velocity, m/s

v — specific volume, kg/m^3
— velocity component, m/s

W — work, J

w — Bénard convection parameter
— specific work, J/kg
— width, m

x — concentration
— coverage
— expansion circuit flow fraction
— position coordinate, m

y — position coordinate, m
— yield in a liquefier

Z — collision number, m^{-3}s^{-1}
— integrated heat conductivity function, W/m$^{5/3}$
— impedance
— partition function

z — fugacity
— position coordinate, m

Greek Letters

α — accommodation coefficient
— linear thermal expansion coefficient, K^{-1}
— Kapitza conductance parameter, W/m^2K^n
— void fraction

β — bulk expansivity, K^{-1}
— condensation coefficient
— geometrical factor in Poiseville flow
— $1/k_BT$

η — efficiency
— phase shift
— viscosity, $N \cdot s/m^2$

θ — angle

Θ — reduced temperature

Θ_D — Debye temperature, K

κ — compressibility, Pa^{-1}
— transient heat transfer parameter, $W^4 \cdot s/m^8$

λ — latent heat, J/kg
— wavelength, m

μ — chemical potential, J
— expansion coefficient, K/Pa, $T \cdot m^3K/J$
— magnetic movement
— roton mass, kg

ν — frequency, s^{-1}
— kinematic viscosity, m^2/s

ξ — coherence length, m

π — reduced pressure

ρ — density, kg/m^3
— resistivity, $\Omega \cdot m$

σ — conductivity, $(\Omega \cdot m)^{-1}$
— Kapitza conductance parameter, W/m^2K^4
— Lennard-Jones potential parameter, J
— scattering cross section, m^2
— Stefan-Boltzmann constant, W/m^2K^4
— stress, Pa
— surface tension, J/m^2

γ — coefficient of the electronic specific heat, J/mole K^2
— Curie constant, K
— Grüneisen parameter
— reduced velocity
— specific heat ratio
— statistical parameter

Δ — roton minimum energy, K

δ — thickness, m
— level splitting in Stark effect, J
— vortex line spacing, m

ε — emissivity
— energy level, J
— Lennard-Jones potential parameter, J

τ — reduced temperature
— time, s

Φ — potential, J
— wave function
— reduced equation of state

ϕ — spreading pressure, N/m
— azimuthal angle

χ — flow quality
— magnetic susceptibility
— vortex interaction parameter

Ψ — wavefunction
— parameter in cylindrical heat transfer

Ω — collision integral
— thermodynamic probability

ω — angular frequency, s^{-1}

Subscripts

a — acceleration, absorbed
B — Bohr
B_0 — Boyle
b — bath, black body
bp — boiling point
C — cold, Curie

c — critical
c_1 — lower critical
c_2 — upper critical
CL — classical
D — Debye
e — electronic, expansion, emitted
eff — effective
exp — experimental
F — Fermi
f — final state, film
fb — film boiling
fc — forced convection
G — Grüneisen
g — gas
gen — generation
gr — gravitational
H — hot, constant field
h — hydraulic, constant enthalpy
i — initial state, incident
ic — internal convection
int — internal
inv — inversion
j — Joule-Thomson
K — Kapitza
k — index
L — vortex line, liquid
LJ — Lennard-Jones
l — liquid
m — maximum, mean
n — normal, normal fluid, index
nc — normal fluid critical
ns — normal-superfluid
p — constant pressure, proton
ph — phonon
pl — const pressure liquid
R — reversible, recovery
r — roton, reduced, radiant
s — superconducting, superfluid, sound, constant entropy, surface, substrate
sat — saturated
sc — superfluid critical
st — isosteric
T — constant temperature, thermal de Broglie

t — transmitted, total
tt — turbulent
u — ultimate
v — constant specific volume
y — yield
λ — lambda point
$\perp$ — perpendicular component
0 — ambient, ground state
1 — first excited state, first
2 — second
3 — of ^{3}He, third
4 — of ^{4}He, fourth

Superscripts

* — critical, normalized parameter, effective
—— — average
— time derivative
A — acoustic mismatch
c — critical
m — empirical power law
n — empirical power law
p — phonon radiation, empirical power law
q — empirical power law
r — empirical power law
α — empirical power law
β — empirical power law