An introduction to thermal physics

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Contents

For Frances, Martin and Penelope

Preface

In recent years there have been marked changes in both the style and the content of physics courses at all levels. The general trend has been towards an increased emphasis on fundamental principles and microscopic explanations. As a consequence, the relative importance attached to various topics has changed, some new ones have been introduced and others, such as geometrical optics, virtually eliminated. Another consequence is that less detailed knowledge of numerous experimental techniques is now expected; in general, only a familiarity with the principles of various methods is required. These changes are reflected in revised syllabuses and call for a new generation of textbooks. It is in the spirit of these changes that this book is written.

The area covered corresponds very roughly to the traditional topics of *heat* and *kinetic theory* together with those parts of *properties of matter* for which there are simple explanations in terms of interatomic forces.

In level, the book is intended for use at universities and technical colleges in physics, engineering, chemistry or other science courses that require an elementary knowledge of thermal physics. It can be used in two ways: either as an introductory text, setting a firm foundation for further work in more specialized courses, or as an account, sufficient in itself for those requiring only a basic knowledge of the subject. It should also be useful in the science libraries of school sixth forms as a reference book that can help to point the way from school physics to the more mature approach of tertiary study. A familiarity with elementary calculus is assumed as its use is essential in the derivation of some of the fundamental results. However, when a result may also be derived without the use of calculus, an alternative derivation is generally given.

SI units are now essentially universal throughout science teaching and the text uses the system exclusively. It also generally follows the current recommendations of the Symbols Committee of the Royal Society as regards conventions for showing physical quantities and their units, and it incorporates the modern definitions of temperature scales.

The development of a sensibility towards the nature and magnitude of physical processes is an essential part of an education in physics and I consider the use of quantitative problems and exercises an essential means to this end. At the end of each chapter I have assembled a collection of problems. Many are original and some are inspired by ideas which have appeared in examination questions and in other texts. The problems are grouped according to the chapter subsections and, in each case, follow a brief summary of the key ideas of the relevant subsection. This makes it possible to work through the problems in parallel with the study of the text, so using them as an aid to learning. The arrangement is also useful for revision purposes. Generally I have avoided the inclusion of discursive questions, except where they are essential to cover certain key topics which cannot be tested quantitatively at that stage of the book. I have not included explicit worked examples separated out within the text. There are several reasons for this, among which is the fact that numerical examples are worked out as part of the narrative, and also, in many cases, the quantitative development of a key result serves to illustrate how that key result may be used.

Despite its title, this is not an easy book, for although it only deals with the *foundations* of thermal physics, the text challenges the reader to think deeply and carefully about the concepts and methods of the subject. It also seeks to show the relevance of the subject by relating these concepts and methods to the everyday physical world. Thus, although a simplistic reading will yield some understanding of thermal physics, more thoughtful study will bring extra rewards.

I should like to thank my wife, Tessara, for her suport and encouragement while I was writing this book, and to thank her and Jean Millar for their help with some of the illustrations. I am also most grateful to C. B. Spurgin whose advice and criticisms as the book took shape were much appreciated.

It is also a pleasure to thank: Dr J. Ashmead and the Institute of Physics for permission to use the photograph reproduced in figure 4.15; Dr A. M. Glazer for supplying me with the X-ray scattering picture from which figure 3.5 was prepared; AGA Infrared Systems AB for supplying me with the thermogram reproduced in figure 6.7; Foster Cambridge Ltd. for the disappearing filament illustration of figure 1.22; RS Components Ltd. for permission to reproduce the thermistor data shown in figure 1.19; and the Escher Foundation at Haags Gemeente-museum, The Hague, for permission to reproduce Escher's *Waterfall* in figure 2.4 and on the cover.

My objective throughout the detailed writing of this book has been to achieve a clear and stimulating exposition: to write a book which is easy to learn from. Those who use it must judge whether I have been successful.

C. J. Adkins
Cambridge, 1986

Units, Symbols and Conventions

This book uses SI (Système International) units and generally follows the current recommendations of the Symbols Committee of the Royal Society as regards symbols and conventions of notation.*

The names and symbols for the SI base units are:

Physical quantity	*Name of SI unit*	*Symbol for SI unit*
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

The SI units of certain common physical quantities have special names. Some of those used in this book are listed in the table below.

