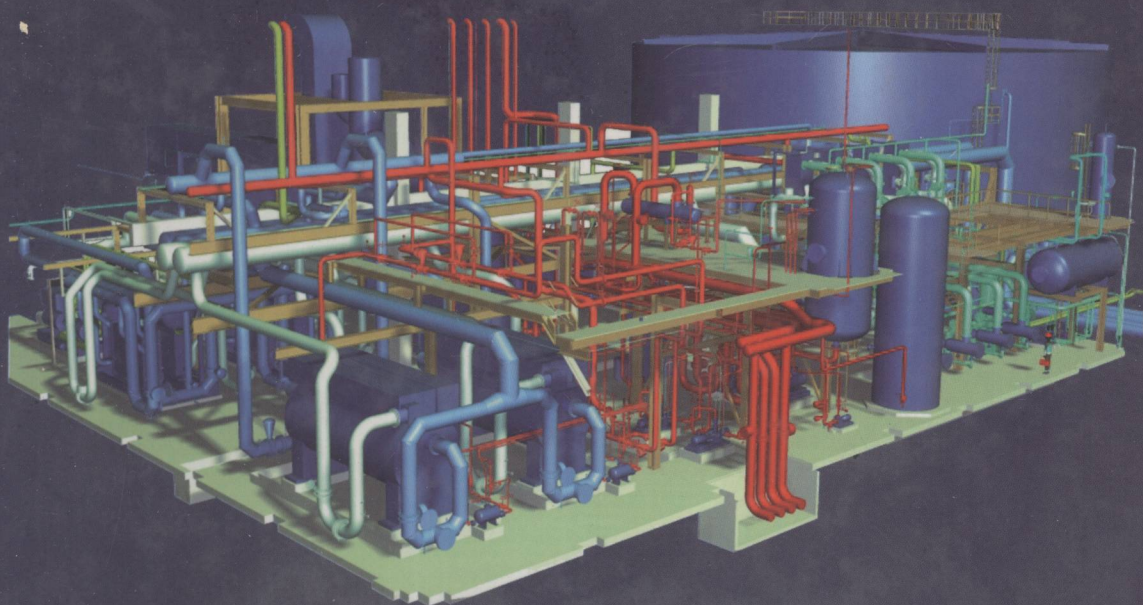


THERMAL ENERGY STORAGE

Systems and Applications



İbrahim Dincer
Marc A. Rosen

TK 11
D583

THERMAL ENERGY STORAGE

Systems and Applications

İbrahim Dinçer

KFUPM, Dhahran, Saudi Arabia

and

Marc A. Rosen

Ryerson Polytechnic University, Toronto, Canada

with contributions from

A. Bejan

Duke University, USA

A. J. Ghajar

Oklahoma State University, USA

K. A. R. Ismail

FEM-UNICAMP, Brazil

M. Lacroix

Université de Sherbrooke, Canada

Y. H. Zurigat

Sultan Qaboos University, Oman



E200201022

JOHN WILEY & SONS, LTD

Copyright © 2002 John Wiley & Sons, Ltd., Baffins Lane, Chichester,
West Sussex PO19 1UD, England

Phone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.co.uk or www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd., 90 Tottenham Court Road, London W1P 0LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons, Ltd., Baffins Lane, Chichester, West Sussex PO19 1UD, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770571.

Other Wiley Editorial Offices

John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Pappelallee 3, D-69469 Weinheim, Germany

John Wiley & Sons Australia, Ltd., 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd., 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada, Ltd., 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Library of Congress Cataloging-in-Publication Data

Thermal energy storage systems and applications / edited by Ibrahim Dincer, Marc Rosen.
p. cm.

Includes bibliographical references and index.

ISBN 0-471-49573-5

1. Heat storage. I. Dincer, Ibrahim. II. Rosen, Marc (Marc A.)

TJ260 .T493 2001

621.402'8—dc21

2001026254

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-471-49573-5

Printed from PostScript files supplied by the author.

