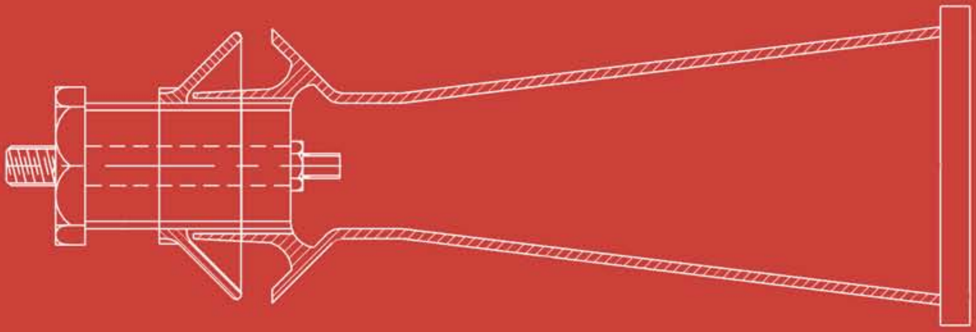
Taylor & Francis
Taylor & Francis Group

Industrial Heating

Principles, Techniques, Materials, Applications, and Design



Yeshvant V. Deshmukh

Industrial Heating

Principles, Techniques, Materials, Applications, and Design

MECHANICAL ENGINEERING

A Series of Textbooks and Reference Books

Founding Editor

L. L. Faulkner

Columbus Division, Battelle Memorial Institute
and Department of Mechanical Engineering
The Ohio State University
Columbus, Ohio

1. *Spring Designer's Handbook*, Harold Carlson
2. *Computer-Aided Graphics and Design*, Daniel L. Ryan
3. *Lubrication Fundamentals*, J. George Wills
4. *Solar Engineering for Domestic Buildings*, William A. Himmelman
5. *Applied Engineering Mechanics: Statics and Dynamics*, G. Boothroyd and C. Poli
6. *Centrifugal Pump Clinic*, Igor J. Karassik
7. *Computer-Aided Kinetics for Machine Design*, Daniel L. Ryan
8. *Plastics Products Design Handbook, Part A: Materials and Components; Part B: Processes and Design for Processes*, edited by Edward Miller
9. *Turbomachinery: Basic Theory and Applications*, Earl Logan, Jr.
10. *Vibrations of Shells and Plates*, Werner Soedel
11. *Flat and Corrugated Diaphragm Design Handbook*, Mario Di Giovanni
12. *Practical Stress Analysis in Engineering Design*, Alexander Blake
13. *An Introduction to the Design and Behavior of Bolted Joints*, John H. Bickford
14. *Optimal Engineering Design: Principles and Applications*, James N. Siddall
15. *Spring Manufacturing Handbook*, Harold Carlson
16. *Industrial Noise Control: Fundamentals and Applications*, edited by Lewis H. Bell
17. *Gears and Their Vibration: A Basic Approach to Understanding Gear Noise*, J. Derek Smith
18. *Chains for Power Transmission and Material Handling: Design and Applications Handbook*, American Chain Association
19. *Corrosion and Corrosion Protection Handbook*, edited by Philip A. Schweitzer
20. *Gear Drive Systems: Design and Application*, Peter Lynwander
21. *Controlling In-Plant Airborne Contaminants: Systems Design and Calculations*, John D. Constance
22. *CAD/CAM Systems Planning and Implementation*, Charles S. Knox
23. *Probabilistic Engineering Design: Principles and Applications*, James N. Siddall
24. *Traction Drives: Selection and Application*, Frederick W. Heilich III and Eugene E. Shube
25. *Finite Element Methods: An Introduction*, Ronald L. Huston and Chris E. Passerello

26. *Mechanical Fastening of Plastics: An Engineering Handbook*, Brayton Lincoln, Kenneth J. Gomes, and James F. Braden
27. *Lubrication in Practice: Second Edition*, edited by W. S. Robertson
28. *Principles of Automated Drafting*, Daniel L. Ryan
29. *Practical Seal Design*, edited by Leonard J. Martini
30. *Engineering Documentation for CAD/CAM Applications*, Charles S. Knox
31. *Design Dimensioning with Computer Graphics Applications*, Jerome C. Lange
32. *Mechanism Analysis: Simplified Graphical and Analytical Techniques*, Lyndon O. Barton
33. *CAD/CAM Systems: Justification, Implementation, Productivity Measurement*, Edward J. Preston, George W. Crawford, and Mark E. Coticchia
34. *Steam Plant Calculations Manual*, V. Ganapathy
35. *Design Assurance for Engineers and Managers*, John A. Burgess
36. *Heat Transfer Fluids and Systems for Process and Energy Applications*, Jasbir Singh
37. *Potential Flows: Computer Graphic Solutions*, Robert H. Kirchhoff
38. *Computer-Aided Graphics and Design: Second Edition*, Daniel L. Ryan
39. *Electronically Controlled Proportional Valves: Selection and Application*, Michael J. Tonyan, edited by Tobi Goldoftas
40. *Pressure Gauge Handbook*, AMETEK, U.S. Gauge Division, edited by Philip W. Harland
41. *Fabric Filtration for Combustion Sources: Fundamentals and Basic Technology*, R. P. Donovan
42. *Design of Mechanical Joints*, Alexander Blake
43. *CAD/CAM Dictionary*, Edward J. Preston, George W. Crawford, and Mark E. Coticchia
44. *Machinery Adhesives for Locking, Retaining, and Sealing*, Girard S. Haviland
45. *Couplings and Joints: Design, Selection, and Application*, Jon R. Mancuso
46. *Shaft Alignment Handbook*, John Piotrowski
47. *BASIC Programs for Steam Plant Engineers: Boilers, Combustion, Fluid Flow, and Heat Transfer*, V. Ganapathy
48. *Solving Mechanical Design Problems with Computer Graphics*, Jerome C. Lange
49. *Plastics Gearing: Selection and Application*, Clifford E. Adams
50. *Clutches and Brakes: Design and Selection*, William C. Orthwein
51. *Transducers in Mechanical and Electronic Design*, Harry L. Trietley
52. *Metallurgical Applications of Shock-Wave and High-Strain-Rate Phenomena*, edited by Lawrence E. Murr, Karl P. Staudhammer, and Marc A. Meyers
53. *Magnesium Products Design*, Robert S. Busk
54. *How to Integrate CAD/CAM Systems: Management and Technology*, William D. Engelke
55. *Cam Design and Manufacture: Second Edition; with cam design software for the IBM PC and compatibles*, disk included, Preben W. Jensen
56. *Solid-State AC Motor Controls: Selection and Application*, Sylvester Campbell
57. *Fundamentals of Robotics*, David D. Ardayfio
58. *Belt Selection and Application for Engineers*, edited by Wallace D. Erickson
59. *Developing Three-Dimensional CAD Software with the IBM PC*, C. Stan Wei
60. *Organizing Data for CIM Applications*, Charles S. Knox, with contributions by Thomas C. Boos, Ross S. Culverhouse, and Paul F. Muchnicki
61. *Computer-Aided Simulation in Railway Dynamics*, by Rao V. Dukkipati and Joseph R. Amyot

62. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*, P. K. Mallick
63. *Photoelectric Sensors and Controls: Selection and Application*, Scott M. Juds
64. *Finite Element Analysis with Personal Computers*, Edward R. Champion, Jr. and J. Michael Ensminger
65. *Ultrasonics: Fundamentals, Technology, Applications: Second Edition, Revised and Expanded*, Dale Ensminger
66. *Applied Finite Element Modeling: Practical Problem Solving for Engineers*, Jeffrey M. Steele
67. *Measurement and Instrumentation in Engineering: Principles and Basic Laboratory Experiments*, Francis S. Tse and Ivan E. Morse
68. *Centrifugal Pump Clinic: Second Edition, Revised and Expanded*, Igor J. Karassik
69. *Practical Stress Analysis in Engineering Design: Second Edition, Revised and Expanded*, Alexander Blake
70. *An Introduction to the Design and Behavior of Bolted Joints: Second Edition, Revised and Expanded*, John H. Bickford
71. *High Vacuum Technology: A Practical Guide*, Marsbed H. Hablanian
72. *Pressure Sensors: Selection and Application*, Duane Tandeske
73. *Zinc Handbook: Properties, Processing, and Use in Design*, Frank Porter
74. *Thermal Fatigue of Metals*, Andrzej Weronski and Tadeusz Hejwowski
75. *Classical and Modern Mechanisms for Engineers and Inventors*, Preben W. Jensen
76. *Handbook of Electronic Package Design*, edited by Michael Pecht
77. *Shock-Wave and High-Strain-Rate Phenomena in Materials*, edited by Marc A. Meyers, Lawrence E. Murr, and Karl P. Staudhammer
78. *Industrial Refrigeration: Principles, Design and Applications*, P. C. Koelet
79. *Applied Combustion*, Eugene L. Keating
80. *Engine Oils and Automotive Lubrication*, edited by Wilfried J. Bartz
81. *Mechanism Analysis: Simplified and Graphical Techniques, Second Edition, Revised and Expanded*, Lyndon O. Barton
82. *Fundamental Fluid Mechanics for the Practicing Engineer*, James W. Murdock
83. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design, Second Edition, Revised and Expanded*, P. K. Mallick
84. *Numerical Methods for Engineering Applications*, Edward R. Champion, Jr.
85. *Turbomachinery: Basic Theory and Applications, Second Edition, Revised and Expanded*, Earl Logan, Jr.
86. *Vibrations of Shells and Plates: Second Edition, Revised and Expanded*, Werner Soedel
87. *Steam Plant Calculations Manual: Second Edition, Revised and Expanded*, V. Ganapathy
88. *Industrial Noise Control: Fundamentals and Applications, Second Edition, Revised and Expanded*, Lewis H. Bell and Douglas H. Bell
89. *Finite Elements: Their Design and Performance*, Richard H. MacNeal
90. *Mechanical Properties of Polymers and Composites: Second Edition, Revised and Expanded*, Lawrence E. Nielsen and Robert F. Landel
91. *Mechanical Wear Prediction and Prevention*, Raymond G. Bayer
92. *Mechanical Power Transmission Components*, edited by David W. South and Jon R. Mancuso
93. *Handbook of Turbomachinery*, edited by Earl Logan, Jr.

94. *Engineering Documentation Control Practices and Procedures*, Ray E. Monahan
95. *Refractory Linings Thermomechanical Design and Applications*, Charles A. Schacht
96. *Geometric Dimensioning and Tolerancing: Applications and Techniques for Use in Design, Manufacturing, and Inspection*, James D. Meadows
97. *An Introduction to the Design and Behavior of Bolted Joints: Third Edition, Revised and Expanded*, John H. Bickford
98. *Shaft Alignment Handbook: Second Edition, Revised and Expanded*, John Piotrowski
99. *Computer-Aided Design of Polymer-Matrix Composite Structures*, edited by Suong Van Hoa
100. *Friction Science and Technology*, Peter J. Blau
101. *Introduction to Plastics and Composites: Mechanical Properties and Engineering Applications*, Edward Miller
102. *Practical Fracture Mechanics in Design*, Alexander Blake
103. *Pump Characteristics and Applications*, Michael W. Volk
104. *Optical Principles and Technology for Engineers*, James E. Stewart
105. *Optimizing the Shape of Mechanical Elements and Structures*, A. A. Seireg and Jorge Rodriguez
106. *Kinematics and Dynamics of Machinery*, Vladimír Stejskal and Michael Valásek
107. *Shaft Seals for Dynamic Applications*, Les Horve
108. *Reliability-Based Mechanical Design*, edited by Thomas A. Cruse
109. *Mechanical Fastening, Joining, and Assembly*, James A. Speck
110. *Turbomachinery Fluid Dynamics and Heat Transfer*, edited by Chunill Hah
111. *High-Vacuum Technology: A Practical Guide, Second Edition, Revised and Expanded*, Marsbed H. Hablanian
112. *Geometric Dimensioning and Tolerancing: Workbook and Answerbook*, James D. Meadows
113. *Handbook of Materials Selection for Engineering Applications*, edited by G. T. Murray
114. *Handbook of Thermoplastic Piping System Design*, Thomas Sixsmith and Reinhard Hanselka
115. *Practical Guide to Finite Elements: A Solid Mechanics* Approach, Steven M. Lepi
116. *Applied Computational Fluid Dynamics*, edited by Vijay K. Garg
117. *Fluid Sealing Technology*, Heinz K. Muller and Bernard S. Nau
118. *Friction and Lubrication in Mechanical Design*, A. A. Seireg
119. *Influence Functions and Matrices*, Yuri A. Melnikov
120. *Mechanical Analysis of Electronic Packaging Systems*, Stephen A. McKeown
121. *Couplings and Joints: Design, Selection, and Application, Second Edition, Revised and Expanded*, Jon R. Mancuso
122. *Thermodynamics: Processes and Applications*, Earl Logan, Jr.
123. *Gear Noise and Vibration*, J. Derek Smith
124. *Practical Fluid Mechanics for Engineering Applications*, John J. Bloomer
125. *Handbook of Hydraulic Fluid Technology*, edited by George E. Totten
126. *Heat Exchanger Design Handbook*, T. Kuppan
127. *Designing for Product Sound Quality*, Richard H. Lyon
128. *Probability Applications in Mechanical Design*, Franklin E. Fisher and Joy R. Fisher

129. *Nickel Alloys*, edited by Ulrich Heubner
130. *Rotating Machinery Vibration: Problem Analysis and Troubleshooting*, Maurice L. Adams, Jr.
131. *Formulas for Dynamic Analysis*, Ronald L. Huston and C. Q. Liu
132. *Handbook of Machinery Dynamics*, Lynn L. Faulkner and Earl Logan, Jr.
133. *Rapid Prototyping Technology: Selection and Application*, Kenneth G. Cooper
134. *Reciprocating Machinery Dynamics: Design and Analysis*, Abdulla S. Rangwala
135. *Maintenance Excellence: Optimizing Equipment Life-Cycle Decisions*, edited by John D. Campbell and Andrew K. S. Jardine
136. *Practical Guide to Industrial Boiler Systems*, Ralph L. Vandagriff
137. *Lubrication Fundamentals: Second Edition, Revised and Expanded*, D. M. Pirro and A. A. Wessol
138. *Mechanical Life Cycle Handbook: Good Environmental Design and Manufacturing*, edited by Mahendra S. Hundal
139. *Micromachining of Engineering Materials*, edited by Joseph McGeough
140. *Control Strategies for Dynamic Systems: Design and Implementation*, John H. Lumkes, Jr.
141. *Practical Guide to Pressure Vessel Manufacturing*, Sunil Pullarcot
142. *Nondestructive Evaluation: Theory, Techniques, and Applications*, edited by Peter J. Shull
143. *Diesel Engine Engineering: Thermodynamics, Dynamics, Design, and Control*, Andrei Makartchouk
144. *Handbook of Machine Tool Analysis*, Ioan D. Marinescu, Constantin Ispas, and Dan Boboc
145. *Implementing Concurrent Engineering in Small Companies*, Susan Carlson Skalak
146. *Practical Guide to the Packaging of Electronics: Thermal and Mechanical Design and Analysis*, Ali Jamnia
147. *Bearing Design in Machinery: Engineering Tribology and Lubrication*, Avraham Harnoy
148. *Mechanical Reliability Improvement: Probability and Statistics for Experimental Testing*, R. E. Little
149. *Industrial Boilers and Heat Recovery Steam Generators: Design, Applications*, and Calculations, V. Ganapathy
150. *The CAD Guidebook: A Basic Manual for Understanding and Improving Computer-Aided Design*, Stephen J. Schoonmaker
151. *Industrial Noise Control and Acoustics*, Randall F. Barron
152. *Mechanical Properties of Engineered Materials*, Wolé Soboyejo
153. *Reliability Verification, Testing, and Analysis in Engineering Design*, Gary S. Wasserman
154. *Fundamental Mechanics of Fluids: Third Edition*, I. G. Currie
155. *Intermediate Heat Transfer*, Kau-Fui Vincent Wong
156. *HVAC Water Chillers and Cooling Towers: Fundamentals, Application, and Operation*, Herbert W. Stanford III
157. *Gear Noise and Vibration: Second Edition, Revised and Expanded*, J. Derek Smith
158. *Handbook of Turbomachinery: Second Edition*, Revised and Expanded, edited by Earl Logan, Jr. and Ramendra Roy
159. *Piping and Pipeline Engineering: Design, Construction, Maintenance, Integrity, and Repair*, George A. Antaki

160. *Turbomachinery: Design and Theory*, Rama S. R. Gorla and Aijaz Ahmed Khan
161. *Target Costing: Market-Driven Product Design*, M. Bradford Clifton, Henry M. B. Bird, Robert E. Albano, and Wesley P. Townsend
162. *Fluidized Bed Combustion*, Simeon N. Oka
163. *Theory of Dimensioning: An Introduction to Parameterizing Geometric Models*, Vijay Srinivasan
164. *Handbook of Mechanical Alloy Design*, edited by George E. Totten, Lin Xie, and Kiyoshi Funatani
165. *Structural Analysis of Polymeric Composite Materials*, Mark E. Tuttle
166. *Modeling and Simulation for Material Selection and Mechanical Design*, edited by George E. Totten, Lin Xie, and Kiyoshi Funatani
167. *Handbook of Pneumatic Conveying Engineering*, David Mills, Mark G. Jones, and Vijay K. Agarwal
168. *Clutches and Brakes: Design and Selection, Second Edition*, William C. Orthwein
169. *Fundamentals of Fluid Film Lubrication: Second Edition*, Bernard J. Hamrock, Steven R. Schmid, and Bo O. Jacobson
170. *Handbook of Lead-Free Solder Technology for Microelectronic Assemblies*, edited by Karl J. Puttlitz and Kathleen A. Stalter
171. *Vehicle Stability*, Dean Karnopp
172. *Mechanical Wear Fundamentals and Testing: Second Edition, Revised and Expanded*, Raymond G. Bayer
173. *Liquid Pipeline Hydraulics*, E. Shashi Menon
174. *Solid Fuels Combustion and Gasification*, Marcio L. de Souza-Santos
175. *Mechanical Tolerance Stackup and Analysis*, Bryan R. Fischer
176. *Engineering Design for Wear*, Raymond G. Bayer
177. *Vibrations of Shells and Plates: Third Edition, Revised and Expanded*, Werner Soedel
178. *Refractories Handbook*, edited by Charles A. Schacht
179. *Practical Engineering Failure Analysis*, Hani M. Tawancy, Anwar Ul-Hamid, and Nureddin M. Abbas
180. *Mechanical Alloying and Milling*, C. Suryanarayana
181. *Mechanical Vibration: Analysis, Uncertainties, and Control, Second Edition*, Revised and Expanded, Haym Benaroya
182. *Design of Automatic Machinery*, Stephen J. Derby
183. *Practical Fracture Mechanics in Design: Second Edition, Revised and Expanded*, Arun Shukla
184. *Practical Guide to Designed Experiments*, Paul D. Funkenbusch
185. *Gigacycle Fatigue in Mechanical Practive*, Claude Bathias and Paul C. Paris
186. *Selection of Engineering Materials and Adhesives*, Lawrence W. Fisher
187. *Boundary Methods: Elements, Contours, and Nodes*, Subrata Mukherjee and Yu Xie Mukherjee
188. *Rotordynamics*, Agnieszka (Agnes) Muszn´yska
189. *Pump Characteristics and Applications: Second Edition*, Michael W. Volk
190. *Reliability Engineering: Probability Models and Maintenance Methods*, Joel A. Nachlas
191. *Industrial Heating: Principles, Techniques, Materials, Applications, and Design*, Yeshvant V. Deshmukh

Industrial Heating

Principles, Techniques, Materials, Applications, and Design

Yeshvant V. Deshmukh

Taylor & Francis
Taylor & Francis Group

Boca Raton London New York Singapore

A CRC title, part of the Taylor & Francis imprint, a member of the
Taylor & Francis Group, the academic division of T&F Informa plc.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2005 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Version Date: 20130925

International Standard Book Number-13: 978-1-4200-2755-6 (eBook - PDF)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (http://www.copyright.com/) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Dedicated to

The memory of my Guru,
(Late) Prof. G.K. (Nana) Ogle

Formerly
The Principal and Head of Metallurgy
Department
College of Engineering—Pune, India

Contents

Appendices

Preface

Heating is an integral part of many processes. It is used in diverse processes such as heat treating, shaping, casting, moulding, and joining fabrication, in one form or another. Food processing, drying, waste disposal, desalining, and many other operations depend on heating. The materials processed are metals, alloys, semiconductors, polymers, textiles, farm products minerals, city and industrial garbage, and so on. Each material and process requires heating methods suitable to its properties and the desired end products.

I came in contact with heating processes and the design field in the early 1960s by chance. Since then the association has graduated to consultation practice involving a wide range of heating problems. Except a few books published in the 1950s, on furnace design for mainly metallurgical industries, I found that there is no book on general design techniques for heating. In the last half-century, there have been substantial developments in heating techniques and related materials. Laser, electron beam, and microwave heating; fiber and fiber-based refractories; and powerful high vacuum pumps are some of the notable advances, that were practically nonexistent in the 1950s. The present book is an attempt to provide design information on the traditional and modern heating processes and auxiliary techniques.

The book is mainly aimed at designers engaged in the design and manufacture of furnaces, laboratory apparatus, and material processing equipment. It will also help the end users or buyers of such equipment to formalize their requirements and arrive at specifications. Research workers can design and specify their experimental setups involving heating. As the coverage of heating processes and allied techniques included in this book is very wide, almost all industries will find it as a useful design guide and source book. It will be advantageous if the reader has some basic knowledge of physics, chemistry, and mathematics upto the under graduate level in science or engineering.

The science of "heat transfer" is at the core of heating processes. The analysis of related heat transfer and estimation of the effective heat transfer coefficient is the first step toward a successful design. The book opens with a review of selected topics in steady state and transient heat transfer. A qualitative description of some topics in fluid mechanics and aerodynamics is also included because of their influence on heat transfer. Mathematical treatment is kept at the minimum possible and more attention is given to concepts underlying the phenomenon. It is my experience that due to years of separation from the academic field, the industrial community, in general, is out of touch with the basic concepts; hence the need for these reviews.

This is followed by fuels, their combustion and combustion devices. Solid fuels are excluded as they are not used in small or medium heating applications.

Garbage and waste incineration is treated in detail. I feel that the growing problem of waste disposal in urban and industrial areas all over the world is bound to make incineration on large scale a necessity in future. All heating-process designers must have at least a preliminary knowledge of incineration combustion and the problems with practical incinerators.

For the same reasons biogas generation and its combustion is included with other traditional fuels.

Electricity as a "fuel" is used in industries on a large scale and in many forms. All these forms are discussed in detail without going deep into electrical engineering. Electric arc is not covered as it is used in large-scale industries.

Auxilliary techniques related to heating, such as vacuum technology, pyrometry, protective atmosphere, and heat exchangers are discussed in sufficient detail. Refractory, ceramic, and metallic materials used in the construction of furnaces are dealt with a view to bring about their useful properties and limitations.

A large number of solved problems are included at each stage. They should help the designer in understanding the underlying principles. The appendices are meant mainly for *clearing* some basic concepts which could not be included in the text. This need arises from still continuing usage of diverse units. This book has used SI units throughout.

The presentation of extensive data, about material properties, in tabular form has been avoided. It is felt that selected data given in various tables and figures should be sufficient for the preliminary design. Abundant data in more precise numerical forms are available in almost all handbooks listed in the references. It is also suggested that for problems involving graphical methods used in transient heating, humidity etc., enlarged accurate graphs available elsewhere should be referred for better precision. What are included in text are reasonable outlines limited by resolution in reproduction.

All the design problems involved in the preliminary estimation of heating can be satisfactorily solved by a hand held scientific calculator. If a number of reiterations are called for, they can be worked out on a computer. Many softwares are available for specialized areas in heat transfer but they are (almost) all dedicated to particular situations. The designer is expected to have access to computational facilities.

An interdisciplinary book of this type is never complete. It is quite likely that some aspects of heating are either left out or not sufficiently covered. I will be thankful to receive constructive suggestions about any errors, omissions, and improvements to make the book more useful.

A second volume is in the planning stage. It will open with a discussion on the estimation of the heat transfer coefficient in practical situations followed by some typical construction features. The major part will consist of a number of fully worked-out designs. Any suggestions for inclusions in this volume will be highly appreciated. Your comments may be directly communicated to me at the address given below.

The preface will remain incomplete if I forget to mention my wife Sumitra. She has been my counselor for all these years. The book was a challenging job due to its complexity and my age. Her constant support, encouragement, and help has made this task a pleasure and fulfillment.

Mangesh Limaye has converted my sketches to computer drawings. He has also typed the manuscript. He has done both jobs with great skill and patience.

I also take this opportunity to express my thanks to the staff of Marcel Dekker for the design and organization; and Sam (Samik Roy Chowdhury) and his staff at ITC (Ashish Bhatnagar, Bhavinder Singh, and Subir Saha) for editorial services and production of the book.

Dr. Yeshvant V. Deshmukh

About the Author

Dr. Yeshvant V. Deshmukh received graduateships in metallurgical and mechanical engineering from the Pune University. Subsequently, he received his doctorate in mechanical and production engineering.

He has over forty years of combined experience in teaching, research, and consultancy in engineering. He has taught undergraduate and graduate classes in metallurgy and mechanical engineering at the Government Polytechnic, Pune and B.V. College of Engineering, Pune where he was a professor and the chairperson of the mechanical engineering department.

His consultancy was mainly in design of furnaces and heating, heat treatment, and other processes.

He is an associate member of the Institution of Engineers (India) and a Fellow of the Institute of the Mechanical Engineers (India). He has written about 10 technical books and contributed extensively to metallurgical and mechanical fields.

Abstract

Heating is an important operation in almost all industrial and domestic processes. A large variety of heating techniques is available at the designer. Some examples are fuel burning, electrical heating, radiative heating, and so on.

There is no book, presently available, which discusses all these diverse heating processes, their principles, choice, design materials, and limitations. This book attempts at providing information about complimentary topics such as vacuum technique, temperature measurement and control, fuels, and protective atmospheres. This makes the book self-contained in all respects.

Heating is an offshoot of the science of "heat transfer" and "fluid mechanics." This serves as a refresher course for the reader and develop an understanding about heating processes.

Waste incineration and biogas generation are specially included topics. They are discussed in detail and will lead to incinerator design. In coming years, these two topics will assume high importance in environment protection.

A large number of solved problems at each stage will help develop confidence in the designer in application of theory-to-practical situations.

Instead of giving large number of tables and data, the book encourages the use of standard handbooks and development of the designer's personal database. However, sufficient data on properties of materials are presented in both graphical and numerical form.

The book should be useful to manufacturers, designers, sales personnel, and users of heating.

Acknowledgments

I am thankful to the following for their help in preparation of this book.

M.S. Gajendragadkar, Dr. P.K. Roy, S.K. Paknikar,
R.S. Marathe of the British Library, PUNE, India
Technical Book Services, PUNE, India

M/s Kanthal AB, Sweden,
Ircon Inc, U.S.A.

Hauck Manufacturing Co. U.S.A.
Ecoflam, Italy

Chapter 1

Introduction

CONTENTS

1.1 IN THE BEGINNING

Fire is perhaps the first natural element that mankind discovered and mastered. Forest fires or volcanoes exhibited this power. It was then used for heating in winter and for cooking. Man was so awed by fire that earlier civilizations deified fire and sun.

In the millions of years that followed, we learned a lot about the production and use of heat. In the last few hundred years the sciences of thermodynamics, heat transmission, heat absorption, and generation were formulated and became the basis of modern industrial growth. Almost all industrial and domestic processes depend on the generation and use of heat. Electricity generation, production, processing and shaping of metals, manufacture of chemicals, and processing and cooking of food all depend on heat. Heating in winter and cooling in summer has made life comfortable and habitable all over the globe.

In this book we will explore some methods of heat generation, and principles of heat transfer and heat absorption. The choice of heat-generation methods is necessarily limited to small and medium heating processes. Large scale or heavy melting, and extraction and refinement of metals and minerals are excluded.

It is our aim to develop sufficient understanding of the underlying principles of heat generation and transmission by various methods that will lead to the design and estimation of the process to suit the intended application.

Before we launch into the details of processes and mechanisms of heat, it is necessary to bear in mind a few underlying thermodynamic principles common to all processes under investigation.

1. Heat will always flow or be transmitted from a higher to a lower temperature.
2. The "state" of heat in a body or in a given region of a body is completely given by the temperature of that point. We will use the Celsius (°C) and the Kelvin (K = °C + 273) scales throughout.
3. Heat generation, transmission, and absorption are basically "inefficient" processes as some heat is always irrecoverably lost. If we consider Q_1 as the heat-generated energy input to the generator and Q_2 as the energy absorbed by the object, the efficiency of the process will be Q_2/Q_1 which will, in any practical process, rarely exceed 30%.
4. It will not be possible to perform exact heat-flow calculations at all stages of even a simple heating process because of losses that will be incurred at every point.

Hence, heat calculations, in a sense, are "imprecise." The design philosophy will be to ensure that the required heating takes place in the designated time with minimum possible losses.

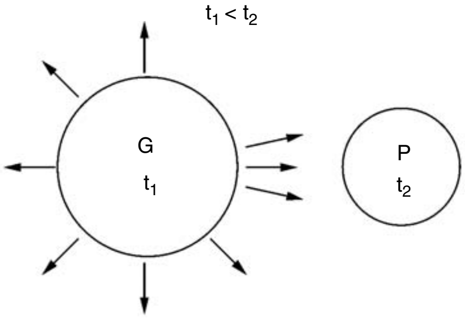
5. We will divide a given process into two primary classes, steady state and transient. In the steady state process the temperatures at all points are stationary, i.e., they do not change with time. In a transient process the temperature changes with time.

   A process will be transient when heating is going on. On reaching the required temperature, it may become steady. Usually we will be interested in only one aspect, either steady or transient.
6. The fraction of generated heat incident on the surface of a body is not totally absorbed. Some is reflected, some transmitted, and only some will be absorbed and will heat the body. Thus, only the last (absorbed) fraction is the "useful" heat. We will discuss these phenomena later in detail. Most of the objects that we are interested in will be opaque and there will be no transmission. However, the medium between the heat generator and the work (air, gases) may also absorb and transmit the heat passing through them.

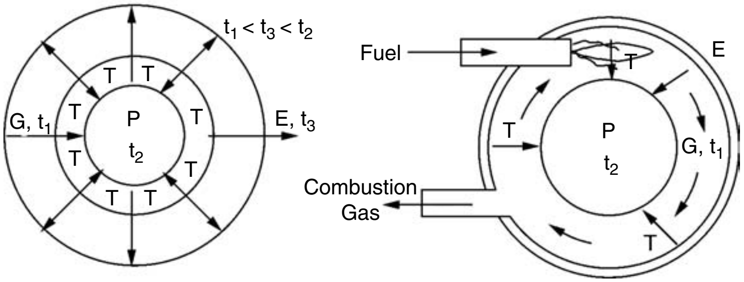
1.2 HEATING SYSTEM CLASSIFICATION

Any heating system will have two main components, the heat generator *G* and the work or the object *P* that is to be heated. Heat will be transferred from the generator to the object by a heat transfer process *T*. Based on these three, a general classification system can be proposed as shown in Figure 1.1.

1. Figure 1.1(A) shows a system that has the generator and the work separated by a distance. Heat is transmitted through the medium in between, as shown by the marked arrows. This is obviously an inefficient system as a considerable portion of the generated heat will be wasted (as shown by the unmarked arrows).



A. “Open System”



B. “Closed System”

Figure 1.1 Systems in which the generator G and the work P are separate.

A pot or a piece of metal placed on an electric plate or gas burner belongs to this system. We call this an “open” system.

The above system can be converted into a “closed” system as shown. We now surround the generator and the work by providing an “insulated” enclosure E. Now all the generated heat will reach the work either directly or via reflection from the enclosure. It is presumed that the enclosure is 100% reflecting.

Most of the indirectly heated resistance furnaces (Figure 1.1(B)) belong to this class. Heat transfer from the generator to the enclosure to the work is an important design factor for this type. Fuel-fired furnaces also belong to this class. An important difference in this

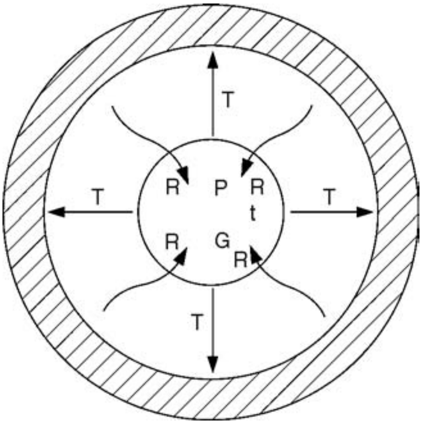


Figure 1.2 Heating system in which "nonthermal" radiation is used to create heat in the work. Heat generator and work are not separate.

type is the heat lost from combustion gases that leave the furnace enclosure. This heat loss is also quite considerable and reduces efficiency despite the presence of the enclosure.

2. Other types of heating systems do not have separate generator and work. By using certain techniques, heat is directly generated in the work as shown in the Figure 1.2. The heat is created by radiation *R* generated in a source *S*. An enclosure may or may not be required. Appreciable amount of heat may be lost from the work if it is heated much above the surrounding. These processes are usually very fast and such heat loss can be minimized. It may appear that these systems are highly efficient. However, the generation of radiation in the source *S* is very inefficient (~ 5–10%) but there are several other advantages which will be discussed later.

    Induction heating, direct resistance heating, and microwave heating belong to this class (Figure 1.3). In induction heating, high frequency (10^3–10^5 Hz) electromagnetic oscillation is created in the work by

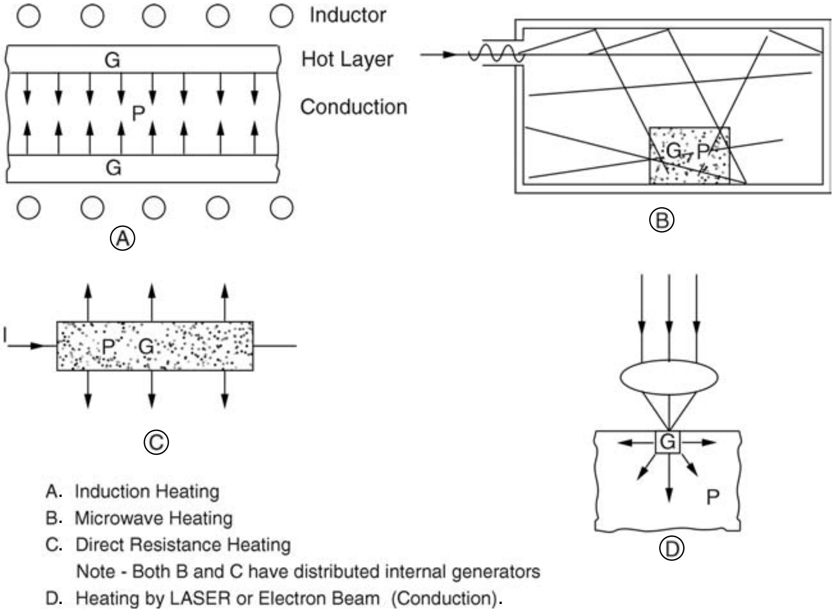


Figure 1.3 Special heating modes.

using an oscillator and an inductor. The work gets heated by the induced eddy current. In microwave heating the work is placed in an electromagnetic field of very high frequency (10^{11}–10^{14} Hz). The molecules of the work vibrate and create heat. In direct electric resistance or capacitive heating the work is made a component of an electric circuit. The power I^2R or dielectric losses in it due to current I produce heat. Later we will discuss all these processes in detail to highlight their individual features.

