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Modern Gas-Based Temperature and Pressure Measurements

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and Gianfranco Molinar

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Preface

Since the beginning of the preparation of this volume, we have been convinced that temperature and pressure measurements should not be separated, particularly in different applications at low temperatures. This belief has made us deeply conscious of the fact that the advanced applications and modern experimental methods of investigation in science and technology need the combination of various professional experiences and approaches.

Although the book is divided into two parts (Part I by F. Pavese and Part II by G. F. Molinar), we have tried to correlate low-temperature and low-pressure measurements as much as possible. We hope that our readers will find this book, which contains a large number of experimental and reference data, useful in their effort to solve measurement problems.

We are pleased to acknowledge our debt to several persons and wish to express our gratitude to them for their valuable cooperation and help: to our research group colleagues at the Istituto di Metrologia "G. Colonnetti" —IMGC (CNR), without whom the knowledge and the experience we built up during many years could not have been acquired; to G. T. McConville, M. Durieux, and K. Grohmann for revisions of and various suggestions for Part I; to V. E. Bean and C. R. Tilford of NIST and G. T. McConville for revisions of and various suggestions for Part II; and to I. Prinetti of IMGC for many valuable suggestions and careful textual revisions.

Last, although the most important, are our families, to whom we express our very special thanks and deep gratitude for putting up uncomplainingly with our too often self-centered demands, and for greatly helping us with unselfish understanding in the preparation of this text.

To them (Ghita, Carlo, and Matteo Pavese; Dida and Daniele Molinar) this book is dedicated.

Franco Pavese
Gianfranco Molinar

Turin, Italy

Introduction

The use of substances that are gaseous at room temperature for temperature measurements and for standards realization is traditional in the cryogenics field. Vapor-pressure thermometry and gas thermometry have been for many years the most common nonelectrical methods for temperature measurements in physics and chemistry. Correspondingly, specific systems have been developed to measure pressure in gaseous media.

Most of the studies on thermophysical properties of these substances were carried out in the first half of the 20th century, but work is still in progress, though with less momentum, especially at NIST (formerly NBS) in the USA as well as in the USSR. As far as its use in metrology is concerned, the adoption of the IPTS-68 in 1968 stimulated new activity, both intensive and extensive, as some of these properties form the basis of low-temperature thermometry. This led to the adoption of the new International Temperature Scale (ITS-90), which came into effect on January 1, 1990.

This activity resulted in a sizable upgrading of the accuracy in the determination of gas properties relevant to temperature standards and to standards traceability to the thermodynamic temperature. New techniques were also developed, which greatly improved the reliability of fixed point realization; the possibility of simplifying the use of the existing standards and of adopting new gas-based standards was explored and some of them are presently in use.

This volume is intended to collect up-to-date information on the latest developments in thermometry and manometry that involve the use of gaseous substances and that are likely to be valid methods also in the future. At present, this information is dispersed in a large number of papers published in international journals and most of the material is probably available only to a limited number of specialists. While other recent books on thermometry deal, in a comparable number of pages, with the *whole* range of temperatures and techniques, the part of the present work devoted to thermometry intends, in the first place, to introduce selected methods, leaving the general description of thermometry to textbooks. Second, being limited to low-temperature and gas-based techniques, the present volume intends to supply the reader with information about the very tools for their implementation. Instead of the usual "Problems," a synopsis of "Solutions" to problems of thermometry implementation is therefore added at the end of each chapter.

As regards manometry and pressure measurements in general, this book fills a gap in the international literature, since no other recent book provides a comprehensive survey of methods for pressure measurements in gaseous media used in the medium- to low-pressure range closely connected with thermometry.

Although both parts of the book give special attention to future-oriented techniques, their approaches in dealing with the subject are very different. Part I is concerned with thermometric techniques for which, except for a few recent exceptions, no commercial devices are available: these types of thermometers must be directly implemented by individual users. Consequently, most of the information collected is intended to help these users to select the best design, from the standpoint both of simplicity and of accuracy, and to be self-sufficient to supply all data necessary for their implementation. On the other hand, for most of the pressure-measuring techniques dealt with in Part II, commercial equipment, particularly in the case of pressure transducers, is available. Accordingly, users can find the basic description of such instruments and all the data necessary for appropriate criteria of selection, in view especially of obtaining the best possible accuracy for thermometric and manometric applications.

The methods and the instruments dealt with, which allow medium- to high-temperature and pressure accuracy to be achieved, are *not* intended only for applications that need the best measurement accuracy of interest for standard laboratories (though the error analysis is always pushed to this level). Rather, they can be used in a broader range of applications. The text does not include methods or instruments intrinsically limited to low accuracy.