Printed and bound in Great Britain by Antony Rowe, Chippenham, Wiltshire.

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Front cover image: Trigeneration Project for World Fair Expo'98 at Lisbon, Portugal with its thermal energy storage (large cylindrical tank in rear) (*Courtesy of Paragon-Litwin, France*)

THERMAL ENERGY STORAGE

Systems and Applications

✎ To my wife, Gülşen, and my children, Meliha, Miray and İbrahim Eren,
for their inspiration.

And to those who have helped and supported me in any way throughout my education and
professional life.

İbrahim Dinçer

&

✎ To my wife, Margot, and my children, Allison and Cassandra, for their inspiration.

And to Frank C. Hooper and David S. Scott, two giants in the field of energy and
wonderful mentors.

Marc A. Rosen

List of Contributors

Dr. Adrian Bejan

Professor

Department of Mechanical Engineering and Materials Science, Duke University

Box 90300, Durham, North Carolina, 27708-0300, USA

E-mail: abejan@duke.edu

Dr. Ibrahim Dincer

Professor

Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals

Box 127, Dhahran 31261, Saudi Arabia

E-mail: idincer@kfupm.edu.sa

Dr. Afshin J. Ghajar

Regents Professor and Director of Graduate Studies

School of Mechanical and Aerospace Engineering, Oklahoma State University

218 Engineering North, Stillwater, OK 74078-5016, USA

Email: ghajar@master.ceat.okstate.edu

Dr. Kamal A. R. Ismail

Professor

Department of Thermal and Fluids Engineering, State University of Campinas

CP 6122, CEP 13083-970, Campinas (SP), Brazil

E-mail: kamal@fem.unicamp.br

Dr. Marcel Lacroix

Professor

Département de Génie Mécanique, Université de Sherbrooke

Sherbrooke, Quebec, Canada J1K 2R1

E-mail: marcel.lacroix@gme.usherb.ca

Dr. Marc A. Rosen.

Professor

Department of Mechanical Engineering, Ryerson Polytechnic University

350 Victoria Street, Toronto, Ontario, Canada M5B 2K3

E-mail: mrosen@acs.ryerson.ca

Dr. Yousef H. Zurigat

Associate Professor

(On leave from Jordan University, Amman, Jordan)

Department of Mechanical and Industrial Engineering, Sultan Qaboos University

Muscat - 123, Sultanate of Oman

E-mail: zurigat@squ.edu.om

Acknowledgements

We are most grateful to the contributors

- Professor Adrian Bejan
- Professor Afshin J. Ghajar
- Professor Kamal A.R. Ismail
- Professor Marcel Lacroix
- Professor Yousef H. Zurigat

who dedicated time and effort to preparing their chapters. Their thoughtful contributions span a range of topics that, taken together, permit the book to provide a comprehensive resource on thermal energy storage.

We also are especially thankful to the many companies and agencies which contributed case studies and other materials for use in the book. These valuable materials have allowed us to ensure that the book has a high degree of industrial relevance and practicality. Included among those deserving acknowledgement are the following:

- American Electric Power, USA
- Baltimore Aircoil International N.V., Belgium
- CHIYODA Corporation, Japan
- CRISTOPIA Energy Systems, France
- CRYOGEL, Ice Ball Thermal Storage, USA
- Environmental Process Systems Limited, UK
- IEA-Heat Pump Center, The Netherlands
- MARCO, Saudi Arabia
- Mitsubishi Chemical Co., Japan
- Paragon-Litwin, France
- Paul Mueller Company, USA
- WS Atkins Consultants Limited, UK

We also appreciate the support and assistance provided by our universities, King Fahd University of Petroleum and Minerals and Ryerson Polytechnic University.

In addition, we are grateful to the support provided by John Wiley & Sons, UK in the development of this book, from the initial idea through to the final product.