Heat transfer in all furnaces of this type is directly related to the surfaces of the generator and to the work taking part in the transfer, and the ratio F_P/F_G becomes a decisive factor in the design.

The heat transfer from the generator to the work takes place over paths through the medium. Thus, the properties of the medium decide the mode and efficiency of transfer. The medium may be air or a special gas or combustion gases, or vacuum and is called the "atmosphere." Thus a classification based on atmosphere arises, such as vacuum furnace, protective atmosphere furnace, salt bath furnace and the like.

3. Two modern heating processes that need to be specially mentioned are laser and electron beam heating. To some extent they belong to both systems mentioned above. A laser is a light beam having a single wavelength and excellent collimation. When focused on the work surface, it produces a spot with very high energy density (~10^5–10^8 W/cm^2) which melts or evaporates the material in the spot. Penetration below the surface is low but deeper penetration is possible (Figure 1.3(D)).

   An electron beam is a stream of high-energy electrons which can be focused on the work with similar power density. Heat is produced when the electrons lose their kinetic energy on impact. The penetration is deeper than that with laser beam heating.

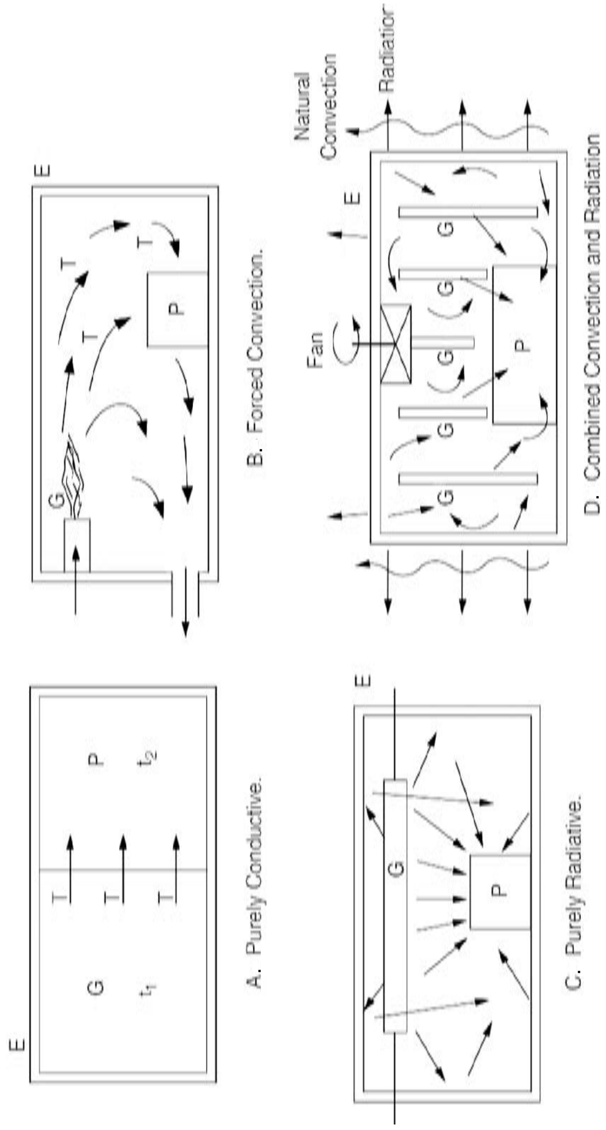
   Both techniques are useful for precision heating/melting at a spot (~ 0.1–2.0 mm diameter) that can be easily controlled. They are useful heat sources for cutting, welding, and drilling operations requiring precision. Energywise, they are highly inefficient but offer many other advantages than any other process can. These techniques are now in commercial use and are discussed in detail.

1.3 CLASSIFICATION OF HEATING MODES

In the heating systems of the first type, i.e., systems in which the generator and the work are separated and enclosed in an enclosure, the heat transfer process shows multiple modes.

If the heat generator and the work are in good contact, the transfer is only by conduction (see Figure 1.4(A)). The conductivities of the two are the decisive factors. However, such direct contact is possible only in rare cases.

The space between the generator and the work is usually filled with air or some process gas (Figure 1.4(B)). Gases are always in natural circulation due to the buoyancy effect. In some



A. Purely Conductive.

B. Forced Convection.

C. Purely Radiative.

D. Combined Convection and Radiation Inside and Outside.

Figure 1.4 Heat transfer modes.

cases, the gases may be in forced circulation induced by a fan or pushed by a flame. The gases pick up heat from the generator and pass it to the work during circulation. This then becomes the main transfer mode and is called "convection" (natural or forced). In such cases, fluid dynamic properties such as viscosity, velocity, and flow channel geometry become the deciding factors in heat transfer.

Hot bodies radiate heat in the space around them. Thus a generator at a higher temperature than the work will radiate heat toward the work (Figure 1.4(C)). No physical contact or intervening gas is necessary. In the system under consideration, heat transfer will take place by radiation in addition to convection. If there is no gas in the intervening space (i.e., there is vacuum), radiation will still take place. Thus radiation is the third mode of heat transfer. It takes place alone or accompanies convection.

This discussion shows that ignoring pure conduction as a rare case, heat transfer between the generator and the work will take place by convection and/or radiation. One such furnace is shown in Figure 1.4(D). Note that in addition to internal radiation and convection (assisted by fan) the exterior is also transferring heat to the surrounding by both processes. We will quantify these modes in the next chapter. In case the transfer takes place simultaneously by both convection and radiation, the temperature of the hot body decides which mode will be dominant. Later we will show that radiation is dominant above about 600°C and convection below this temperature.

In high-temperature furnaces heat transfer is mainly by radiation. Low-temperature furnaces are convective furnaces and proper circulation of gases in the enclosure and around the work are their main design features.

In fuel-fired furnaces the flame is the main radiator and the inside enclosure surface is a secondary radiator. Both contribute toward radiant heat transfer to the work. The combustion gases evolving from the flame circulate in the enclosure and contribute to heat transfer by convection. The placement of the burners and the location of the gas exit port, with respect to the work and the enclosure, become important for obtaining maximum heat transfer to the work.

Vacuum furnaces are purely radiative. As the radiation from the generator also strikes the vessel it is necessary to use reflectors and cool the vessel wall with water circulation.

Heat transfer in laser and electron beam heating is mainly by conduction but has some peculiarities. Heat is created at the focal spot on the surface and is conducted to lower layers (Figure 1.3(D)). A considerable amount of incident energy is lost by reflection. The temperature at the spot is very high and some of the surface layer is melted, evaporated, and splashed. This makes the beam go deeper but the bulk transfer is by conduction. Because of high energy density the process is very fast and complete (through) heating requires a fraction of a minute. As intense heat is created on a very small spot, laser and electron beams are known as "concentrated heat sources."

In direct contact resistance heating, capacitance heating, and microwave heating (Figure 1.3(B) and Figure 1.3(C)), heat is created uniformly throughout the work on an atomic or molecular scale. Hence, transfer phenomena are not significant.

Induction heating heats a relatively thin surface layer (0.5–3.0 mm) (Figure 1.3(A)). The heat is then conducted to the inner layers. Due to concentration of heat generation on the surface and conduction to the interior, induction and laser heating offers a possibility of heating only to the desired depth by controlling the time of radiation.

Note that once the heat flux reaches the surface of the object it is carried inside by conduction only.

1.4 AUXILLIARY TECHNIQUES

While discussing convection in Section 1.3, we have seen the importance of proper circulation of gases in the furnace enclosure. The stream of gases may be smooth (laminar) or with eddies or recirculation (turbulent). These two types exhibit different flow patterns when they pass over walls, single or bulk work objects, and ducts. Consequently the heat transfer from such streams is also significantly affected. Gases in furnaces are generally at or near atmospheric pressure. When at extremely low pressure, such as in vacuum, they exibit an altogether different behavior.

Many parts of furnaces require water-cooling to keep their temperature low. This is usually achieved by circulating water through these parts. Here our object is to remove the heat. We have to consider heat transfer to the water flowing through the cooling channels. We again come across a type of flow and its effects on heat transfer. This will help us to decide the quantity of cooling water and the pump capacity required.

Considering the importance of gas and water circulation in heating processes we will review the underlying principles of related “fluid dynamics” in a separate chapter.

To protect metal from oxidation at high temperature and to bring about some changes in the composition of surface layers (e.g., carburizing, nitriding, etc.) special protective atmospheres or vacuum are used along with many heating processes. The generation and control of these atmospheres and vacuum are discussed in separate chapters.

The success of a heating process is determined solely by measuring and monitoring the temperature. A wide range of measuring techniques for high temperatures (pyrometry) are available. It is of paramount importance to choose a proper pyrometer for measurement and control of the given process. Pyrometry and temperature control are discussed separately.

Let us begin our discussions with heat transfer processes and proceed to auxiliary techniques. Solved examples at each stage will make the underlying design technique clear.

References

7 7. Refractories

7.2 CLASSIFICATION OF REFRACTORIES

Refractories are mainly inorganic oxides or their mixtures. These oxides, and hence the refractories, are classified into three classes — acidic, neutral, and basic. This classification is based on their resistance to the slags produced in metal extraction, glass making, cement, and other chemical manufacturing. Acid refractories resist attack from slags predominant in silica (SiO_2). Basic refractories resist the attack of slags containing CaO and MgO. Neutral refractories are unaffected either by acid or basic slags. The degree of slag resistance varies among various oxides. Thus, silica is most acidic and calcium oxide is most basic. Based on these criteria the oxides forming refractories are arranged on a ‘‘scale’’ given below. Fire clays dominant in SiO_2 are acidic, but as their Al_2O_3 content increases they become increasingly neutral. Pure Al_2O_3 is completely neutral. Refractories containing magnesite (MgO) and dolomite (CaO, MgO) are basic. Other compounds used as refractories such as carbides, carbon, graphite, zirconia, etc., are considered neutral. This book excludes all furnaces and reactors that produce slag. Hence, the above mentained method of classifica tion is not discussed further. For general use in industrial furnaces fire clay refractories are mostly used in all forms and for parts of furnace structure (walls, roof hearths, doors, etc.). Other refractories that are occasionally used are pure alumina, pure silica, and silicon carbide among others. These refractories are discussed in more detail in the subsequent section.

7.2.1 Fire Clay Refractories

These mainly consist of silica (SiO_2) and alumina (Al_2O_3) in varying proportions. These two oxides form a continuous system of phases. These phases are Tridymite — A silica (SiO_2) mineral stable between 870 and 1470 ˚ C. Crystobalite — A silica mineral stable between 1470 and 1723 ˚ C. SiO , TiO , Al O , Cr O , Fe O , MgO, CaO Acidic Neutral Basic 2 2 2 3 2 3 2 3 ← → Mullite — A silica-alumina mineral ($Al_6Si_2O_{13}$) having a melting point 1850 ˚ C and stable at all temperatures. Fire clays also contain impurities and bonding agents in small amounts. These are classified according to their duty such as Super duty — Containing more than 45% Al_2O_3 and pyrometric cone equivalent (PCE) greater than 33. They have good resistance to thermal shock and good mechanical strength. High duty — They have alumina content similar to super duty but a lower PCE (31-33). Medium duty — They have a still lower PCE (29–31). Low duty — They have a PCE of 15–28. Thus, it can be seen that as the duty becomes less severe, the PCE value, i.e., the refractoriness, strength, and abrasion resistance, along with the cost, also lowers. For general purpose medium-size furnaces, medium- or high-duty fire clay is adequate for temperatures up to 1550

° C.

For higher temperatures up to 1700 ° C, super-duty fire clay is the best. Low-duty fire clays can be used up to 1400 ° C but have low strength and low thermal shock resistance. They are best used as backing layer for higher grades. Almost all the above grades are also available as insulating bricks. These have similar thermal properties but due to a high porosity, they have low thermal conductivity and low strength. Fire clay refractories containing more than 72% silica are known as “semisilica bricks.” These can be used up to 1450 ° C.

They have good dimensional stability.

7.2.2 High Alumina Refractories

These refractories contain 48–99% alumina and are classified according to alumina content. They consist of mullite (Al_6SiO_{13}) and corundum (natural Al_2O_3) along with bauxite and clays.

Their impurity content is lowered to improve refractoriness. High alumina bricks have a high density, PCE value higher than fire clays, good mechanical strength and creep resistance, and can be used up to 1850 ° C. Their cost increases with increasing alumina content.

These refractories find use in melting furnaces, incinerators, cement kilns and the like. In industrial heating where temper atures are as high as 1500–1800 °C, high alumina refractories are the only choice. They have good electrical resistance at high temperatures and are gas-tight (low porosity) and hence, are used for heating element supports, insulators and muffles for laboratories, and light duty high temperature industrial furnaces (e.g., semiconductor processing). Other varieties of high alumina refractories are alumina chrome and alumina-carbon refractories. Phosphate bonded alumina bricks are used for aluminium melting furnaces.

7.2.3 Silica Refractories

These types of refractories contain 94–98% silica and very low amounts of FeO and Al_2O_3. They have TiO_2 and CaO up to 1.5–2.5%. Silica bricks have good resistance to acid slags and have good mechanical strength as well. If not processed properly, they show a permanent volume expansion up to 15% and have low thermal conductivity. They are useful up to 1700 °C and are mainly used for glass-melting furnaces. Vitrified or fused silica is another variety containing >98% silica. They are produced from fused quartz. They have volume stability only up to about 1100 °C. This type is resistant to most chemicals (except strong alkalies) and is widely used for laboratory ware, furnace tubes, etc. It can be polished to obtain good, glass-like transparency.

7.2.4 Carbon and Graphite Refractories

These contain 98% or more carbon in various crystal forms blended with pitch, resins, and petroleum derivatives. Carbon is easily oxidized in atmospheres containing oxygen or oxidizing gases such as CO. Hence, these refractories can be used where there is no direct access to oxygen. Such conditions exist in a vacuum or in inert atmosphere furnaces and also at places where carbon is covered by metal or slag (e.g., blast furnace bottom). Carbon blocks prepared by blending and pressing can be easily machined to intricate shapes such as tubes and nozzles. Currently carbon is also produced in fiber form which can be further processed to obtain tapes, cloths, blankets, and so on. Carbon can be used (with above restrictions) for temperatures up to 2000 ° C. It has good electrical conductivity and high resistance to slags, chemicals, and gases. It has been used for electrical resistance heating elements. Graphite bonded with clays and tar or pitch is used to manufacture foundry crucibles.

7.2.5 Silicon Carbide (SiC) and Carborundum

This is a major special refractory and is made by fusing silica and coke at 2000 ° C. It is available in various purity grades. Silicon carbide is extremely inert and difficult to bond. It is bonded with clay or silicon nitride. It is used in electrical heating elements (up to 1550 ° C) for furnace parts (up to 1800-2000 ° C). It has good spalling resistance and is very hard and strong. Compared to other refractories, it has very high thermal conductivity.

7.2.6 Zircon Refractories

These are zirconium silicates containing 67% ZrO_2 and 33% SiO_2 together with binders, etc. These are difficult to shape, have good resistance to acid slags, and good thermal shock resistance.

7.2.7 Zirconia Refractories

These are made from pure zirconium oxide (ZrO_2), which has a very high melting point (2680 ° C) but shows dimensional changes at high temperature. By certain stabilizing techniques, it is possible to control sudden dimensional changes and cracking. It is very costly and does not find wide use in general furnaces.

7.3 INSULATING REFRACTORIES AND MATERIALS

During its operation a furnace develops a high temperature on its inner side which is called the hot face. The outside, i.e., cold face temperature, is the atmospheric temperature. Hence, there is a considerable temperature difference between the hot and cold face under which heat flows out. This heat is totally wasted but unavoidable. However, this loss can be reduced by using a material with low thermal conductivity for furnace construction. Such low thermal conductivity materials are known as “insulating materials.” Many insulating materials have an upper useful temperature beyond which they cannot be used. They are also mechanically weak and cannot be loaded. This limits their direct use in furnaces. Materials of this class are cork, asbestos, glass fiber, and wood. Fire clay materials (alumino-silicates) can be processed to give a low thermal conductivity. This is achieved by creating voids or pores in them. These pores reduce the density and make the bricks lightweight. Porous fire clay bricks are good insulators and are reasonably strong up to about 1000 ° C. Hence, they are more suitable than the materials discussed in the previous paragraph. Porous fire clays are not as strong as dense bricks and hence cannot be used for the hot face. These bricks are easily machinable. Ceramic and mineral fiber materials in various forms constitute the third category of insulating materials. Their conductivity, density, and specific heat is low. Ceramic fibers can be used for both hot and cold faces; rock and mineral wool can be used at 700 °C maximum. These materials have no mechanical strength. They are also very costly. Hence, there is no one insulating material which will satisfy all requirements. We take advantage of the fact that the temperature difference between the hot and the cold face is in the form of a gradient. Hence, a wall or roof can be constructed from a number of layers of different materials suitable for the temperature range of that layer. This is called a composite wall. The thickness of layers can be adjusted to give the most economic and effective loss reduction. Various commonly used insulating materials and their important properties are given in Table 7.1. The design aspects are discussed elsewhere.

7.4 MANUFACTURE OF REFRACTORIES

7.4.1 Raw Materials

Besides a few exceptions, the raw materials for manufacturing refractories are natural minerals and clays. These are

TABLE 7.1 Properties of Some Common Insulating Materials

Material	Density kg/m ^{3}	Maximum Temperature °C	Thermal Conductivity W/m °C	Specific Heat kJ/kg °C
Light weight				

fireclay

65-80% SiO 2 450-800 950 0.15-0.25 0.835

Light weight

fireclay

35-50%

Al 2 O 3 500-1000 1100-1250 0.45-0.55 0.837

Ceramic fiber

blanket

40-50%

Al 2 O 3 , SiO 2 64-130 900-1400 0.17-0.25 1.03

Ceramic fiber

blanket

95% Al 2 O 3 50-90 1600 0.09-0.21 1.07

Rockwool 150-200 750 0.033-0.037 @ 150-200 kg/m 3 0.418 - 0.852

Asbestos 150-fiber 600-800 board 550 0.13-0.15 0.837

Glasswool 150-200 300-450 0.037-0.040 0.66

Glass fiber

(mat) 12.0-80 350-450 0.035-0.040 0.66

Mica 2900 500-550 0.52-0.60 0.837

quartzite, quartz (SiO 2), kaolin (AlSiO 4), dolomite CaMg(CO 3) 2 ,

calcium carbonate CaCO 3 , magnesite MgCO 3 , sillimanite

AlSiO 4 , alusite Al 2 SiO 5 , chrome ore (Fe, MgCrAl)O 4 , Zircon

sand ZrSiO 4 , graphite, and many others. The mined raw materials contain many impurities. Sea water is an important source of magnesium. Pure alumina (Al_2O_3), silicon carbide (SiC), corundum (Al_2O_3), and mullite ($Al_6Si_2O_{13}$) are some of the raw materials which are prepared synthetically at great expense. Some refractories are made from carbon or contain carbon products, which are by-products of coke and oil production processes. Besides the gross chemical compositions cited above, the actual mineral crystals that go into the formation of a raw material are also very important. For the same chemical composition, the crystal structures can be quite different and will show different properties. During the manufacturing (firing stage) and when used in a furnace, the original crystal structures may change. This will result in abrupt expansion or change in other properties such as mechanical strength. Hence, it is necessary to find out the actual crystal structure of the constituents. Identification of the crystal structures and their bonding with other minerals constitute the separate science of mineralogy. There are vast numbers of mineral classes. The same is the case for different clays. Broadly speaking, the manufacturing process of almost all refractories follow the same sequence. There are minor dif ferences which are not discussed here. All the mined raw materials are crushed, ground, and separated according to the lump or grain size. Either before or after the size reduction, it may be necessary to wash the mineral to reduce impurities, gangue minerals, and extraneous matter. Next, a very important stage is to mix the ground constituents to obtain a proper blend of chemical composition, minerological content, and desired grain size distribution. It is the variation in blending that decides the future properties of the refractories. The mix is again ground and homogenized in mixers. It is at this stage that binders, such as clays, are also added to the mix. The required amount of water is also added at this stage. There are many methods of manufacturing standard refractory shapes. The most common method is the forming of the shape in a mold under high pressure (~ 200 N/mm^2). Complicated shapes which are difficult to press are shaped by slip casting. A slurry of raw material mix and water is poured in a plaster mold. Water is absorbed by the mold and a shape (semi-dry) is produced. A few years ago the process of isostatic compaction was brought from the laboratory to the production floor. The raw material is filled in elastic rubber bags having the required shape. The bags are deaired and sealed. They are then charged into a pressure vessel and subjected to enormous hydrostatic pressure. The material is compressed from all sides. This results in a dense precision product. The process can also be carried out at high temperatures. Isostatically pressed shapes are far superior than the press formed ones. However, the process is costly and is used for special refractories only.

In the next stage, the green, lightly bonded shapes are carefully dried in large kilns. Drying produces steam which can damage the product by cracking or breaking. Removal of water also produces shrinkage, i.e., substantial change in dimensions. Hence, utmost care is necessary at this stage. The product is now strong enough for handling. Final strength and shape is produced in the next stage of firing or sintering. Here the shapes are stacked on flat cars and passed through a tunnel kiln. The cars pass at a predetermined speed and are subjected to a definite cycle of preheating, firing (heating) at 1200-1800 ° C, and cooling. At this temperature the various constituent minerals react and produce a strong bond and some shrinkage. The actual thermal cycle used depends on the phases (crystal structures) of the constituents and their interrelationship (phase diagram).

Many types of furnaces are used depending on the thermal cycle and the volume of production. The shapes are then measured for dimensional accuracy. Their crystallographic structure is also checked along with the outer appearance. The shapes are then cleared for dispatch. The shapes so produced are very hard and cannot be machined. Special refractory shapes are sometimes ground to produce a dimensional accuracy of 1.0 mm. It is again pointed out that what is described above is only a broad outline of the manufacturing process. Individual refractories may require slightly varying procedures.

7.5 REFRACTORY SHAPES

There are many standard and nonstandard shapes of refractories. It is always economical to use the standard sizes (as far as possible) in furnace construction as they are readily available. The basic shape available all over the world is the standard 9" brick which has the dimensions 9" × 4 " × 2 " (or 230 × 115 × 65 mm) and has a volume of 101.25 cu. in. (~1660 mm 3). Besides the standard brick, other standard shapes are small, straight, soap, key, jamb, tile, end skew, side skew, arch, split, circle brick, featheredge, neck, etc. Some of these shapes are shown in Figure 7.1. It is necessary to consult manufacturers’ literature to check the standard shapes offered. The circle brick is a sector of a circle of given diameter and is available in many sizes. Similarly, the arch brick is used to build the furnace roof or arch of a given span and again a range of spans is offered. Shapes are ordered by numbers or volume. Usually a 9" brick equivalent is used for this purpose. The standard 9" brick has a volume 101.25 in.^{3} The volumes of other shapes are determined in units of 101.25 in.^{3} The nonstandard shapes available are special or modified standard shapes. Burner blocks (quarls) and corner pieces are some examples of this type. It is necessary to consult the manufacturer for these shapes. If he has already made the shape, the mold is ready and the cost will be less than a specially manufactured shape. Along with the shapes, the manufacturer also supplies standard anchors or hooks with which the refractory walls are built.

1 2 1 2 Figure 7.1 Some typical refractory shapes.

Almost all the refractory types (compositions) are available in standard shapes. Many refractories such as pure oxides (Al_2O_3, SiO_2, ZrO_2), and alumino silicates (mullite, kayanite) are produced in tube form. Both rectangular and circular tubes (up to 150 × 150 mm or 150 mm diameter) are made. These are used for laboratory furnaces, pyrometer sheaths, etc. Other shapes available are rods, tiles, small crucibles, etc. All these shapes are manufactured by pressing or extrusion.

7.6 UNSHAPED REFRACTORY PRODUCTS

These products contain the same raw materials plus minor additions of plasticizing, bonding, and other surface active chemicals and minerals. These materials are offered in various formulations such as gunning and ramming mix, castables, mortars, cements, monolithics, and mastics. They are used for lining repairs, brick laying, hearth construction and so on. Almost all types of refractories are available in these forms. They can be used for hot or cold repairs. It is necessary to follow the manufacturers' instructions for their successful use. Castable mixes can be used to cast an uncommon shape at the site. Some formulations are heat-setting and some require careful curing or drying. These formulations are mainly used in process furnaces such as steel convertors, and cement kilns. For the furnaces discussed in this book, unshaped products are mainly useful for hearth-making and crack-sealing. An interesting unshaped refractory form is paints or washes. These are based on zircon ($ZrSiO_4$) and alumina or fire clay. They can be applied on refractories or metal sur faces. They improve the heat transfer characteristic of the lining by improving emissivity at high temperatures (up to or more than 1500°C). The lining life also increases on the use of paints and washes. They are applied by spraying or brushing.

7.7 REFRACTORY FIBERS

We have seen in previous sections that refractories are available in shaped and unshaped forms. A third type of refractory form is fibers or filaments. From these we can get both shaped and unshaped products. The fiber form of refractories is a result of developments over the last twenty-five years. The general outline of fiber manufacture is as follows: A synthetic or mixed composition of the refractory is melted at a high temperature. The melt is then poured in the form of a stream. Air is blown into the stream so that it breaks the stream into fibers which solidify. By carefully adjusting the melting temperature, the speed of stream, and the velocity of air, the fiber length and diameter are controlled. The fibers so produced have lengths of about 200 mm and diameters 2–4 μm. By using textile manufacturing techniques, the fibers are converted into cloth and blankets of various thicknesses and lengths. By the addition of resins and other bonding materials the fibers are converted to rigid boards and paper. Spinning the fibers produces ropes and felts. Along with these shapes the fibers are also formulated into unshaped forms such as mortars, moldable mix, wet wraps, and cements. Unprocessed loose fiber is also offerred as a packing material for insulation. Presently, the following materials are available in fiber and fiber-made forms: All fire clay compositions, alumino silicates such as mullite and kyanite, corundum, pure silica, and zircon. Besides regular refractories, fiber materials made from glass, rock fiber, and slag are also available. This list is continuously growing due to new formulations and processes. The fiber form offers many distinct advantages over regular pressed solid forms. A few main points to be noted are: 1. For the same chemical composition the fibers have extremely low thermal conductivities. This is due to low density inherent to the porosity and voids. 2. Low density also gives low specific heat, hence, heat storage is also very low. 3. Very good thermal shock resistance as there is no expansion. 4. Good chemical, steam, and water resistance. 5. Can be easily cut into required shapes and quickly installed. No curing required. 6. Intricate shapes can be produced by molding or vacuum forming. 7. They can also be used for hot face. 8. They are resilient and make good acoustic barriers. 9. Due to their light weight, fiber boards make for much stronger and lighter roofs than parches. Compared to these advantages a major disadvantage is that the mechanical strength, hardness, and abrasion resistance is poor. Hence, they can only be used in places having no mechanical load such as wall faces and roofs. If there is both mechanical load and elevated temperature, the structure is built with appropriate solid forms (bricks) and faced with fiber forms. Furnace hearths usually take the load from charge. Hence, fibers are not suitable for making hearths. A short summary of the important properties of fiber products is given in Table 7.2. Detailed information about the properties and applications is best obtained from the manufacturers as there are some differences among various proprietary products.

7.8 PROPERTIES OF REFRACTORIES

The performance of a refractory in service depends on many factors. These factors are related to certain measurable properties. Similarly, the refractory construction is carried out at room temperature and is used for service at a higher temperature. Hence, the properties at both room and high temperature are required to be known and matched. These properties also serve as a guide for quality control in manufacturing.

TABLE 7.2 Properties of Ceramic Fibers and Rock Wool

Type	Ceramic fiber			Rock wool		
Form	Bulk fiber	Blanket	Board	Bulk fiber	Blanket	Board
Density kg/m3	80–100 delivered 50–250 installed	64–128 Standard 96–128 High duty	250–300	150	150	50–200
Maximum Temperature °C	1260–1400	1260–1400	1260–1600	700–750	700–750	700–750
Thermal Conductivity W/m°C	0.140	0.133 0.126 0.120	0.079	0.03–0.05	0.04–0.06	0.04–0.1
Application	Expansion Joints, Sealing Molding	Lining Insulation	Hot, face lining	Insul		

7.8.1 Room Temperature Properties 1. Chemical composition — The major constituents and their contents in a refractory decide its class, i.e., acidic, basic, high alumina fire clay, etc. Minor constituents such as alkali oxides, carbonates, iron oxide, titanium oxide, etc., decide the chemical performance. The chemical analysis also indicates whether the raw materials chosen are correct and the mixture is homogenous. 2. Minerological constituents — These are determined by microscopic and X-ray techniques and provide information about the constituent minerals, their crystal structure, and phases. These decide the performance in firing as well as in service at high temperature. 3. Bulk density and porosity — Bulk density and porosity provide information about the heat storage capacity and porosity indicates the correctness of pressing and drying. Density is quoted in kg/m 3 and porosity is expressed in percentage. Porosity also indicates the insulation capacity (thermal conductivity). Highly porous refractories are good thermal insulators. 4. Abrasion resistance — Refractories are subject to rough handling during manufacture and also to abrasion with process materials (furnace charge, slags) and dust-laden gases at high temperature. Abrasion resistance determines the resistance to such erosion. It is determined by abrading the refractory on a standard surface (e.g., silicon carbide) when loaded under a standard weight. 5. Cold crushing strength — A refractory sample is loaded at a standard increasing rate and the load at the breaking point is noted. This breaking load divided by the area under load gives the cold crushing strength. This test gives a good indication about load bearing capacity, handling, and shipping capacity and also provides information about the strength of the bond obtained after firing.

7.8.2 High Temperature Properties 1. Refractoriness — This is the maximum temperature which a refractory withstands before undergoing permanent change of shape. Refractories do not have welldefined melting temperatures. They start softening rather than melting in a certain temperature range. Refractoriness is determined by a pyrometric cone test. A number of standard pyrometric cones having different softening points and a similar cone of the test refractory are heated in a furnace under standard conditions. At the softening temperature the test cone and a matching standard cone buckle or collapse. The number of this cone (ASTM standard) is reported as the refractoriness of the test piece, called the “pyrometric cone equivalent” (PCE) number. In practice, the actual maximum temperature of service is about 100–200°C less than that indicated by the PCE number. 2. Dimensional stability —All refractories show a permanent change in dimensions at the firing stage of manufacture. These changes are very slow at the end, and hence, remain incomplete. When fired in a furnace in service, the lining is heated to a high temperature for a long time. This tends to complete the remaining dimensional change. These changes, though small and slow, have to be considered in lining design. The test report indicates changes in linear dimensions on heating for a standard time and required test temperature. The dimensional change may be expansion or shrinkage depending upon the type and temperature. Apart from the permanent dimensional changes, the refractories undergo the usual linear expansion and contraction on heating and cooling. These dimensional changes are very important in lining design. They are required to be compensated for by designing proper expansion joints. Sudden changes in temperature will produce thermal shocks. If not taken care of by expansion joints and cushions, the lining will be subjected to high internal stress leading to cracking or collapsing. Most of the refractories in fired condition show a fairly linear relation for expansion (contraction) and temperature. Silica bricks are an exception to this. They show a high expansion rate of up to about 800°C and then subside to a very slow linear rate. Unfired refractories such as cements, gunning, ramming mixes and castables show drastic dimensional change due to both permanent and reversible expansion. 3. Thermal expansion and creep under load — All refractories are subjected to some load at high temperatures. For the furnaces considered in this book, the bottom will carry the load of the charge as well as self weight. The walls will be loaded mostly with self weight and will be under compression. If the roof is made of unsuspended brick arch, it will be quite heavy. Thus different parts of the furnace lining will be under different loading conditions. They will show a permanent change of dimension with time, i.e., creep. This permanent change (usually subsistence) is determined by loading a sample at standard (75 × 10 4 kg/m 2) load at increasing temperature and time. The phases present, density, porosity, and bonding between particles determine the creep properties. 4. Thermal conductivity — Due to the difference between the inside and outside temperatures, all refractories conduct considerable heat to their surroundings. This heat is unavoidable wastage. The conductivity is reported in W/m °C. It changes (usually increases) with increasing temperature and the values of the temperature coefficient of conductivity are also available. Insulating refractories are highly porous and have low thermal conductivity. The thickness of the lining, usually consisting of an inner layer of dense refractory and outer layer(s) of insulating refractory, is determined by the permissible heat loss and conductivity. For some applications such as recuperators and regenerators, a high thermal conductivity is desirable. 5. Thermal spalling —Some refractories, especially those undergoing thermal cyclic load and gas or slag attack, lose their exposed surface layers. This is known as spalling. Spalling can be reduced by proper choice and lining design. 6. Specific heat — A lining absorbs and retains a considerable amount of heat in service. The retention of heat depends on the specific heat and density, i.e., thermal mass. Thus, for quick heating and cooling we require a lining with low specific heat and density. Insulating refractories have a low thermal mass due to the large number of air pores that give low density. There are many other properties of refractories that are occasionally useful in special designs. Selected properties of some refractories relevant to the furnaces and considered in this book are given in Table 7.3, Figure 7.2, and Figure 7.3.

7.9 SELECTION OF REFRACTORIES

We have reviewed the main types of refractories and their important design and service properties in previous sections. The choice of refractories chosen from the available materials basically requires matching the properties with the requirements determined at the design stage. Each design will have its peculiar demands and will need an individual choice. Most of the time there is no single refractory that is suitable. We then have to choose different refractories for different parts or make the best compromised selection. The fol lowing guidelines will be helpful.

