RADIOMETRIC TEMPERATURE MEASUREMENTS

I. Fundamentals

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Experimental Methods in the Physical Sciences

RADIOMETRIC TEMPERATURE MEASUREMENTS

I. Fundamentals

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I. Fundamentals

EXPERIMENTAL METHODS IN THE PHYSICAL SCIENCES

Thomas Lucatorto and Albert C. Parr, *Editors in Chief*

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In memory of David P. DeWitt – a pioneer, teacher, and friend

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Edited by Z. M. Zhang, B. K. Tsai, and G. Machin

PREFACE

Temperature measurement and control has played and continues to play a vital role in many scientific and technological advances. Radiometric temperature measurement, that is the measurement of temperature based on thermal radiative emission, has a long history from fundamental studies of Planckian emission, to many industrial applications including iron and steel production and materials and chemical processing, to playing a fundamental role in the realization and dissemination of successive international temperature scales. Radiation thermometry is attractive in many challenging temperature measurement situations because it is a noncontact, nonintrusive, and fast technique.

Thermal radiation is governed by the fundamental physical laws established over one hundred years ago by Kirchhoff, Stefan, Boltzmann, Wien, and, in particular, Planck. These laws directly link emitted blackbody radiation, total or spectrally resolved, to the thermodynamic temperature of the emitting source. Actual practical measurements by radiation thermometry, however, are prone to a number of uncertainties associated with, for example, surface emissivity and environmental effects such as absorption by dust or smoke and reflected ambient radiation. While a number of books have been published on thermometry, in general, no comprehensive book devoted to radiometric temperature measurement has been published since the publication in 1988 of *Theory and Practice of Radiation Thermometry*, edited by D.P. DeWitt and G.D. Nutter.

In recent years, there have been tremendous developments in instrumentation. For instance, infrared focal plane arrays can now produce images with a spatial resolution of order 10 μm with a temperature resolution of 0.01 K. While the expert in the field can keep abreast of these rapidly advancing techniques through the information presented at periodic international temperature symposia and through the technical literature, it is very difficult for a newcomer to find a definitive up-to-date summary of the practice of radiation thermometry. This book aims at filling that gap by covering basic theory, measurement fundamentals, standards and calibration, and summaries of current practice of radiation thermometry in different technical fields at a level accessible to the newcomer but also comprehensive enough to provide the information needed to understand and bring to bear the latest technique to a particular radiometric temperature measurement problem.

This two-volume set on *Radiometric Temperature Measurement* (I. Fundamentals and II. Applications) is written for those who will apply radiation thermometers in industrial practice, who will use thermometers in scientific research, who design and develop thermometers for instrument manufacturers, and who will design the thermometers to address particular measurement challenges. These volumes are more than a practice guide. We hope that by presenting the fundamental principles and pointing out the pitfalls in applying radiation thermometry in various settings, our readers will gain knowledge in: (1) the proper selection of the type of thermometer; (2) the best practice in using radiation thermometers; (3) awareness of the uncertainty sources and subsequent appropriate procedure to reduce the overall measurement uncertainty; and (4) understanding of the calibration chain and its current limitations. We have also added a large number of references at the end of each chapter as a source for those seeking a deeper or more detailed understanding.

The author(s) of each chapter were chosen from a group of international scientists who are experts in the field and specialist(s) on the subject matter covered in the chapter. It is intended that together the two volumes will form a comprehensive summary of the current practice of radiation thermometry. The first volume concentrates on the fundamental aspects, while the second volume mainly focuses on the industrial and practical applications. In the fundamental volume, Chapter 1 provides a historical overview of radiation thermometry, explains the basic fundamentals and commonly used terms, and lists the various types of radiation thermometers. The concepts of temperature, its scale realization, calibration, traceability, measurement, uncertainty analysis, and future approaches, are extensively elaborated in Chapter 2. The basic theory on blackbody radiation, radiative properties, and the electromagnetic wave theory are discussed in Chapter 3. Chapter 4 focuses on the design and characterization of radiation thermometers. Chapter 5 addresses the theoretical and computational characterization of isothermal and nonisothermal blackbody cavities by analytical and Monte Carlo methods. In Chapter 6, radiance sources used for calibration such as fixed-point blackbodies, variable temperature blackbodies, cryogenic blackbodies, high stability and other tungsten-based lamps are described. Chapter 7 is an overview of some complementary surface temperature measurement techniques, such as thermal reflectance, interferometry, ellipsometry, and photothermal radiometry with application examples.

The volume on applications begins with a review of the state-of-the-art industrial applications of radiation thermometry, including a critique of multiwavelength thermometry (Chapter 1). Chapter 2 describes experimental characterization of blackbody cavities with an extensive survey on the measurement techniques. Chapter 3 focuses on the application of optical fiber thermometry for semiconductor processing, with an emphasis on rapid thermal processing and *in situ* calibration of lightpipe thermometers using thin-film thermocouples. Chapter 4 reviews the state-of-the-art practice of radiation thermometry in the steel industry, highlighting specific manufacturing processes. Chapter 5 deals with thermal imaging in firefighting and other thermographic applications along with standards of measurement and application. Chapter 6 discusses remote sensing of earth and sea surface temperatures and reviews different instruments and their measuring capabilities. Finally, Chapter 7 covers four aspects of clinical radiation thermometry: ear thermometry, medical thermal imaging, medical pulsed photothermal radiometry, and microwave radiometry for clinical applications.

This two-volume set is a tribute to David DeWitt (1934–2005) who has been an inspiration for us and to many others in the radiation thermometry community. In his last eight years, he dedicated his research to temperature measurement and calibration for rapid thermal processing in microelectronics manufacturing industry. He will always be remembered as a leader in the fields of radiation thermometry and heat transfer engineering.