We also are thankful to Mr. Mohammed Mujtaba Hussain (graduate student of Dr. Dinçer) for his effort in sketching most of the figures.

Last, but not least, we thank our wives, Gülşen Dinçer and Margot Rosen, and our children Meliha, Miray and İbrahim Eren Dinçer and Allison and Cassandra Rosen. They have been a great source of support and motivation, and their patience and understanding throughout this project have been most appreciated.

İbrahim Dinçer
Marc A. Rosen

Figures 1.4; 2.7; 3.2 and 3.3 and Table 2.6 are reproduced by permission of John Wiley & Sons, Ltd. Figure 2.5 is reproduced by permission of Charles E. Bakis. Figure 3.5 is copyright Prentice Hall Inc. Figures 3.6; 3.19; 3.22 and 3.23 and Table 3.7 are reproduced by permission of IEA Heat Pump Centre. Figures 3.7; 9.7–9.9 and Tables 3.4 and 3.6 are reproduced by permission of Springer-Verlag, GmbH. Figures 3.9; 3.17; 4.1–4.3; 6.4; 6.10–6.13; 6.17; 8.14–8.23 and 8.38–8.44 and Table 4.2 are reproduced with permission from Elsevier Science. (See the individual figures and tables for reference sources.) Figure 3.16 is reproduced by permission of GSA Resources Inc. Figures 3.18; 11.19–11.22 and 11.23 are reproduced by permission of CRISTOPIA Energy Systems. Figures 3.24; 11.14 and 11.24 are reproduced by permission of Environmental Process Systems Limited. Figures 3.40; 11.11–11.13 are reproduced by permission of International District Energy Association. Courtesy of Paul Mueller Company from proceedings at the IDEA College-University Conference, New Orleans, Louisiana, February 1999. Figures 3.42–3.45 and the table on page 190 are reproduced by permission of Cryogel. Figures 3.46; 3.47; 11.7–11.10 and Tables 3.11–3.14 are reproduced by permission of Baltimore Aircoil International. Figures 5.4; 6.2; 6.16; 6.18 and 11.1 and Tables 6.1 and 11.1 are reproduced by permission of American Society of Heating, Refrigerating and Air Conditioning Engineers www.ashrae.org. Figures 6.6–6.9 6.14 and 6.15 are reproduced by permission of the American Society of Mechanical Engineers. Figures 6.19 and 8.2–8.9 and Table 4.1 are reproduced by permission of Taylor & Francis, Inc., <http://www.routledge-ny.com> (See the individual figures and tables for reference sources.) Figures 11.2–11.5 and Table 11.2 are reproduced by permission of WS Atkins Consultants Ltd. Figures 11.15–11.17 and Tables 11.4–11.6 are reproduced courtesy of Paragon-Litwin. Figure 11.6 is reproduced by permission of Ghaleb Abussaa'. Figures 11.25 and 11.26 are reproduced by permission of Sandia National Laboratories. Figure 11.27 is reproduced by permission of Kyushu Electric Power Co., Inc. Figure 11.28 is reproduced by permission of Rocky Mountain Research Institute. Table 2.1 is reproduced by permission of Aspes AG, Zürich. Table 2.3 is reproduced by permission of Electrosources Inc. Tables 3.2 and 3.3 are reproduced by permission of CADDET Energy Efficiency. Table 6.2 is reproduced by permission of International Solar Energy Society (ISES).

Preface

Thermal energy storage (TES) is an *advanced energy technology* that has recently attracted increasing interest for thermal applications such as space and water heating, cooling and air-conditioning. TES systems have enormous potential to facilitate more effective use of thermal equipment and large-scale energy substitutions that are economic. TES appears to be the most appropriate method for correcting the mismatch that sometimes occurs between the supply and demand of energy. It is therefore a very attractive technology for meeting society's needs and desires for more efficient and environmentally benign energy use.