7.9.1 Thermal Requirements

These are established by following data: 1. Type of furnace – such as horizontal muffle, car bottom or belt oven 2. Temperature – maximum temperature, rate of heating and cooling, temperature at different zones

TABLE 7.3 Properties of General Purp

os

e

R

ef

ra

ct

or

ie

sClassMainconstituentsDensityk
g/m3Refractoriness°CSofteningt
emperatureunderload°CColdcompe
nsationstrengthMN/m2Specifiche
atkJ/kg°CSilica96-97%SiO2Al2O3
<0.5-1.0%1800-19001700-1750160
0-170030-350.73-1.2SemiSilica8
8-90%SiO28.0-9.0%Al2O317001710
1600-170030-350.8-1.4FireClay6
0-62%SiO230-32%Al2O31900170014
50-155030-350.8-1.2Highduty36-
38%SiO254-56%Al2O3240017801550
-164025-320.9-1.2Mullite20-22%
SiO270-73%Al2O3220018501600-17
0065-700.65-0.75HighAlumina>85
%Al2O32600-29001800-20001570-1
92065-730.8-1.2Magnesite85-90%
MgO2700-2800>17501450-155030-3
20.9-1.2ChromeMagnesite63-75%M
gO6-10%Cr2O33000>17001350-1500
30-500.8-1.2Zircon30-35%SiO255
-66%Zr2O3330025801820-187098-1
960.6-0.8Zirconia80-98%ZrO23-4
%CaO/MgO4000-45002480220014-40
0.5-0.7SiliconCarbide93-50%SiC
26002000-2200200040-750.8-1.14
-30%SiO2CarbonGraphite>98%C135
0-160020002000—0.8-2.03. Size and shape of furnace—heating area height, cylindrical, or rectangular 4. Temperature gradient across the walls and general permitted heat losses to atmosphere 5. Operation cycle — continuous, or batch type 6. Heat stored in the walls and structure (this is very important for batch type,

cyclic operation)

Figure 7.2 Thermal conductivity of selected refractories. 7. Total heat input, type of fuel, impact of flame on the walls, placement of electrical heaters 8. Load exerted by charge — single charge, small charge in containers, large heavy charge distribution of charge weight on hearth

Figure 7.3 Expansion of common refractories temperature. Properties of refractories related to above requirements are: 1. Refractoriness and refractoriness under load 2. Dimensional stability—expansions and volume changes 3. Thermal conductivity, specific heat, and density 4. Creep and thermal shock resistance

7.9.2 Mechanical and Chemical Requirements

These are indicated by following design data: 1. Type of charge, expected and permissible oxidation, scale produced, type and quantity 2. Combustion products—gases, temperature and composition, ash and its composition 3. Methods of charging and discharging, mode of charging through door, roof, and bottom 4. Furnace construction and load on the walls, roof, hearth, at atmospheric and service temperatures, thermal cycles 5. Flue dust, rate of flow of flue gases 6. Heating, direct or indirect Related properties are 1. Chemical composition and physical shape of charge 2. Cold and hot compressive strength 3. Surface texture of refractory — smooth, rough, medium 4. Size tolerances offered 5. Gas permeability 6. Resistance to slags, hot ash, dust For most of the furnaces discussed in this book, fire clay refractories (of suitable grade) and ceramic fiber shapes are quite suitable for the design of hot face walls, roofs, and hearths. These are complemented with matching unshaped products such as cements, castables, coatings, etc. There will be a few exceptions which will be pointed out at that stage. Insulating materials that are commonly used are ceramic, slag, rock, wool or loose fiber, asbestos, glass fiber, and insulating fire clay bricks.

These data, though useful as a guide for estimation, cannot be directly used in design. This is because the actual combination of stress and environment in practice is quite different than that used in the laboratory. It is safer to use data supplied by the manufacturer or conduct your own (short-time) tests.

Oxidation resistance of some commonly used metals and some alloys based on them is given with the maximum useful temperature in Table 8.1.

8.3.1 Corrosion by Other Gases

There are some instances when metals come in contact with gases other than air at high temperatures. Carburizing and nitriding operations are carried out in alloy muffles and containers. The atmosphere inside the muffle consists of a mixture of gases containing CO, CO_2, H_2O, H_2 N_2, and trace hydrocarbons like CH_4. In such an atmosphere ordinary muffle alloys absorb carbon, which leads to the formation of carbides, especially chromium carbide (Cr_3C_2). The carbides so formed migrate toward grain boundaries and weaken the metal. Similar reactions take place in ammonia (NH_3) leading to the formation of nitride gases containing sulfur in the form of SO_2 and H_2S which will react with metals, forming sulphide scale. Sulphide scale formation leads to flaking and spalling. Nickel does not form carbide and nitride while iron and chromium easily react with both, forming stable carbide and nitride. Hence, alloys for resisting carbon and nitrogen penetration contain large amounts of nickel and little or no iron. Nickel is prone to sulphide formation. Alloys to resist sulfur attack contain high chromium and 1.0-2.0% aluminum. The above discussion shows that there is no one alloy which will resist the attack of all harmful gases and a proper choice must be made to get satisfactory service life. Note that in many applications, the part (muffle) has to resist hot gases from flame, oxygen attack from the outside, and process gas from the inside. The metal choice then becomes quite critical.

TABLE 8.1 Oxidation Resistance of Some Commonly Used Metals

No.	Metal	Nature of Oxide	Oxidation (Heat) Resistance in Air
1	Mg	Loose oxide	Very poor (150-200 ° C)
2	Ta, Mo, W, Nb, Zr, Ti	Thick, loose oxide spalling	Poor (500 ° C)
3	Cu, Fe, Ni, Co	Thick with defects spalling	Fair (400-500 ° C)

4	Al, Sn, Cr, Be, Mn	Dense, adherant oxide film	Good (400 °C)
5	Ag, Au, Pt	No oxidation	Excellent but uneconomical. Only special or laboratory use (> 1000 °C)

8.4 MELTING POINT AND PHYSICAL STABILITY

All metals have a melting temperature. Alloys have a melting temperature range. Melting restricts the maximum temperature to which a metal can be exposed in any form or environment. Later, we will see that the strength of metals decreases with increasing temperature. Near its melting point, the metal shows practically no strength and starts to exhibit a viscous flow. Hence, the actual temperature to which a metal can be used as an engineering component is much less than the melting temperature. There are other complicating factors such as stress and environment, which restrict the maximum useful service temperature. It is therefore not possible to quote any rule. It is observed though, that many metals and alloys can be safely used up to about 0.3–0.4 × T_m where T_m is the melting temperature (°C). Alloying and other strengthening techniques have extended the useful temperature much above the iron-chromium-aluminum alloy (Kanthal), which has a melting temperature (T_m) 1500 °C and maximum service temperature (T_s) 1300–1400 °C. Approximate melting temperatures of some metals and alloys are given in Table 8.2.

TABLE 8.2 Melting Temperature of Metals and Alloys

Temperature Range ° C	Metal Melting Temperature (° C)
3300-4500	Graphite (Sublimes ~ 4200), Tungusten (3370)
2750-300	Tantalum (2870), Rhenium (3180)
2200-2750	Columbium (2415), Molybdenum (2620), Boron (2300)
1650-2200	Platinum (1750), Rhodium (1865), Titanium (1795), Chromium (1650), Zirconium (1850), Vanadium (1710)
1100-1650	Manganese (1260), Cobalt (1845), Nickel (1450), Iron (1540), Nickel alloys (1460), Stainless Steel (Austenitic 1450), Berylium (1285), Steels (1450)
700-1100	Copper (1085), Brass, Bronze (1040), Silver (960), Other Bronzes (1000), Aluminum Bronze (1085)
200-700	Aluminum and alloys (650), Magnesium alloys (600), Zinc (420)

The table shows that there is a very little choice of metals for use above 1600 ° C. Only refractory metals and graphite are available but they all require a special atmosphere or vacuum. There are no metals available above about 2200 ° C. The choice for temperatures up to 1400 ° C is very wide, especially in the range of 600-1000 ° C. All commonly used metals are in this range.

8.5 LINEAR EXPANSION

All materials show linear expansion when heated. This arises due to increasing lattice or molecular vibration. This expansion or dilation is reversible, i.e., increased dimension is recovered when original temperature is restored. Typical linear expansion coefficients for metals and alloys of interest to us are given in Table 8.3. Note that the values given are for comparison only. Actual values will depend on composition and pretreatment. The coefficient has no units as it is measured in the same units, e.g., (m/m length $\times 10^{-6}$).

TABLE 8.3 Mean Coefficient of Linear Expansion for Selected Metals

Metal/Alloy	Temperature range °C	Coefficient of linear expansion $\times 10^{-6}$/°C
Inconel 600	20–1000	16.7
Inconel 601	20–1000	17.8
Incoloy DS	20–1000	18.7
Aluminum	20–600	28.7
Graphite	20–600	3.5
Molybdenum	20–2100	7.2
Platinum	20–1000	10.2
Tantalum	20–2200	7.8
Tungusten	20–2400	5.8
Carbon and low alloy Steel	20–600	13.5
Austenitic S.S.	20–600	15.5
Ferritic S.S	20–750	11.2
Cast Iron Spheroidal Graphite and Alloy	20–400	12–18

In the design of furnace parts or components, this expansion, though small, must be taken into account and accommodated for. If restricted, considerable internal stresses are set up and give rise to bending, buckling, and distortion. Many high temperature applications involve fabrication by welding. The location of the weld joint and room for expansion are very important for long life. Linear expansion should not be confused with creep. The latter arises due to plastic flow under stress and is irrecoverable.

8.6 CAST IRONS

There are many types of cast irons. They are generally classi fied according to the shape of the graphite and the structure of the matrix. There is also a class of alloy cast irons which contains nickel, chromium, silicon, or molybdenum. Cast irons are cheap compared to special heat resistant alloys but their use in heating applications is limited due to low tensile strength and difficulties in fabrication. In a sense, they are brittle in tension but can take large compressive loads (150–300 N/mm ^{2}) depending on type. Fabrication is possible only by casting, machining, and welding. Hence, they are suitable only for heavy sections under compression. Ordinary flake graphite cast irons can be used up to about 400°C, beyond which they show extensive dimensional growth and flaking. ‘‘Growth’’ of cast irons is different from thermal expansion and creep. Nodular cast irons contain graphite in nodular form and have a pearlitic or ferritic matrix. They have limited tensile strength and are called ‘‘ductile irons.’’ These irons are suitable for service up to about 500°C and show little growth and flaking. Alloy cast irons (nodular) have been used up to 800°C. They contain nickel, silicon, and molybdenum. Chromium cast irons (C.I.) have good oxidation resistance. The properties of selected C.I.s are given in Table 8.4.

TABLE 8.4 Cast Irons for High Temperature

S

er

vi

ce For mechanical and other properties refer to handbooks. (Source Metals Handbook, Vol.1, ASM 8th Ed., 1961) No Type Composition Maximum service Temperature °C C Si Mn Ni Cr Cu/Mo 1 Ordinary flake graphite 3.4-3.8 1.8-2.8 0.5-0.8---450-500 2 Ordinary nodular graphite 3.2-4.1 1.8-2.8 0.5 0.8---500 3 Medium silicon flake graphite 1.6-2.5 4.0-6.0 0.4 0.8---900 4 High chromium flake graphite 1.8-3.0 0.5-2.5 0.3-1.5 5.0 15-35 1100 5 High nickel flake graphite 1.8-3.0 1.0-2.75 0.4-1.5 14.0-30.0 1.75-5.5 7.0/1.0 816 6 NiCrS: flake graphite 1.8-2.6 5.0-6.0 0.4-1.0 13-32 1.8-5.5 10/1.0 950 7 Aluminum flake graphite 1.3-1.7 1.3-6.0 18-25Al 1100 8 High Si Nodular 2.8-3.8 2.5-6.0 0.2-0.6 1.5--900 9 20% Ni Nodular 2.9 1.75-3.2 0.8-1.5 18-22 1.75 2.50-700 10 30% Ni Nodular 3.0 2.0 3.0 1.8 2.4 21-24 0.50-600

8.7 STEELS AT HIGH TEMPERATURE

Plain carbon steels containing 0.2–0.4% carbon and small amounts of silicon and manganese are ferritic or pearlitic. They are cheap, weldable, and available in all forms. They oxidize above 400–500°C and are suitable for low or medium (elevated) temperature parts such as structural frames, supports, panels, etc. Painting improves corrosion resistance. Low alloy steels containing 0.15% carbon and 1.2% molybdenum or chromium show slightly better properties and can be used for parts requiring intermittent service at temperatures up to 500-600°C. Chromium steels containing up to 20-24% Cr have good oxidation resistance but will show spalling under thermal cycling. They can be used up to 800°C. Austenitic stainless steels are resistant to corrosion by oils, fumes, moisture, and many gases up to 450°C. They retain their surface shine and cleanliness up to 450°C after which the surface may tarnish or blacken, but corrosion resistance is good up to 650-800°C. High alloy steels contain large amounts of chromium and nickel along with small amounts of Mo, Cb, Ti, Al, etc. They can be used up to 1150°C. Table 8.5 shows the properties of selected heat resistant steels. Reference should be made to handbooks as the number of commercially available heat resistant steel is very large.

8.8 SELECTION OF METALS FOR HIGH TEMPERATURE APPLICATION

We have seen in previous sections that at high temperatures, metals will fail by excessive stress or by reaction with their environment. Hence, these two cases become the deciding factors in the choice of metals. The following general remarks will help to make a preliminary choice. Note that there can be exceptions due to some combinations of temperature, stress, and environmental attack.

TABLE 8.5 Constitution and High Temperatu re Properties of Selected Plain Carbon and All oy

S

te

el

sTypeMainConstituents%TensileStrengthN/mm2(MPa),°CStressfor1.0%elongationin10,000hMPa/@°CStressforrupturein10,000hMPa/@°COxidationtemperature°CandApplicationsCCrNiMo/V25200400600Plaincarbon0.2---450463371Oxidation>400°CFurnacestructurePlaincarbon0.4---602630460dododododoOxidation>400°CFurnacestructureLowalloy0.151.2-2.0-0.6-1.0510510500293Oxidation>550°CCrsteel0.0620--5414004322 16----Oxidation>600°CRefractorysupportsAusteniticS.S0.1188-121-2Mo/Ti630-432378Oxidationat850°CResistanttoorganiccorrosionHighalloy0.12512656-556432Oxidationat1000°C.Muffles,belts,potsandbaskets.(AllSteelsinannealedornormalizedcondition.)13640039500192400545002164508553030445010553085600397001166005470069650487009365062700 1. Aluminum is the cheapest choice if the temperature does not exceed 300°C. It is quite resistant to oxidation and attack by CO 2 and moisture, and finds application in ovens, dryers etc. 2. Ordinary (plain carbon) steels have adequate strength up to 400-500°C, but do not possess a high oxidation resistance. They are cheap and easy to fabricate in a variety of forms such as rods, strips, and wires, and structurals. Ordinary or nodular cast irons are sometimes better than steels in oxidation. They have two limitations. They cannot be formed; and the cast section is thicker and heavier than steels. Oxidation and dimensional instability is the second limitation. Inability to take tensile loads limit their use to compressive stress. 3. Low alloy steels containing 1-3% chromium and small amounts of molybdenum and vanadium can be used up to 600-700°C. They can be easily fabricated and have better oxidation resistance than plain carbon steels or cast irons. They should be used in normalized or annealed conditions. 4. Low corrosion resistance of steel at high temperature can be improved by plating or impregnation. Chromium plating is frequently used. It helps to reduce oxidation and improves reflectivity. Impregnation of the surface with an oxide layer improves resistance to oxidation and attack by molten salts and carburizing chemicals. 5. In some applications, steel parts can be cooled by water or air circulation. This keeps their temperature at an acceptable level. 6. Metallurgically, the metal to be used should have a single phase (e.g., ferrite and austenite) and a large grain size. Generally, alloys hardened by heat treatment are not suitable because a prolonged high temperature breaks the hardening phase such as with martensite. The exception is dispersion-strengthened alloys. 7. For design purposes, short time tensile test data (e.g., Figure 8.3) and combined creep-rupture data (e.g., Figure 8.2(C)) are useful. Such data are available in handbooks or manufacturers' publications. Before making use of such data it is necessary to make an estimate of the desired ‘‘life’’ of the part and expected stresses. 8. In design and fabrication keep in mind the linear expansion. Some useful hints are: • Avoid sharp corners or edges. • There should be no welds at corners or edges. • Corrugated sheets are better than flat ones. • Use the same section throughout. • Allow free expansion at the ends to prevent bending, buckling, distortion, or sagging. • Baskets, fixtures, trays, etc. used in heat treatment undergo repeated heating and cooling under a stressed condition. The effects of expansion and thermal fatigue are more severe in such cases. 9. Next in cost to plain and low alloy steels are the various stainless steels (S.S.). There are two main types of S.S. that are suitable for our purpose. Ferritic S.S. — These contain 8–25% chromium and about 0.15% carbon. The chromium forms an oxide layer and protects from oxidation and furnace gases. Ferritic steels are used up to 600°C. The chromium oxide layer breaks off after repeated heating and cooling. Austenitic S.S. — These contain 18–25% chromium and 8–20% nickel with about 0.08–0.1% carbon. These steels can be used up to 700°C without appreciable oxidation. However, they are not suitable for sulfur bearing gases. Austenitic stainless steels have excellent resistance to oxidation up to about 400°C and are not affected by gases and substances associated with food processing. Hence, they find major applications in ovens for baking, etc. 10. Nickel and nickel chromium alloys dominate the temperature range from 600 to 1100°C and are the costliest. They offer several advantages if properly fabricated and used and thereby prove economical. There are many alloys based on Ni and Cr. They contain small amounts of aluminum, titanium, molybdenum, and balance iron. Most of these alloys are proprietary and are recommended for individual situations. The alloys are available in all forms such as rod, plate, sheet, wire, and tube. They can be easily welded. They have austenitic, single-phase structure. Some of the alloys can be hardened by dispersion or solution strengthening. Some alloys offer excellent resistance to process gases and molten salts. The properties of some nickel alloys frequently used in high temperature furnaces are given in Table 8.6. There are many other heat-resistant alloys used in machinery such as boilers, turbines, jet and automotive engines, etc. These are not considered here. 11. Beyond about 1200˚C, the only metals available are refractory metals — tungsten, molybdenum, and tantalum. They are very costly compared to nickel alloys. Their availability is limited to simple shapes such as sheets, rods, and wires. They oxidize easily beyond about 600˚C and have to be protected by special gases, or inert gases, or vacuum. At temperatures beyond 1200˚C they have low strength. The maximum useful temperature when properly protected are tungsten–2560˚C, molybdenum–1900˚C, and tantalum–2400˚C. Their main use is in radiation shields, resistors, furnace tubes, boats, crucibles, etc. For processing high purity metals as in semiconductor manufacture, platinum or platinum alloys are used up to 1600–1700˚C. They are extremely costly but can be used in air and are easy to fabricate. 12. Metals have high specific heat and conductivity. Heat absorbed or conducted away represents thermal loss. Hence, the amount of metal fittings and furniture in the heating zone should be the minimum required.

TABLE 8.6 Selec

ted Nickel Base Alloys, Properties, and Appli ca

ti

on

sComposition

T

en

si

le

S

tr

en

gt

hN/mm2Elongation%AlloyNiCrFeCSiAlPoint°C20°C700°C1000°C20°C700°C1000°CApplicationsInconel6007214-178-100.150.5–1370-142562036575505161Goodoxidationresistanceupto1150°C.Heattreatmentfurnaces,saltbaths,rollers,belts.Inconel60158-6321-24B0.10.51.0-1300-13707503605052 53–Oxidationresistanceupto1250°Cincludingsulfurgases.Boxes,baskets,muffles.Incoloy800H30-3519-23B0.05-0.1–0.150.61355-138552030 0–5570–Resistanttooxidation,sulfur,andcarburizing.Fixtures,sheaths,conveyorbelts.IncoloyDS34-4117-19B0.080.151.92.6–1330-14006203356538 4975Muffles,furnaceparts,rollers,chains,fans,fixtures.Nimonic75B18-2150.080.151.00.2Ti1340-138085042080305750Muffles,furnaceparts,rollers,chains,fans,fixtures.(Courtesy–HenryWiggin&Co.Ltd.U.K)Melting Summing up, the choice of metals and alloys should be made by considering the temperature, type of service (continuous or intermittent), expected life, oxidation, and possible corrosion, the most important criteria being the cost. In many cases the choice is a compromise. Metals and alloys used for resistance heating elements are discussed in chapter 9.

11 11. Concentrated Heat Sources

11.1 LASER

11.1.1 Introduction

The term laser is derived from ‘‘light amplification by stimulated emission of radiation.” Broadly speaking, it is an ordered beam of monochromatic light. The theoretical possibility of such a beam was described by A. Einstein (~ 1917) and the first working laser was produced by T. Maiman in 1960. This first device was based on a doped ruby single crystal and had a very low power (mW). In subsequent years, rapid developments in technology and worldwide research led to the development of a wide variety of laser generators with beam powers from a few watts to several kilowatts. Lasers were soon realized as potential concentrated energy (CE) devices that can be commercially used for material processing. A focused beam of laser radiation can develop extremely high energy (heat) concentration (~$10^4 - 10^8$ W/cm^2) on a small area (~ 10^{-2} cm^2) on the work surface. A large number of application areas were discovered to which new ideas are being constantly added. The use of laser as a ‘‘tool” is being exploited for processing all types of materials. Because of its delicacy and pre cision, it is also increasingly used in surgical operations. Besides the above-mentioned application areas laser is being used in communication, surveying, printing metrology, analytical chemistry, holography, and several other fields. However, these applications are based on properties such as monochromaticity, coherence, and low divergence, and are beyond the scope of this book. A very large number of atoms and molecules display lasing (i.e., emission of monochromatic, stimulated, and coherent radiation) when properly excited. Consequently a variety of commercial lasers are available. They are broadly classified as solid state lasers, molecular lasers, semiconductor lasers, excimer lasers, gas lasers, dye lasers, and so on. In this book we are interested in so-called ‘‘power lasers” which can be used for heating, i.e., having a power output of the order of 10^4–10^8 w/cm^2 for sufficient time. Presently, only two lasers are found to be suitable for such power applications. One is a solid state laser called Nd-YAG laser, which can give an output up to 1.0 kW. The other is a gas (molecular) laser based on CO_2 and is called the CO_2 laser. It is the most powerful laser presently available and can give an output up to 20 kW. For very small power requirements the ruby laser is used, which has an output of a few mW.

11.1.2 Generation of Laser Beam

The physics of the generation of laser beams by atoms and molecules is a very complex phenomena and a specialized branch of physics. In this book we are concerned only about the properties and application of laser beams for material processing (heating). The details of atomic and molecular processes leading to laser generation (lasing) are not important for these applications. What follows is a general and simplified account. For theoretical detail treatment, consult specialized literature

energy levels or bands which are associated with a definite energy E . When the atom is unexcited, lowest energy levels are occupied. The amount of electrons that can occupy a given level is fixed and decided by the laws of quantum mechanics. It is expected that the reader is familiar with the basic atomic theory. Atoms can be excited by the application of high voltage, high temperature, and many other techniques. On excitation the electrons acquire higher energy and jump to an appropriate higher energy level. On removal of excitation the excited electrons in the higher level go back to their original lower level position. In doing so they get rid of the excess energy by emitting photons or light and other radiation. If the energy in the higher level is E_2 (electron volts) and that in the lower level is E_1 the frequency n (and wavelength l) of the emitted radiation is given by the well-known relation: (11.1) where C is the velocity of light ($\sim 3 \times 10^{10}$ cm/sec). In laser parlance the process of excitation of electrons to a higher level is called ‘‘pumping.” The return journey from a higher level to a lower one is called ‘‘decay.” The decay may take place in one step from E_2 to E_1 or a number of steps (such as $E_2 \rightarrow E' \rightarrow E'' \ldots E_1$) of successively lower energy. According to the quantum theory the energy levels are discrete (definite) for a given atom/molecule. Hence, for satisfying the equation all the three variables E_1, E_2, and n must be compatible for radiation emission. In the intermediate steps of decay, if there is no compatibility, that decay is emissionless. For lesser generation, the lasing medium is selected so that it has a three- or four-level decay in which one intermediate state satisfies the conditions of the equation. Besides the selected decay levels discussed above, the excitation and decay occurs at many levels and the resulting general light emission is called ‘‘fluorescence.” Consider a substance having a four-level electronic struc ture with energy increasing from level 1 to 4 (Figure 11.2). In an unexcited state, level 1 is fully occupied by electrons. On excitation the electrons in level 1 will be pumped to level 4 creating vacancies in (the otherwise full) level 1. This is called ‘‘population inversion.” On removal of excitation the electrons in level 4 will decay to level 3. This decay is emissionless. A further transition is from level 3 to 2 where the decrease in energy satisfies Equation (11.1) and a radiation of frequency n will be emitted. The electron will then decay to level 1 without emission and thus return back to its original position. The photons (radiation) emitted during the transition from level 3 to 2 will stimulate other electrons (undergoing the same 3 → 2 transition) to emit radiation of the same frequency n. This emission is not only of the same frequency (n) but is also in the same direction and in phase with the original emission. This process is called ‘‘stimulation” and is the beginning of the laser beam formation. Continued excitation (pumping) reinforces the beam,

n l = − = E E h C 2 1

Figure 11.2 Laser emission by stimulation amplification.

increasing its intensity. A laser cavity is made by enclosing the lasing substance in the space between two mirrors (Figure 11.3) at two ends. One mirror is fully reflecting and the other is partially transmitting. The mirrors are perfectly parallel to each other. When the radiation beam of stimulated radiation strikes the fully reflecting mirror it is reflected, i.e., turned back toward the cavity. On its journey to the second mirror it stimulates more electrons to transition 3 → 2 and emits radiation of the same frequency, same direction, and same phase. The beam intensity thus increases further. This is called ‘‘cavity gain.” On striking the semitransparent mirror, some radiation leaves the cavity as a coherent laser beam. The remaining radiation is reflected back and continues to travel to the fully reflecting mirror with increasing intensity. The beam thus keeps traveling between the two mirrors and builds a resonance due to the particular distance (L) between the mirrors. This is a simplified account of laser generation. The pumping action in some solid state generators is achieved by using high energy photons emitted by a powerful flash light (see ruby and Nd-YAG lasers in the next sections). In gas lasers the pumping is achieved by high voltage discharge. Other radiation not compatible with the stimulated radiation escapes the cavity, and adds to the cavity loss. Note that the input energy in a laser is that which is sup plied to the pumping source.

11.1.3 Noteworthy Points about Lasers

Laser is a clean source of energy. There are no combustion gases. It is a beam of photons having no mass and charge. They do not exert any pressure on the work.

Figure 11.3 Building up of laser beam by stimulation and cavity resonance.

Laser is unaffected by air or any gas surrounding the work. It is affected only by plasma (ionized gas). Heating by laser does not require a closed surrounding like a furnace. Being a beam of light (mostly infrared), radiation can be transmitted over considerable distances by using a pipe (wave guide) and mirrors. Low power beams can be transmitted by using a relatively flexible optical cable. Hence, the laser source (generator) and the work can be separated. By using a microscope and related optics the beam can be located precisely on the spot which is to be heated. A coordinated controlled work stage in combination with a microscope will enable the spot to be successively located at different sites on the work surface. The focused spot has a radius of a fraction of a millimeter which enables heating of a very small spot ($\sim 0.01\ mm^2$). Heating is thus confined to a very small area. This makes the following operations possible: 1. Welding of fine wires to each other (e.g., thermocouple junctions) or to integrated circuits or components. 2. Drilling (piercing or burning) of very small (10-500 mm) diameter holes. The heating time is very short (~ msec). It depends on the work size and the pulse duration. This short time span restricts the heat affected zone (HAZ), hence, there are no internal thermal stresses. The power density (w/cm^2) of a laser beam is very high (10^4-10^8 w/cm^2), hence, a very high power is concentrated on a very small area. At these power levels virtually any known material (metals, ceramics, glass, or polymers) can be melted or vaporized. This is achieved by controlling the beam power and the duration of heating. Light particles (photons) do not have any electric charge. Their interaction with the work atoms or molecules of the work does not involve the completion of an electric circuit (in contrast to electron beams). Similarly, the heating does not involve setting up an internal electromagnetic field as in induction or dielectric heating. The heat evolution is purely by the impact of photons with the free electrons and atoms or molecules of the work. It is because of this reason that a laser beam heats any material. This property makes lasers useful for processing any material or any combination of materials (e.g., dissimilar metal joining, ceramic cutting, drilling, etc.) Cutting, drilling, or similar operations are carried out by a light beam used as a tool, and material removal is by precise melting and evaporation. In conventional machining, material removal is achieved by the impact of a hard tool on the work, i.e., by shearing off the material, piece by piece. The friction involves considerable unwanted heating. Usually we have to use a cutting fluid to reduce the friction and remove the heat. Laser machining does not require any coolant. Heating rates achieved by a laser beam are very high and the spot is precisely located where required. Machining is therefore very fast and precise. There is very little swarf. The cut edge or welded joint is smooth and clean. Generally no post heating (machining) operations are required. Laser machining does not require costly fixtures. The only facility required is a good programmable coordinate table with the required degrees of freedom. A programmable coordinate table makes it easy to change the work-piece or the site. Laser operation is quiet and no gases are evolved, hence it is eco-friendly. The laser beam and its profile can be precisely controlled and manipulated by techniques such as Q switching, pumping control, filters, lenses, TEM control, etc. More than one laser generator (of the same wavelength and type) can be optically coupled to obtain higher power levels.

11.1.4 Limitations of Lasers

Laser heating is not a bulk heating process like furnace heating. The heat production is limited to a very small spot. Hence, laser processing is restricted to very small areas. Thus, laser is useful for micro-machining or micro-heating. Due to the peculiar nature of the spot and work material interaction laser beams cannot penetrate deep (like a drill). The depth of penetration is usually restricted to a few mm. To keep the laser beam focused on the work surface it is usually necessary to isolate the work table from the beam generator. Laser optical components like mirrors and lenses do deteriorate with time. They are costly to repair or replace. Laser maintenance can be costly and is a specialized job. Holes drilled by laser have a tapered shape. This taper is more pronounced for deep holes. Similarly, the hole edge of the top surface has a splashed edge due to melt flushing. Laser radiation (especially focused) is damaging to the eyes and skin. Proper precautions, as recommended by the manufacturer, must be observed.

LASERS FOR MATERIAL PROCESSING

11.1.5 CO_2 Laser

This is a molecular gas laser and is the most powerful laser presently available. The lasing medium is CO_2 gas in which lasing occurs due to changes in vibrational energy levels of CO_2 molecules. The lasing wavelength is in far infrared at 10.6 mm. The lasing medium consists of a mixture of CO_2, N_2, and He in the proportion 2:2:3. Addition of N_2 and He helps lasing of CO_2 and gives higher output and efficiency. Addition of He also helps to remove heat as it has a better conductivity. The pumping is achieved by a high voltage 1–3 kV and high frequency (1–3 kHz) DC discharge. The construction of a typical CO_2 laser is shown in Figure 11.4. This is a fast, axial flow-type generator. There are transverse flow designs which can give higher power outputs. The lasing action occurs in a glass tube resonator. The tube has a fully reflecting mirror at one end and a partially transmitting window at the other end. Both the window and the mirror have a large radius and concave shape. The tube has a row of alternate positive and negative electrodes connected to a high voltage pulsing DC supply and controller. The gas mixture gets considerably heated during lasing. Some CO_2 is decomposed to CO and O_2. To remove the heat and the contaminants the gas is drawn off and cooled by a recirculating arrangement shown in Figure 11.4. Fresh gas is added when required. The axial gas flow rate is about 300

Figure 11.4 CO_2 laser.

m/sec. The flow is maintained by a roots blower. The pressure inside the tube is less than the atmospheric pressure. The output of CO_2 lasers increases with tube length and gas pressure. There is a limit to the tube length. Lasers containing several tubes in parallel are constructed to give a tube length of several meters; however, they are cumbersome to construct and keep in alignment. Lasers having a transverse flow are now available, giving an output of more than 20 J. The gas pressure in a transversely excited atmospheric (TEA) pressure type CO_2 laser is nearly atmospheric ($\sim 10^5$ Pa). The discharge pulse frequency is 10–100 kHz. Commercial CO_2 lasers have an output of up to 20 kW with a maximum efficiency of 20 kW. CO_2 lasers have a wavelength of 10.6 μm with considerable line width. As these wavelengths are in the far infrared region almost all the optical materials normally used, such as quartz and glass, are unsuitable. The mirror, window, and all other optical components in the beam manipulation system are made of materials such as KCl, NaCl, Ga, As, Ge, Zn, Se. These are costly materials. Mirrors are of the gold-surfaced metallic type with water cooling. The optical components dete riorate and require replacement or resurfacing. Low power (3-100 W) CO_2 lasers have a sealed tube, i.e., no gas recirculation. These are not very useful as a heat source. Fast axial and transverse flow CO_2 lasers are the main types used today as power lasers in material processing. They are generally used in continuous mode but can be pulsed in the 1-10 ms range. The beam of CO_2 lasers can give various TEM modes though the fundamental (TEM_{00}) mode is more common. CO_2 lasers can be Q switched. The output can be controlled to produce a step or ramp pattern. The gas tube (resonator) may have external cooling. High power CO_2 lasers used for machining have a gas assist system to supply a reactive (air, oxygen) or inert (argon, helium) gas flow on the work surface at the hot spot. There are other gas lasers based on CO, N_2, NO_2, H_2O, etc. The CO_2 laser dominates the fields.

11.1.6 Nd-YAG Lasers

This is a solid state laser based on garnet (a mineral) doped with the rare earth element neodymium (Nd). The garnet used has a formula $Y_3Al_2O_{12}$ and is called yttrium-aluminum garnet, a synthetically grown single crystal having a diameter of 3.5-16 mm and a length of 45–250 mm. About 1–1.5 Nd is uniformly dispersed in it (doping) while the crystal is grown. The ends of the rods are highly polished and made exactly parallel. The pumping medium used is intense white light produced by xenon flash lights or fluorescent discharge tubes. The output of these ‘‘pumps” can be controlled by varying the input energy and supply frequency. The flash tube and the laser rod (medium) are enclosed in an internally reflecting container. There are various designs.

The design shown in Figure 11.5 uses an elliptically shaped enclosure with the flash tube and the laser rod situated at the foci. This improves the pickup of the pumping light. The enclosure may be air- or water-cooled. The pulse width and frequency is controlled by an external power and frequency source for the flash light. Recent versions of Nd-YAG laser use solid state diodes in place of flash lights. Similar Typical Properties of Commercial CO$_2$ Laser Wavelength 10.6 µm with several lines Transverse modes Multimode. TEM 00 (Gaussian) is commonly used Output power (continuous) 1–10 kW commonly available Pulsed output 10^{-3}–10^{-2} J Gas pressure 10^{4}–10^{5} Pa Gas consumption 0.2–2.0 m^3/h Flow Fast axial or transverse Beam diameters 5–25 mm Efficiency 10–20% Beam divergence 1–3 mrad Figure 11.5 Solid state laser, e.g., ruby or Nd YAG type.

lasers with less power output are neodymium yttrium glass (Nd glass) and yttrium lithium fluoride (Nd YLF) lasers. Nd-YAG lasers can be operated in both pulsed and contin uous modes. The operation is usually in TEM 00 mode. The laser can be Q switched. The mirror and window at the end of the rod are made of quartz with suitable metal reflective coatings. The laser rod and mirrors deteriorate due to internal defects, thermal fatigue, and atmospheric corrosion. Defective rods require replacement. In most cases mirrors can be recoated.