In Part I basic concepts of temperature and temperature scale are introduced, together with a short review of the different temperature definitions, so that the reader may be made aware of the difficulties involved in defining temperature, especially when it becomes lower and lower.

The use of well-specified thermodynamic states of condensed gases as temperature fixed points (within the temperature range 2.2–220 K) is then illustrated, and the most effective method for their realization, the sealed-cell method, is fully described.

In subsequent chapters, thermometric methods exploiting a pressure–temperature relationship are described. For the gaseous state and for the range 1–300 K, the different types of gas thermometers are discussed, with special emphasis being given to the constant-volume type, not only as an absolute thermometer, but also as an interpolating thermometer (as required by the ITS-90, but in a broader temperature range) and as a simple and practical self-contained device.

In connection with condensed gases, vapor-pressure thermometry is described for the helium isotopes in the range from 0.3 to 5 K and for its implementation with other gases in the range up to 300 K; special attention is given to simplified realizations using sealed devices.

The ^{3}He melting-curve thermometry is then introduced as the most promising, accurate temperature-measuring means below the present range of the ITS-90.

The last chapter of Part I offers a survey of the hardware specifically required for the implementation of these types of thermometry and considers in particular the modern use of closed-cycle refrigerators above 4 K and the use of gases in temperature control.

In Part II gas pressure measurements are considered in the range from 100 Pa to 100 MPa, in connection with the former applications to thermometry. Modern primary standards for accurate pressure measurements of gaseous media are reviewed with a detailed and comprehensive description of their best use.

Liquid-column manometers are described for absolute, gauge, and differential pressure measurements in the range from a few pascal to less than 0.3 MPa. Subsequently modern gas-operated piston gauges are extensively discussed for absolute pressure measurements up to about 5 MPa, relative pressure measurements up to 100 MPa, and differential pressure measurements.

Liquid manometers and piston gauges are particularly described, analyzing each physical quantity affecting pressure measurement uncertainty.

A survey is made of pressure transducers, particularly of those used for differential measurements and others which can be employed directly in a cryogenic environment. Problems involved in the assessment of their metrological characteristics, mostly stability with time and thermal cycling, are discussed connected with their use as transfer standards. Typical procedures to be used for a correct data acquisition and calibration of significant parameters of pressure transducers are given.

The gas-based fixed points (triple points, critical points,...) available in the considered pressure range are reviewed from the standpoint of their use as transfer standards for interlaboratory comparisons.

Physical quantities and phenomena that affect pressure measurements are thoroughly discussed, as they must be taken into account to obtain high accuracy when using primary standards. In this context, special attention is devoted to a specific and controversial problem of cryogenic measurements: the thermomolecular pressure-difference effect.

Appendix A introduces and comments on text of the International Temperature Scale of 1990 (ITS-90). Its implementation, which always requires gas-based thermometry types below 0°C, is discussed in detail in Part I.

Extensive reference data are supplied in the Appendixes. They include: a comprehensive list of temperature (with values in ITS-90) and pressure fixed points; relevant thermophysical data and advice for their specific use in thermometric and manometric fields, given in the form of data sheets for each of 15 substances commonly used in manometry and thermometry; tables for the main manometric and piston gauge corrections (according to ITS-90) with specific examples of accuracy evaluation.

Finally, an extensive bibliography is included in the References of Part I and Part II which covers all the subjects discussed, and which includes a "Further Readings" section for the main topics.

List of Acronyms

AGT	acoustic gas thermometer
ASMW	Amt für Standardisierung, Messwesen und Warenprüfung (G)
BCR	Bureau Communautaire de Référence of the European Economic Community
BIPM	Bureau International des Poids et Mesures
CCM	Comité Consultatif pour la Masse et les Grandeurs apparentées
CCT	Comité Consultatif de Thermométrie
CGPM	Conférence Générale des Poids et Mesures
CIAME	Commission Interministerielle des appareils électriques et électroniques de mesure (F)
CIPM	Comité International des Poids et Mesures
CSIRO	Commonwealth Scientific Industrial Research Organization (AA)
CVGT	constant volume gas thermometer
DCGT	dielectric constant gas thermometer
EEC	European Economic Community
ICVGT	interpolating constant volume gas thermometer
IEC	International Electrotechnical Commission
IMGC	Istituto di Metrologia "G. Colonnetti" of the Italian National Research Council
INM	Institut National de Métrologie, du Bureau National de Métrologie (BNM) (F)
IPRT	industrial platinum resistance thermometer
IPTS-48	International Practical Temperature Scale of 1948
IPTS-68	International Practical Temperature Scale of 1968
ISA	Instrument Society of America
ISO	International Standards Organization
ITS-90	International Temperature Scale of 1990
IUPAC	International Union of Pure and Applied Chemistry
IUPAP	International Union of Pure and Applied Physics
KOL	Kamerling Onnes Laboratorium (NL)
LNE	Laboratoire National d'Essais (F)