This book is research-oriented, and therefore includes some practical features often not included in other, solely academic textbooks. This book is essentially intended for use by advanced undergraduate and graduate students in various disciplines ranging from mechanical to chemical engineering, and as a basic reference for practicing energy engineers. Analyses of TES systems and their applications are undertaken throughout this comprehensive book, providing new understandings, methodologies, models and applications, along with descriptions of several experimental works and case studies. Some of the material presented has been drawn from the most recent information available in the literature and elsewhere. The coverage is extensive, and the amount of information and data presented can be sufficient for several courses, if studied in detail. We strongly believe that this book will be of interest to students, engineers and energy experts, and that it provides a valuable and readable reference text for those who wish to learn about more about TES systems and applications.

The first chapter addresses general aspects of thermodynamics, fluid flow and heat transfer to furnish the reader with background information that is of relevance to the analysis of TES systems and their applications. Chapter 2 discusses the many types of energy storage technologies available. Chapter 3 deals extensively with TES methods, including cold TES. Chapter 4 addresses several environmental issues that we face today, and discusses how TES can help solve these problems. Several successful case studies are presented. Chapter 5 describes how TES is a valuable tool in energy conservation efforts that can help achieve significant energy savings. Chapter 6 delves into sensible heat storage systems and experimental and theoretical heat transfer aspects of stratified storage. Chapter 7 deals with a number of modeling aspects of latent heat storage systems, while Chapter 8 covers heat transfer with phase change in simple and complex geometries. Chapter 9 describes the thermoeconomic analysis and optimization of TES systems, and provides several illustrative examples. Chapter 10 covers energy and exergy analyses of a range of TES systems, along with various practical examples. Chapter 11 discusses many practical TES applications and case studies.

Incorporated through this book are many wide-ranging, illustrative examples which provide useful information for practical applications. Conversion factors and thermophysical properties of various materials are listed in the appendices in the International System of Units (SI). Complete references and a bibliography are included with each chapter to direct the curious and interested reader to further information.

İbrahim Dincer
Marc A. Rosen
June 2001

Contents

List of Contributors

Acknowledgements

Preface

1	General Introductory Aspects for Thermal Engineering	1
1.1	Introduction	1
1.2	Systems of Units	2
1.3	Fundamental Properties and Quantities	2
1.4	General Aspects of Thermodynamics	7
1.5	General Aspects of Fluid Flow	23
1.6	General Aspects of Heat Transfer	37
1.7	Concluding Remarks	52
	Nomenclature	52
	References	55
2	Energy Storage Systems	57
2.1	Introduction	57
2.2	Energy Demand	59
2.3	Energy Storage	59
2.4	Energy Storage Methods	60
2.5	Hydrogen for Energy Storage	87
2.6	Comparison of ES Technologies	91
2.7	Concluding Remarks	91
	References	92
3	Thermal Energy Storage (TES) Methods	93
3.1	Introduction	93
3.2	Thermal Energy	95
3.3	Thermal Energy Storage	96
3.4	Solar Energy and TES	117
3.5	TES Methods	122
3.6	Sensible TES	123
3.7	Latent TES	141
3.8	Cold TES (CTES)	159
3.9	Seasonal TES	207
3.10	Concluding Remarks	209
	References	210
4	Thermal Energy Storage and Environmental Impact	213
4.1	Introduction	213
4.2	Energy and the Environment	214
4.3	Major Environmental Problems	215