The flash lights used have a typical life time of 10 6 cycles. In some (older) designs separate mirrors are not used. The polished rod ends are given a reflective coating.

11.1.7 Ruby Lasers

This was the first successful laser produced about 42 years ago and is still finding commercial applications. In construction, the ruby laser is similar to the Nd-YAG laser described earlier. The laser medium or cavity is made from synthetically grown ruby single crystals. Ruby is a Al 2 O 3 or corundum. At the time of crystal growing, about 0.5% chromium is added and uniformly distributed. The lasing and stimulation takes place in the chromium atoms. Pumping is achieved by flash lamps around the ruby rods which

Typical Properties of Commercial Nd-YAG Laser Wavelength 1.06 μm continuous or pulsed Transverse mode TEM 00 Pulse energy 30 mJ-100 J Pulse duration 0.2-20 msec Pulse repetition rate 10 -3 -10 3 Hz Efficiency 2-5% Continuous operation 10-30 W common-up to 100 w available Q switched operation 200 mJ-3 J Q repetition frequency 1-50 kHz Pulse duration Few milliseconds are 45–250 mm long and have a diameter of 5–15 mm. Ruby is hard, mechanically strong, and has a good stability against radiation damage. Irregularities in crystal structure and uneven distribution of Cr and other impurities lower the efficiency. Ruby lasers emit in the visible red region and have a wavelength of 0.6943 µm. They have a pulse output with a repetition frequency ~ 1.0/sec. The pulse energy is ~ d few J and duration ~ 1 msec. This laser can be Q switched to give a peak power up to 10^6 watts for 10^{-9} sec.

11.1.8 Longitudinal Modes of Laser Beam

A laser beam is a result of atomic/molecular stimulation and the resonance of the light waves so produced in the cavity. This process is already reviewed in the preceding section. Ideally, the resonance should occur only at one wavelength or frequency giving a single mode, monochromatic output (Figure 11.6) at wavelength l_o. In practice, the resonance occurs at many wavelengths due to the cavity dimensions and broad energy levels among which lasing and electron transfer occurs. The output beam is thus multimodal, i.e., it consists of many wavelengths centered about the main mode l_o. Some of the modes are absorbed by the cavity losses and in reflection at the mirrors. Those escaping in the beam are symmetrically situated about the main wavelength. The output of a laser is thus a beam having a predominant wavelength (or frequency) and a line width Δl or Δn. The line width of a given laser depends on the cavity dimensions, material of mirrors, electronic structure of the lasing medium, and defects or impurities in it. Numerically the line width can be defined as the ratio Δl / l o or Δg /g o . For example, a low pressure CO_2 laser beam has a dominant wavelength 10.6×10^{-6} m and a line width 60×10^{6} Hz. The line width will be (11.2)

where C is the velocity of light (3×10^{10} cm/sec). Δn l/ /C o Figure 11.6 Wavelength distribution. A Nd-YUG laser has a wavelength of 1.06×10^{-6} m and a line width of 1.2×10^{11} Hz. Thus, the numerical line width is about 4.2×10^{-3} showing much broadening compared to a CO_2 laser. The line width can be controlled to some extent on laboratory laser setups. The fluorescent emission has a very broad spectrum (Figure 11.6) showing a number of strong or weak lines as there is no gain due to resonance. The above calculations show that even with line broadening, the laser beam is still highly monochromatic.

11.1.9 Focusing Properties of Lasers

A TEM 00 laser beam emerging from the window of the generator is a coherent and collimated beam having essentially a single wavelength O. For practical purposes, the beam can be assumed to have a diameter (aperture) equal to that of the window at the emergence point (see Figure 11.7) and a divergence q. This beam is conveyed to the work by a suitable arrangement of mirrors and focused on the work surface. The focusing is done by a suitable converging lens having a diameter D and a focal length F. Normally such a beam, when focused by a converging was (convex lens or combination lenses), should be thought of as coming to a point focus, i.e., having an infinitely small area. In practice, the beam focuses on a spot having a significant radius (r f) and area. Whenever a collimated beam passes through an opening (aperture) it bends (diffracts) and acquires a divergence of angle q.

If there are a number of apertures, diffraction will occur at each aperture and the beam will have a diameter larger than the original. The typical divergence of a laser beam is 1–5 mrad. Such a Line width = × × × = × − − 60 10 3 10 10 6 10 2 12 10 6 10 4 7 / . . Figure 11.7 Some characteristics of laser beams.

divergent beam focuses on a spot having a minimum radius r o given by (11.3)

where F is the focal length of the focusing (convergent) lens.

This shows that the spot diameter increases with focal length and angle of divergence. The angle of divergence q is related to the wavelength l and the lens (aperture) diameter D by the equation (assuming that the beam fills the aperture) (11.4) As the wavelength is fixed, q can be decreased by increasing the aperature (lens and beam size) D. The original beam diameter is fixed by the laser generator window. The beam can be expanded by using beam expanders. These are Galilean telescopes (used reversely) and give a magnification (increase in diameter) from 5 to 20. The divergence angle will be reduced by about one order. Substituting for q in Equation (11.3) (11.5) Thus, by using a beam expander and a lens of large diameter the spot radius can be decreased to a limit. Also note that large diameter lenses will have a longer focal length F which will increase the spot size. It is therefore necessary to strike a balance between F and D. Another basic limitation on spot size arises from a phenomenon called ‘‘spherical aberration” (Figure 11.7). Spherical aberration arises from the fact that the rays of light coming from different parts of a lens get focused at different spots on the axis (axial aberration) and on the focal plane (lateral aberration). Thus, spherical aberration will always give a focal spot and not a point. r F o = q q l = 1 22. D rad r F D o = 1 22. l Spherical aberration can be reduced by using special aspheric lenses; however, applicable optical materials and their properties put a limit to the possible correction. In summary, the focus of a laser beam produces a spot having a significant diameter. For many other reasons the practical ‘‘spot” is always larger than that calculated theoretically. A TEM 00 beam has a Gaussian distribution throughout and the focal spot also inherits this. So, the power level is very high on the central spot and diminishes toward the edge. Consequently the material reaction varies from the spot center to the edge. The beam edges are trimmed by the aperture, which allows only about 86% energy to pass through.

11.1.10 Collimation

Scientific and industrial applications of radiation (light) usually involves focusing of a well-defined beam by a focusing lens system. An ordinary source of light (like an incandescent bulb) emits radiation all around, i.e., through a solid angle of 4p steradians. It is virtually impossible to collect all this light and channel it into a beam. The process of obtaining a well-defined beam of light, consisting of parallel rays is called ‘‘collimation.” Most of the apparatus using an ordinary bulb catch a small portion of the radiation by a collimator consisting of a suitable lens and a long tube. This arrangement creates a parallel beam having divergence (~ few degrees). A laser beam is inherently collimated, i.e., it consists of parallel rays requiring no further collimation. The beam has a diameter equal to that of the window (mirror) through which it emerges. There is very little divergence (~ 10 -3 rad). This beam is easy to focus on relatively small areas (~ 10 -1 mm) creating a high energy density. The divergence can be further reduced by using a beam expander. This is a Galilean telescope used in a reverse manner so that the light enters the eyepiece and exits through the objective. The beam diameter can be increased by a factor of 5–20. This makes it possible to use a large diameter focusing lens (Figure 11.7).

11.1.11 Coherence

This property is also inherent like collimation in a laser beam. A collimated beam from an ordinary light source consists of parallel rays but the wave fronts of individual rays are not synchronized with each other and the collective wave front is not well defined (Figure 11.7). In a laser beam the individual wavefronts are perfectly synchronized to present a straight and collective wavefront.

This synchronization is inherent and persists in both space and time. It can be imagined as the perfectly drilled marching of a group of soldiers showing synchronization at all steps at all times. The main application of coherence is in measurement systems using laser, and in holography. They involve splitting the beam into two parts, passing them through different paths, and then recombining them to form a well-defined pattern. Coherence is not treated in detail as it has no major significance in laser heating.

11.1.12 Depth of Focus

The laser beam coming out of the focusing lens converges to a focal spot (see Figure 11.8) of radius r_f and diverges beyond. Assume that the intensity I_o at the focal spot has a Gaussian distribution, then before and beyond the spot the intensity will remain Gaussian but will continuously decrease with distance z from it. The depth of focus (z_f) is the distance between the focal plane and two symmetrical planes before and beyond. The intensity of the beam on these planes has a chosen ratio with that on the focal plane, (e.g., $I_z/I_o = 0.5$, etc.). Thus with respect to the

focal plane at z = 0, the depth of focus will have two values = I z . If the radius at focal spot is r o then its radius r z at a (chosen)

distance z is given by (11.6) r r z r z o o = + [ ] � � � � � � � � � � � 1 2 2 1 2 ( ) / l p where l is the wavelength. (11.7) This value of z is the theoretical ‘‘depth of focus” and is

called ‘‘Rayleigh range.” For practical purposes, it is more convenient to assume a

r z /r o ratio of 5–10%. The calculations show that the form of

Equation (11.7) remains the same except for a numerical factor

(k) so that (11.8)

Where Substituting for r o in Equation (11.8) gives (11.9)

Figure 11.8 Concept of focal spot diameter and depth of focus of

a laser beam. If r r z r z o o / = = 2 2 p l z k r o = p l 2 r F D o = l p /2 z k F D p = 2 2 l Equation (11.9) relates the depth of focus to the focusing

lens parameters F and D. It shows that for a large value of z,

the focal length F should be large and the diameter D small. A basic lens equation is (11.10) where n is the relative refraction coefficient and R 1 and

R 2 the curvature of the two faces of the lens. For a given optical material n is constant. To obtain a

large value of F, R 1 and R 2 must be large, i.e., the lens diam

eter D should be large. This shows that the requirement of

small D and large F is self-contradictory. The depth of focus

is therefore fixed when D is fixed by the beam diameter.

When a laser beam is incident on a material surface it is desirable that the beam is exactly focused on it. This will give maximum incident power (and hence efficiency). The material surface evenness, focusing accuracy, and machine vibrations are some of the factors which make exact focusing impossible. The concept of the depth of focus makes it possible to estimate the reduction in incident energy if the exact focus is missed. In laser drilling and some other applications the depth and shape of the heat is affected and the machined zone changes with the position of the focus with respect to the surface. It is necessary to intentionally defocus the beam to achieve correct machining. The depth of focus is useful in beam defocusing as it gives an estimate of the incident spot size and energy.

EXAMPLE 11.1

A germanium lens used on a CO_2 laser has a clear aperture of 18.7 mm and a focal length 16.95 mm. The wavelength of the laser is 10.6 µm. Assume that the aperture is completely filled by the beam.

Calculate 1. The theoretical depth of focus. 2. The depth of focus at a 10% increase in focal diameter. 1 1 1 1 1 2 F n R R = − − ▯ ▯ ▯ ▯ ▯ ▯ ▯ ( )

Solution

We first calculate the focal spot radius r o by using the relation F = 16.95 mm, l = 10.6 × 10 -3 mm, D = 18.7 mm Theoretical depth of focus z For 10% increase in r o From equation (11.6) r F D o = l p /2 r o = × × × = − 16 95 10 6 10 18 7 2 0 0612 3 . . . / . p mm z r z o = = × × = − p l p 2 2 3 0 0612 10 6 10 . . 1.11 mm r r z o = 1 1. r r z r z o o = + � � � � � � � � � � � � � � � � =1 1 1 2 2 1 2 ( ) . / l p ( ) . . . . . l p p z o r z 2 2 2 3 1 21 1 0 458 0 0612 10 6 10 0 508 � � � � � � = − = × × × = − mm

EXAMPLE 11.2

A laser beam of wavelength 1.06 µm has a diameter 3.0 mm

when coming out of the generator. The beam is expanded in a beam expander having a mag

nification by a factor of 10. It is proposed to use a quartz lens having a transmission

of 85%. Now determine: 1. The angle of diversion of unexpanded or raw beam 2. The diversion angle after expansion 3. The focal spot diameter for the raw beam 4. Focal spot diameter for expanded beam

Solution

The raw beam has a diameter of 300 mm and the wavelength

1.06 µm. The angle of diversion is On expansion the beam diameter is 3 × 10 = 30 mm The angle of diversion of the expanded beam is q l q r D = = × × = × = × = − − − 1 22 1 22 1 06 10 3 0 4 3 10 10 3 26 3 4 4 . . . . . ' " rad (0.43 mrad) 246.4 degrees 1 q 2 3 5 1 22 1 06 10 30 4 3 10 = × × = × − − . . . rad (0.043 mrad) Comparing q 1 and q 2 shows that the diversion is decreased

by one order after expansion. The raw beam has a diameter of 3.0 mm. Assume that the

diameter of the quartz lens used is 4.3 mm and its focal length

is 8.1 mm. The radius of the focal spot will be The expanded beam has a diameter of 30 mm. Assume

that the lens used has a diameter of 31.5 mm and a focal length

of 40 mm. The spot radius will be This shows that the expanded beam gives a fine focus

(hence, more energy density).

EXAMPLE 11.3

A laser beam has 0.1 cm focal spot and a power density q o

(W/cm 2). A steel plate is to be treated by this beam for cutting.

Determine the time required for cutting a thickness h (< 0.2 cm)

and the cutting rate. Density of steel 7.8 g/cm 3 Latent heat of evaporation 7 × 30 J

Solution

We will first determine the heat required for cutting by consid

ering a thickness of 0.1 cm under the spot. r F 01 3 8 1 0 43 10 3 48 = = × × = − q . . . μm r F 02 3 40 4 3 10 1 72 = = × × = − q . . μm Area and volume of steel 0.1 cm thick and diameter 0.1 cm is Latent heat of vaporization L B = 7 × 10 3 J/g Heat required for vaporization of material having thick

ness h cm is If the cutting time is t (sec), the heat given is The time required is In time t a length equal to one spot diameter (0.1 cm) is

cut. For continuous cutting the speed per min will be

11.1.13 Transverse Modes in Lasers

In the previous section we have discussed the generation and

characteristics of longitudinal modes in a laser cavity. A cm V cm At a density g/cm Weight g/mm thickness = × = × = × × = × = = × × = × − − − − p p r 0 05 7 8 10 0 05 0 1 7 85 10 7 8 7 85 10 7 8 6 1 10 2 3 2 2 4 3 3 4 3 . . . . J h h = × × × × = × − 6 1 10 7 10 42 7 3 3 . . = × × = × × × = × − q q t o o area time J h 7 8 10 42 7 3 . . as calculated above.t t h q h q o o = × = × − 42 7 7 8 10 10 3 3 . . / sec 5.47 sec = ×60 0 1. t cm/min There are other complex modes that occur in the cavity

due to a variety of reasons. Broadly speaking, these are due to the limited transverse dimension of cavity (e.g., diameter), the curvature of mirrors, diffraction of electromagnetic waves, etc. These modes are called transverse electromagnetic (TEM) and affect the outgoing beam, both spatially and temporally (timewise). They produce complex patterns of dark and bright shades (Figure 11.9). The result (from our point of view) is a symmetrical but nonuniform power distribution through the beam cross-section. The patterns are classified and numbered. The simple TEM mode which is useful for our purpose is the TEM$_{00}$ mode, in which the intensity and, hence, power has a Gaussian distribution as shown in Figure 11.9. It has a central spot of maximum intensity which decreases exponentially in the radial direction. The beam radius is defined as the distance from the center to a point at which the intensity is reduced to 0.135 ($1/e^2$) of its maximum value at the center so that the power (area under the $I - r$ curve) is 86.5% of the total area. Some other TEM patterns are also shown in Figure 11.9. These are not used in material processing and are therefore not discussed further. One useful aspect of the TEM$_{00}$ mode is that it retains its

Gaussian pattern throughout. The beam emerging from the generator and the final focal spot are both Gaussian though the beam diameter is different. The transverse mode of other TEM patterns change as they progress and undergo reflections or refraction in the beam manipulation and focusing systems. Commercial lasers used in material processing (power lasers) are adjusted for the TEM 00 mode.

11.1.14 Temporal Characteristics of Lasers

Laser generators have two distinct features. They are pulsed or continuous. Pulsed lasers have a periodic output in short bursts or pulses. The pulse duration is in the 10^{-3} –10^{-6} sec range. The pulses are repeated after a time interval called the ‘‘pulse repetition rate” which has a wide range depending on the type of laser and mode of operation. Repetition rates from 0.1 to 10^3 Hz are possible. Solid state lasers, like ruby and Nd YAG, which are pumped by flash lamps show a pulsed output.

Figure 11.9 Transverse modes of laser beams.

A typical uncontrolled pulsed output is shown in Figure 11.10(A). The output consists of equally spaced spikes. The energy (intensity) increases to a maximum and then slowly decays. This is called a ‘‘free running pulse.” This type of pulse is obtained by controlling the frequency of pumping lights or discharge circuits. Total energy (J) in a pulse will be the area under the I – t curve. For small generators it is of the order of 10^{-3} J. The power in the pulse will be average energy/sec (W), i.e., I_{an}/t (Figure 11.10(B)). It is generally in the range of 1.0–30 W. Pulse characteristics are measured by an oscilloscope trace or by a suitable calorimeter. All the reported values of energy and power are for TEM$_{00}$ mode. Pulse discharge can be controlled by adjusting the pumping frequency and cavity optics. A controlled pulse is shown in Figure 11.10(B). The energy increases quickly to a peak value and decreases to a plateau. If the pulse repetition rate is fast, we get a quasi or semi-continuous pulse. In heating applications the pulse represents a ‘‘dose” of energy incident on the material surface. The intensity of the dose is in watts/unit area (e.g., W/cm^2), applied for the pulse duration time t sec. It is important to choose a proper pulse power to achieve the proper temperature at the required site. A lower power will not raise the temperature to the required level. A higher dose will produce a very high temperature which will spoil the operation. We will discuss this point in more detail in subsequent sections.

11.1.15 Q Switching of the Laser Beam

This is a very interesting way of changing the pulse shape as shown in Figure 11.10(C). The cavity in a Q switched laser contains a device called the Q switch. There are many types of Q switches such as a rotating prism or mirror, electro-optic or electroacoustic devices. These devices are switchable reflectors i.e., they will totally reflect the beam or allow it to pass through when a signal is applied. The position of the Q switch in a cavity is shown in Figure 11.10(B). In the beginning, the switch is turned on along with the pumping source. No laser beam is produced as there is no resonant cavity. The pump keeps on exciting the electrons to a higher level resulting in a buildup of a large population in the higher level. On switching off the Q switch, a resonant cavity is suddenly available. A powerful pulse of very high peak intensity but very short duration (~ 10^{-9} sec) emerges. The shape of a Q-switched pulse is shown in Figure 11.10(C). Q switching thus produces very powerful pulses (~ 10^8 W) of short duration. The pulse repetition can be ~ 10^3 Hz. Q switching is very useful for precision cutting, drilling, and welding of thin sheets, fine wires, etc. All the three lasers of interest to us, viz. the ruby, Nd-YAG, and CO_2 can be Q switched. Another variety of a

Figure 11.10 Typical laser outputs.

Q-switched pulse is the mode-locked pulse shown in Figure 11.10(D). It has roughly the same overall pulse shape but is made of a number of synchronized subpulses. Mode locking arises from multimode (frequencies) generation of longitudinal waves. Mode locking is achieved by generating a broad line width and adjusting the cavity losses. Regular Q-switched and mode-locked Q-switched pulses are sometimes simultaneously generated. A technique somewhat similar to Q switching is called ‘‘cavity dumping.” Here the laser is continuously pumped and the beam is ‘‘stored” in the cavity (similar to charging a capacitor). On a signal the stored beam is dumped out in one large energy pulse of short duration.

Continuous Output

Some lasers like CO_2 and Nd-YAG give a continuous output as shown in Figure 11.10(E). The amplified output shows a wavy or spiked trace. In fact, CO_2 laser is almost always operated in CW (continuous wave) mode. The output power is $10–10^4$ W. There is no control as in a pulsed output. The power incident on a material surface is controlled by moving the work or the laser beam to adjust the dwell time. Nd-YAG and ruby lasers rated as lower (10–100 W) are generally pulse operated.

11.1.16 Application of Lasers for Material Processing

For material processing the important attributes of laser are: 1. Generation of very high temperature on a very small area of the material surface in a very short time. 2. Absence of any protective atmosphere. 3. Practically no heat affected zone. 4. The laser cannot penetrate deeper than about 2.0 mm at the maximum. It is more suitable and efficient for thin work. These attributes make it possible to heat any material to any desired temperature up to its boiling, burning, or charring point. Consider a material heated from room temperature T_o (~ 25°C) to progressively higher temperatures. For our analysis, we will divide all materials into two categories. 1. Materials like metals, ceramics, glass, etc., which will progressively melt, boil, and evaporate. 2. Materials which do not melt, but char, burn, or disintegrate at higher temperatures, like wood, textile, and rubber. When heated, materials absorb heat according to their specific and latent heats. The temperature-heat content characteristics for the two categories are shown in Figure 11.11. For the first category, the heat absorbed from T_o to and above T_b will be (per unit mass) $H_1 = C_S (T_m - T_o)$ up to melting point (T_m °C) $H_2 = L_m$ latent heat (L_m) during melting $H_3 = C_l (T_b - T_m)$ up to boiling point (T_m °C) $H_4 = L_b$ latent heat (L_b) during boiling $H_5 = C_n (T_f - T_b)$ up to final temperature (T_f) ΣH = Total heat required.

Figure 11.11 Energy, power pulse duration for laser applications. For the second category the heat required will be $H = C_s (T_F - T_o)$. Depending on the process to be carried out, the material will be required to be heated to any temperature from T_o to T_f by supplying the necessary heat at the process location. If the heat supplied is less than that required, the process will be incomplete or unsuccessful. If it is much more than required, the material will melt or boil and evaporate. It is therefore necessary to achieve a balance between heat requirement and supply. In laser heating there is practically no control on the energy of the beam. Control can be exerted by adjusting the time of laser application. In a pulsed laser, time is controlled by pulse duration. For a continuous laser, time is adjusted by moving the process material. Typical application areas for different temperatures, power densities required, and interaction time are indicated in Figure 11.11. Consider heating of 0.4% carbon steel having the following average properties: Heat required (J) per g for heating from 25 to 2860°C in various steps will be $H_1 = 0.57(1500 - 25) = 840$ $H_2 = L_m = 268$ $H_3 = 0.76(2860 - 1500) = 1033$ $H_4 = L_b = 6720$ The above calculations show that heat required for heating to about 1000°C for processes such as heat treatment is about 556 J/g. Density 7.67 g/cm^3 Melting point (T_m) 1500°C Boiling point (T_b) 2860°C Specific heat of Solid (C_s) 0.57 J/g°C Latent heat of melting (L_m) 268 J/g Specific heat of liquid (C) 0.76 J/g°C Latent heat of boiling (L_b) 6720 J/g Heat required for melting, as in welding, is 840 + 268 = 1100 J/g. Heat required for evaporation, as in cutting or drilling, is 840 + 268 + 1033 + 6720 = 8860 J/g, and the major part is that of the latent heat of boiling.

11.1.17 Laser-Material Interaction

A laser beam incident on and absorbed by a material, generates heat. This heat (at least in the beginning) is concentrated on the focal spot. Later it is transferred to the interior mostly by conduction. The laser source may be a pulsed or a continuous one. If a single pulse is incident on the spot it transfers a single “dose” of energy (J) to the material during the pulse duration (10 -3 sec). If required, more pulses can be given at an interval equal to the pulse repetition frequency. In the continuous wave (CW) source the energy supply is continuous. The required power is transmitted by adjusting the time of exposure. The transfer of energy to the material surface, its absorption, and transfer is governed by a very large number of variables. These can be divided into two categories. 1. Properties of the laser beam and the beam transfer and focusing optical train. 2. Properties of the work material, such as thermal conductivity, reflectivity, etc. Many of the material properties are dependant on temperature and time. The interplay of these two categories makes it virtually impossible to develop a satisfactory theoretical approach for laser material interactions that will be applicable in all situations. Our aim is to establish a method for estimating the temperature field in a laser-heated material for a given laser power or vice versa. Hence, the treatment of the interaction problem that follows is largely empirical. With some modifications the treatment can also be applied to the electron beam (EB)-material problem. The laser-material interaction-related zone is shown in

Figure 11.12. The variables affecting the process can now be

identified as follows: 1. Laser beam Wavelength, frequency – l , Hz Mode – TEM 00 or other Emission – Continuous (CW) or pulse Pulse duration – sec Pulse repetition frequency – PRF Hz - Adjustable Yes/No Power – W Q switching – Yes/No Divergence angle Beam diameter 2. Beam manipulation Optics – Mirrors, lenses, material and absorption Focal length – f (cm)

Figure 11.12 Energy transfer from laser beam to work. Depth of focus – cm Interchangeable lenses – Yes/No Focal spot radius – r f (cm) Monitoring microscope – Yes/No Power measurement – Yes/No Shutter and diaphragm – Yes/No 3. Material properties Type of material – Metal, polymer, ceramic Reflectivity and its dependance on surface finish, wavelength, temperature, etc. Thermal conductivity – K (W/cm°C) Specific Heat – C (J/g°C) Thermal diffusivity – a (cm 2 /sec) Density – r (g/cm 3) Latent heat of fusion L M – J/g Melting temperature T M – °C Latent heat of fusion L B – J/g Boiling temperature T B – °C Thickness h – cm Processing required – cutting, welding, etc. 4. Machine related Work manipulation, axes, manual, automatic, programmable shielding, assisting gas control. The behavior of materials on heating is shown in

Figure 11.11. On heating a metallic, ceramic, plastics, and glass

materials will melt at the melting temperature and will

absorb heat due to specific heat and temperature rise. At

melting temperature T m they will absorb the latent heat of

fusion L M . If heating is continued further, the heat will be absorbed

up to the boiling temperature T B and on continued heating, the latent heat of boiling L_B will be absorbed. The vapor so produced will blow out with or without gas assistance. The heat input to the material through the focal spot will have to be controlled to obtain the required processing temperature. Thus, for heat treatment the temperature required will be less than T_M. For welding it will be $>T_M$ and less than T_B. The depth to which the material gets heated depends on the thermal diffusivity and time. Materials such as wood, paper, cloth, etc., do not melt; but they get charred or evaporated or burn on heating. For all types of cutting and drilling operations on both types of materials the temperature required is higher than the boiling or the burning temperature T_B. Approximate temperature ranges, the power densities required, and observed interaction times are also shown in Figure 11.11. A generalized commercial laser beam system is shown in Figure 11.13.

11.1.18 Reflectivity and Absorptivity

When radiation strikes a surface, a part of it is absorbed and the rest is reflected. The fraction of incident energy absorbed is called absorptivity (A). Reflectivity (R) is the fraction that is reflected. Hence, (11.11) It is the absorbed fraction of incident energy that is useful for heating by laser. Hence, reflectivity represents a direct loss. The reflectivity of a material surface is governed by many interrelated factors (see Figure 11.14). The surface condition is perhaps the most important. Clean, smooth, and polished surfaces are almost 100% reflective whereas oxidized, rough surfaces can have an absorptivity of about 70%. Very clean and polished surfaces are difficult to process by laser. It is sometimes necessary to coat these with antireflective coatings. Reflectivity depends on the wavelength of the incident beam. Figure 11.14 (B) shows that the absorptivity is poor for the far infrared wavelength of a CO_2 laser (which is a commonly used power laser) and is better for a ruby laser (which does not have enough power!). R A= -( )1 Figure 11.13 A generalized laser beam system. Absorptivity which is low (~ 8%) at low temperature, increases to about 14-16% at higher temperatures. This has a direct effect on heating. The initial low heating rate due to high reflectivity increases quickly as the surface temperature rises. The angle of incidence also decides reflectivity. Best absorption is obtained when the angle of incidence is 90°. Lastly, absorptivity increases with the energy density (w/cm 2) of the incident beam (Figure 11.14(D)). This may be due to faster temperature rise with a powerful beam. Reliable data on reflectivity and absorptivity are scarce. The figures available may not be reproducible in each situation. For estimating, a reflectivity of 70–80% may be assumed after beginning the process. At the start, a 10% absorptivity

Figure 11.14 Absorptivity of metals, typical behavior.

appears to give reasonable estimates (applicable for very short, ≤ 1msec pulse durations). When heating involves melting and evaporation, a higher apparent absorptivity (~ 50–70%) may be used.

11.1.19 Laser Penetration

Theoretical aspects of concentrated source-material reaction were already introduced in Section 4.7. We have discussed the heating of the surface with time on exposure to a laser beam. We will now consider the penetration of heat along the vertical (z) axis. Here ‘‘penetration” is understood as the depth to which the material is heated to the desired temperature. It is assumed that the absorbed heat flows only in z direction and the related physical properties are constant. If heating is to be done for surface treatment such as hardening, the desired temperature is less than T M and higher or equal to the desired hardening or phase transformation temperature. For applications such as welding, the heating temperature is higher than T_M and lower than T_B. For drilling and cutting operations the temperature desired is higher than T_B so that the material evaporates through the full thickness.

There is no single equation to predict the depth of penetration for all the processes given above. For heating below the melting temperature T_M we can use Equation (4.33), Equation (4.36) to calculate the temperature at the desired depth z and time t, i.e., T(z, t). This equation is strictly applicable for continuous laser or for pulsed laser in the time regime $t \leq t_i$. Once the beam is discontinued (or the pulse is over), only the surface cools immediately. Due to the superheat ($T_M - T_P$) the heating still continues for some time. This heating is not calculated from the equation. Thus, the critical heating and cooling rates essential for heat treatment cannot be applicable over the full depth of penetration.

If heating is continued for a longer time, heat will be lost by conduction outside the target zone. For welding, it is essential to obtain a temperature $\geq T_M$

without evaporation. Melting absorbs additional heat as latent heat L_M. This heat will have to be supplied by a CW beam or from the superheat ($T_B - T_M$) obtained from the pulse.

Roughly, the penetration depth h(cm) obtained when the surface is heated to T_B can be estimated as (11.12) There is no satisfactory equation to predict the velocity of the solid-liquid boundary as the melting progresses. Penetration depth with lasers having power less than 800–1000 W is about 0.1 to 1.5 mm. Penetration increases with laser power. Thus laser welding in its normal form can be applied to microwelding (welding of small, thin materials). With lasers having power more than 1–5 kW, larger penetration can be obtained because of ‘‘keyholing.” Depth up to 20 mm has been obtained. Laser drilling or cutting involves vigorous vaporization.

The vapor so produced is blown or burned by a suitable gas jet.

This exposes a fresh surface for vaporization. Thus, material removal is very fast. As the evaporation front recedes from the focal spot, the intensity of beam decreases and evaporation stops due to inadequate energy supply. This restricts the cutting and drilling depths to a maximum of 1–3 mm depending on the laser power. Gas blowing with air or oxygen increases the depth. Reflectivity (or absorptivity) greatly affects all laser heating processes. A suitable allowance for this must be made in estimating laser power requirements. The time duration of heating is the most important control variable. A shorter time will produce lower temperature and penetration. A longer time will heat the surface to an undesirably higher temperature resulting in plasma generation and thermal shock. The heat affected zone (HAZ) will also be broad. The penetration depth can be controlled by slightly defocusing the beam so that the focus spot is little above or below the material surface. Remember that the beam energy is maximum at the focus spot and will decrease away from it. h T M = 3 45.

11.1.20 The Temperature Field

Laser heating applications involve a wide temperature range as discussed in Section 11.1.9. In this range the material undergoes a change of state from solid to vapor. The heat flow is from the surface to the interior. There is no one equation that can be used to calculate the temperature field in the material. Available equations are quite complicated and are applicable under limited conditions only. The laser energy input is of two types, continuous wave (CW) and pulse. Separate equations are involved for these two types of inputs. We treat the input as a point source having a uniform energy density and a circular shape of radius r f . The heat flow in the material is assumed to be unidirectional (direction z, Figure 11.12) in the process time t sec. The change in thermal properties with temperature is neglected. For a continuous point source the equation chosen is (11.13)

where T (z, t) = Temperature on axis at depth z and time t q o = Input power density W/cm 2 a = Thermal diffusivity cm 2 /sec K = Thermal conductivity w/cm˚C r f = Radius of focal spot cm t = Exposure time sec (The ierfc functions in the brackets are integrated complementary error functions which are available in tabulated form.) The temperature at surface T (0, t) is given by (11.14) The power density required to obtain a certain temperature T at the surface is (11.15) T z t q t K ierfc z t ierfc z r t o f (,) / = − + ( ) � � � � � � � � � � 2 2 2 2 2 1 2 a a a T t q t K q t K o o (,) . 0 2 1 1284 = = a p a q KT t o = 0 856. a The limiting temperature at the surface when t → ∞ is (11.16) If the input is a pulse we have to consider two time regimes.

The first regime is from 0 to t i where t i is the pulse duration (S).

In this time the pulse energy (J) is deposited on the surface and is heated to a temperature T. In the second regime which lasts from t i to t the deposited energy heats the interior. There is no fresh energy input. We again assume that both regimes are of sufficiently small duration to assure an essentially unidirectional heat flow. The temperature distribution in the first regime is given by (11.17) Here t≤ t i . At the end of the first regime (t = t i) the surface has attained

a temperature T(0, t 1) which will decrease logarithmically in the

second regime. The temperature distribution is now given by (11.18)

where t > t i and

Q o = Pulse energy (J)

r = Density (g/cm 3)

c = Specific heat (J/g°C)

A = Spot area = p r f 2 (– cm) The power density q o to obtain a certain temperature at

the surface T(0, t i) will be given by (11.19)

which is similar to Equation 11.17 as t → ∞, T → T o , i.e., sur

rounding or initial temperature. T t q r K o f (,)0 = T t q t K ierfc z t o i (,)∞ = 2 2 a a T z t Q A c t z t o (,) ( ) / = – � � � � � � r pa a 1 2 4 exp 2 q K T t o i = 0 884. a W/cm 2 We can rearrange Equation 11.19 above to obtain the

pulse time t i to heat the surface to the required temperature. (11.20) In Equation (11.19) and Equation (11.20) we can substi

tute T M or T B in place of T to obtain the power density required

for melting or boiling temperature at the surface. In cutting and drilling operations we are interested in

continuous evaporation from the surface and have to consider

the latent heat of evaporation L B (J/g). The power density for

vigorous evaporation is given by (11.21) A continuous laser power q is given in watts. For a pulsed

laser what we know is the average or total energy in the pulse

(Q an or Q) and the pulse duration t i (sec). This can be converted to watts as (11.22) If r f is the spot diameter (cm) the power density is (11.23)

11.2 ELECTRON BEAM HEATING

11.2.1 Introduction

An electron is a fundamental particle carrying a fixed negative charge (–e) and having a mass (m). It can be accelerated to tremendous velocities by an electromagnetic field. This increases the kinetic energy of the electron. When a beam of electron (EB) so accelerated strikes a target matter, it loses kinetic energy, which is converted into heat in the target. This is the principle of electron beam heating. t K T q i o = 0 79 2 2 2 . a q L t c B n r a = � � � � 1 2/ q Q t a i = n W q Q t r o a i f = × n p 2 W/cm 2

Note that the beam itself is ‘‘cold” and the heat is created inside the target. An electron beam can be precisely focused (like a beam of light) by an electromagnetic focusing coil which acts as a lens. The charge on the electron thus enables the electrons to be accelerated to high energy and also to concentrate the energy on a small spot by focusing. The heat created is focused on a small spot (d ≤ 1.0 mm) and an extremely high temperature is created locally. Thus the target spot can be melted or evaporated in a very short time (~ few msec). The bulk target material is essentially unaffected. Due to the tremendous kinetic energy, the beam can penetrate the target to a considerable depth. All the above-mentioned characteristics of the electron beam make it an ideal heat source for welding, small scale melting, or evaporation applications. In the next sections we will discuss in detail the generation, control, properties, and applications of the electron beam (EB) as an industrial heat source.