Angles, though formally defined so as to be dimensionless (see Appendix, section A.1), are sometimes considered as supplementary units:

Physical quantity	*Name of SI unit*	*Symbol for SI unit*
plane angle	radian	rad
solid angle	steradian	sr

The International System has a set of prefixes which may be used to construct decimal multiples of units.†

Multiple	*Prefix*	*Symbol*	*Multiple*	*Prefix*	*Symbol*
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f			
10^{-18}	atto	a			

Physical quantity	*Name of SI unit*	*Symbol for SI unit*	*Definition of SI unit*	*Equivalent forms*
force	newton	N	$\mathrm{m\,kg\,s^{-2}}$	$\mathrm{J\,m^{-1}}$
energy	joule	J	$\mathrm{m^{2}\,kg\,s^{-2}}$	$\mathrm{N\,m}$
pressure	pascal	Pa	$\mathrm{m^{-1}\,kg\,s^{-2}}$	$\mathrm{N\,m^{-2}}$, $\mathrm{J\,m^{-3}}$
power	watt	W	$\mathrm{m^{2}\,kg\,s^{-3}}$	$\mathrm{J\,s^{-1}}$
electric charge	coulomb	C	$\mathrm{s\,A}$	$\mathrm{A\,s}$
electric potential difference	volt	V	$\mathrm{m^{2}\,kg\,s^{-3}\,A^{-1}}$	$\mathrm{J\,A^{-1}\,s^{-1}}$, $\mathrm{J\,C^{-1}}$
electric resistance	ohm	Ω	$\mathrm{m^{2}\,kg\,s^{-3}\,A^{-2}}$	$\mathrm{V\,A^{-1}}$
electric capacitance	farad	F	$\mathrm{m^{-2}\,kg^{-1}\,s^{4}\,A^{2}}$	$\mathrm{A\,s\,V^{-1}}$, $\mathrm{C V^{-1}}$
inductance	henry	H	$\mathrm{m^{2}\,kg\,s^{-2}\,A^{-2}}$	$\mathrm{V\,A^{-1}\,s}$
frequency	hertz	Hz	$\mathrm{s^{-1}}$	

* *Quantities, Units and Symbols*, The Royal Society (London, 1975).

† μ, the prefix meaning one millionth, is the Greek letter *mu*.

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C. J. Adkins
Frontmatter
More information

Symbols for units are always printed in roman (upright) type while symbols for physical quantities such as p for pressure are printed in italic (sloping) type.

The value of a physical quantity is always equal to the product of a numerical value and a unit. Thus, the physical quantity, the mass m_e of the electron is given by

$$m_e = 9.11 \times 10^{-31}\,\mathrm{kg}$$

In this equation, the magnitude and unit of the physical quantity are equated across the equals sign. An equivalent dimensionless equation is

$$m_e/\mathrm{kg} = 9.11 \times 10^{-31}$$

Here, the solidus (/) on the left hand side represents division in the usual way: the physical quantity (mass of an electron) is divided by a unit of mass (the kilogram) and the result is a pure number, 9.11×10^{-31}, the number of kilograms in the mass of one electron.

The use of the solidus to represent division of a physical quantity by a unit may be applied in several other ways.

a) *More complex equations* relating physical quantities may often be written concisely and unambiguously using the solidus notation. For example, the molar heat capacity at constant pressure of copper C_{pm} depends on thermodynamic temperature T at low temperatures according to the equation

$$C_{pm}/\mathrm{kJ\,K^{-1}\,mol^{-1}} = 1.94\,(T/\Theta)^3$$

where $\Theta = 348\,\mathrm{K}$ is the 'Debye Temperature' of copper. Here, $\mathrm{kJ\,K^{-1}\,mol^{-1}}$ is the unit in which the heat capacity is measured so that the left hand side is a dimensionless number. Similarly, the term in brackets on the right is dimensionless because both T and Θ are temperatures measured in kelvins. Clearly, the number 1.94 is also dimensionless to that the equation is dimensionally homogeneous throughout. An alternative way of giving the same information would be to write

$$C_{pm} = a(T/\Theta)^3$$

where

$$a = 1.94\,\mathrm{J\,K^{-1}\,mol^{-1}}$$

In this form, dimensional quantities are equated across the equals sign. But it is *wrong* to write

$$C_{pm} = 1.94\,(T/\Theta)^3$$

for this equation is dimensionally inconsistent: the left side has dimensions of heat capacity while the right side is dimensionless. The equation only 'works' if C_{pm} is measured in the right units. An equation should express a physical fact; and since a true physical fact is true regardless of how (in what units) it is measured, this last form is unacceptable.

b) *In tables and graphs* the numbers entered or plotted are dimensionless so that the labelling of the table headings or graph axes should also be dimensionless. Thus, a graph of pressure against temperature might have its axes labelled 'pressure/mmHg' and 'temperature/K' respectively. The result of dividing the physical quantity pressure by the unit of pressure mmHg is a pure number, and so is the result of dividing temperature by kelvins. The axes are therefore calibrated in pure numbers and it is the relationship between two pure numbers which the graph displays. It is *not* correct to label the axes 'pressure (mmHg)' and 'temperature (K)' because, following normal notation, these would mean either pressure multiplied by mmHg and temperature multiplied by kelvins, or pressure, a function of the unit mmHg, and temperature, a function of the kelvin. Either alternative is nonsense. Nevertheless, such forms have been used in the past with the meaning 'the numbers on this axis give the magnitude of the pressure when it is measured in mmHg', etc. Clearly, there is no need to have to adopt a special meaning to the use of brackets when the solidus notation is physically and mathematically correct and totally unambiguous.