4.4	Environmental Impact and TES Systems and Applications	221
4.5	Potential Solutions to Environmental Problems	221
4.6	Sustainable Development	223
4.7	Illustrative Examples and Case Studies	228
4.8	Concluding Remarks	232
	References	233
5	Thermal Energy Storage and Energy Savings	235
5.1	Introduction	235
5.2	TES and Energy Savings	237
5.3	Additional Energy-Savings Considerations for TES	240
5.4	Energy Conservation with TES: Planning and Implementation	242
5.5	Some Limitations on Increased Efficiency	243
5.6	Energy Savings for Cold TES	245
5.7	Concluding Remarks	257
	References	257
6	Heat Transfer and Stratification in Sensible Heat Storage Systems	259
6.1	Introduction	259
6.2	Fluid Flow and Heat Transfer Aspects	261
6.3	Performance Measures	264
6.4	Experimental and Theoretical Foundations	270
6.5	One-Dimensional Models	276
6.6	Two-Dimensional Models	288
6.7	Conclusions	295
	Acknowledgements	296
	Nomenclature	296
	References	298
7	Modeling of Latent Heat Storage Systems	303
7.1	Introduction	303
7.2	Porous Medium Approach	304
7.3	Conduction-Dominated Phase Change	306
7.4	Contact Melting	315
7.5	Convection Dominated Phase Change	318
7.6	Conclusions	326
	Acknowledgements	327
	Nomenclature	327
	References	329
	Appendix A	335
	Appendix B	335
8	Heat Transfer with Phase Change in Simple and Complex Geometries	337
8.1	Introduction	337
8.2	Phase Change around Cylindrical Geometry	339
8.3	Solidification of PCM inside a Spherical Capsule	353

8.4	Plane Finned Geometries for Latent Heat Storage Applications	360
8.5	Phase Change around Isothermal Finned Cylinder	369
8.6	Conclusion	379
	Acknowledgements	379
	Nomenclature	380
	References	382
9	Thermodynamic Optimization of Thermal Energy Storage Systems	387
9.1	Introduction	387
9.2	Sensible Heat Storage	388
9.3	Series of Sensible-Heat Storage Units	392
9.4	Storage Followed by Removal of Sensible Heat	394
9.5	Latent Heat Storage	396
9.6	Series of Latent-Heat Storage Units	400
9.7	Other Configurations and Storage Models	405
	Nomenclature	407
	References	408
10	Energy and Exergy Analyses of Thermal Energy Storage Systems	411
10.1	Introduction	411
10.2	Theory: Energy and Exergy Analyses	413
10.3	Thermodynamic Considerations in TES Evaluation	426
10.4	Exergy Evaluation of a Closed TES System	430
10.5	Appropriate Efficiency Measures for Closed TES Systems	442
10.6	Importance of Temperature in Performance Evaluations for Sensible TES Systems	452
10.7	Exergy Analysis of Aquifer TES Systems	456
10.8	Exergy Analysis of Thermally Stratified Storages	465
10.9	Energy and Exergy Analyses of Cold TES Systems	483
10.10	Exergy-Based Optimal Discharge Periods for Closed TES Systems	495
10.11	Concluding Remarks	500
	Nomenclature	501
	References	504
	Appendix: Glossary of Selected Exergy-Related Terminology	508
11	Thermal Energy Storage Case Studies	511
11.1	Introduction	511
11.2	Ice TES Case Studies	512
11.3	Ice Slurry CTES Case Studies	533
11.4	Chilled Water CTES Case Studies	536
11.5	PCM Used CTES Case Studies	547
11.6	PCM Used Latent TES for Heating Case Studies	555
11.7	Sensible TES Case Studies	557
11.8	Concluding Remarks	560
	References	561

1

General Introductory Aspects for Thermal Engineering

I. Dincer

1.1 Introduction

Thermal energy storage (TES) is one of the key technologies for energy conservation and therefore is of great practical importance. One of its main advantages is that it is best suited for heating and cooling thermal applications. TES is perhaps as old as civilization itself. Since recorded time people have harvested ice and stored it for later use. Large TES systems have been employed in more recent history for numerous applications, ranging from solar hot water storage to building air conditioning systems. The TES technology has only recently been developed to a point where it can have a significant impact on modern technology.