11.2.2 Generation of Electron Beam

A general industrial setup for producing and controlling an electron beam is shown in Figure 11.15. The electrons are produced by indirectly heating a negatively charged cathode made from a material such as lanthanum hexaboride, which releases electrons on heating to 1400–1600°C. The heating filament is made of tungsten. The cathode heater assembly is sealed and has a life of 200 h. The released electrons are collected and directed forward by the cathode cup. A bias cup controls the electrons moving ahead. This acts like a grid in a triode vacuum tube. An anode cup with a hole in the center is next. It is positively charged and accelerates the incident electron stream which passes through the hole. The emerging beam is shaped by a coil below the anode. The potential difference which acclerates the electrons to high energy is applied between the cathode (−ve) and anode (+ve) by a high voltage cable. A ceramic high voltage insulator electrically separates the anode and cathode. Depending on the design and application the voltage is between 80 and 150 kV and is variable to suit the requirements.

Figure 11.15 Electron beam machine.

The whole arrangement, known as the “electron generator,” is installed in a casing. There is vacuum connection on the side and an isolation vacuum valve at the bottom of the casing. A chamber next to the electron gererator contains the focusing coil and deflection coil. The focusing coil focuses the beam on a small area on the work or target. It also adjusts the distance (l) between the focusing coil and the target. This distance and the focus spot diameter are important process parameters. The work is situated in a vacuum work chamber located below. There are arrangements such as a coordinate table, holding devices, etc., in the work chamber. A vacuum connection evacuates the chamber to about 10^{-2} to 10^{-4} torr. The work can be remotely manipulated inside the chamber to bring the required location in the beam path. Electrons on impact (at high velocities) on the target surface generate X-rays which can be hazardous, hence the chamber is protected by proper shields. The observation window is made from lead glass which is opaque to X-rays. Electrons in the beam on impact with gas molecules in the air lose their energy. Hence, the whole process is carried out in vacuum. The generator compartment requires a higher vacuum ($\sim 10^{-6}$ torr), hence it is isolated from the work chamber and has a separate high vacuum system for pumping. There is an optical observation system through which the spot and the beam action can be observed. The deflection coil deflects the beam about the central spot. Some machines have a beam tracking arrangement so that the beam can follow a programmed path. The current in the high voltage circuit (cathode-anode) is a few milliamperes. Extensive water-cooling arrangements are made in the generator. The work chamber can be of a small size ($0.5\ m^3$) to a very large one ($2–5\ m^3$) depending on the requirements. An electron beam carries a current (due to the charge) and the circuit between the anode and the work has to be completed. This is achieved by grounding the work (0 V). It is then necessary that the work is conducting. This is why EB can only operate on metals.

11.2.3 Characteristics of EB

Charge ($-e$) on the electron = 1.6×10^{-19} coulombs (C) Mass of the electron (me) = 9.1083×10^{-31} kg If an electron (initially at rest) is placed in an electric field of intensity E (V/m), it will experience a force F which will cause it to move with a velocity U (m/sec) toward the positive. The work done when an electron moves under a force F in

a field having a voltage V is given by (11.24) The kinetic energy acquired by the electron due to the

work Equating the work and energy substituting for e and m e , the values given above (11.25) Thus, if the cathode-anode voltage is 80 kV It is difficult to establish a formula for the focal spot diame

ter of EB as a large number of variables are involved. It involves

some machine parameters, and the data given by the manufac

turer is useful for that particular machine. There are several Word done = eV = 1 2 2 m U e eV m U U eV m e e = = 1 2 2 2 U = 600 n km/sec U = × = × 600 80 10 1 7 10 3 5 . km/sec Kinetic energy 1 2 J = = × × × = × − m U e 2 31 8 2 15 9 1083 10 1 7 10 2 1 315 10 . (.) .

measurement techniques that can be used to measure the actual

diameter produced under given operating conditions. The spot

diameters generally available are in the range of 10 −3 −1.0 cm.

The diameter decreases with increasing accelerating voltage. If

the beam current (I) and accelerating voltage (V) are known, the

total beam power is I × V and the power density (11.26) can be calculated. Typical power densities for EB are in

the range of 10 5 −10 8 w/cm 2 . High energy electrons penetrate a metal target to a con

siderable depth. The electrons collide with the free electrons

and the ionic lattice. At each collision some energy is lost

which is converted into heat. The number of collisions under gone before the electron comes to rest (very low kinetic energy) is a statistical phenomena. Due to each collision the direction of the electron changes and the incident beam scatters inside the target. The depth(d) to which the electrons penetrate is given by

where V = Accelerating voltage and r the target density (g/cm 3) Thus, if V = 75 kV and r = 7.8 g/cm 3 d = 2.6 × 10 −12 × (75 × 10 3) 2 × 7.8 = 0.114 cm At 100 kV d = 0.203 cm

11.2.4 EB — Noteworthy Points

An electron beam can be continuous or pulsed. It is initiated by the application of current to the cathode and accelerating voltage between cathode and anode pulsing can be easily achieved by switching the power. During their journey from the cathode to the target, the electrons will suffer energy loss if they collide with gas molecules in the air. To avoid this loss the entire apparatus has q I V d = · ×(/)p 2 4 w/cm 2 d r= × − 2 6 10 12 2 . /V to be kept under vacuum. The need for vacuum (~ 10 −4 to 10 −6 torr) is one of the disadvantages of EB. Small machines have a single vacuum system. Larger machines have a high vacuum system for the electron beam generator. The work chamber, which is isolated from the generator, has a separate, large capacity, and medium vacuum system. As mentioned before, an electron beam can operate only on metallic (conducting) targets. The energy density in the spot is very high (~ 10^8 w/cm^2) and is easily controlled by the high voltage and the focusing currents. This enables the creation of very high temperatures at the spot. There is no temperature limit. Any metal or alloy can be melted or evaporated at the spot. Due to vacuum there is no oxidation at the target. Due to the electric control, the beam can be deflected so that it can scan the required target area. It can be tracked or programmed to follow a particular path over the target surface. Due to local heating of a small area in a very short time (~ 1.0 msec) the heat affected zone is very narrow or nonexistent. Deep penetration, narrow heat affected zone, no temperature limit, easy control on the time and energy of the beam, and clean environment (no oxidation) make EB an ideal heating method for welding. Virtually any metal or dissimilar metals can be precision welded. Depending on the work manipulating system and the size of the work chamber, very small or relatively large assemblies can be welded on production scale. Hence, EB is used for electronic welding (microwelding), automotive components, rocket components, etc. EB is also used for special alloy melting, vacuum sputter ing, drilling etc.

11.2.5 EB — Material Interaction

When an EB strikes the target it penetrates to a considerable depth until its kinetic energy is fully absorbed by the target lattice and free electrons. The main body of heat is created below the surface and acts essentially as an internal volume source of heat. If the beam is pulsed, a certain ‘‘dose” of energy is deposited as heat which then spreads around in the target. In the case of a continuous beam the penetration is deeper and may pierce the target. As the process time is short (0.1–2.0 sec) the heat flow is mainly in the up-and-down stream of the beam. The beam and the target reaction produces emissions which consist of target atoms, ions, electrons, and X-rays (Figure 11.16). Due to the intense heat and sublimation, plasma or vapor or small molten drops are also produced. In fact, by using an apropriate spectrometer these emissions can be used for chemical analysis and characterization of the target material. The hot spot also gives out thermal radiation. The heat spreads up and melts the material. The expansion of the material and occluded gases produces vigorous currents. This causes spurting and the molten metal is ejected out. The heat that spreads downward causes melting mostly confined to a conical volume pointing downward. The energy distribution in the focal spot is gaussian with a peak at the center.

Figure 11.16 Electron beam-target interaction. For deep penetration the beam is focused at a distance lower than the target surface. This is achieved by adjusting the current in the focusing coil. It changes the distance l between the coil and the focal spot. Thus, this distance l and the focusing coil current are critical parameters. There is no exact analytical method of predicting the penetration depth, spread, and temperatures in the reaction zone.

Control is established by the accelerating voltage, cathode current and the focusing coil currents, and pulse time. Like the laser beam, the target material has some reflectivity which reduces the efficiency.

11.2.6 Commercial EB Equipment

The specifications of commercial EB machines usually contain the following specifications: Anode voltage kV and range of variation Beam current mA Pulse operation Pulse repetition rate – Hz Pulse duration and range – msec Beam diameter – mm Vacuum system – Pressure limits – mbar, torr Pumping time Beam deflection and scanning – mm^2 Focusing parameters – Lens to target distance Beam viewing and tracking (optional) Work chamber volume – m^3 , length, width, and height Coordinate table length, width, range, and programming Gun positions – standard and optional Work piece – Maximum dimensions accomodated Additional manipulation axes Total power requirement kW Auxiliaries – Transformer Water requirement – m^3/h Operational data are supplied by the manufacturer to suit customers’ requirements Servicing and spare parts supplied by the manufacturer

12.2 UNITS FOR VACUUM

The fundamental unit of vacuum is that of pressure, which is Pascal (Pa, N/m^2). However, vacuum is always quoted with reference to environmental or atmospheric pressure which is 10^5 Pa, or 1 bar, or 760 mm Hg. One bar is defined as 750 mm Hg.

Hence, units commonly used for vacuum are 1 torr = 1.0 mm Hg = 10^3 µ Hg (micron) = 133.3 Pa or 1 mbar = 10^2 Pa For conversion 1 mbar = 7.5×10^{-1} torr = 750 microns or 1 torr = 1.33 mbar = 1000 microns As far as possible, we will use torr in our discussion as it appears more frequently in literature. Thus, vacuum is quoted in 10^{-n} torr where n is a whole number. Hence, 1 atmosphere is 7.5×10^{-1} torr. Subsequent lower pressures will be 10^{-1}, 10^{-2}, etc. Low pressures (not much lower than atmosphere) are quoted in mm of water (kg/m^2) or mm of Hg. Another unit we will be coming across when dealing with vacuum systems is “throughput” (Q). This is defined as the product of the pumping speed (S) and the inlet pressure (P), i.e., Q can also be considered as the quantity of gas in pressure × volume units at a specified temperature. Q can be quoted in Pa × m^3/sec, or more conventionally as torr × liter/sec. Throughput will be useful in calculating pumping capacity, system leaks, and outgassing.

12.3 VACUUM PUMPS

Vacuum or low pressure is achieved in a container or vessel by removing the air or gases in it. The devices used for this are collectively called “vacuum pumps.” There are many types of vacuum pumps in use. Some of them are “true” pumps. They draw the gas out by suction, compress it, and discharge it into the atmosphere. These are mechanical pumps. They operate at high pressure but have limited displacement, pressure, and range. Next are the blowers such as roots pumps. They operate at low pressure but have a large displacement. Principally, blowers only push the gases and are not pumps. For low pressure in the vacuum range (10 − 3 -10 − 9 torr) diffusion and molecular pumps are used. They trap gas molecules physically or mechanically and push them ahead. These pumps are displacement or drag pumps and can operate at low pressures only. They always require a backing pump. Q P S d dt = × = n For higher vacuum (10 − 5 -10 − 12) there are many devices such as ion pumps, and cryo pumps. They are based on various phenomena displayed by gas molecules at very low pressures. A brief review of the operating principles and characteristics of some vacuum pumps for use in (760 to 10 − 5) torr range are discussed in this section. For more information about these and other pumps refer to special books in the Bibliography , and manufacturers’ literature.

12.3.1 Positive Displacement Pump

These are purely mechanical pumps. They create a vacuum inside a “cylinder” by a moving piston; gas is drawn in, compressed, and discharged into the atmosphere at a slightly higher pressure than the atmospheric one. Thus their discharge is always at atmospheric pressure. Hence these pumps are at the exit end of a vacuum pumping system. The discharge pressure is regulated by a spring loaded valve. Though theoretically, the intake pressure of these pumps is supposed to be zero, in actuality, it is of the order of 10^{-1} to 10^{-3} torr due to leakage and other problems. Commercial positive displacement pumps have a rotary piston. Two common designs are shown in Figure 12.1(A) and Figure 12.1(B). The rotary pump in Figure 12.1(A) has a solid shaft rotating eccentrically in the cylinder. A ring with a sliding ring is mounted on the shaft and carries a slider. The contact point between the cylinder and the ring on one side and the slider on the other side divides the cylinder into two cavities. The slider also acts as the gas inlet. The gas is received, compressed, and discharged through the spring-loaded valve. As the gas heats during compression, the pump is cooled by oil around it.

There may be additional cooling pipes to circulate the water and cool the oil. Figure 12.1(B) shows a sliding vane pump. The eccentrically rotating shaft has a diametrical slot carrying two radial vanes. The inner ends of the vanes are connected by springs. The outer ends rotate in contact with the inner surface of the cylinder. Thus, two rotating cavities are created. Air or gas is received via the intake port, compressed, and discharged through the spring-loaded valve. This pump is also oil-immersed.

Figure 12.1 Positive displacement pump.

Both pumps usually have a gas ballast facility. Through this, the measured quantity of air is injected into the compressed gas a little before discharge. If the gas being pumped has moisture or other condensable vapors, these condense during compression due to reduction in volume and vapor saturation. The condensed vapors create corrosion problems and also contaminate the oil. The injected ballast prevents condensation, allowing vapors to escape with the exhaust. Gas ballasts raise the ultimate (minimum vacuum) pressure and thus reduce the pump capacity.

Limitations and Advantages of Mechanical Pumps

1. These are the only available pumps that can discharge the pumped air directly into the atmosphere.
2. They have a constant pumping speed from atmospheric to about 1.0 torr pressure. At lower pressures the speed drops rapidly, as shown in Figure 12.2. The lowest attainable pressure is about 10 – 3 torr.
3. At lower pressures, the pump cannot compress the

drawn gas to discharge (atmospheric) pressure and thus pumping is effectively stopped. 4. Due to rubbing between various parts there is considerable friction and wear. Hence, the pump speed is limited to about 350–700 r/m. 5. The gas ballast solves the condensation problem but raises the ultimate pressure. 6. The ultimate vacuum (pressure) can be lowered by using two pumps in tandem. A large capacity fore pump draws air from the vessel, compresses it, and discharges it into the backing pump which compresses it still further and discharges it into the atmosphere. The pumping characteristics of this arrangement are shown in Figure 12.2. 7. These pumps are excellent for roughening, i.e., quickly reducing the pressure to about 1–10 – 2 torr so that other pumps (blower or diffusion) can take over for further pressure reduction. 8. Pumping capacities available are 10 to 1000 m 3 /h.

12.3.2 Roots Pump

This pump is a blower and is mainly used as a booster or enhancer for positive displacement pumps. The construction of a typical roots pump is shown in Figure 12.3. Two counter-rotating rotors of approximately the same shape, rotate in a housing. The clearance between the rotors, and the rotors and housing is 75 to 300 microns. This clearance makes the rotation free (without contact) and hence r/m is possible without friction. The inlet and outlet ports are as shown. The outlet port is smaller than the inlet. During rotation, gas molecules are trapped between the casing and the rotors and are transported toward the outlet. There is not much compression, hence, this is a low-pressure

Figure 12.2 Pressure-speed characteristics of a typical positive displacement pump.

Figure 12.3 Roots pump (Blower).

high-discharge pump. The pumping speed (l /sec) depends on the lobe-casing volume and r/m. Some blowers have spiral shaped rotors. The compression ratio is about 1:10. Blowers with a capacity of 500–2000 m^3/h are available. Due to the peculiar manner of trapping and pushing the gas, a blower has different speeds for different gases. Typical pressure-speed characteristics of roots blowers are shown in Figure 12.4. Some peculiarities of roots pumps: 1. A roots pump is really a blower. It pushes a high volume of gas at low pressure. Hence, it cannot be used at high pressures, i.e., the initial stages (roughening) of vacuum. 2. The maximum permissible pressure difference is 50–60 torr. If connected to discharge directly to the atmosphere (760 torr) it draws out a large volume initially. When the pressure in the vessel drops, it cannot develop enough output pressure and develops considerable heat. It is therefore necessary to back the blower with a rotary pump. 3. Such a combination of the blower and rotary pump can be used in the 760–10^{-3} to 10^{-4} torr range. The ultimate pressure is about 5×10^{-5} torr. 4. The pumping speed depends on the r/m. The usually available speeds are 1000–3000 r/m but higher speeds are possible. 5. As there is considerable heat generation, the blowers have elaborate water cooling. 6. The size (rating) of the backing pump has an effect on the blower performance. Usually, a backing pump of about 1/10 pumping speed is used. 7. Blowers have a maximum pumping speed of about 0.05–0.1 torr, below which the speed drops. At 0.001–0.01 torr the speed is 50–75% of the maximum. 8. Blowers are free from oil contamination. 9. Positive displacement pumps are useful up to a maximum of 1.0 torr while diffusion pumps can pump efficiently from 10^{-2} to 10^{-3} torr. Hence, there is a gap between 1 and 10^{-2} torr when a diffusion pump is connected directly to a rotary pump. Blowers are very useful to cover this gap. Hence, diffusion pumpblower-rotary pump is the best combination.

Figure 12.4 Pressure-speed characteristics of a roots pump.

10. Roots pumps can be connected in series or parallel to handle large amounts of gases containing condensable vapors.

12.3.3 Diffusion Pumps

In these pumps the air molecules coming from the vessel are caught up or trapped by a stream of vapor and are carried along with it toward the exit (foreline). In principle, the pumping action is similar to an ejector pump. The pumping medium, i.e., the vapor is produced at the base of the pump by boiling a suitable fluid. As the vapor carrying the gas descends, it condenses on the cold walls of the pump casing. The trapped air or gas molecules are released near the lower end and are drawn out by the suction from the foreline. The vapor stream is produced in two or more stages by the jet assembly over the top of the boiler (Figure 12.5).

Figure 12.5 Oil diffusion pump.

A further enhancement in pumping is obtained by an ejector or booster in the foreline. The pump walls and foreline are cooled by water. This cooling removes the heat of condensation and reduces the back streaming of vapor to the vacuum vessel. The pumping speed is determined by the area (diameter) of the inlet and what is called the H_o factor. This factor is 0.3–0.5. For air the pumping speed S is given by $S \approx 2D^2$. Diffusion pumps with diameters of 25–1200 mm and air pumping capacities from 10–100,000 (l/sec) are available. In earlier days mercury was used as the pumping fluid. It is still used in small laboratory-type pumps. Presently, all commercial pumps use synthetic oils and are sometimes called “oil diffusion pumps.” Among many desirable properties of the pumping oils, the following are most important: 1. Low vapor pressure 2. High molecular weight 3. Low latent heat of evaporation 4. Noncorrosive and nontoxic A number of synthetic oils are developed. They are proprietary formulations based on hydrocarbons, silicones, and other organic groups. The boiler has a sealed electric heater. The oils may consist of a single compound or a number of compounds. In the latter case a “fractionating pump” is used.

Different components vaporize at different pressures and rise to different jets. Noteworthy points about diffusion pumps 1. Pumping characteristics of a typical diffusion pump (P-S curve) is shown in Figure 12.6. The figure shown is typical for pumping air. Note that at pressures higher than 10 −3 torr, the speed drops down, and somewhere between 10 −2 −5 × 10 −3 it becomes practically zero. For pressures lower than 10 −3 the speed is constant up to about 10 −7 torr. 2. The maximum constant speed depends on the inlet size (dia D). Theoretically, there is no lower limit. In practical pumps, the ultimate or blank off pressure is about 10 −9 torr. The ultimate pressure depends on the back-streaming of oil from the pump to the vacuum vessel. The back-streaming is avoided by using a trap or baffle at the inlet to condense the oil vapor. 3. Diffusion pumps draw the gas with the vapor stream. The drawn gas is collected in the foreline where it acquires a higher pressure, which is called the “foreline pressure.” 4. As the diffusion pump can pump only from about 10 −3 torr, it is necessary to connect a mechanical pump between it and the atmosphere. This mechanical pump must have an intake pressure lower than the foreline pressure. If it is not so, air collected in the foreline cannot be drawn out. 5. Thus, there is a maximum limit to the foreline pressure. If pressure higher than this limit is reached, it will start affecting the pumping speed at the inlet of the diffusion pump. This limiting pressure is called the “fore pressure tolerance” of the diffusion pump. This is an important design parameter when selecting

Figure 12.6 Typical P-S curve for a diffusion pump. the diffusion-mechanical pump combination. The fore pressure tolerance (at full load) is given by the manufacturer. It is usually between 15 and 50×10^{-2} torr. The backing pump must have an intake pressure lesser by at least one order. 6. Diffusion pumps require water-cooling. The water requirement as well as the power required for the oil boiler is given by the manufacturer. Diffusion pumps have no moving parts. They do have oil which may produce back-streaming vapors. 7. As the diffusion pumps can start pumping only at about 10^{-3} torr, it is best to use a roughening pump directly connected to the vessel. The diffusion pump is connected in line after the vessel pressure reaches 10^{-3} torr, as shown in Figure 12.6. 8. When the vessel is very large (≥ 5 m^3) a number of diffusion pumps are connected in parallel to achieve a quick pump-down time. Diffusion pumps are mounted vertically. They are connected to the vessel via a short, large-diameter pipe or an elbow. The conductance of these must be taken into account when deciding the pump capacity. These connections often contain a baffle or trap to condense oil vapors backstreaming into the vessel. The traps and baffles also have a conductance which significantly lowers the available pumping capacity.

12.3.4 Molecular Pumps

These pumps are based on the phenomenon of molecular impact in a low pressure regime. If a gas molecule strikes a surface, it rebounds in all possible directions that have no relation to the angle of incidence. At low pressures ($< 10^{-3}$ torr) the molecules have a large mean free path. Thus, when molecules strike a surface, some of them rebound in a direction which is more or less parallel to the surface. If the surface is moving at a fast speed, these molecules will be carried along the surface, i.e., they will be pumped away. There are two main types of molecular pumps based on this principle. The molecular drag pump uses a high speed rotating disk and a spiral pumping path. These pumps have many mechanical problems and are now superceded by turbo molecular pumps. A typical turbo molecular pump is shown in Figure 12.7(A). It consists of several pairs of stator and rotor blades with angular grooves on their edges as shown in Figure 12.7(B). There are several configurations of this. The one shown in the figure has a central inlet with blade pairs on both sides, an outlet on one side, and an integral motor. The clearance between the blades is about 1.0 mm (much smaller than the mean free path ~10 2 -10 3 m). The rotor blades are rotated at 10,000-20,000 r/m by the motor. Gas molecules are drawn in the stator grooves and pumped by the rotor grooves. The number of grooves, their angle, the clearance, and the speed are critical design factors. Higher r/m increases the pumping speed and limitation appears to be the bearings. Pumps with capacities 1000-20,000 l/min are available. The pressure-speed characteristics of turbo molecular pumps are shown in Figure 12.8. The pump starts pumping from about 10 -2 torr and has a constant speed down to 10 -9 torr. It is thus necessary to use a backing pump. Turbo molecular pumps are oil free and are not affected by condensable vapors. They are better but costlier than diffusion pumps. Because of their very high speed they have mechanical problems. These pumps are mainly used in electron beam machines, solid state processing, etc., where vacuum higher than 10 -5 torr is required.

12.4 PUMPING SYSTEM DESIGN

12.4.1 Selection of Vacuum Pumps

After reviewing various aspects of vacuum pumps and vacuum systems we can now tackle the main problem of the designer, i.e., how to select the pump or pumps required to achieve the given vacuum pressure in the given time and to sustain it during the given process time. The various available pumps have their characteristic pressure range and pumping speed. They give optimum performance within these limits. The following are the general operational ranges of these pumps: The ultimate pressure of these pumps is usually much less than the ranges given above.

Figure 12.7 Turbomolecular pump.

Figure 12.8 Pressure-speed characteristics of a turbo molecular pump.

Mechanical pumps 760-0.1 torr

Roots pumps 760-10 -3 torr With input/output pressure difference of about 40 torr.

Diffusion pumps 10 -2 -10 -7 torr

Turbo molecular pumps 10 -3 -10 -9 torr with cryogenic trap or 10 -3 -10 -7 without traps. This tells us that with the exception of low vacuum of about 10 -1 or 10 -2 torr, no one pump can produce higher vacuum. Another important point is that only mechanical, i.e., positive displacement pumps, can pump out at atmospheric pressure. Hence, in virtually all the pump combinations, the mechanical pump will be the output or the last pump and will have to be used as the backing pump. Consider the pumping speeds (l/min). Following are the typical speeds of various available pumps: This shows that pumps applicable for low pressures have high pumping speeds. This is fortuitous because at low pressures the volume of gas to be pumped out is large (PV = Constant).

However, the pumps will have to be matched to their fore and backing pumps and the conductance of the piping. The output of the mechanical pump can be increased by connecting two or more pumps in series (compound) or in parallel. After we reach a pressure of about 10 -3 torr there will be outgassing from the vessel, its furniture, and components. The gas load due to outgassing can be estimated from the available data but such estimates could be very different (generally lower) than the actual one. The pumps should be capable of taking up this load and maintaining the vacuum. Outgassing generally subsides or comes to equilibrium with pumping. On further evacuation there will be an additional gas load due to the process. This load will arise at the process pressure and temperature, and can be estimated with reasonable accuracy. The process gas load will continue throughout the process time. The pumps will have to take up this load and maintain pressure at the level required by the process.

Mechanical pumps 400-40,000 l/min
Roots pumps 10,000-50,000 l/min
Diffusion pumps 3,600-540,000 l/min
Turbo molecular pumps 3,000-25,000 l/min

The normal leaks and permeation will also pose an additional load but this is generally negligible compared to the outgassing and process loads. The piping used to connect the vessel and the pumps will have conductance, as discussed in Section 12.5. The size (diameter) of the plumbing will be dictated by the flange size of the chosen pump. The length will depend on the system layout but should be the shortest possible. For a given pipe or fitting, or their combination, the conductance will depend on the flow regime, i.e., turbulent, viscous, intermediate, or molecular. Conductance will lower the actual speed available at the input and, hence, will influence the pump selection.

12.4.2 Calculation of Pumping Speed

In the beginning, the whole system will be at atmospheric pressure (P_A). We will assume that the system contains dry air. The first stage of evacuation will be roughening, i.e., to bring down the pressure (P_R) to 1–10^{-1} torr. A positive displacement pump is used for this. If a time t min is assumed for roughening, (12.1)

where V = Effective volume of system (l)

S_P = Pumping rate (l/min) This is modified by using the factor K for different pressure ranges as given in Table 12.1. We can also use this equation to determine the roughening pump speed S_P, for pump selection. If the air contains substantial moisture, a gas ballast will have to be used, which will raise the P_R from 10^{-1} to 1.0 torr.

The roughening pressure can be lowered to 10^{-2} and a higher pumping speed can be obtained by using a compound pump. t V S P P t V S P P P A R P A R = = ln or 2.3 log The roughening pressure can be lowered further to 10^{-3} to 10^{-4} torr by using a roots pump as the forepump and backing it by a rotary displacement pump. In the absence of outgassing loads, the combination will have a fairly flat P-S characteristic. If outgassing exists, the blower capacity (S_B) will have to be matched to the gas load. A roots blower can also be used to the evacuate directly to the atmosphere at the very beginning of evacuation. Blowers have large pumping speeds and can bring down the system pressure to about 100–10 torr in a very short time. After this, the blower could be backed by a mechanical pump. This arrangement will require elaborate plumbing. Experience has shown that a blower works best when backed by a mechanical pump having a capacity of about 1/10 of the blower. For pressures below 10^{-3} torr to about 10^{-8} torr, a diffusion pump will have to be backed by a blower or a mechanical pump. It is in this pressure range that most of the outgassing load will appear. The pump capacity should be adequate to remove the outgassing, process gas load, and maintain the system pressure at the desired level. Diffusion pumps have very large pumping speeds. To realize these speeds the fore line pressure will have to be at least one order below the maximum tolerable value. This will be supplied by the manufacturer. It will be about 0.18–0.30 torr. The gas flow in the pressure range of 10^{-3}–10^{-8} torr is in the molecular or intermediate range and the conductance of pipes and traps in the suction line must be considered. TABLE 12.1 Pressure Range, Torr Service Factor K 760-100 1.0 110-10 1.25 10-5 × 10 -1 1.5 5 × 10 -1 -2 × 10 -4 2.0 5 × 10 -2 -2 × 10 -4 4.0 Instead of a diffusion pump we can use a turbo molecular pump in the 10 -3 -10 -10 torr pressure range. The pump has a flat S-P characteristic and is oil-free. However, it has a low capacity and is expensive; hence, it is mainly used for special applications. It will have to be backed by a blower or a mechanical pump. The layout of a typical vacuum system will be as shown in Figure 12.9. The example that follows will make clear the process of pump selection.

12.5 CONDUCTANCE AND PUMPING SPEED

The vacuum chamber and the pumps are connected by pipes. There may be one or more pumps, and the connecting plumbing may be quite complex. Besides the pipes, it contains many other components such as traps, baffles, valves, and elbows. The plumbing offers considerable resistance to the flow of gases and affects the pumping speeds. In vacuum parlance this resistance is called “conductance (C).” Each component has its own conductance. The total conductance of a system is calculated by considering their way of connection, i.e., in series, parallel, etc. This is similar to the calculation of the resistance of an electric circuit containing a number of resistors.

Consider a simple system as shown in Figure 12.9(A),

where the vessel and pump are connected by a large, straight,

circular pipe. Let S P = Pumping speed of pump l/sec S E = Effective speed available at the vessel The two speeds are different because of the conductance

offered by the intermediate pipe which consumes some part of

the pump speed. Thus, S P and S E are related by the following

relation: (12.2)

where C is the conductance of the pipe. The units for C are the

same as S E and S P , i.e., l/sec or m 3 /sec, etc. 1 1 1 S C S E P = + Figure 12.9 Typical vacuum line. If there are more pipes connected in series, the total con

ductance C is given by (12.3)

where C 1 , C 2 , C 3 , etc., are the conductances of individual pipes.

If these are arranged in parallel, (12.4) Let us consider the relative magnitudes of the quantities

in Equation (12.3) and Equation (12.4). If C = S P then S E = S P /2, hence, only 50% of the pump

speed is available at the vessel. If C < S P lesser speed is avail

able. If C > S P more speed is available. Thus, at C = 4 S P 80%

of the pump speed is available at the vessel. Note that 100% is

never available at the vessel. (Unless of course when 1/C = 0 !).

This also shows that if the conductance C is limiting, there is no use increasing the pump speed; i.e., a larger pump is not

necessarily a solution. The conductance of a pipe depends on the flow regime,

i.e., viscous, intermediate, or molecular (see Table 12.2) and on

the geometry of the pipe. For a circular pipe of length L (cm) and diameter D (cm)

carrying air at 20°C at average pressure P (torr), the conductance C is given by (12.5) The above equation applies for viscous regime only. As

seen before viscous regime exists if P × D ≤ 0.5 torr cm. If P × D is between 0.5 and 0.005 the flow is in intermediate range and the conductance is given by (12.6) Here, the first term is the conductance due to viscous

flow, and the second term is for the molecular flow. 1 1 1 1 1 2 3 C C C C = + + + ... C C C C= + + + 1 2 3 ... C D L P= � � � � � � � 180 4 C D L P D L = × � � � � � � � + − 3 3 10 10 2 4 3 . For the molecular flow, where P × D ≤ 0.005 the conductance for air at 20°C is given by (12.7) This equation shows that in the molecular flow regime

the conductance is independent of pressure. If L ≤ D, the

above equation can be written as (12.8)

TABLE 12.2 Characteristics of Vacuum Systems Vacuum

Characteristics Low Medium High Ultrahigh

Pressure Range

(typical) mm

Hg (torr) 760-1 1-10 -3 10 -3 -10 -7 10 -7 -10 -10

Number of

molecules per

m 3 (N AV =10 26) 10 25 -10 22 10 22 -10 19 10 19 -10 13 10 19 and less

Mean free path

(cm). For air

at 20˚C

(approximate

for comparison only.) 4.5 × 10 -3 0.45 4.5 × 10 3 4.5 × 10 4.5 × 10 6

Viscosity and

thermal

conductivity Independent of Pressure Depends on mean free path/ Mol.dia. Directly proportional to pressure Both phenomenon practically absent

Gas Flow* Viscous Mixed Molecular Molecular to no flow at very low pressure

* This also depends on the pressure, viscosity and vessel, pipe dimensions. C D L s = 12 1 3 . l C D s = 9 1 2 . l Equation 12.8 can also be modified to take into account

the end corrections which arise due to the entry aperture

between the vessel and the tube. Equation (12.7) and Equation (12.8) also show that to have

a large conductance, i.e., more pump speed at the vessel, the

connecting pipe should have a large diameter and short length. Besides the simple tube connection between the pump

and the vessel, another connection commonly used is a right

angle elbow. The conductance of an elbow can be calculated

from the above equations by substituting D´ for D where

where L ax = Axial length (cm) and D = Diameter (cm) of the elbow For more complex shapes and their conductance, consult

12.6 BAFFLES AND TRAPS

These are devices to remove condensable vapors from the air or gas being pumped out. There are several sources of condensable vapors in a vacuum system. The air always contains moisture or humidity. At the right combination of pressure and temperature, the gas is saturated and the vapor and moisture are condensed. Various materials used in the construction of the vessel give out large amounts of water vapor at the outgassing stage.