The editors sincerely thank all of the chapter authors for their outstanding contributions and hard work. We also express appreciation to Dr. Tom Lucatorto and Dr. Albert C. Parr, the series editors, for their constant encouragement during this process and their careful review of the chapter contents. Finally, we would like to thank our families for their full support and enduring patience throughout the writing and editing of this book.

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NOMENCLATURE

A	surface area (m^2)
A_n	projected area (m^2)
A'	directional absorptance of a semitransparent material
a_λ	absorption coefficient (m^{-1})
$\mathbf{B}$	magnetic induction or magnetic flux density (T or Wb/m^2)
c	phase velocity of electromagnetic wave (m/s)
c_0	speed of light in vacuum (m/s)
c_1	first radiation constant (W m^2)
c_{1L}	first radiation constant for spectral radiance (W m^2/sr)
c_2	second radiation constant (m K)
c_3	third radiation constant (m K)
c_p	specific heat at constant pressure (J/(kg K))
c_v	specific heat at constant volume (J/(kg K))
$\mathbf{D}$	electric displacement (C/m^2); dynamic matrix
D	density of states
D^*	detectivity (m Hz$^{1/2}$/W)
d	diameter or film thickness (m)
$\mathbf{E}$	electric field vector (N/C or V/m)
E	irradiance (W/m^2); energy (J); magnitude of electric field (V/m)
e	elementary charge (C)
f	distribution function
f_r or f_t	bidirectional reflectance (or transmittance) distribution function
$\mathbf{H}$	magnetic field vector (A/m or C/(m s))
h	Planck's constant (J s)
$\hbar$	Planck's constant divided by 2π, $h/2\pi$, J s
I	Radiant intensity (W/sr)
i	$\sqrt{-1}$
$\mathbf{J}$	electric current density (A/m^2)
$\mathbf{k}$	wavevector (m^{-1})
k	Boltzmann's constant (J/K); also magnitude of wavevector (m^{-1})
L	radiance (W/(m^2 sr))
L_λ	spectral radiance (W/(m^2 μm sr))
$\mathbf{M}$	magnetization vector (A/m or C/(m s))
M	exitance (W/m^2); molecular weight (kg/kmol)
M_{em}	self-exitance or emitted exitance (W/m^2)
m	mass (kg)
m_e	electron mass (kg)
N_A	Avogadro constant (mol^{-1})

n	real part of refractive index or refractive index; number density (m^{-3})
$\tilde{n}$	complex refractive index
$\mathbf{P}$	dipole moment per unit volume (C/m^2); propagation matrix
$\mathbf{p}$	momentum vector ($m\mathbf{v}$ or $\hbar\mathbf{k}$) (kg m/s); dipole moment (C m)
p	pressure (Pa or N/m^2); magnitude of momentum (kg m/s); magnitude of dipole moment (C m)
Q	heat or radiant energy (J)
q	heat transfer rate (W)
q''	radiative heat flux (W/m^2)
R	universal gas constant (J/(mol K)); gas constant (J/(kg K)); electrical resistance (Ω or V/A); detector responsivity (V/W or A/W)
R'	directional-hemispherical reflectance
R_e	electrical resistivity (Ω m)
r	radius or radial coordinate (m); also Fresnel reflection coefficient
$\mathbf{S}$	Poynting vector (W/m^2)
S	entropy (J/K); detector output signal (V or A)
S_j	strength of the jth phonon oscillator
T	temperature (K)
T'	directional-hemispherical transmittance
T_λ	radiance temperature (K or °C)
T_t	total radiance temperature (K or °C)
t	temperature (°C); time (s); Fresnel transmission coefficient
u	energy density (J/m^3)
V	volume (m^3); voltage (V)
$\mathbf{v}$	velocity (m/s)
v	specific volume (m^3/kg), also speed (m/s)
x, y, z	coordinates (m)

Greek Symbols

α'	directional absorptivity
β	phase shift (rad)
β_λ	attenuation coefficient (m^{-1})
γ	scattering rate (rad/s)
δ_λ	radiation penetration depth (m)
ε	dielectric function or relative permittivity; also emissivity
ε_0	electric permittivity of vacuum (F/m or $A^2 s/(N m^2)$)
$\tilde{\varepsilon}$	complex dielectric function
ε'	directional emissivity
η	efficiency
θ	polar or zenith angle (rad)
θ_B	Brewster's angle (rad)
θ_c	critical angle (rad)

κ	extinction coefficient (i.e., imaginary part of the refractive index)
λ	wavelength (m)
μ	relative magnetic permeability; also mobility ($m^2/(V\,s)$)
μ_0	magnetic permeability in vacuum (N/A^2)
ν	frequency (Hz)
ρ	density (kg/m^3); electric charge density (C/m^3)
ρ'	directional-hemispherical reflectivity
σ	Stefan–Boltzmann constant ($W/(m^2\,K^4)$); electric conductivity (A/V)
σ_λ	scattering coefficient (m^{-1})
τ	relaxation time (s); internal transmissivity; spectral transmittance
Φ	scattering phase function
ϕ	azimuthal angle (rad)
Ω	solid angle (sr)
ω	angular frequency (rad/s); solid angle (sr); scattering albedo
ω_p	plasma frequency (rad/s)

SUBSCRIPTS

0	vacuum
1,2,3	medium 1,2,3
B, b or bb	blackbody
e	electron
em	emitted
h	hole
i	incident
L	radiance
m	medium
r	reflected
t	total (integration over all wavelengths or frequencies)
λ, ν	spectral property in terms of wavelength or frequency

SUPERSCRIPTS

h	hemispherical
p	TM wave or p (parallel) polarization
s	TE wave or s (perpendicular) polarization
$'$	used to signify a directional radiative property
*	complex conjugate