In general, a coordinated set of actions has to be taken in several sectors of the energy system for the maximum potential benefits of thermal storage to be realized. TES appears to be an important solution to correcting the mismatch between the supply and demand of energy. TES can contribute significantly to meeting society's needs for more efficient, environmentally benign energy use. TES is a key component of many successful thermal systems and a good TES should allow minimum thermal losses, leading to energy savings, while permitting the highest possible extraction efficiency of the stored thermal energy.

There are mainly two types of TES systems, i.e. sensible (e.g. water, rock) and latent (e.g. water/ice, salt hydrates). For each storage medium, there is a wide variety of choices depending on the temperature range and application. TES via latent heat has received a great deal of interest. The most obvious example of latent TES is the conversion of water to ice. Cooling systems incorporating ice storage have a distinct size advantage over equivalent capacity chilled water units because of the large amount of energy able to be stored as latent heat. TES deals with the storing of energy by cooling, heating, melting, solidifying or vaporizing a substance, and the energy becomes available as heat when the process is reversed. The selection of a TES is mainly dependent on the storage period required, i.e. diurnal or seasonal, economic viability, operating conditions, etc. In practice, many research and development activities related to energy have concentrated on efficient energy use and energy savings, leading to energy conservation. In this regard, TES appears to be one an attractive thermal application and exergy analysis as an important tool for analyzing TES performances.

We begin this chapter with a summary of fundamental definitions, physical quantities, and their units, dimensions, and interrelations. We consider introductory aspects of thermodynamics, fluid flow, heat transfer, energy and entropy.

1.2 Systems of Units

There are two main systems of units: the *International System of Units* (Le *Système International d'Unités*), which is normally referred to as SI units, and the *English System of Units*. SI units are used most widely throughout the world, although the English System is traditional in the United States. In this book, SI units are primarily employed. Note that the relevant unit interconversions and relationships between the International and English unit systems concerning the fundamental properties and quantities are listed in Appendix A.

1.3 Fundamental Properties and Quantities

In this section we briefly cover several general aspects of thermodynamics to provide adequate preparation for the study of TES systems and applications.

1.3.1 Mass, time, length, and force

Mass is defined as a quantity of matter forming a body of indefinite shape and size. The fundamental unit of mass is the kilogram (kg) in SI and the pound mass (lb_m) in English units. The basic unit of time for both unit systems is the second.

In thermodynamics the unit *mole* (mol) is commonly used and defined as a certain amount of a substance as follows:

$$n = \frac{m}{M} \quad (1.1)$$

where n is the number of moles, m the mass, and M the molecular weight. If m and M are given by gram and gram/mol, we get n in mol. For example, one mol of water, having a molecular weight of 18 (compared to 12 for carbon-12) has a mass of 0.018 kg.

The basic unit of length is the meter (m) in SI units and the foot (ft) in the English system.

A force is a kind of action that brings a body to rest or to change the direction of motion (e.g. a push or a pull). The fundamental unit of force is the Newton (N).

The four aspects, e.g. mass, time, length and force, are interrelated by the Newton's second law of motion, which states that the force acting on a body is proportional to the mass and the acceleration in the direction of the force, as given in Equation 1.2:

$$F = ma \quad (1.2)$$

Equation 1.2 shows the force required to accelerate a mass of one kilogram at a rate of one meter per square second as $1 \text{ N} = 1 \text{ kg m/s}^2$.

It is important to note the value of the earth's gravitational acceleration as 9.80665 m/s^2 in the SI system and 32.174 ft/s^2 in the English system, and it indicates that a body falling freely toward the surface of the earth is subject to the action of gravity alone.

1.3.2 Pressure

When we deal with liquids and gases, pressure becomes one of the most important components. Pressure is the force exerted on a surface, per unit area, and is expressed in bar or Pascal (Pa). The related expression is

$$P = \frac{F}{A} \quad (1.3)$$

The unit for pressure in the SI is the force of one Newton acting on a square meter area (or the *Pascal*). The unit for pressure in the English system, is pounds force per square foot, lb_f/ft^2 .