It is reported that the outgassing “gas” is about 75% water vapor. The charge to be processed in vacuum also has absorbed water vapor which is released at the right pressure. In a high or medium vacuum system the outgoing vapor enters the diffusion pump and condenses there along with the pumping fluid (usually oil). The oil gets contaminated, thus affecting the pumping rate. Elastomers and seals give out hydrocarbon vapors during evacuation. These vapors also condense and contaminate the oil. ′ = +D L D ax (.)1 33 What is discussed above is the source of vapors going out from the vessel. One other source of vapor goes in to the system. This is the oil vapor escaping from the pump inlet into the vessel. If the pumping system contains only a roots pump or a mechanical pump, the outgoing vapors can be removed by a gas ballast arrangement. The condensing vapors lower the ultimate pressure of the pump. Roots pumps are unaffected by the presence of vapors. The diffusion pumps are the type mostly affected by the presence of vapors. It is therefore necessary to remove the vapors by condensation before they enter the diffusion pump. Traps and baffles are such devices. They are located between the vessel and the fore pump. Technically, baffles provide a zigzag path for the vapor so that it meets cold surfaces and condenses before entering the pump. Traps are intentionally cooled or refrigerated to condense the vapors. Both devices condense the vapors and the condensate remains in the device. It re-evaporates upon heating and enters the system. To minimize this, there is a baffle valve which isolates the vessel from the pump. The arrangement of these and some typical baffle and trap designs are shown in Figure 12.10. Traps are cooled by water circulation, dry ice, refrigeration, liquid nitrogen, or air depending upon the cooling requirements. The condensate, either liquid or solid, is removed (emptied) when the system is off. Alternately, the vapors are absorbed by a suitable molecular absorbant (e.g., activated charcoal or other synthetic material). Theoretical calculations of the baffle and trap conductance is tedious. It is best to rely on manufacturers' data.

12.7 OUTGASSING

All materials, when exposed to low pressure, release gases. This phenomenon is called “outgassing.” Either during manufacturing or in subsequent processing and handling, materials absorb gases such as water vapor, hydrogen, and oxygen. These gases are linked up with the chemical structure of the materials. If they are bonded with the surface layers, only then are they said to be “absorbed.” On the other hand, they may be dissolved in the material and evenly distributed throughout. Some gases may be occluded in the surface defects (e.g., cracks) and some may be in the form of small bubbles. There are many other forms or mechanisms of absorption of gases by material surfaces. These are subjects of study in surface sciences. It should be remembered that these gases are not present because of surface uncleanliness. Otherwise, clean surfaces would also have absorbed gases (in fact, more). In the construction of vacuum furnaces and accessories we use metals, polymers and rubbers (gaskets), glasses (view ports), ceramics, etc., and all these materials have absorbed gases mainly on their surfaces. On exposure to vacuum (and temperature) the absorbed

Figure 12.10 Vacuum foreline with traps.

gases are evolved. The pressure at which a material outgasses, and the rate of evolution varies from material to material, its processing history, and prior exposures. An elevated temperature (baking) helps outgassing. At elevated temperature the material outgasses at a higher pressure and at a faster rate. One common fact about all materials is that the rate of outgassing first increases and then diminishes with time. Most materials outgas in 10 −2 −0 −4 torr pressure range. Evolution of absorbed gases is called “desorption.” Organic materials like elastomers and polymers give out additional gases due to chemical decomposition. They are generally blends of several chemicals with the main polymer. These chemicals evaporate or decompose at low pressure and elevated temperature. On exposure to vacuum for a prolonged time, many materials release gases due to diffusion from internal layers or permeation of atmospheric gases through them. All vacuum systems show leaks. These may arise from manufacturing defects (e.g., faulty welding, improper seal, design, etc.) or due to aging with use or need of maintenance. In a well-designed and maintained system, these leaks are taken care of by the pumping system. Outgassing of many construction materials is extensively studied. Outgassing rates are measured in throughput per unit area, i.e., torr × liters/sec × cm 2 and are published in specialist literature. A few are quoted below. The above quoted rates are for comparison only. Actual rates depend on surface condition and time in vacuum. Many metals contain lead, sulfur, zinc, cadmium, and other low melting point impurities or alloying elements. These vaporize on exposure to vacuum. In general, alloys like stainless steel, mild steel, etc., have very high vapor pressure and do not add to outgassing. Surface dirt, grease on the vessel, or charge outgas and further load the system. In conclusion, outgassing poses an unpredictable and uncontrollable problem in the design of pumping systems. At about 10^{-2} the outgassing produces a gas load and raises the vessel pressure. The pumping system should be capable of handling this additional gas load at low pressure and stabilizing the vacuum to the desired level in reasonable time. As compared to outgassing, vaporization and diffusion evolve vapors and gases at a very slow rate and the evolution continues at a constant rate for a very long (many days) time. Hence, they pose a permanent, steady but predictable problem. After outgassing, the pumping system comes to equilibrium with vaporization. This puts a limit on the ultimate (long term) vacuum that can be obtained in a given system. The outgassing problem can be reduced by heating the

vessel during the roughening stage. This is called “bake out.”

A temperature of 200–400˚C is used. Due to the combination

of heating and vacuum, the exposed surfaces outgas quickly.

This reduces the outgassing load at lower pressure and the

required vacuum is produced in a shorter time. Bake out is Stainless steel, aluminum 1.5 × 10 −9 Mild steel 5 × 10 −7 Teflon 5 × 10 −6 Neoprene 2 × 10 −4 Porcelain 6 × 10 −7

limited to surface outgassing (desorption) only. Surfaces once

baked out will reabsorb gases if exposed to the environment.

EXAMPLE 12.1

A furnace having 2.0 m 3 volume is to be evacuated to 10 −3 torr.

Initially the furnace is filled with dry air at atmospheric pres

sure and 300 K.

Assume: 1. Constant furnace temperature (300 K) 2. Air contains 21.0% O 2 and 79% N 2 by volume 3. R = 287 J/kg K

Now determine: 1. The quantity of air initially present 2. The air remaining in the furnace after evacuation to 10, 1, and 10 −3 torr

Initially, V = 2.0 m 3 , P 1 = 10 5 Pa, T = 27˚C Finally, V = 2.0 m 3 , P 2 = 10 torr = 1.333 × 10 3 Pa, T = 27˚C Repeating the calculations for P 3 = 1.0 torr and P 4 = 10 −3 torr, we get P V m RT 1 1 5 1 1 10 2 287 300 = × × = × ×m ∴ =m 1 2 3256. kg P V m RT m 2 2 3 2 1 333 10 2 287 300 = × × = × ×. ∴ =m 2 0 03. kg m m 3 4 0 003 0 3 = = × − − . . kg (1.0 torr) 10 kg (10 torr) 5 3 Comparing m 1 and m 2 , the air removed in bringing the

pressure from 1 atmosphere to 1/750 atm is i.e., 98.7% of air is pumped out in the first stage leaving

behind only 1.3%. Subsequent stages will progressively pump out more air

but the remainder will never be zero!

12.8 VACUUM PUMPING (PRESSURE-TIME RELATIONS)

Consider the evacuation of a vessel having a volume V m 3 by

a pump with a pumping speed S m 3 /sec.

Assume 1. There are no leaks or gas evolution (outgassing) 2. The pump speed is constant at all pressures 3. The resistance (conductance) of the connecting pipes and fitting is negligible Gas pumped out in time dt at a vessel pressure dp = V dp/dt Gas removed by pump = S P giving (12.9) If in time t the pressure goes down from P 1 to P 2 , the

above equation on integration gives (12.10) (12.11) The above equation is applicable between 760-1.0 torr. In

this range the gas flow is viscous and the outgassing is negli

gible. Mechanical pumps (rotary vane, blowers) used in this

range show a fairly constant pumping speed. 2 3256 0 03 2 2956. . .- = kg dp P S V dt= t V S P P = in 1 2 t V S P P = 2 3 1 2 . log The useful application range of this equation can be

extended by including a factor K so that (12.11) The factor K is empirical and is usually supplied by the

pump manufacturer as a service factor. Typical service factors

are given in Table 12.1. Mechanical pumps cannot be used at pressures below

1.0 torr as their pumping speed drops rapidly to zero at about

10 -2 torr. The range can be extended to 10 -4 by using two

pumps in series such as a blower followed by a rotary pump

or two blowers in series. Equation (12.11) can be
rearranged to the form (12.12)

which will show that the pressure is reduced by a
logarithmic

decay and is zero only after infinite time, irrespective of
the

limitations of the pump. The design problem for vacuum
systems is how to reduce

the pressure to a desired value in a reasonable pump down

time and hold it there for the required process time.
Equation (12.12) is used when the pumping speed (S) is

constant, i.e., the S-P characteristic is flat. Outside the
con

stant S range, the curve slopes and we will have to use an

equation based on constant throughput Q, (= P × S). (12.13)
If this part of the characteristic curve is not a straight

line, it is divided into small segments. The equation is
sepa

rately applied to each segment and the time values are added

to get the total time for evacuation in that range. The use
of these equations will be clear from the solution

of the following problems. When the outgassing load is
constant in the molecular

range and when there are no process gases, we can use the t
K V S P P = 2 3 1 2 . log sec P P e kt 2 1 = − t V Q P P=
−( ) 1 2

pumping speeds demanded by the required throughput for

time calculation.

EXAMPLES

Data

Vessel-mild steel cylindrical vessel 1.2 m diameter and 1.5 m height. Initially the vessel contains dry air at 760 mm pressure and 30°C temperature. Volume – $1.7\ m^3$ (1700 l)
Surface Area – $5.65\ m^2 = 5.65 \times 10^4\ cm^2$ Outgassing rate (0–10h) Mild steel – 4.2×10^{-7} torr l/sec cm^2
Elastomer – 2×10^{-4} torr l/sec cm^2 Glass – 1.16×10^{-9} torr l/sec cm^2 Gasket (elastomer) – length 0.4 m–400 cm
Exposed thickness – 0.15 cm

EXAMPLE 12.2

The above discussed vessel is to be evacuated to 1.0 torr in about 15 min. Calculate the pumping speed and select a suitable pump. Disregard outgassing and the conductance of the pipe between the pump and the vessel.

Solution

The pump has to discharge at atmospheric pressure, hence, a positive displacement or mechanical pump is required. The data mention “dry” air but some amount of moisture (at least humidity) is expected. Mechanical pumps can handle the moisture by introducing ballast. The pumping capacity will be reduced by ballast. Ultimate pressure without ballast will be about 10^{-2} torr. With gas ballast it will be about 10^{-1} torr (single stage). The vessel pressure required is 1.0 torr. Hence moisture, if present, will not be a problem. The pumping speed-pressure characteristics (Figure 12.11) show a constant speed in the range 760–1.0 torr. Hence, we can apply Equation (12.1), i.e., V = 1700 l, t = 15 min = 900 sec, P 1 = 760 torr, P 2 = 1.0 torr Substituting The pressure range is on the high side, hence, K = 1.1 Nearest available pumps are (from manufacturers' data) Calculating evacuation times for both t V S P P t K V S P P = = × × in or log 1 2 1 2 2 3. S V S K= × ×2 3 760 1 . log S = × × × × = 1700 15 60 2 3 1 1 2 88 13 76 . . . . /secl l or = 826 /min Single stage /min Two stage /min S S = = 750 1000 l l t t = × × × = = × × × = 1700 750 2 3 1 1 2 88 16 5 1700 1000 2 3 1 1 2 88 12 4 . . . . min min Figure 12.11 Typical pumping characteristics of vacuum pumps. Hence, any of these pumps can be used. The single stage

750 l/min will be cheaper.

EXAMPLE 12.3

The same vessel is connected to the pump by a pipe having

diameter 30 mm and length 1.2 m. Calculate the conductance

of the pipe and the pump capacity if the evacuation from 760

to 1.0 torr is to be done in 15 min.

Solution

In the given pressure range (760–1.0 torr), the gas flow will be

molecular. Let us check this. For molecular flow D × P > 5 × 10 –1 cm · torr

Hence, the molecular flow is confirmed. The conductance in this range is given by l = length = 120 cm If a pump of capacity P is chosen the effective speed P E

is given by

Substituting D P D P = = + × = × >> × – 3 0 760 1 2 3 380 . ( )/ cm, ~ 380 torr 5 10 1 C D P S = × ×184 4 l l C = × × = × 184 3 380 120 4 72 10 4 4 . /secl 1 1 1 P P C E = + 1 1 1000 1 4 72 10 4 P E = + ×. The second term on LHS is very small and can be

neglected. Hence, the pumping speed is unaffected by the pipe

conductance.

EXAMPLE 12.4

The same vessel is to be evacuated to 10 -3 torr in about 15 min.

Choose a suitable pump. Calculate assuming there is no out

gassing.

Solution

We have a choice of pumps in the given situation. 1. Rotary piston pumps with an ultimate pressure about 10 -4 torr are available. These are two-stage pumps. 2. We can use a roots blower backed by a mechanical pump. The rotary pump shows a constant speed (flat) behavior

from 760 to about 10 -2 torr and a constant throughput from

10 -2 to 10 -4 torr. Time required for lowering pressure from 760 to 10 -2 torr is In this range K = 2. Arbitrarily, we assume a pumping

time 10 (< 15) min Nearest pump available is a two-stage rotary pump

with a pumping capacity 3333 l/min and an ultimate pres

sure 10 -4 torr. t K V S P P = = 2 3 1 2 . log sec = = 2 0 1700 10 2 3 3816 1 2 . . / log min P P l For finding out the amount of time to pump from 10 -2 to

10 -3 torr, we can use the constant throughput equation 6 × 10 -6 min This shows that the pressure reduction from 10 -2 to 10 -3

is practically instantaneous. This is so because there is practi

cally no gas load (outgassing). We can reduce the pump capacity by allowing 15 min for

pressure reduction from 760 to 10 -2 torr. This gives S = 2544 l/min Nearest available pump is 1660 l/min. For this, the pump

ing time is 23 min Let us consider a combination of a roots pump backed by a mechanical pump. Assume 1. The mechanical pump evacuates down from 760 to 10 torr. 2. The roots pump evacuates between 10 and 10 -3 torr. t V Q P P P P S t = − = × = × = × = × − − − ( ) ( ) 1 2 5 5 2 3 760 3333 25 10 1700 25 10 10 10 Throughput torr /minl t = × 1700 1600 2 3 4 88. . 3. The maximum permissible pressure difference between the inlet and outlet of the roots pump is 60 torr. We use a mechanical pump to reduce pressure from 760

to 10 torr in 10 min Nearest pump is a single-stage rotary piston pump of

1000 l/min capacity and 2 × 10 -2 ultimate pressure. The recal

culated pumping time is t = 0.8 min

EXAMPLE 12.5

The vessel in the previous problems is to be evacuated to 10 -5

torr and maintained at that pressure for one hour. The pumps to be used are a diffusion pump, backed by a

roots pump, backed by a mechanical pump, which exhausts

into the atmosphere. The vessel and its components start outgassing at about

10 -3 torr and contains for 1 h to 10 -5 torr at a constant rate. The diffusion pump is connected to the vessel via: 1. A straight pipe 50.0 cm long. 2. A right angle elbow having each leg 25.0 cm long. 3. A baffeled elbow with molecular transmission probability 0.35.

Now determine: 1. Pumps required. 2. Time to reach 10 -5 torr from 10 -3 torr.

Solution

As the evacuation process involves outgassing at pressures

10 -3 and lower, we have to design the pumping requirement

starting with the diffusion pump. S = × × × × = 1 1 2 3 1700 1600 760 10 812 . . / log minl The surface area of the vessel is 5.65 × 10 4 cm 2 and the

outgassing rate is 4.2 × 10 -7 torr l/sec . cm 2 .

Outgassing load

from vessel is (I) The elastomer area Elastomer outgassing rate is 2 ×10 –4 torr · l/sec·cm 2 . Hence,

the outgassing load from elastomer is (II) Total outgassing rate is (III) The outgassing starts at 10 –3 torr and continues to 10 –5 torr. The gas load at 10 –3 torr (IV) At 10 –5 torr it is (V) 4 2 10 5 65 10 2 37 10 7 4 3 . . . × × × = × · – – torr /secl = × = × = length exposed surface 400 0.15 60 cm 2 = × × = × · – – 2 10 60 12 0 10 4 3 . torr /secl = + × = × · – – (.) . 2 3 12 10 14 3 10 3 3 torr /secl = × = – – 14 3 10 10 14 3 3 3 . . /secl = × = × – – 14 3 10 10 14 3 10 3 3 2 . . /l sec The conductance of the elbow-trap will lower the pump

ing speed of the pump. Let us choose a diffusion pump with a capacity (P C),

2 × 14.3 × 10 2 P C 30 × 10 2 l/sec Manufacturers' literature shows an oil diffusion pump

having a capacity 3000 l/sec at 10 –5 torr. It has three stages

and an inlet diameter 250 mm. Mean free path of air at pressure P is Hence, at 10 –5 torr, λ = 4.86/10 –5 = 4.86 × 10 5 cm at 10 –4 torr, λ = 4.86/10 –4 = 4.86 × 10 4 cm at 10 –3 torr, λ = 4.86/10 –3 = 4.86 × 10 3 cm The ratio D/ λ for various pressures is at 10 –5 torr, D/λ = 4.86/10 –5 = 4.86 × 10 5 cm at 10 –4 torr, D/λ = 4.86/10 –4 = 4.86 × 10 4 cm at 10 –3 torr, D/λ = 4.86/10 –3 = 4.86 × 10 3 cm Hence, the flow will be molecular throughout. If the diffusion pump is connected to the vessel by a cir

cular pipe 250 mm dia. and (say) 500 mm long pipe, the con

ductance is given by C = 12.1 × D 3 /L Substituting, l = 4 86. /P cm C = × = 12 1 25 50 3781 3 . / /l sec The effective pumping speed P is given by Actual required speed is 1430 l/sec Hence the chosen diffusion pump is adequate. We can,

however, choose a slightly smaller pump. The introduction of the pipe has reduced the chosen

capacity by 1673/3000 ~ 56% Let us consider a plain right-angle elbow connecting the pump and the vessel. The conductance of the elbow is given by

where L 1 and L 2 are the lengths of each leg of the elbow and D

is the diameter (both in cm). Assume that each leg is 25.0 cm long, D = 25.0 cm Substituting Thus, the pumping speed with elbow is short of the required

speed 1470 l/sec and we will have to modify the elbow, or choose

a larger pump, or do away with the slightly reduced capacity. Consider now an elbow with a baffle. This is a component

of a complex shape and we will use the probabilistic method. 1 1 1 1673 P P C P E C E = = l/sec C D L L D = × + + 12 1 1 33 3 1 2 . . C = × + + × = 12 1 25 25 25 1 33 25 1180 3 . . /l sec 1 1 30 10 1 11 8 10 1297 2 2 P P E = × + × = . l/sec The molecular conductance of a given passage C is obtained

from

where C O = Conductance of aperture with an opening of area equal to that of the given passage = 3.64 (T/M) 1/2 A T = Absolute temperature (K) M = Molecular weight of gas (g·mol −1) Pr = Transmission probability Pr is calculated and published in special books Assume T = (273 + 30) = 303 K M = 28.98~29.0 for air (g·mol −1) A = π × (25 2)/4 = 490 cm 2 C O = 3.64 × (303/28.98) 1/2 × 490 = 2018 l/sec The probability Pr for a trapped elbow is about 0.35 (This

value is taken from manufacturers’ literature). The conductance of the baffle elbow is The pump speed with this elbow is This capacity is less than the minimum required speed,

1473. Hence, a larger pump is required when using a baffle/elbow C C O = × Pr C = × × = 5 765 10 0 35 5765 3 . . /l sec 1 1 1 1 30 10 1 11 8 10 1202 2 2 P P C P E C E = + = × + × = . /secl

combination. Next available pumps have 4000 and 5500 l/sec

speed. The above calculations will have to be repeated to check their suitability.

12.9 CALCULATION OF PUMPING TIME

For determining the pumping time from 10 -3 to 10 -5 torr, we will assume that the pump chosen has sufficient capacity to handle the required throughput through the connecting pipes, valves, baffles, etc. It is estimated that the volume of the pump and connecting piping is of the order of the volume of the vessel. This shows that the total pumping volume is 1700 × 2 ≅ 3000 l. The calculated outgassing load is 14.3 × 10 -3 torr ·l/sec. At 10 -5 torr the speed is 1430 l/sec, similarly at 10 -4 torr it is 143 l/sec and at 10 -3 torr it is 14 l/sec. If we plot the required speed against the pressure on log × log plot, we get a straight line showing a speed decreasing with increasing pressure. The usual pumping time equation can be applied if we split the pressure range (10 -3 to 10 -5 torr) into suitable steps. The smaller the chosen range, the more accurate will be the time estimate. Let us split the pressure range as follows: 1. 10 -3 -5 × 10 -4 torr Average speed 37 l /sec 2. 5 × 10 -4 -10 -4 torr Average speed 87 l /sec 3. 10 -4 -5 × 10 -5 torr Average speed 457 l /sec 4. 5 × 10 -5 -10 -5 torr Average speed 1000 l /sec Applying the equation to first range t V S P P = in 1 2 t 1 3 4 2 3 3000 37 10 5 10 56 = × = − − . log sec Similarly Total time = 120.3 sec, say 2.0 min. Thus the time to pump from 10 -3 to 10 -5 torr is about 2 min as calculated. We may apply a service factor of about 5 so that the total time is about 10 min. Note: There are other methods of calculating the time more accurately. However, for a preliminary estimate, the above given method is adequate. The service factor is mainly dependent on the pump combination, conductance of plumbing, and experience.

EXAMPLE 12.6

The same vessel as in the previous problems is evacuated from atmospheric to 10^{-5} torr pressure by a diffusion pump 30×10^2 l/sec with an effective speed 12×10^2 l/sec. The critical backing pressure (fore pressure tolerance) for this pump is 0.35 torr. Now determine: 1. The backing pump(s) required 2. The time required

Solution

The outgassing load from 10^{-3} to 10^{-5} torr (as calculated in the previous example) is 14.3×10^{-3} torr ·l/sec. The diffusion pump has a speed of 30×10^2 l/sec. The maximum throughput of diffusion pumps is generally at 10^{-3} torr. The maximum throughput of the chosen diffusion pump will be $3000 \times 10^{-3} = 3.0$ torr ·l/sec The maximum fore pressure tolerance of this pump is 0.3 torr. Discharge at this pressure is $3/0.3 = 10$ l/sec or 600 l/min. t t t 2 3 4 55 3 4 5 4 8 = = = . . . sec sec sec The backing pump chosen should have a capacity larger than 600 l/min at 0.3 torr. Let the required capacity be 700 to 800 l/min. If we choose a positive displacement pump (mechanical pump) the pumping capacity of medium pumps is limited to about 300-400 l/min at 0.3 torr and rapidly increases at higher pressures exceeding 0.3 torr. Thus, a mechanical pump alone is not suitable. If we are required to use the gas ballast

the speed decreases still further. We will have to back the diffusion pump by a roots blower

or booster. This booster will further have to be backed by a

mechanical pump. The final choice is to use a blower to reduce the pressure

from 10-10 -3 torr and a mechanical pump in the 10–760 torr

range. Manufacturers' literature shows a roots pump having a

capacity 45 l/sec at 0.3 torr which reduces to about 40 l/sec

at 10 -2 torr. Hence it has an adequate backing capacity. More

over, its capacity (speed) at 1–10 torr is also 35–45 l/sec. The throughput of blower at 8–10 torr is 8 × 40 to 10 × 40,

i.e., 320–400 torr l/sec. Literature shows both a sliding vane and a rotary piston

pump with speeds of 350–370 l/min. These are single or dou

ble stage pumps. We choose a sliding vane pump having a

speed 2500 l/min or 41.6 l/sec at 760 to 1.0 torr, and an ulti

mate pressure 10 -2 torr. The final choice of pumps is 10 -5 – 10 -3 torr, diffusion pump 3000 l/sec 10 -3 – 10 torr, roots pump 45 l/sec 10 – 760 torr, mechanical pump 41 l/sec The time to evacuate from 760 to 10 torr is t 1 1 5 2 3 1700 45 760 10 276 = × × = . . log sec Time for reducing pressure from 10-10 -3 torr Total time to reach 10 -3 torr from 760 torr Pumping from 10 -3 to 10 -5 is achieved by the diffusion pump

which has a flat pressure speed characteristic showing constant

speed. The time required is (as estimated in the previous exam ple) 5-10 min. Hence, time for pumping from atmospheric pressure to 10 -5 torr is = 23-28 min or about 30 min (1/2 h)

12.10 MEASUREMENT OF VACUUM

Gauges used for the measurement of low pressures are different from those used for normal pressures. Ordinary Bourdon tube gauges can be used from 760 to 0.5 torr, which is only the beginning of the vacuum range. Just as in the case of pumps, there is no one gauge useful for vacuum measurement at all ranges. Every gauge has its applicable pressure range. In many instances more than one gauge is used to cover different pressure ranges. There are three main types used in the 760-10 -5 range.

1. Mechanical Gauges: 1.0-10 -3 torr
2. Conductivity Gauges: 1.0-10 -4 torr
3. Ionization Gauges: 10 -3 -10 -9 torr

The only gauge which directly measures the vacuum pressure is the MacLeod gauge. In this gauge, a gas sample of known volume, from the vacuum system, is isolated and compressed to a known volume. The difference in the pressure is measured on a liquid (mercury) coloumn. MacLeod gauges can be used from 10 to 10 -6 torr. However, the instrument requires manual operation and is intermittent. It cannot be used for

t 2 3 1 5 2 3 1700 45 10 10 780 = × × = - . . log sec = + = + = ≅ t t 1 2 276 780 1056 sec 18 min.

industrial applications. However, because it gives absolute pressure measurement, it is used for the calibration of other gauges. Hence, the MacLeod gauge is not discussed further.

12.10.1 Mechanical Gauges

This type of gauge is similar to the aneroid barometer. It contains a metal box or capsule with a very thin diaphragm on one side. The diaphragm is connected with fine linkage to a pointer. The capsule is evacuated to very low pressure ($\sim 10^{-8}$ torr). It is enclosed in a chamber (see Figure 12.12) which is open to the vacuum. Thus, the diaphragm is subjected to the vacuum pressure of the system from the outside and to its own vacuum from the inside. This pressure differential causes the diaphragm to deflect proportionally. The deflection is amplified mechanically by the linkage and exhibited by the pointer.

Figure 12.12 Mechanical and electro-mechanical vacuum gauge.

The linkage is replaced by a sensor and an electronic system in some designs. Diaphragm gauges can be used in the range 10^{-1}–10^{-4} torr. Due to their all-metal construction they can be baked to 180°C for outgassing. These are simple and rugged devices independent of atmospheric pressure, and are sensitive. They are affected by temperature and aging. With electronic sensing, they can be used for an extended range up to 10^{-8} torr and remote control.

12.10.2 Conductivity Gauges

Thermal conductivity of a gas is a function of its density, i.e., pressure in the 1.0-10^{-5} torr pressure range. In gases, thermal conduction takes place because of the impact of molecules with the hot body (or heat source). As the pressure decreases, the number of molecules in a given volume decreases and their mean free path increases. This reduces the number of impacts and, hence, the conductivity (Figure 12.13(A)). Conductivity gauges are based on the indirect measurement of conductivity of a hot filament placed in vacuum. There are two major types of conductivity gauges. 1. Thermocouple Gauge The construction of a thermocouple gauge is shown in Figure 12.13(B). A filament suspended at the ends is heated by an electric current. The filament is made of platinum or nickel alloy. A chromel constantan or similar base metal thermocouple made from thin wire is welded to the filament. The emf of the thermocouple depends on the filament temperature, which in turn depends on thermal conductivity (i.e., heat transfer by conduction). The measuring circuit contains the cold junction compensation. The envelope of filament and thermocouple is open to vacuum. As the pressure decreases, the filament temperature increases and is measured on an indicator calibrated in pressure.

The useful range of a thermocouple gauge is 1.0-10^{-4} torr depending on the design. It is rugged and gives continuous readings. Electrical variations in the filament current or aging affects the accuracy of the gauge. 2. Resistance or Pirani Gauge In construction, the Pirani gauge is similar to the thermocouple gauge except that the envelope contains only the filament, as shown in Figure 12.13(C). The filament is heated at a constant voltage. The change in conductivity due to vacuum, is reflected in the change in resistance. By using a Wheatstone bridge the resistance is measured and interpreted in pressure. A similar compensating resistance is used in the adjacent leg of the bridge. Recent designs use a thermistor instead of the filament. The general useful range of the Pirani gauge is 1.0–10 -4 torr, which in some designs is extended to about 10 -6 torr. This is a rugged instrument giving continuous reading (with a self-balancing bridge). Readings are affected by contamination with vapors.

Figure 12.13 Thermal conductivity vacuum gauge.

12.10.3 Ionization Gauge

If an ionizing particle such as electron or proton strikes a gas molecule, the later is ionized. A positive ion and electrons are produced. These products can be collected on oppositely charged electrodes (cathode, anode). The resulting current will be proportional to the number of ions, which in turn, is proportional to the pressure. This proportionality is generally nonlinear. In construction, ionization gauges are similar to electronic valves or vacuum tubes with one end open to the vacuum. The principle of ionization gauges is shown Figure 12.14(A). There are many variations in the design. It is not possible to discuss all of these. Moreover, many designs incorporate some method of shaping the interelectrode field to enhance the capture of ions and develop a better current. Most of the advanced gauges are used for measuring vacuum of > 10 -9 torr and hence are beyond the scope of our discussion. One such gauge is the Bayard Alpert gauge, which is used in the ultra-high vacuum range (10^{-9}–10^{-12}). Only two basic ionization gauges commonly used in the 10^{-5} range are described. Ionization gauges remove molecules from vacuum and hence, may act as a “pump” in the envelope.

Cold Cathode (Penning) Gauge

The construction of a Penning, or cold cathode, vacuum gauge is shown in Figure 12.14(B). The tube is essentially a diode. The central electrode has a rectangular window shape and is positively charged to about 2 kV. Surrounding the anode is a rectangular (solid) cathode which acts as the electron generator. The envelope is open to vacuum. On the outside is a permanent magnet with its field at a right angle. The combined electric and magnetic fields make the ion path very long, thus increasing ionization and the resulting current. The gauge is used in the range 10^{-4}–10^{-7} torr. The current produced is large enough and does not require amplification. The response is nonlinear. Due to the large degree of ionization there is a risk of contamination and pumping. Compared to other ionization gauges, Penning gauges are cheaper. They are bulky due to the permanent magnet. They are not very accurate but are good for general vacuum duty where high accuracy is not required.

Figure 12.14 Ionization vacuum gauge.

Hot Cathode Gauge

These gauges are like a triode or tetrode with one or more grids generally placed between the anode and the cathode. The cathode is hot, i.e., thermionic, and is made of thoriated tungsten. It is heated to about 350-450˚C. The general construction is shown in Figure 12.14(C). One end of the envelope is open to vacuum. The hot filament releases electrons which ionize the gas molecules. The grid is at a negative potential and collects the positive ions. This creates a grid current. Similarly, the electrons are collected at the anode and create a current in the anode circuit. In another version, the grid is positively charged and the surrounding cathode is negatively charged. The ratio of the ion and electron currents is proportional to the pressure. The measuring circuits are not shown but the electron current is kept constant so that the ion current is directly proportional to the pressure. The gauge has different responses to different gases. Hot cathode gauges are useful in the 10 -3 -10 -9 torr range. There is a risk of filament burnout and contamination. The gauge is not robust and generally not used for industrial applications.

‘‘Alphatron” Ionization Gauge

A radioactive material continuously emits α, β, and γ radiation. The α radiation is helium nuclei with a charge of +2 and is least penetrating. They ionize a gas molecule on impact. Alphatron vacuum gauges use a small mass of radioactive material as a source of α radiation. Thus, compared to the previously described ionization gauges, the Alphatron is a passive device. The construction of an alphatron gauge is shown in Figure 12.15(A). The radiation source is a radium salt rolled into a gold foil. It has an activity of 1.5–100 microcuries and so is quite safe. The source, in the form of a very small packet or capsule, is kept on a tray attached to the anode chamber. The cathode or ion collector is a wire centrally located and insulated from the cathode. One end of the envelope is open to vacuum. A single chamber gauge can measure vacuum in the 1.0–10^{-4} range. Figure 12.15(B) shows a double chamber gauge. The small chamber can measure in the 760–1.0 torr range. Thus the gauge can be used for continuous vacuum readings from the atmosphere to 10^{-4} torr. Ionization produces a very small current ($\sim 10^{-12}$ A) and needs amplification. The output is linear. Though the gauge head is cheap and rugged, the instrumentation makes this gauge expensive.

Choice and Installation of Gauges 1. In a vacuum system, gauges are located in all the lines connecting the vessel and the various pumps. 2. The actual gauge to be installed at a point should cover the pressure range expected in that line. Thus the pressure will be lowest in or near the vessel. It will be higher in the line between the pumps and highest at the outlet to the atmosphere. 3. If some process is to take place in the vessel, locating the gauge in the vessel is avoided to guard against spattering and contamination. This also reduces the connection through the wall and attendant leakage. 4. For a small pressure difference (1–10^{-1} torr) mechanical gauges are used. 5. A high vacuum gauge for a vessel is generally located in the pipe or elbow outside the vessel. 6. All gauge envelopes are miniature vacuum vessels and are affected by their own outgassing. 7. In large systems pressures are monitored and controlled from a central panel. This requires remote sensing gauges (ionization alphatron, thermocouple) and extensive instrumentation. There are many other gauges available for higher vacuum ranges. These are not discussed here as they are beyond the arbitrarily chosen limit of 10^{-5} torr for this book. Pressure-wise classification of vacuum, applicances, and gauges is shown in Figure 12.16.

Figure 12.15 “Alphatron” ionization gauge.

Figure 12.16 Vacuum, classification, gauges, and applications.

14 14. Temperature Measurement

14.2 THERMOCOUPLE PYROMETERS

These pyrometers, invented long ago, still dominate the field of temperature measurement. The basic principle behind thermocouple is known as the Seebeck effect which states that, “In a circuit made of two different metals, if one junction is kept at a temperature t_1, and the other at a lower temperature t_2 then an e.m.f. E is created in the circuit (Figure 14.1(A)) which is proportional to the temperature difference ($t_1 - t_2$), i.e., $E = K_s(t_1 - t_2)$ (14.2)

where K_s is the proportionality constant known as the Seebeck coefficient. The junction at the higher temperature (t_1) is called the hot junction and the other junction at the lower temperature is called the cold junction. A basic thermocouple pyrometer operating on the Seebeck effect is shown in Figure 14.1(B).