c) The solidus notation is also useful for *changing the units in which a physical quantity is measured*. It reduces conversion of units to routine algebra. Suppose the speed u of a car is $90\,\mathrm{km\,h^{-1}}$ and we wish to find its speed in $\mathrm{m\,s^{-1}}$. We are given $u/\mathrm{km\,h^{-1}} = 90$ and we want $u/\mathrm{m\,s^{-1}}$. Following the normal rules of algebra we may write

$$u/\mathrm{m\,s^{-1}} = (u/\mathrm{km\,h^{-1}}) \times (\mathrm{km/m}) \times (\mathrm{s/h})$$

The first bracket on the right is the number given, the second is the pure number which results from dividing 1 km by 1 m, namely 1000; and the third term on the right is the pure number which results from dividing the unit of time, 1 s by the unit of time 1 h, namely 1/3600. Thus,

$$u/\mathrm{m\,s^{-1}} = 90 \times 1000 \times 1/3600 = 25$$

or

$$u = 25\,\mathrm{m\,s^{-1}}$$

Finally, we list the symbols used in this book.

ROMAN LETTERS

a	constants
b	constants
c	molecular speed
d	distance
	infinitesimally small change in
e	spectral emissive power
	electronic charge
	base of natural logarithms
f	number of degrees of freedom
	a function
g	acceleration of free fall
h	Planck constant
i	an integer
k	Boltzmann constant
l	mean free path
m	mass
n	number of moles
	number density
p	pressure
r	radius, distance
t	Celsius temperature
	time
x	a variable
y	a variable
z	coordination number
	a variable
A	area
C	heat capacity
	capacitance
E	Young modulus
	electromotive force
	electric field strength
F	force
H	scale height
I	current
J	joule
	current density
K	kelvin
	bulk modulus
L	length
	latent heat
	inductance
	Lorenz number
M	molar mass
P	power
	probability
Q	heat
	charge
R	resistance
	molar gas constant
S	entropy
	molecular diameter
T	thermodynamic temperature
U	internal energy
V	volume
	potential difference
$\mathscr{V}$	speed
W	work

GREEK LETTERS

Letter	*Name*	*Meanings*
α	alpha	spring constant, linear expansivity, absorptivity
β	beta	cubic expansivity
γ	gamma	ratio of principal heat capacities, surface tension
δ	delta	small change in
Δ	delta (cap.)	finite increment of
ε	epsilon	energy, emissivity
η	eta	viscosity, efficiency
θ	theta	angle
Θ	theta (cap.)	empirical temperature
κ	kappa	compressibility
λ	lambda	thermal conductivity, wavelength
μ	mu	one millionth
ν	nu	frequency
π	pi	ratio of circumference to diameter of circle
ρ	rho	density
σ	sigma	electrical conductivity, Stefan–Boltzmann constant
ϕ	phi	potential
Φ	phi (cap.)	flux density
ω	omega	angular frequency
Ω	omega (cap.)	solid angle, ohm

MATHEMATICAL NOTATION

$+$	plus
$-$	minus
$=$	equal to
$\neq$	not equal to
$\approx$	approximately equal to
$\propto$	proportional to
$<$	smaller than

$>$	larger than
$\leqslant$	smaller than or equal to
$\geqslant$	larger than or equal to
$\ll$	much smaller than
$\gg$	much larger than
$\langle a \rangle, \bar{a}$	mean value of a
$f(x)$	function of x
$\lim_{x \to a} f(x)$	the limit to which $f(x)$ tends as x approaches a
Δ	finite increment of
δ	small change of
$\frac{\mathrm{d}f}{\mathrm{d}x}$	differential coefficient of $f(x)$ with respect to x
$\left(\frac{\partial f}{\partial x}\right)_y$	partial differential coefficient of $f(x, y)$ with respect to x when y is held constant
$\mathrm{d}f$	total differential of f (infinitesimal change in f)
$\int f(x)\,\mathrm{d}x$	the integral of $f(x)$ with respect to x
$\oint f(x)\,\mathrm{d}x$	the integral of $f(x)$ with respect to x around a closed path
$\mathrm{e}^x, \exp x$	exponential of x
e	base of natural logarithms
$\ln x$	natural logarithm (logarithm to the base e) of x
$\lg x$	common logarithm (logarithm to the base 10) of x