Here, we introduce the basic pressure definitions, and a summary of basic pressure measurement relationships is shown in Figure 1.1.

Atmospheric pressure. The atmosphere that surrounds the earth can be considered a reservoir of low-pressure air. Its weight exerts a pressure which varies with temperature, humidity, and altitude. Atmospheric pressure also varies from time to time at a single location, because of the movement of weather patterns. While these changes in barometric pressure are usually less than one-half inch of mercury, they need to be taken into account when precise measurements are essential.

Gauge pressure. The *gauge pressure* is any pressure for which the base for measurement is atmospheric pressure expressed as kPa (gauge). Atmospheric pressure serves as a reference level for other types of pressure measurements, e.g. gauge pressure. As is shown in Figure 1.1, the gauge pressure is either positive or negative, depending on its level above or below the atmospheric pressure level. At the level of atmospheric pressure, the gauge pressure becomes zero.

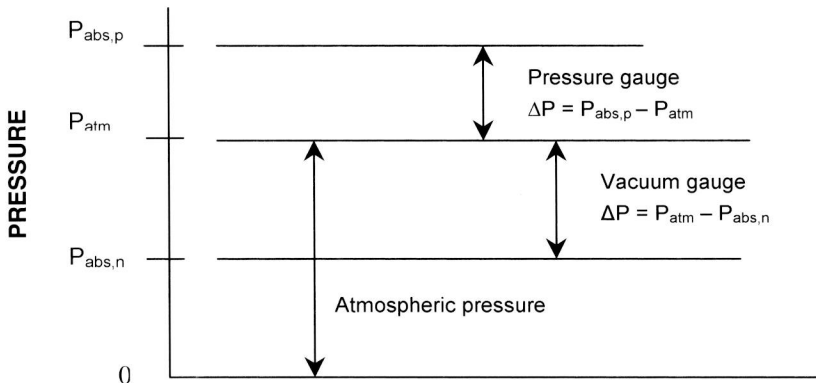


Figure 1.1 Illustration of pressures for measurement.

Absolute pressure. A different reference level is utilized to obtain a value for absolute pressure. The absolute pressure can be any pressure for which the base for measurement is full vacuum, being expressed in kPa (absolute). In fact, it is composed of the sum of the gauge pressure (positive or negative) and the atmospheric pressure as follows:

$$\text{pressure (gauge)} + \text{atmospheric pressure} = \text{pressure (absolute)} \quad (1.4)$$

For example, to obtain the absolute pressure, we simply add the value of atmospheric pressure. The absolute pressure is the most common one used in thermodynamic calculations, despite having the pressure difference between the absolute pressure and the atmospheric pressure existing in the gauge being read by the most pressure gauges and indicators.

Vacuum. It is a pressure lower than the atmospheric one and occurs only in closed systems, except in outer space. It is also called the *negative gauge pressure*. In fact, vacuum is the pressure differential produced by evacuating air from the closed system. Vacuum is usually divided into four levels: (i) low vacuum representing pressures above one Torr absolute (a large number of mechanical pumps in industry are used for this purpose; flow is viscous), (ii) medium vacuum varying between 1 and 10^{-3} Torr absolute (most pumps serving this range are mechanical; fluid is in transition between viscous and molecular), (iii) high vacuum ranging between 10^{-3} and 10^{-6} Torr absolute (nonmechanical ejector or cryogenic pumps are used; flow is molecular or Newtonian), and (iv) very high vacuum representing absolute pressure below 10^{-6} Torr (primarily for laboratory applications and space simulation).

It is important to note another additional level, at which the *saturation pressure* is the pressure of a liquid or vapor at saturation conditions.

1.3.3 Temperature

This is an indication of the heat energy stored in a substance. In other words, we can identify hotness and coldness with the concept of temperature. The temperature of a substance may be expressed in either relative or absolute units. The two most common temperature scales are the Celsius ($^{\circ}\text{C}$) and Fahrenheit ($^{\circ}\text{F}$). In fact, the Celsius scale is used with the SI unit system and the Fahrenheit scale with the English engineering system of units. There are also two more scales, the Kelvin scale (K) and the Rankine scale (R), that are sometimes employed in thermodynamic applications.

