Thermal Properties of Matter

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This book is dedicated to the memory of the inspirational Professor Julius Sumner Miller who brought the joy and adventure of physics into the homes of most Australian families with his 'Why is it so?' ABC television series. Teaching by the use of physical demonstrations accompanied by a constant stream of unanswered questions lured many of us to try and repeat these demonstrations and find our own answers to his questions. Professor Miller held a visiting position in the School of Physics at the University of Sydney for many years and enriched the teaching culture by the use of demonstrations. It is hoped that some of this teaching culture is captured in the demonstrations, examples, and stories given in this book.

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Preface

This book originated from the lecture notes of a course, conducted by the author at the University of Sydney, on the properties of matter given to students with little or no background in physics. Many of these students would have undertaken a one-semester course on an introduction to physics. All of these students were undertaking degrees in the biological, medical, or environmental sciences. Consequently, many examples given in this book have a biological or environmental flavour. Moreover, it is by no means an exhaustive book on thermal physics, but is quite narrow in its scope and is only concerned with the basic thermal properties of matter, as reflected in the title of the book.

Acknowledgments

Many thanks to Nicki Dennis for finding my lecture notes on this topic and suggesting that they could be made into a book. Also, I’m grateful to Chris Benson for the production of this book.

Author biography

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Joe Khachan is an Associate Professor in the School of Physics at The University of Sydney, Australia. His field of research is experimental plasma physics with a focus on the generation of clean and sustainable energy from the fusion of atomic nuclei in the plasma. He obtained his Physics Honours and PhD degrees from the University of New South Wales, Australia, and has been actively involved in research and education for more than 30 years. His fields of research have covered both the solid and plasma states of matter.

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Symbols

α Temperature coefficient of linear expansion (K^{-1})
β Temperature coefficient of volume expansion (K^{-1})
γ Ratio of heat capacities
ε Permittivity
κ Dielectric constant
λ Wavelength (m)
ρ Density (kg m^{-3})
$\mathbf{B}$ Magnetic field (T)
C Molar heat capacity (J kg^{-1} K^{-1})
f Frequency
k Thermal conductivity (W m^{-1} K^{-1})
R Ideal gas constant (8.31 J mol^{-1} K^{-1})

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Chapter 1

Introduction

The ancient Greeks believed that all matter was composed of four elements: earth, water, air, and fire. By a remarkable coincidence (or perhaps not), today we know that there are four states of matter: solids (e.g. earth), liquids (e.g. water), gases (e.g. air) and plasma (e.g. ionized gas produced by fire). The latter state is beyond the scope of this book and we will only look at the first three states. Although on the microscopic level all matter is made from atoms or molecules, everyday experience tells us that the three states have very different properties. The aim of this book is to examine some of these properties and the underlying physics.

Many simple substances (i.e. compounds) consist of atoms held together by covalent bonds forming molecules. The molecules of a substance can be attracted to others by electrostatic forces (dipole–dipole, van der Waals, hydrogen bonds, etc). These cohesive forces are much weaker than the covalent bonds. Other substances, such as table salt, consist of atoms which have gained or lost electrons and therefore have a charge; the attraction between these ions is called the ionic bond. There are a few substances that consist only of atoms. One example is the noble gases (helium, argon, etc) which do not form molecules, and another is metals, but the nature of the metallic bond is not a topic for this book. From now on we will generally speak of the particles comprising a substance without specifying atom, molecule, or ion.

Solids are composed of particles held together by cohesive forces or ionic bonds. If these forces are strong, the particles are tightly bound to one another and matter is said to be in the solid state. If we increase the kinetic energy of the atoms, by, say, heating them, then we will show later that they are further apart on average. This increase in average distance results in weaker cohesive forces, which in turn can lead to matter being in the liquid or gaseous state.

Example: Consider cooling water by placing it in the freezer. It turns to ice when it reaches a sufficiently low temperature because the kinetic energy of the water molecules becomes less than the cohesive bond energy and so water turns to a solid (ice). If on the other hand we 'heat up' the water, which means we make the kinetic

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energy much greater than the cohesive energy, then water turns to gas or water vapour.

Example: Many solid properties depend on temperature and atomic bonds. For example, diamond conducts heat four times faster than copper at room temperature. If you can make a defrosting board out of a giant slab of diamond, then your frozen chicken will defrost four times faster!

A crushing demonstration
Liquid nitrogen boils at a temperature of −196 °C. If a fresh rose is placed in liquid nitrogen and then removed, it can be smashed so that it will shatter like glass. That is, its mechanical properties are temperature dependent.

We will look at the thermal and mechanical properties of matter and how they relate to the behaviour of atoms on the microscopic level. At this point we will briefly describe the difference between mechanical and thermal properties.

Mechanical properties are the response of matter to applied forces. These properties are controlled largely by the interatomic forces or the interatomic potential energy. **Thermal properties** are the response of matter to applied heat. These properties are controlled largely by interatomic motions or kinetic energy. Most of the mechanical and thermal properties of matter are adequately described by classical mechanics, such as potential and kinetic energy. So it is assumed that you have some knowledge of these concepts.