Figure 14.1 A Seebeck effect . Two other effects are associated with the Seebeck effect. 1. Peltier effect states that the Seebeck effect is reversible. If in a circuit of two dissimilar metals a direct e.m.f. is impressed (say with a cell or battery) then one of the junctions becomes hot and the other cool. The Peltier effect is the principle on which thermo-electric refrigeration is based. At least up to now, these cooling devices cannot economically compete with mechanical refrigeration. They have their advantages and limited applications. 2. The Thompson effect states that if in a current carrying a conductor, two points are at dissimilar temperature, then heat is either evolved or absorbed by the conductor. The direction of heat reverses with the reversal of the direction of the current. Both the Peltier and Thompson effects are of no use in pyrometry and hence, are not discussed in detail. There are some practical corollaries which we can derive from the above three laws of thermoelectricity.

Corollary 1:

A thermoelectric circuit made of the same material will not produce any e.m.f. even though the two junctions are at different temperatures. The circuit must be made of two dissimilar metals.

Figure 14.1 B Thermocouple pyrometer.

Corollary 2:

If a circuit made of two dissimilar metals contains other conductors and if the junctions of these extra materials are at same temperature, the thermoelectric e.m.f. produced will not be affected by the presence of the extra conductors. It will be the function of the difference of hot and cold junction temperatures only.

Corollary 3:

Consider a circuit made in two parts from two dissimilar metals. Let the hot and cold junction temperatures in the first circuit be t_1 and t_2 and let those in the second circuit be T_2 and

T

. Also, let $t_1 > t_2 > t_3$. The e.m.f. produced in the two circuits will be $E_1 = K_s(t_1 - t_2)$ and $E_2 = K_s(t_2 - t_3)$ If we now consider one circuit of the same metals with

junctions at t_1 and t_3 the e.m.f. produced will be
(14.3)

Corollary 4:

In the Thompson heating and cooling of a conductor, both difference of temperature and a preestablished current are necessary. Only one condition cannot produce the effect.

14.3 PROPERTY REQUIREMENTS OF THERMOCOUPLE MATERIALS

1. The useful temperature range of a thermocouple should be a little less than their melting points. Like all metals, the thermocouple metals lose their mechanical rigidity at temperatures near melting. Generally, the alloys chosen can be used up to a temperature 100- 150 ° C less than the melting temperature. If a thermocouple consists of two metals (or alloys), then the above criteria will apply with respect to the alloy with the lower melting point. E K t t E E s3 1 3 1 2 = − = +( ) 2. The chosen thermocouple should produce a large e.m.f. in the temperature range. A very small e.m.f. is difficult to measure with consistent accuracy. 3. As far as possible, the relation between the e.m.f. and the temperature should be linear. Such linear e.m.f. can be easily measured on a simple voltmeter. With electronic circuits it is possible to linearize a nonlinear relation but these instruments are costly. 4. The e.m.f. temperature relation should be continuous, i.e., without any gaps or jumps. 5. The thermocouple metals must be resistant to the effects of the atmosphere in the measurement environment (oven, furnace, etc.) 6. The thermocouple is usually made from wires. The alloys should have sufficient workability for the production of wires. Similarly, it should be possible to make these alloys with accurate composition and purity. Impurities, if not controlled, will affect consistency and reliability.

14.4 PRACTICAL THERMOCOUPLES

Considering the requirements of good thermocouple materials discussed in the previous section, a number of thermocouples have been evolved and standardized. In earlier days the metals were manufactured by a few manufacturers. Hence they had proprietary names such as Chromel, Alumel, and Constantan. With the availability of ultra-purity constituent metals, sophisticated melting furnaces (e.g., vacuum induction melting), and fast and accurate analytical methods (e.g., spectrography), the number of manufacturers has increased. They have marketed similar thermocouples, differing only in some minor constituents. Previously, thermocouples were classified in two categories: “noble” and “base metal.” This classification was based on constituents. Base metal couples were of metals or alloys such as iron, copper, manganese, nickel, and chromium. The noble metal couples were made from platinum and its alloys. Presently, all commercial thermocouples are classified by letter designation such as B, E, J, S, and T. This designation was suggested by ASTM and is now adopted all over the world. The designation does not depend on composition but by the E vs. t relation shown by the couple. Thus, even though the minor constituents are different, couples offering the same E, t relation belong to the same class. Table 14.1 shows the classification of widely used commercial thermocouples and their useful temperature range. The standardization of thermocouple wires is made by accurately determining the e.m.f. E and temperature “t” relation. For this the reference or “cold” junction is kept at 0˚C. This reference junction temperature is internationally agreed upon. Hence, all the E and t data are reported with the tacit understanding that the reference junction is at 0˚C. The National Institute of Standards and Technology (U.S.) and manufacturers of metals have published such calibration data tables for all the standard thermocouples. The tables usually quote e.m.f. produced at every 1.0˚C difference. The data are fit into a standardized relation such as (14.4) The values of constants a_0 , a_1 ,…. or a_0', a_1', etc., are also accurately determined so that any interpolation can be done from the numerical tables. The calibration is carried out by keeping the “measurement” or “hot” junction in a pure metal whose solidification temperature is standardized. The couple is dipped in a crucible containing the metal. It is then heated to a higher temperature so that the metal gets liquified. It is then cooled so that the solidification takes place at a constant temperature. The e.m.f. produced is recorded as a standard output. There are internationally agreed primary and secondary calibration points. Primary points are the boiling point (B.P.) of O_2 , −182.97˚C, B.P. of water, +100˚C, solidification of silver and gold, 960.8°C

and 1063.0°C, respectively, etc. E a a t a t t a a E a E = + + + = ′ + ′ ′ + + ▯▯▯▯▯ 0 1 3 2 0 1 2 2 L Lor TABLE 14.1 Common Thermocouples, Classification, and Temperature Range No. Positive Wire (P) Negative Wire (N) Traditional Type International Designation ASTM Normal Temperature Range °C Occasional Use Highest Temperature 1. Pt70Rh30 Pt94Rh6 Noble B 871–1705 1750 2. Ni90Cr10 Ni45Cu55 Constantan Base E 0–800 850 3. Fe Ni45Cu55 Constantan Base J 0–700 760 4. Ni90Cr10 NICROSYL Ni95Mn2Al2Si1 NISIL Base K 0–1200 1260 5. Ni84.5Cr14Si1.5 Ni95.5Si1.5Mn0.4 Base N 0–1200 1260 6. Pt87Rh13 Pt Noble R 0–1500 1700 7. Pt90Rh10 Pt Noble S 0–1480 1700 8. CuNi45Cu55 Base T −184–+370 370 9. W95Re5 W74Re26 — Experimental Vacuum 1000–2700 2800 10. W W74Re26 — Experimental Vacuum 1000–2600 2800 11. Graphite with boron doping Graphite — Vacuum 2000 2000 Secondary points are solidification temperatures of mer

cury, tin, aluminum, copper, nickel, tungsten, etc. Further details of thermocouple calibration are beyond

the scope of this book. Reference may be made to specialized

ships for standardized thermocouples is shown in Figure 14.2. It

can be seen that many thermocouples show a nonlinear rela

tion. This nonlinearity can be corrected by using an indicator

Figure 14.2 EMF-temperature relations for standard thermocouple.

with a specially ruled scale piecewise, or nowadays, electroni

cally carrying out a piecewise linearization. The hot junction of a thermocouple is made by twisting

the wires together to form a mechanical joint. This joint is then welded to form an electrically homogeneous junction. This welding is done to form a bead. The welding is a delicate process, especially for thin wires. Precleaning and fluxing give a sound joint.

14.5 COLD JUNCTION COMPENSATION

The Seebeck effect, when applied to a standard thermocouple, requires that the temperature of one of the junctions (cold junction) must be kept constant. In an industrial environment or in any practical application, the cold junction is located outside and exposed to atmospheric temperature. This temperature changes according to the time of the day, the season, and the surrounding industrial environment. The standard calibration data for thermocouples are based on the cold junction temperature maintained at 0°C. In laboratories this condition is satisfied by keeping the junction in a mixture of melting ice and water. It is not practical or feasible to maintain the cold junction at 0°C in an industrial environment. Consider in the first instance that the cold junction be kept at a constant nonzero temperature t_2 with the hot junction at a temperature t_1. The e.m.f. measured will be due to the difference $t_1 - t_2$. The standard e.m.f. from the tables is based on the difference t 1 − t 0 . Thus, (14.5)

with the condition that (t 1 − t 0) > (t 1 − t 2). Thus, the indicator temperature will be less than the standard value by an amount t 2 − t 0 . In practice, the temperature t 2 (environmental temperature) is not constant. Hence, the error t 2 − t 0 is also variable. E K t t E K t t s s std mes = − = − ▮ ▮ ▮ ( ) ( ) 1 0 1 2 Devices or designs to remedy this source of error in temperature measurement are known as “cold junction compensation.” A number of such compensation methods are available. 1. If the accuracy of measurement required is not high (say = 10 to 15˚C) the simplest and cheapest method is to forward the indicator needle to the assumed environment temperature. This will automatically add the assumed constant temperature to the measured temperature. 2. The indicator needle in some instruments is connected to a bimetallic spring. The spring expands or contracts on changes in environmental temperature. Thus, the needle moves forward or backward on the scale. This automatically compensates for the cold junction temperature. This method is better than the first method but still not accurate enough. 3. In some designs an artificial cold junction is kept in a miniature oven in the instrument. The temperature of this “oven” is kept higher than the maximum possible environmental temperature and is controlled by suitable circuits. This produces a constant error at all times. The required error voltage is automatically added to the measured voltage. 4. Some instruments use a thermistor in the thermocouple circuits. The resistance of the thermistor, and therefore the voltage, drop across it, changes with the environment temperature and compensates for the error. There are other sophisticated methods of compensation.

These are not discussed here. For the furnace designer it is necessary to keep in mind two points. 1. For accurate temperature measurement some kind of cold junction compensation must be provided. 2. The compensation method to be selected will depend on the desired accuracy, reliability, and the cost.

14.6 COMPENSATING WIRES

Thermocouple wires are manufactured in two grades—standard and precision. Both grades are quite costly. In most of the industrial furnaces and ovens, the temperature indicator or the controller is situated on a control panel which is at a considerable distance from the furnace. It is uneconomical to take the thermocouple wires over such distances. The thermocouple wires are terminated at the junction box outside the furnace. From the junction box to the panel, other special but cheaper wires called compensating cables are used. The temperature of the connection plate is generally in the range of 50 to 150°C and the reference junction in the instrument is in the range of 60 to 80°C. The compensating wires are so chosen that they produce the same e.m.f. as the thermocouple wires in the temperature range of 150 to 50°C so that no error results due to the termination of the thermocouple wires at the junction box (see corollary three above). Compensation wires for different thermocouples are standardized and color coded. The color codes are not internationally standardized. In the U.S. standardization, which is followed in many countries, the thermocouple wires have red jackets for all negative wires (N) and different colors for positive wires (P), e.g., J, K, T, E, N thermocouple positive wires are white, yellow, blue, purple, and orange colors. Extension or compensatory wires have different colors for positive and negative wires and the cable has usually a brown jacket. It is vital to observe the correct polarity when connecting compensating cables to the thermocouple. A wrong connection (e.g., +ve thermocouple to –ve compensating cable) will result in considerable error.

14.7 CONSTRUCTION OF THERMOCOUPLES

Industrial thermocouples are constructed to withstand the rigors of the industrial environment for a long time. Bare thermocouples get corroded or oxidized by furnace gases and fail within a very short time. The thermocouple wires are insulated from each other by using twin bore ceramic insulators usually made of alumina or mullite. The assembly is then inserted in a ceramic sheath in the shape of a one-end-closed tube. Many materials are used for the sheaths. Some common sheath materials are given in Table 14.2. When choosing a sheath, the temperature, environment, porosity, and thermal fatigue must be considered. Metallic sheaths are also used either alone or as an outer cover for ceramic sheaths. If used alone, the hot junction is electrically insulated by a ceramic piece or powder. The assem bled thermocouple can be up to 1 to 1.2 m long. At the other end, the thermocouple is connected to terminals in a junction box. From these terminals compensating cables are taken out and connected to the indicator. The construction of a typical thermocouple is shown in Figure 14.3. However, depending on the end use, many different designs are available.

TABLE 14.2 Thermocouple Sheath Materials

Sheath Material	Maximum Temperature°C
Carbon steel	550
Cast iron	700
Pure iron	700
18-8 Stainless steel	950
28 Cr stainless steel	1100
Chromel, Nichrome	1100
Incoloy, Inconel	1100
Fused silica	1050
Fire clay	1050
Silimanite, Mullite	1550
Silica, Alumina	1600
Silicon carbide	1650

14.8 SELECTION OF THERMOCOUPLES

The following points should be considered when selecting a thermocouple for a given application. 1. The normal temperature range and the maximum occasional temperature to which the thermocouple is to be used. This information will be useful in knowing which of the standard thermocouples are available for this range. 2. Operation of the furnace—continuous or batch type. If the latter is considered, what is the cycle time and how many batches are to be processed in a day or a week?

Figure 14.3 Construction of an industrial thermocouple.

Thermocouples are prone to thermal fatigue. Their life is affected by the heating-cooling cycles. Base metal thermocouples of type E, J, K, N, and T are more affected than precious metal couples of B, N, R, and S. 3. The furnace atmosphere can be oxidizing, reducing, inert, or vacuum. The atmosphere to which different thermocouples can withstand are listed below. This shows that types J and T thermocouples can withstand both the oxidizing and reducing atmosphere, but their useful temperatures are only 760 and 370°C, respectively. Heat treatment furnaces generally have a reducing atmosphere and the temperatures are 800– 1200°C. For this application, the cheapest choice will be type K but this will have a limited life due to corrosion and aging. Type N is the next choice for higher temperatures. It will have a better stability (physical and thermoelectrical) than K but will be somewhat costlier. Type R and S (Pt-Pt, Rh) can be used in oxidizing and inert atmospheres up to 1480°C while type B can be used to 1700°C under similar conditions. These thermocouples will have a long life but cannot be used in reducing (heat treatment, sintering, etc.) atmospheres. They are much more costly than the base metal types. Currently, there is a growing trend to avoid reducing atmospheres and use vacuum instead. Only B type thermocouples are suitable but they must be covered by a suitable impervious sheath and also by an outer metal sheath (if the temperature and atmosphere permits). 4. The response of a thermocouple to changes in temperature is also an important factor. A thermocouple will indicate the correct furnace or object temperature when it reaches that temperature. This is achieved by conduction of heat through the sheath and conduction Type Atmosphere K, E, N, R, S Oxidizing and inert J,T Oxidizing and reducing B Oxidizing, inert, and vacuum through the bead (not junction). Conduction is a slow process. The sheath is ceramic and has an inherently low conductivity. Additionally, if the thermocouple wires have a large diameter, they will take time to heat up. Thus a thermocouple has a slow response. It can be improved by using thinner sheaths and wires but this will be at the cost of service life and rigidity. Note that this response factor has nothing to do with the controller/indicator response. 5. Thermocouples and the related control system are important components of the total cost of the furnace. The total expected life of the system and the cost of repairs, replacements, and calibration in this period must be given consideration in costing. The relative initial cost of precious metal couples is much more than base metals but they give better service for a long time. 6. Small furnaces usually require only one thermocouple, strategically placed in the furnaces. Precision furnaces, though small, may require more thermocouples to maintain the required temperature near the charge. Larger and multizone furnaces also require more thermocouples than one.

14.9 RADIATION PYROMETRY

14.9.1 Principle of Radiation

A body at a temperature higher than its surrounding emanates electromagnetic radiation. The intensity of this radiation is proportional to the fourth power of the absolute temperature of the radiating body. This is the Stephen Boltzman's law of radiation. The radiation can be directly measured by using a sensor or it can be compared to the radiation of a body of known temperature. This is the principle of radiation pyrometry. There are several types of instruments incorporating radiation measurement. One immediate advantage of this method is that there is no contact between the measuring instrument with the hot body, and at least in principle, the body and the instrument can be far apart as long as they "see" each other. We will come across "radiation" in detail when we discuss heat transfer (Chapter 3). Here only relevant facts are reviewed. A hot body emits radiation all over the electromagnetic spectrum. The intensity of this radiation depends on the wavelength and the absolute temperature. At a given temperature the total energy emitted at all wavelengths is given by the Stephen Boltzman Law: (14.6)

where

E_T = Total energy emitted by unit surface (W/m ^{2}) T = Absolute temperature of the emitting body (K)

C_o = Stephen Boltzman constant (5.669×10^{-8} W/m ·k ^{4}) The total energy will be the area under the E_λ plot against wavelength λ for the given temperature T as shown in Figure 14.4. Note that the radiant energy is spread all over

Figure 14.4 Radiation intensity of a black body. E C T T o

$= (\ )^4$ W/m^2

the spectrum and the intensity is different for each wave length. At the extreme ends, i.e., X-rays and far infrared and radio wavelengths, the intensity is very low. Most of the energy is between 0.5 to 10 µm region. An enlarged portion of the E_λ against λ part of Figure 14.4 is shown in Figure 14.5 at various temperatures. The intensity E_λ at a given wavelength and temperature is given by Plank's radiation law. (14.7)

where

λ = Wavelength (µm)

T = Absolute temperature (K)

C_1 = Constant (3.69×10^{-16} W/m^6)

C_2 = Constant (1.44×10^{-2} m, K)

C_0 = Stephen Boltzmann's constant Equation 14.6 and Equation 14.7 are for black body radiation. In practice we have to consider the emissivity ε of the radiating body. Hence the equations applied in practice are (14.8) and (14.9) Radiation pyrometers are based on Equation 14.8 and Equation 14.9.

14.9.2 Practical Problems

The application of Equation (14.8) and Equation (14.9) in practice raises several problems and puts limitations on radi ation pyrometry. These are discussed below briefly. 1. The wavelength region having high intensity is between 0.1 to about 10 µm. In this region, 0.1 to 0.4 E C e C C T l l = − − 1 5 2 0 1 / W/m 3 E C T T = 0 4 ( ) W/m 2 E C e C C T l l = − − 1 5 2 0 1 / W/m 3 Figure 14.5 Variation of monochromatic emissive power (Eλ W/m2) with wavelength (λ) and absolute temperature (K) for a black body. is the ultraviolet region, 0.4 to 0.7 is the visible region, and 0.7 onward is the infrared region as shown in Figure 14.6. As the temperature of interest increases, the radiation becomes stronger toward shorter wavelengths. Hence, the practically applicable region for all temperatures is limited to approximately 0.5 to 8 µm, which lies in the visible (0.5–0.7 µm) and infrared (0.7 + 8.0 µm) region. 2. Any instrument built to sense the radiation will have to be enclosed to avoid dirt, dust, gases, etc., present in the industrial environment.

Figure 14.6 Transmission power of selected optical materials. Such an enclosed instrument will have to be provided with windows and other optical components through which it can “see” the radiating body. All the optical materials have their own characteristic transmissivity, i.e., they allow only particular wavelengths to pass through with sufficient intensity. For other wavelengths, they are opaque. Transmission power for many optical materials for various wavelengths is shown in Figure 14.6. It can be seen that ordinary glasses (crown glass, quartz, pyrex, ruby, etc.) have good transmission in ultraviolet and the visible region, but are opaque to infrared. Thus, glass windows are of no use at wavelengths higher than 2.5 µm. Barium fluoride and zinc sulphide windows have only about 60–80% transmission in the infrared and visible region. Calcium fluoride has good overall transmission. The last three materials can hardly be called glasses and their optical forms are very costly. Thus, the spectral region that can be seen gets limited by the window and the optical material chosen. 3. Radiation pyrometers will require a sensor which will sense the incident radiation and generate a measurable signal (usually electrical voltage). Radiation pyrometers traditionally used thermal detectors as sensors. Thermal detectors are usually thermopiles made of a number of thin gauge thermocouples connected in series. Their hot junctions form the radiation sensing surface. This face is coated black to form a black body. Thermopiles can detect signals (radiation) of all wavelengths and are ideal. However, they depend on being heated by radiation, and hence depend on heat transfer and are therefore slow. Further, their signal is very low (Figure 14.7(A)) and they require cold junction compensation. A number of semiconductor sensors are developed which depend on the quantum effect of incident radiation to generate a signal. They are based on materials like silicon, lead sulphide, indium antimonide, etc. (Figure 14.7(A)). Their response is practically instantaneous but it is selective to wavelength. A “good” signal is obtained over a narrow band. Thus, silicon is suitable only around 0.8 to 0.9 µm and lead sulphide around 1.0 to 2.0 µm. Thus, the sensor used in an instrument also limits the wavelengths that can be sensed. 4. Radiation pyrometers do not require contact with the radiating body, hence there is a distance (sometimes considerable) between the two. The medium inbetween is industrial atmosphere laden with dust, smoke and gases such as CO_2, water vapor, and reaction products. The dust particles scatter the radiation passing through them. CO_2 and water vapor selectively absorbs radiation as shown in Figure 14.7(B). Measurement of the radiation in the absorption bands should therefore be avoided. This again narrows the spectrum region of sensing. The absorption by these gases also depends on their concentration (partial pressure) in the air and the distance (optical path) between the object and the pyrometer. 5. It was mentioned when discussing the principles of radiation that the intensity of radiation of a nonblack body depends on its emissivity. Thus, for the same temperature there are two bodies with different temperature readings. The emissivity is a function of the surface condition, the wavelength, and temperature. Thus, radiation pyrometers will require some kind of emissivity correction. Many times, data available on emissivity are sufficient. The above problems reduce the universality of radiation pyrometers. In practically all situations the pyrometer will have to be selected and tuned to the problem. In real situations the placement of the sensing head with respect to the object is also to be assessed carefully to avoid background and external radiation affecting the incident beam.

Figure 14.7 (A) Response of thermal detectors, (B) Radiation absorption by gases.

14.10 DISAPPEARING FILAMENT PYROMETER

The tungsten filament of an electric bulb is a radiator. The intensity of radiation depends on the current flowing through it. The maximum temperature at the rated voltage is about 2800 to 3000°C. The minimum visible radiation is at 600°C. Hence we can obtain the radiation between 600 to 2800°C by changing the current. The disappearing filament pyrometer uses the tungsten filament as a radiation source. Its radiation is compared with the radiation from the object. The object radiation is obtained in the background. The filament is in the foreground when seen through the eyepiece. By varying the current with a rheostat, the intensity of the filament radiation is so adjusted that at some current the filament disappears against the background. The intensity of the background and the filament is then equal. The ammeter in the lamp circuits is calibrated in °C. Hence the temperature of the object is read on the ammeter.

The construction of a disappearing filament pyrometer is shown in Figure 14.8. The whole instrument is built in the shape of a gun. A switch in the handle puts the lamp on when pressed. The handle also contains batteries. The ammeter is usually located at the back near the eyepiece. Note the focusing optics and the set of filters. The latter are to adjust for the shift of

$E_T - \lambda$ graph with increasing temperature and the changes in emissivity. The following points are noteworthy about this instrument: 1. It is very simple, portable, and easy to operate. 2. It operates in the visible region. 3. Personal error may arise due to defective eyesight, color blindness, etc. 4. Like other radiation pyrometers, this pyrometer also does not require contact with the body and hence is useful for melting furnaces, etc. 5. The response is not quick, as the operator has to adjust the rheostat. 6. The measurements are not continuous. 7. It cannot be directly used for objects, such as the sun.

Figure 14.8 Disappearing filament pyrometer.

14.11 RADIATION PYROMETERS

The construction of a typical radiation pyrometer is shown in Figure 14.9. It generally consists of two parts — the sensing head and the electronic part. The sensing head is a sealed box and contains all the optics for sensing and sighting. The box has a window of a suitable optical material through which the radiation beam enters. There are suitable filters and diaphragms to condition the beam which is then separated into two parts. The central part is reflected by a mirror and taken to the sighting optics. Through this beam, the instrument is focused on the target or radiating body. The surrounding beam is reflected and focused on the detector by a pair of concave convex mirrors. The signal, which is created at the detector, is carried by a cable to the electronics part. Here the signal is amplified. Again, control adjusts the signal for emissivity. The response of the detector is nonlinear and it is linearized and conditioned and fed to the indicator/controller/recorder. The indicator is usually digital. The detector is thermal or semiconductor type. The construction of a thermal detector is shown in Figure 14.10. This detector requires a cold junction compensating device which is situated in the sensor box near the detector. In this type, the sighting optics can be situated directly behind the sensor as its center is open. The thermocouples used are of type K or N, i.e., base metal (e.g., chromel-alumel). They are made of very thin wires and their hot junctions are blackened to simulate a black body. Eight to ten thermocouples are situated radially and connected in series. This sensor can sense all the wavelengths passing through the windows (usually glass or quartz). Semiconductor sensors have a response time of 0.01-0.025 sec. Depending upon the optics chosen, they can sense 0.65 to 10 µm radiation and can be used in the temperature range of 0-3500°C with an accuracy of 0.75% (full scale). The

Figure 14.9 Monochromatic radiation pyrometer.

sensors may be sensing a very narrow wavelength band (e.g., 0.9, 1.0, 1.6 µm) or a broad band (8–14 µm). Sometimes the sensing of the beam is obstructed and this causes incorrect readings. Such situations arise when 1. The object is too small so that the target area is incompletely filled. 2. Dust, smoke, or steam obscure the line of sight. 3. The windows are covered with dust or dirt and are difficult to clean. 4. Emissivity of the object changes due to surface conditions and composition. 5. Due to intermediate obstructions such as safety grills, furnace parts, and handling equipment the object cannot be observed fully.

Figure 14.10 Thermal sensor.

The above difficulties can be solved in some situations by using a two-color pyrometer. A two-color pyrometer senses two different wavelengths from the incident radiation. This can be achieved by using two separate detectors or a rotating filter disc as shown in Figure 14.11. A double detector device will sense the two wavelengths at the same time. A rotating filter disc will have a time lag in the two responses. If the two wavelengths are chosen properly they will be affected equally by the above mentioned obstructions. Thus their effect will be cancelled if we take the ratio of the intensities. This ratio will then depend only on the temperature of the object. There is a limit up to which the loss of signal due to obstructions will not affect the temperature reading. This limit depends on the design and measurement situation and can be 5:1–25:1. The two wavelengths chosen are 0.7 and

Figure 14.11 Principle of two-color pyrometer.

1.8 µm and 1.55 and 1.68 µm. These instruments are used in heat treatment furnaces, foundries, kilns, ovens and the like.

It is necessary to carefully assess the situation and locate the instrument to avoid reflected rays entering the beam.

14.11.1 Advantages of Radiation Pyrometers

1. There is no contact between the object and the sensing head. 2. Because there is no contact and the response is quick, the temperature of the moving bodies can be measured, e.g., ingot being rolled, flowing liquid metal, etc. 3. As long as the target area is fully covered, the temperature of small objects can be accurately measured. 4. There is (at least theoretically) no upper limit for temperature. 5. The instrument can be used for a wide range of materials during their processing such as rolling, extrusion, point drying, ovens for plastic, rubber, and paper. 6. Portable, battery operated, and handheld models are also available.

14.11.2 Limitations

1. The available optical and sensor materials pose a practical limit on the wavelengths that can be measured. 2. These pyrometers are not as universally applicable as thermocouples. Radiation pyrometers require careful assessment of the problem and choice of the suitable instrument. 3. Radiation pyrometers have a quick response and good accuracy but are costlier than thermocouples. 4. The temperature of objects with a thick scale cannot be measured accurately. 5. Emissivity correction is required.

14.12 MISCELLANEOUS TEMPERATURE-RELATED DEVICES

14.12.1 Temperature Indicating Colors

These are made from pure metals, eutectics, alloys, intermetallic compounds, and inorganic salts. They all have a calibrated single melting point or a very narrow solidus-liquidus gap. The calibration is equal to 1% and is available in the temperature range of 38–1371°C. These materials are formulated in the form of sticks, liquids, pellets, stickers, and labels. They are used to mark the object to be heated (like a chalk) or are placed on the object in the furnace. When the object surface acquires the calibrated temperature, these markings change their color or disappear, thus giving an indication of the temperature. These markers are very useful to monitor furnace linings, furnace charge, and for calibrating the furnace pyrometer.

14.12.2 Bimetallic Devices

The basic temperature sensing element in these devices consists of a thin strip made of two different metals. One of the metals has a low coefficient of thermal expansion and the other has a high coefficient. The strip is made by corolling or electrodeposition. When such a bimetallic strip is heated, it bends due to expansion. The angle of bending is proportional to the temperature (or to the temperature difference with the ambient). The metals or alloys used for the strip must have the following properties to make a good instrument: 1. The difference between the expansion coefficients should be very large. 2. Bending should be proportional to the temperature over a wide range. 3. The expansion must be reversible and there should be no thermal fatigue and corrosion. 4. The strip should be available in various thicknesses. A number of bimetals are commercially available. The high expansion component is an alloy of iron, nickel, chromium, and manganese. Low expansion alloy is made from iron and nickel. They are applicable in the range of −30 to +300°C. The construction of a typical bimetallic thermometer is shown in Figure 14.12. The sheath encased strip is firmly fixed to the bottom of the sheath. The other end is fixed to a bar attached to a simple dial indicator. These thermometers are used for low temperature ovens and domestic apparatus. They are used as indicators and cheap and simple temperature controllers. They are of simple and rugged construction. Temperature indication and control can be achieved to 5°C in the range 80 to 350°C.

14.12.3 Bimetallic Energy Regulators

This is an interesting device which can be used for the temperature control of small and large furnaces and appliances.

Figure 14.12 Bimetallic thermometer.

The principle of operation of an energy regulator is shown in Figure 14.13. A bimetallic strip has a resistance heater wound around it. One end of the strip is fixed. The free end has a contact attached to it. There is a movable contact opposite the contact on the strip. This contact is moved by a spring and knob. The movement of the knob adjusts the separation distance between the contacts. When put in the ON position, the contacts touch each other. The strip heater is put on and the strip is heated. This causes bending and separation of contacts which cuts off the heater. The strip cools and straightens. Again the contacts touch and the heater is turned on. Thus, an ON-OFF cycle depends on initial contact separation which is adjusted by the knob. The ON-OFF cycle affects the outgoing supply similarly. The power supply to the furnace is thus put on an ON OFF cycle. This controls the energy supplied during a given time span. Hence, the name “energy regulator.” Due to the cyclic supply the temperature of the furnace is indirectly controlled. The contacts are rated at 3–15 amps but can be supplemented by high rating electromagnetic contactors to control larger furnaces. The following points about energy regulator are noteworthy: 1. The instrument has a simple construction and is very inexpensive. 2. It is completely independent of the furnace. 3. There is no temperature measuring component. 4. The temperature is controlled independently on a time cycle. 5. Precise control is not possible. 6. The degree of temperature control obtained for a given time cycle will depend on the thermal design and operation of the furnace. 7. A separate pyrometer will be required to measure the temperature. 8. There is no upper limit for temperature as far as the regulator is concerned. 9. Control can be obtained at 20-30˚C about the desired value.

Figure 14.13 Bimetallic energy regulator.

14.12.4 Throwaway Tips

When measuring the temperature of molten metals like steel, cast iron, and nickel alloy the pyrometer is required to be dipped in the molten metal at temperatures exceeding 1500˚C. The mol ten metals are extremely reactive and turbulent, which exposes the pyrometer to an extreme environment. This reduces its life. To overcome this problem the pyrometers are made of throwaway tips or hot junctions. The tips are made of very thin Pt-Pt, Rh wires embedded in alumina powder and packed in thin metal or cardboard tubes. These tubes are plugged in the metal stem of the pyrometer. The tips (or the thermocouple) last for a very short time and then burn off. However, this time is sufficient to obtain a temperature reading. Each tip cab be used only once, hence, the name “throw away tip.” However, they are quite inexpensive. For cast iron and some steels, the solidus and liquidus temperatures can be correlated to the carbon and silicon content. Hence, with proper recording instruments, the throw away tips can be used for determination of carbon, silicon, etc., in cast irons.

14.13 TEMPERATURE INDICATORS

In the previous sections we have reviewed the various types of sensors available for sensing the temperature, their advantages, and choice. Every type of sensor will require some indicator to display the sensed temperature. In this section we will review the indicators commonly used and then the limitations.

Bimetallic sensors use a dial-gauge-type mechanical indicator working on a rack, a gear train, and a needle indicator moving on a graduated dial. Mercury in steel tube thermometers works on pressure changes in the sealed tube due to the expansion of mercury. A simple burden tube indicator graduated in temperature scale is used for display, mainly used to measure low temperature. Measuring the temperature of flue gases, oil quenching tanks in heat treatment, and hard anodizing bath temperature are some of the examples. The simplest indicator is a millivoltmeter with a dial big enough to read the temperature to the required accuracy. Some type of cold junction compensation is provided. As the indicator needle moves by a mechanical movement of a current carrying suspended coil, it does not have much power and sensitivity. Readings are usually restricted to 10°C. The instrument is delicate but inexpensive and simple. It is used for portable pyrometers. Thermocouples produce a small e.m.f. proportional to the temperature. Depending upon the object condition it is constantly charging. The best instrument to measure small voltages is the potentiometer. Here the test voltage is balanced against a known comparable voltage. Balancing is done by moving a contact against a slide wire. The exact balance is obtained when there is no current. Thus this is a null method of measurement and hence very sensitive and accurate. However, the manual process of balancing takes time. To overcome the time problem and to obtain quick and continuous readings, automatic balancing potentiometers were developed. Here the thermocouple e.m.f. is amplified and used to drive a servo motor to move the moving contact for balancing. At the null point the servo motor automatically stops. Thus, the pointer continuously moves from one balance point to the next. As the pointer is motor-driven its movement is powerful and can be used to drive the pen of a chart recorder. It can also be used to actuate the controller. Self-balancing indicators are quite rugged. They are very sensitive and accurate and can be easily adapted to changes in the measuring range. They have a complicated construction, are very costly, and are not portable. They require an external pyrometer for their working. The Wheatstone bridge used with resistance pyrometers can be made self-balancing. Currently, the indicators used on all types of pyrometers are digital. They display the temperature in numbers, thus dispensing with the dial and pointer. In digital indicators the analog voltage signal from the thermocouple is converted into a digital signal (numerical signal) and displayed on a counter. The details of their working are beyond the scope of this chapter. These instruments are very fast and accurate. They require very little external power and due to developments in integrated circuits, they are very small in size. Hence they can be used on portable as well as panel instruments. Their indicating numbers are well-lighted so that there is no difficulty in reading. They are very fast acting, accurate, and sensitive. The working details of all indicators discussed above are unimportant for the furnace designer. Enough information is given to make a choice for projected furnaces.