Degree Kelvin is a unit of temperature measurement; zero Kelvin (0 K) is equal to absolute zero and equal to -273.15°C . The K and $^{\circ}\text{C}$ are equal increments of temperature. For instance, when the temperature of a product is decreased to -273°C (or 0 K), known as *absolute zero*, the substance contains no heat energy and all molecular movement stops. The saturation temperature is the temperature of a liquid or vapor at saturation conditions.

Temperature can be measured in a large number of ways by devices. In general, the following devices are common in use:

- **Thermometers.** In thermometers, the volume of the fluid expands when subjected to heat, thereby raising its temperature. In practice, thermometers work over a certain

temperature range. For example, the common thermometer fluid mercury becomes solid at -38.8°C and its properties change dramatically.

- **Resistance thermometers.** A resistance thermometer (or detector) is made up resistance wire wound on a suitable former. The wire used has to be of known, repeatable, electrical characteristics so that the relationship between the temperature and resistance value can be predicted precisely. The measured value of the resistance of the detector can then be used to determine the value of an unknown temperature. Amongst metallic conductors, pure metals exhibit the greatest change of resistance with temperature. For applications requiring higher accuracy, especially where the temperature measurement is between -200°C and $+800^{\circ}\text{C}$, the resistance thermometer comes into its own. The majority of such thermometers are made of platinum. In industry, in addition to platinum, nickel (-60°C to $+180^{\circ}\text{C}$) and copper (-30°C to $+220^{\circ}\text{C}$) are frequently used to manufacture resistance thermometers. Resistance thermometers can be provided with 2, 3, or 4 wire connections, and for higher accuracy at least 3 wires are required.
- **Averaging thermometers.** An averaging thermometer is designed to measure the average temperature of bulk stored liquids. The sheath contains a number of elements of different lengths, all starting from the bottom of the sheath. The longest element which is fully immersed is connected to the measuring circuit to allow a true average temperature to be obtained. There are some significant parameters namely sheath material (stainless steel for the temperature range from -50°C to $+200^{\circ}\text{C}$ or nylon for the temperature range from -50°C to $+90^{\circ}\text{C}$), sheath length (to suit the application), termination (flying leads or terminal box), element length, element calibration (to copper or platinum curves), and operating temperature ranges. In many applications where a multi-element thermometer is not required, such as in air ducts, cooling water and gas outlets, a single element thermometer stretched across the duct or pipework will provide a true average temperature reading. Despite the working range from 0°C to 100°C , the maximum temperature may reach 200°C . To keep high accuracy these units are normally supplied with 3-wire connections. However, up to 10 elements can be mounted in the averaging bulb fittings, and they can be made of platinum, nickel or copper, and fixed at any required position.
- **Thermocouples.** A thermocouple consists of two electrical conductors, of different materials connected together at one end (the so-called *measuring junction*). The two free ends are connected to a measuring instrument, e.g. an indicator, a controller or a signal conditioner by a reference junction (the so-called *cold junction*). The thermoelectric voltage appearing at the indicator depends on the materials of which the thermocouple wires are made and on the temperature difference between the measuring junction and the reference junction. For accurate measurements, the temperature of the reference junction must be kept constant. Modern instruments usually incorporate a cold junction reference circuit and are supplied ready for operation in a protective sheath, to prevent damage to the thermocouple by any mechanical or chemical means. Table 1.1 gives several types of thermocouples along with their maximum absolute temperature ranges. As can be seen in Table 1.1, a copper-constantan thermocouple has an accuracy of $\pm 1^{\circ}\text{C}$, and is often employed for control systems in refrigeration and food processing applications. The iron-constantan thermocouple with its maximum of