m.c.	melting curve (mc as subscript). Also referred to as melting line (m.l.).
n.b.p.	normal boiling point (nbp as subscript)
NIM	National Institute of Metrology (CN)
NIST	National Institute of Standards and Technology (formerly NBS) (USA)
NML	National Measurement Laboratory (also DAP, Division of Applied Physics of CSIRO) (A)
NPL	National Physical Laboratory (UK)
NPL-I	National Physical Laboratory (India)
NRC	National Research Council (Canada)
NRLM	National Research Laboratory of Metrology (J)
OIML	Organization Internationale de Métrologie Légale
PTB	Physikalische-Technische Bundesanstalt (G)
RIGT	refractive index gas thermometer
RGA	residual gas analyzer
RM	reference material
SPRT	standard platinum resistance thermometer
SRM	standard reference material
s.s.t.	solid-to-solid transition (sst as subscript)
T_{58}	former ^{4}He vapor-pressure scale
T_{62}	former ^{3}He vapor-pressure scale
T_{68}, t_{68}	Kelvin and Celsius temperature in IPTS-68
T_{76}	Kelvin temperature in EPT-76
T_{90}, t_{90}	Kelvin and Celsius temperature in ITS-90
TC	thermocouple thermometry
t.p.	triple point (tp as subscript)
VNIIFTRI	(also PRMI) State Institute for Physicotechnical and Radio-technical Measurements (USSR)
v.p.	vapor pressure (vp as subscript)
WG2	Working Group 2 of CCT on Secondary Thermometry

Notes to the Reader

1. All temperature data are referred to the new International Temperature Scale 1990 (ITS-90). This is correct except when otherwise stated, because in some cases there are real needs to express some relevant data with reference to the old IPTS-68 temperature scale.
2. All the uncertainties are declared at the one sigma ($1\hat{\sigma}$) level, except when otherwise stated. This is necessary because sometimes we are reporting data from literature where either uncertainties are not declared or it is impossible to recalculate the $1\hat{\sigma}$ level uncertainty.
3. All notations are made according to IUPAC recommendations (IUPAC, 1988). In some cases, however, American rather than British spelling has been used (e.g., meter rather than metre and liter rather than litre).

Contents

Part II Pressure Measurements in the Range from 10^2 Pa to 10^8 Pa

Part I

Temperature Measurements in the Range from 0.1 K to 300 K

Introduction

Part I describes modern methods for measuring temperatures lower than 0 °C based on the use of substances that are gaseous at room temperature. The lower limit of the temperature range where these substances can be used is arbitrarily set at ≈ 0.1 K, but ^{3}He melting-curve thermometry, described in Chapter 5, extends down to ≈ 0.001 K.

Figure I. shows the typical range for each of these gas-based types of thermometry. The present state of the art allows a top measurement accuracy of ± 0.1–0.3 mK for all of them.

Each of the fixed points described in Chapter 2 realizes a single temperature value. Gas thermometry, described in its various forms below 0 °C in Chapter 3, can be used as well above room temperature. Vapor-pressure thermometry too, described in Chapter 4, can be used above room temperature: each substance spans only a narrow interval of the whole temperature range, and in some intervals no substance is available.

Finally, Chapter 6 describes thermostats that are used for performing all these thermometric measurements, and temperature controls and devices that are based on the use of gases.

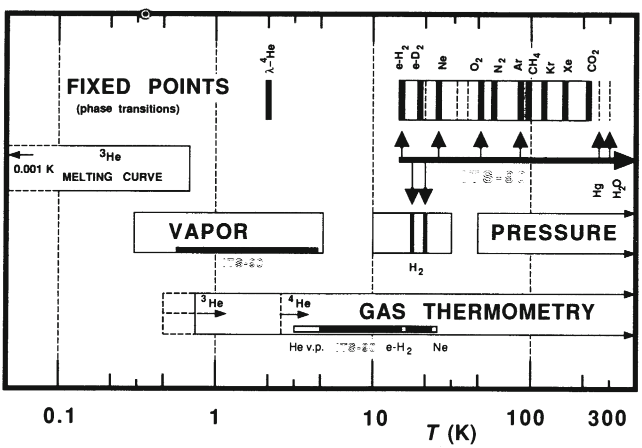

Fig. I.1. Typical range of gas-based thermometry types.