14.14 TEMPERATURE CONTROLLERS

For many heating operations, simple indication is not enough (e.g., heat treatment). It is necessary to control the temperature within certain limits or to control the heating and cooling rates, etc. For processes like zone melting or semiconductor, the temperature has to be maintained virtually constant, or within a very narrow band for a long time. Where temperatures involved are not high (< 400°C) simple control instruments based on bimetallic switching action are sufficient. These controllers are called thermostats. They can maintain the temperature within a range of 10 to 20°C. For higher temperatures, narrow temperature variations, and longer times, electronic controllers are used. It is not possible to discuss their design or circuits here as they belong to a specialized field of electronics and control engineering. We will review their control actions broadly so that the furnace designer can make a choice of suitable controller. Typical time-temperature cycles of a furnace are shown in Figure 14.14(A). The cycles can be divided timewise in three sections. Section I is heating from initial temperature to set temperature Ts, the second part (section II) shows the maintenance of Ts for a long (process) time. Lastly, section III shows cooling. The second cycle shows that heating and cooling are done in steps: $T_0 \rightarrow T_1 \rightarrow T_s$ for heating and $T_s \rightarrow T_2 \rightarrow T_0$ for cooling. These are the cycles desired. The first controller cycle called On-Off, controls bands on the lower side $T_s - \Delta T$. The width of the band ΔT is adjustable.

Figure 14.14 Temperature Control Cycles.

It is also possible to have different widths on high and low sides. The signal from the sensors is compared with the control band. If it lies out of the band, a switch operates to put the heater on or off as necessary. As only two control actions, on or off are available, the temperature is maintained fluctuating within the band. To obtain better control there may be two or more switches in series. Thus, for the off signal, the first switch will then turn off the second heater as required. This is the simplest controller and is suitable for large furnaces and wide control limits. The thermal mass of the furnace gives a slow control action. Figure 14.14(C) shows the action of the proportional controller. On sensing the deviation of actual temperature from the set point Ts, the controller will take remedial action but will overshoot. This will initiate the next action to reduce the overshoot. These actions will continue giving temperature oscillations until the temperature is stabilized a little above or below the set point. This controller is better than the on-off control. The final deviation, i.e., the set-off, can be controlled or the oscillations can be reduced but cannot be removed. Proportional controllers are suitable for furnaces having low thermal mass and fast heating rates. The next control option is the floating control. The controller senses the temperature against the allowable variation band. If the temperature is outside the band, the control device (motor, valve transformer tap, etc.) takes control action and, brings the temperature within the band. Once within the band, the controller action stops until an out-of-band signal is received. Thus, the controlled temperature oscillates within the band. Mathematical operations on the controlled signal, with respect to time, can be performed electronically or numerically on a computer. Thus, its differential co-efficient dT/dt will give information about the slope of the controlled variable. Similarly, its integration $\int T\, dt$ will give its rate of approach to the set point and the direction of approach. Controllers that can perform differential and integral operations are called “derivative” and “integral” controllers. In actual control, these control actions are not used singly but in combination with proportional controllers. This gives proportional and integral controllers, (P,I) and PID controllers offering proportional, integral, and derivative actions. Normally, controllers can be set for any combination. The control response of PID controllers is shown in Figure 14.14(D) and Figure 14.14(E). PID controllers are useful when there are sudden changes in temperature. For example, the door of a furnace opened in midcycle (say for loading, etc.) and the temperature is drastically lowered due to loss of condition. These controllers are very costly. They are also used for precision furnaces. All the controllers discussed above produce an output signal of the desired type. This signal is required to be amplified and matched to the controlling device. The controlling devices are relays, contactors, motorized valves, solenoid valves, etc. They require considerable power for their operation. When specifying a controller, the designer must carefully consider the following points. 1. The operation cycle — continuous or batch. 2. Allowable variations in set temperature, i.e., width of the control band. 3. Duration of the cycle. 4. Possible interference in operation. 5. The thermal inertia of the furnaces as a whole, both with and without load. Remembering that simply specifying a sophisticated controller does not guarantee required temperature control. It has to be matched with the furnace and the load.

moisture. The temperatures involved are low (80-250 °). Drying is used in many diverse processes, each with its own peculiarities. Consequently, the variety of dryers available is large. Some typical dryers are briefly discussed. Baking, like drying, is a low temperature process. It is mainly used in the food industry but has applications in many fields. The purpose of baking may be to make the article from dough (bread, cakes), to give crispness, to increase the taste or appearance, to improve bonding, and so on. Some representative baking ovens are presented to bring out their design features. Fans are used in many furnaces and ovens. They are mainly used for the circulation of gases and supply air to the burners. Fan-induced air flow is also used for convective cooling. Considering these applications, a short and limited introduction to fans is also included. This should be helpful to the designer in choosing a proper fan for a given application from manufacturers' literature. A short postscript on recently available materials appears at the end. The use of most of these materials in heating is not yet well established. However, they are sure to play an important role in the future.

15.2 SOME TYPICAL FURNACES

15.2.1 Rotating Hearth Furnace

This is a continuous type of furnace in which the hearth is made in the form of a flat, circular ring. It forms the bottom of a cylindrical furnace. The hearth rotates around its center while the furnace (i.e., the walls and top) is stationary. The hearth is rotated by a gear drive which may be located at the center or the outside. A radial partition wall separates the charging and discharging doors. A number of tangential burners are fixed on the upper side of the outer walls. Combustion gases exit through a port located opposite the discharge door. In large furnaces the hearth moves on a circular rail track. The construction is outlined in Figure 15.1. The following features make this type of furnace an attractive proposal for many applications: 1. The circular, rotating hearth makes these furnaces very convenient and compact preheating units for process applications such as forging or extrusion. 2. Large-sized furnaces have a hearth width up to 5.0 m so that medium to heavy-sized work pieces can be easily accommodated. 3. Variable rotational speeds and indexing makes the operation flexible. A heating cycle to suit any material can be easily adjusted.

Figure 15.1 Rotating hearth furnace. 4. It is possible to build smaller units having hearth widths up to 0.5 m. These small units can be used for light jobs such as heating for press working, intermediate annealing, and even drying or baking. 5. Large furnaces are usually oil and gas-heated. Smaller furnaces can use electricity or LPG. 6. As the charging and discharging doors are adjacent, one operator can carry out both the operations. 7. Linear continuous furnaces usually require some means of moving the work pieces through. In rotary furnaces no such mechanisms are necessary. 8. Instead of the hearth, the roof can be made as rotating. This will enable work pieces to be hung on the roof. They will receive uniform heat from all sides. 9. Some sealing arrangement will be required between the moving hearth and stationary walls to prevent the ingress of cold air or escape of hot gases.

10. The number, position, and capacity of the burners is an important design factor. This will help to adjust the desired heating and soaking periods.

11. The hearth can be divided into a number of zones by using hanging (chain) curtains.

12. If the burners are well above the workpieces, the major heating mode is radiation.

15.2.2 Automatic Integral Quench Furnace

Hardening heat treatment of steels requires heating the work to a certain temperature and quenching it in a suitable medium of a much lower temperature. The practical hardening cycle involves heating to hardening (austenizing) temperature at a certain rate and then holding it (soaking) at that temperature for a certain time. The heating rate and soaking time depends on the steel composition and size of the work. The quenching medium is usually oil. Figure 15.2 shows a modern furnace in which all the operational sequences are carried out automatically. A typical cycle may be Loading → Heating → Soaking → Quenching → Unloading. The quenching tank and quenching operation is part of the system, hence the name ‘‘integral quench” furnace.

Figure 15.2 Automatic integral quench furnace.

The central part of the system is the furnace. It may be electrically or radiant-tube heated. A protective atmosphere is introduced at the top and circulated by a fan. The hearth has alloy rails on which the load rests. The furnace has two air operated doors, one in front and the other in the back walls. A complex charging/loading/pushing mechanism is located in front. The loading rolls and rails are accurately aligned with the hearth rails. The load charging/pushing is accomplished by forked racks which can be raised or lowered by an air-operated mechanism. The prepared (loaded) work baskets are kept on the rollers. An electric motor moves the rocks and baskets into the furnace chamber. A quenching system is located next to the back door. After heating and soaking, the load baskets are pushed out on the air-operated quench frame. A quench tank is located below the frame. The frame and tank are located in a steel quenching chamber. On receiving the hot load, the frame lowers it into the quenching tank. Thus the quenching operation is achieved without loss of heat or time. After the predetermined time in the tank, the frame and load are raised and discharged (pushed) over to the run out table through the unloading door. The protective atmosphere is discharged through the intermediate door and occupies the space above the quench tank, before burning at the flame curtain at the discharging door. This arrangement protects the hot load for a short time before quenching. A flame curtain is also provided at the front door. A matching gas generator provides the required protective atmosphere. The whole operating cycle, temperatures, loading, discharging, etc., is automatically sequenced so that no operator is necessary. Control is exercised from a separate station which can be located away from the furnace. The quenching tank has a large capacity and is provided with circulators and heat exchanges to obtain uniform temperature and circulation. The typical furnace size is 600 × 900 × 450 mm with a quench tank holding 3000 l of oil. Larger units are available. These furnaces are extremely suitable for production jobs.

15.2.3 Vacuum Gas Furnace

Heat treatment of high alloy steels such as all types of tool steels presents some peculiar problems. These steels are machined or shaped in an annealed (soft) condition. The shapes are quite complicated and have varying thicknesses. Typical examples are dies, press tools, forging tools, cutting tools, etc. After machining they are hardened and tempered. Hardening requires thorough heating to temperatures in the order of 1000-1200 ° C followed by quenching (fast cooling) by a suitable coolant (quenchant). Tempering requires reheating of quenched articles to 600-1000 ° C, at a certain rate and then slow cooling at a certain rate. To avoid oxidation both operations require heating in a protective atmosphere. Quenching poses problems of distortion and fracture. If quenching is carried out by using a cool inert gas, the cooling rate is less severe than that obtained by oils or water. This reduces or often eliminates the problem of distortion or cracking. Vacuum-gas furnaces are designed for using a vacuum atmosphere for heating and an inert gas such as dry, pure nitrogen for quenching or slow cooling. As both vacuum and inert gas are used in the same enclosure, they pose interesting design problems. Heating is usually done by indirect electrical heating. Some vacuum tempering designs may be (externally) heated by gas, as the temperatures are low. A typical vacuum-gas hardening furnace is shown in Figure 15.3. The furnace is of the cold-wall vacuum-type having a horizontal cylindrical shape. The main body has a cooling jacket. The door ④ is also water-cooled and has a gasket to provide a vacuum-tight seal. Heating is achieved by indirect electrical heaters ③ placed radially. Either graphite or molybdenum heating elements are used. Both types require a low voltage, high current supply. The work is usually kept in a basket and is supported by a combination of molybdenum and graphite supports. The vessel is evacuated through the vacuum port ⑤ . The vacuum system consists of a diffusion pump backed by a roots blower and a mechanical pump.

Figure 15.3 Vacuum gas heat treatment furnace (For description see text).

For the quenching or tempering operation, dry pure nitrogen is supplied to the evacuated chamber through the opening until the desired pressure (2–3 Bar) is reached. The cool nitrogen enters the chamber radially through graphite nozzles, and surrounds the work from all sides so as to obtain an even cooling rate. The gas coming out of the nozzles gets heated on contact with the work and the hot furnace interior. It is axially drawn out by a fan through the compact heat exchanger ⑥ . Its temperature is brought down to less than 150 °C and is recirculated via channel to the nozzles and the chamber. The path of gas circulation is shown by arrows. The heat exchanger fluid is water and is admitted through the passage. The circulation goes on until the whole chamber cools to about 150 °C and then the door is opened. This safeguards the graphite/molybdenum heating elements. The same or a similar furnace is used for a subsequent tempering operation. Here, the temperature is lower and a nitrogen atmosphere is kept throughout the tempering period. It can be seen from the figure that the design of the furnace is quite complicated. It requires several auxilliary systems and a complex sequencing and control system. Specifications of a commercial furnace of this type are given below. Work space 800 × 800 × 1200 mm Overall size 2500 × 3200 mm long Max. temperature 1350 °C Temperature uniformity 5 °C in work space Heating power 200 kW-3 ph Fan motor 60 kW Vacuum 10^{-2}–10^{-5} mbar Leakage rate $< 1 \times 10^{-3}$ mbar/sec Weight of charge 1000 kg max Quenching gas Dry, pure N_2 Gas pressure during hardening 1.5–6 bar For one quenching Gas consumption 10 m^3 Water consumption 20 m^3/h quenching

15.2.4 Linear Continuous Furnaces

As the name suggests these furnaces have a straightthrough movement of charge. The through movement may be achieved either by pushing work loaded baskets through or by placing the work on a continuous, moving mesh belt. A typical linear continuous furnace is shown in Figure 15.4. The furnace consists of three main zones — preheating, heating, and cooling. The preheating zone operates at a low temperature (100–500 ° C) and is used for drying, dewaxing, or general preheating. This is followed by the heating zone at the required process temperature (900–1500 ° C). Heating on both zones is achieved by resistance elements, metallic or nonmetallic. The heating zone may be nominally divided into three parts. The first part will bring the work to the desired temperature (heating). The second part will maintain the temperature for some time (soaking). This can be achieved by varying the power input to the zones. The third or end part of the furnace will have no heating elements and will act as a slow cooling zone. Many processes such as sintering and brazing, require a protective atmosphere which is usually reducing. Such reducing atmospheres are harmful to most of the resistance heating material. To avoid a reaction between the atmosphere and the heaters, a metallic alloy inner muffle is used to separate the atmosphere and work from the heaters. Small sections and short furnaces may use a ceramic inner muffle. For achieving the required properties in the work, a certain temperature-time combination is required in the heating zones. The temperature or its gradient in the zones is maintained by a suitable temperature control system. The time is adjusted by adjusting the belt speed. With these two controls the furnace can be adjusted to process a variety of materials. In a pusher pipe furnace the control is obtained by timing the introduction of a new work basket in the furnace. The same basic design can be used for baking operations. The temperature required is of the order of 250–300 °C. The cooling zone is usually not required. Baking evolves water vapor and carbon dioxide; hence the heating is best done in a stainless steel inner muffle. Embedded and sealed heating elements are used. A very large variety of these furnaces are commercially available. Molybdenum, tungsten, or graphite heating elements with hydrogen as the protective atmosphere are available up to 2000 °C. The load capacity of mesh belts is a limiting factor. Commercially, Ni-Cr, Ni-Cu, monel, inconel, or stainless steel belts are available, which can be used up to 1100 °C. For higher temperatures only pusher-type designs are possible with

Figure 15.4 Linear continuous furnace (Mesh Belt type).

roller hearths. The protective atmosphere is generally introduced in the central zone. It flows toward the doors where the chain and flame curtains are situated. A circulating fan may be used.

15.3 INCINERATORS

The production and accumulation of garbage in urban areas all over the world is assuming alarming proportions. Toxic and lethal by-products from chemical industries are polluting rivers and beaches and have already posed health problems. Incineration or burning off is one of the attractive (and sometimes the only) solutions. The incineration process has been studied and developed in highly industrialized countries. However, it is rarely used in undeveloped or developed countries. It is with the desire to create an awareness of the technology of incineration that a limited review is taken in this chapter. The nature and properties of ‘‘garbage” as a fuel are already discussed in Chapter 5. The following points need consideration when designing an incinerator: 1. Types of Garbage Garbage can be classified on the basis of its origin. I. Municipal garbage — This is collected from streets, bins, beaches, and public places. II. Establishment garbage — This garbage originates from hospitals, restaurants, small nonchemical industries, etc. III. Kitchen or household garbage — From individual homes or residential buildings. IV. Special garbage — From chemical industries, slaughterhouses, food processing plants, markets, etc. There can be many more types depending upon local industries and population. 2. Composition of Garbage Like other fuels (such as oil and gas) garbage does not have a single composition. The constituents depend on origin, geographical location, seasonal consumption trends of local populations, and many other factors. Thus, there are wide limits within which the composition varies. For example, the moisture content in municipal waste can vary between 10–40% depending on the season. 3. Combustion problems Due to variations in composition, the combustion of garbage cannot be carried out in a single stage and requires additional external fuel like gas or oil. Combustion is therefore invariably carried out in two stages.

In the first stage (~ 600–800 ° C), the moisture is converted to steam and readily combustible constituents such as grass and paper are burnt. The steam and unburnt (pyrolized) gases flow to the next stage. Additional air and fuel are supplied to the gas in the next stage. Here complete combustion takes place. The waste gas is now essentially nontoxic and consists of CO_2, N_2, H_2O, etc. The temperature is 800–1000 ° C. 4. Waste gas from large incinerators usually require additional treatment such as cleaning, dust precipitation, and cooling. Depending upon the operational practice, it may be possible to recover some of the waste heat by using a recuperater or waste heat boiler. A large amount of ash is collected below the grates or in the post incineration chamber. This arises from metals and glass in the garbage. It is used for road building, ballasts, etc. To make the incineration more easy and economical, it is necessary to separate large pieces of metal, glass, and stones, etc., from the garbage. This can be done mechanically or manually. Three representative incinerator designs are discussed next. Note that there are many possible variations depending on the type and amount (T/day) to be incinerated, local avail able fuel, legal restrictions on waste gas constituents, water availability, and location and transport facilities.

15.3.1 Large Scale Municipal Incinerator

The typical municipal garbage has a nominal composition. Dry dust, leaves, and wood 4–44% Food, vegetable, and organic matter 8–30% Paper cardboard 20–30% Metals 5–10% Rags, ropes, and textiles 2–10% Plastics 1–6% Unclassified 1–10% Moisture 5–35% The range is extremely wide. The volume of garbage is very large ($1 - 3 \times 10^3$ T/day). A typical municipal incinerator is shown in Figure 15.5.

Due to high volume, the loading is carried out by mechanical means such as a grab crane. The garbage is charged on the inclined, moving grate. Burners over and below the grate raise the temperature to 600-800 °C. The moisture is evaporated and dry combustible matter starts burning. Combustion is completed as the mass reaches the end of the grate and is removed through the doors at the bottom. Gases and steam evolved from combustion pass to a post incineration chamber. It is supplied with excess air and the temperature is raised to 1000-1200 °C by the auxiliary burner.

Figure 15.5 Typical municipal garbage incinerator.

The combustion is completed as the hot gases pass forward. The gas pressure is controlled by a damper in the waste gas flue. Gas cleaning and dust precipitation is done before the gas is released into the atmosphere through the stock. Incineration reduces the garbage volume by more than

90%. Sorted out glass, metals, plastics, and ash are saleable by-products.

15.3.2 Medium or Small Scale Incinerator

In these designs the volume required to be handled is not large (200–2000 kg/day), hence the charging is done manually.

A U-type design is shown in Figure 15.6. The basic design is similar to that in Figure 15.5. The U construction has made the incinerator compact and hence, suitable for small or medium establishments. Gas cleaning and precipitation is usually unnecessary unless the charge contains hazardous chemicals. A tall stack is adequate. Cremation of human bodies and incineration of dead animals and surgical waste are carried out in this type of incineration.

They usually operate on electricity, gas, or light oil such as diesel.

15.3.3 Domestic or Office Incinerator

Domestic garbage contains moisture, food, and vegetable matter as the main constituents, along with small amounts of paper, plastics, glass, and metals. Office garbage mainly contains all types of paper as the major constituent. Small amounts of chemicals, rubber, plastics, glass, and metals are the minor constituents. A small hospital or clinic's garbage contains bandages, dressings, and cotton swabs in large amounts. Plastic syringes, bottles, tubes, tissue paper, organic matter such as dried blood, tissues, and discarded medicines constitute the rest. There is also a lot of moisture.

Figure 15.6 Small scale incinerator.

The volume is small (5–50 kg/day). The main requirements are a compact design, easy operation, and clean waste gas. A typical incinerator of this type is shown in Figure 15.7. Outwardly the incinerator looks like a vertical-loading domestic washing machine. The incineration chamber is like a basket with a grill or grate at the bottom. A part of the wall is perforated for the gas to exit. There is a gas burner (or electric heater) for primary heating. The combustion gases pass through a secondary chamber that is the bottom part of the stock. An auxiliary burner located here completes the combustion. Air is drawn in through grills at the bottom. Ash is collected in a drawer located below the grate.

15.4 HEAT EXCHANGERS

Heat exchangers are accessories used in heating/cooling processes to transfer waste heat from one fluid to other. Thus it involves two fluids, one hot and the other cool. Both fluids may be gases or liquids or one gas and the other liquid. The hot fluid flows through a tube heating the tube surface, while the cold fluid flows over the tube and picks up heat from the hot fluid via the tube surface. Thus, the heat is exchanged between the fluids. It is also possible to achieve the same result by having the hot fluid flow over the tube while the cold fluid flows through. Heat exchangers find wide applications in chemical and mechanical engineering. Almost all internal combustion engines (except small ones) require a separate heat exchanger (radiator) to cool the engine coolant. Similarly, air conditioning and heating require heat exchangers. Chemical industries use them to heat or cool process products and intermediates. Combustion furnaces produce large amounts of flue gases which leave the furnace at a high temperature. If directly released into the atmosphere, considerable heat is wasted. If passed through an exchanger, at least some of the heat can be recovered by heating fresh air for combustion. It is also possible to obtain hot water or steam from flue gas heat exchangers called ‘‘recuperators.” Large induction heating plants use considerable quantities of water for cooling. The hot water is usually passed through an exchanger, cooled, and then reused. Hardening/quenching operations heat up the quenching media (oil or water). It is necessary to cool these in between quenching batches. Thus, there are many heating processes in which the

Figure 15.7 Domestic incinerator.

use of a heat exchanger is necessary and economical. Modern vacuum gas quenching furnaces heat the metal to the hardening temperature under vacuum. Quenching is achieved by introducing a cool gas (usually nitrogen) in the furnace. The gas picks up heat from the charge. A compact heat exchanger situated ‘‘inside” the furnace cools the gas and recirculates it over the charge. This is done to conserve the costly gas. Another class of heat exchangers used in large furnaces is called ‘‘regenerators.” These are operated in a cyclic fashion. For a certain period the flue gas is passed through them, so that the regenerator body (usually refractory) absorbs heat. In the next period, cold air is passed through the heated brick work to pick up heat. This cycle is repeated. The furnaces and equipment discussed in this book are not likely to use regenerators. Hence, these are not discussed further.

15.4.1 Classification of Heat Exchangers

There are a vast number of heat exchanger designs and many schemes for their classification. As our interest in these devices is limited, we will adopt a classification based on the flow mode of the two heat exchanging media. The simplest heat exchanger (Figure 15.8) is a tube in a tube heat exchanger. The hot fluid flows through the inner tube and the cold fluid through the outer tube. The temperatures are t_1 and t_2, ($t_1 > t_2$). Heat transfer from the hot fluid to the cold takes place through the wall of the inner tube. The outer tube is insulated to prevent heat loss. In the figure, both fluids flow in the same direction, i.e., ‘‘parallel flow.” The fluids can flow in opposite directions, i.e., ‘‘counter flow.” The change in the temperatures of the fluids, as they pass through the exchange, are also shown in the figure. An important factor involved in the heat transfer between the fluids is the area of contact or length of contact. In a simple tube exchanger this area is very small and hence this type of exchanger has limited applications. The heat transfer coefficient in this and all other types of exchangers will depend upon the flow conditions, i.e., the Reynolds numbers of the two fluids. Usually the flow is laminar or transitional (Re 3×10^3 to 5×10^4). To increase the thermal contact surface, the hot fluid is given a number of passes through or inside the outer tube. This gives rise to shell and tube exchangers (Figure 15.9). Some shell and

Figure 15.8 Simple heat exchanger.

tube exchangers are shown in the figure. The two fluids are called the ‘‘tube side” fluid (f_1) and the ‘‘shell side” fluid (f_2).

Figure 15.9(A) shows a single-shell two pass-design while Figure 15.9(B) shows a single-shell six-pass exchanger. Figure 15.9(C) shows a single-pass shell, single-pass, multi tube design. Here the fluid passes through the shell only once but there are four or more parallel tubes. Note the baffles which help to circulate the shell side fluid around the tubes.

The temperature distribution of the fluids through the exchangers remains essentially similar to that shown in the figure. These types of exchangers are useful in recovering or dissipating heat from coolants or quenchants. Besides parallel and counter-flow arrangements a third common scheme uses ‘‘cross” flow. Here one fluid (usually hot) flows through the tubes while the second fluid flows over the tubes at a right angle to the tube axis. A single tube cross-flow arrangement is shown in Figure 15.10. If the flow conditions of the outer fluid (f_2) are kept suitable (laminar or transient) heat is transferred via the tube wall by conduction and convection as the fluid-wall contact is good. Single tube

Figure 15.9 Some typical shell/tube heat exchangers.

cross-flow heat exchangers are of little practical use as the surface area of the tube is very limited. Practical designs of this type use tube banks as shown in Figure 15.10(C), Figure 15.10(D). Two types of tube arrangements are used. Figure 15.10(C) shows an ‘‘inline” arrangement while Figure 15.10(D) shows a ‘‘staggered” arrangement. In both types the tubes are placed at regular longitudinal and cross pitches x_l and x_t . These pitches are related to the tube diameter d, such as $x_l = p \times d$ and $x_t = q \times d$. The tubes are welded to the header plates. These exchangers are extensively used for recovery of heat from waste gases. A typical cross-flow heat exchanger for recovery of heat (flue gas recuperator) is shown in Figure 15.11.

Figure 15.10 Cross-flow heat exchangers.

Heat exchangers of interest to us are constructed from welded steel. For temperatures higher than about 500°C, special heat-resistant alloys are used. For large furnaces and high temperatures the exchangers are constructed from refractory bricks and special shapes. In some applications there are severe restrictions on the size and weight of the exchangers. Some special furnaces (e.g., vacuum and gas quench), all automotive applications, and small air conditioners have such requirements. In these cases ‘‘compact heat exchangers” are used. We have seen that the surface available for the exchange is a key factor in the exchanger design. The tube surface area in the exchange is increased by using a finned tube. The fins may be on the internal, external, or both surfaces as shown in Figure 15.12(A), Figure 15.12(B), Figure 15.12(C), and Figure 15.12(D). To achieve further improvement in the heat transfer coefficient the construction is made from aluminium or copper.

Figure 15.11 Typical cross-flow flue gas recuperator. Figure 15.12 Compact heat exchangers.

Compact heat exchangers (Figure 15.12(D)) are used at low temperatures ($< 400^\circ$C). The fluids are air, gas, and water. Heat exchangers are costly and require regular maintenance as they are prone to corrosion, scaling, and clogging. They significantly increase the capital and running costs. They usually require pumps, compressors, or fan drives for fluid circulation. Investment in heat exchangers is justified in following conditions: 1. When the investment is recovered by the saving in the cost of fuel. 2. They are mandatory by the environmental regulations. 3. Where irrespective of the costs involved, they are necessary (e.g., aviation, space, and military applications).

15.4.2 Convective Heat Transfer over Tube Banks

In the previous section we have seen how the fluid circulation and heat transfer takes place with a forced flow over a single tube. It was observed that the heat transfer coefficient depends on the circulation of the fluid around the tube, i.e., the wetted perimeter, which in turn depends on the Reynolds number Re_d, based on the tube diameter, and the arc of contact between the tube and the fluid, is small (under any Re_d). Hence, for practical purposes it can be concluded that a single tube is of very little use when large quantities of heat are required to be transferred from or to a tube. In such situations a number of tubes are used so that the surface available for exchange is also quite large. The arrangements are called ‘‘tube banks.’’ The tubes are arranged symmetrically in a regular pattern. Two arrangements are more common, the ‘‘inline’’ and the ‘‘staggered’’ as shown in Figure 15.13. The tubes are arranged in rows at a certain pitch x. The pitch of tubes at right angles to the flow is called the transverse pitch x_t. The distance between the axes of tubes between two adjacent rows is called the longitudinal pitch x_l. Both the longitudinal and transverse pitches are related to the external diameter of the tubes d_2 so that $x_l = p \times d_2$ and $x_t = q \times d_2$, where p and q may be equal or different. The Reynolds number Re_d is based on the velocity at the narrowest path in the bank. For ‘‘inline’’ arrangement, the

Figure 15.13 External convection over tube banks.

narrowest path is x t − d 2 . For ‘‘staggered’’ arrangement, it depends on both pitches x t and x l as can be seen from the triangle ABC in Figure 15.13(B). The narrowest path may be along AB or AC(BC). The velocity V is given by V ∞ x t = V (x t − d 2) and where υ is the kinematic viscosity (m 2 /sec) taken at temperature at the entry to the bank. The mean heat transfer coefficient is given by the correlations between Nusselt (Nu), Reynolds (Re d), and Prandtl (Pr) numbers with a correlation factor . For inline tube banks (15.1) For staggered tube banks (15.2) Both the correlations are applicable in the range Re d = 10 3 − 2 × 10 5 . There are correlations available for other Reynolds numbers but they are not of interest to us. Similarly, there may be small differences in the numerical constants between correlationships available from various sources. Pr w refers to the Prandtl number at wall temperature. For air and gases the term (Pr/Pr w) can be neglected. For rough estimates the correction factor may be taken as 1.2 to 1.5. The result obtained from the above correlations gives an accuracy of 10–15%. The heat transfer coefficient obtained from the above correlations is the mean value applicable to the tubes after the second row. For the first two rows, the coefficient is 60 and 90%, respectively. This arises due to nonuniform flow over the first two rows. Correlations and tables are available for various parameters and coefficients involved in the calculation of tube banks. As our purpose is only to estimate the probable heat and Chapter 4). These sources also give information on the calculation of pressure drop in the bank.

15.4.3 Heat Exchanger Calculations

There are many approaches to the design of heat exchangers. They are all based on three basic equations of heat balance of the exchanger. Consider a simple tube in a tube exchanger, as shown earlier in Figure 15.8, involving an exchange between two fluids, f_1 (hot) and f_2 (cool). Let t'_{f1} and t''_{f1} be the temperatures of fluid f_1 at the inlet and outlet of the exchanger. Similarly, let t'_{f2} and t''_{f2} be the temperatures of fluid f_2.

Let A be the area of contact (m^2). Heat lost by the fluid f_1 will be (15.3) Assuming that the outer tube containing f_2 is well insulated, the heat taken up by f_2 (15.4) The heat transferred from f_1 to f_2 is Q and is given by (15.5) Note that subscripts 1 and 2 denote the properties of fluid f_1 and f_2, respectively. So that $\dot{m}$ = Mass flow rate (kg/sec) ρ = Density (kg/m^3) C = Specific heat (J/kg°C) h = Heat transfer coefficient (w/m^2 °C) λ =

Thermal conductivity of wall (w/m˚C) δ = Tube wall thickness (m) Q C m t t= ′′ − ′ • r 1 1 1 1 1 ( ). Q C m t t= ′′ − ′ • r 2 2 2 2 2 ( ). Q hA t= ( ).∆ In Equation (15.5), there are three decisive terms: h, A,

and ∆t. Each term needs close inspection. Heat will be transferred first from f 1 to the tube wall and

the heat transfer coefficient will be h 1 . Heat will then be con

ducted from the inner to the outer surface of the tube and will

depend on the thermal conductivity λ of the wall. Finally the

heat will be transfered from the wall to f 2 and this will take

place with a heat transfer coefficient h 2 . Hence, the heat transfer coefficient h in the Equation

(15.5) will by the overall heat transfer coefficient and will be

given by (15.6) When the fluids are passing through the exchangers, their

temperatures are continuously changing. Hence, the problem

arises as to which temperatures are to be used in the Equation

15.3 to Equation 15.5. We will have to use mean temperatures

for the fluids. As the change in temperature between the inlet

and outlet is not linear (see Figure 15.8(C), Figure 15.8(D) we

can use an arithmetic mean for small temperature differences,

but it is more appropriate to use “log mean temperature”

(LMTD) given by (15.7) All the physical properties of both the fluids will be those at the mean temperatures. The area of contact A can be easily determined from the geometry of the exchanger for simple shell tube exchangers. For finned surfaces, this area is different on each side of the wall. When estimating the heat exchanger required for a process the required area of contact is unknown. Equation (15.5) is then used to determine the area (A). If the tube (inner) size is known, the length and number of tubes can be determined from mass flow rate m through the tube. h h h = ° + + 1 1 1 1 2 d l w/m C 2 t t t t t t m = – 1 2 1 2 2 3. log The heat transfer coefficients h 1 and h 2 are calculated by the methods discussed earlier in Chapter 3. Usually the transfer takes place by forced convection on both sides of the tube. If the temperatures are high (>600°C) the contribution of radiation to the heat transfer will be significant. In detailed calculations for design there are some correction factors involved. These are not considered here as our purpose is only that of estimation. The examples that follow will make the estimation process clear.

EXAMPLE 15.1

Design a heat exchanger for recovering heat from flue gas flowing at 2 m 3 /sec at 450°C. The heat is to be recovered by using a cross-flow exchanger using a staggered steel tube bank. The external diameter of the tubes is 55 mm and the internal diam

eter 50 mm. The lateral and longitudinal spacing is equal and

is 1.25 × external diameter. The initial temperature of air is 25˚C and the final desired

temperature is 250˚C. The volumetric flow rate of air is 2.5 m 3 /sec. Determine 1. The overall heat transfer coefficient 2. The length of tubes 3. Number of tubes 4. Distribution of tubes in rows Data Flue gas output 2m 3 /sec Flue gas density 1.3 m 3 /kg Temperature at gas intake (t 1) 450˚C Initial temperature of air (t 2) 25˚C Final temperature of air (t 2) 250˚C Volumetric flow rate of air 2.5 m 3 /sec Exchanger tubes ext/int diameter 55/50 mm Arrangement of tubes staggered Lateral spacing = Longitudinal spacing 1.25d 2 Velocity of air over narrowest section 6 m/sec of tube bank Mean velocity of the flue gas 10 m/sec through tubes V 1 Solution Mass flow rate of flue gas m • 1 = 1.3 × 2 = 2.6 kg/sec Arithmetic mean temperature of air

At this temperature, the properties of air (from the tables) are Density ρ 2 = 0.854 kg/m 3 , Sp. heat C 2 = 1.013 kJ/kg˚C Conductivity λ 2 = 3.49 × 10 -2 w/m.˚C, Viscosity υ 2 =

27.80 m 2 /sec Prandtl no. Pr 2 = 0.684 Mass flow rate of air m • 2 = volume flow × density = 2.5 × 0.854 = 2.14 kg/sec Heat transferred from flue gas to air Q = m 2 × C 2 × (t 2 – t 2) = 2.14 × 1.013 × (250 – 25) = 488 kW Assume the mean temperature of flue gas (t 1 m) is 350˚C. At 400˚C, the specific heat of flue gas C 1 m = 1.1356 kJ/kg˚C. t m 2 250 25 2 137 5 140= + = ˚ − ˚. C ~ C t t Q m C m 1 1 1 1 3 3 450 488 10 2 6 1 1356 10 285 ′′ = ′ − = − × × × = ˚ • . . C Mean flue gas temperature This is much higher than the assumed temperature

(350˚C). Reiteration shows that at t 1 m = 367˚C, the flue gas outlet

temperature t″ 1 = 284˚C, and the mean temperature is 368˚C.

Hence, t 1 = 450˚C, t″ 1 = 284˚C, t 1 m = 368˚C. At 368˚C the properties of flue gas are ρ 1 = 0.555 kg/m 3 , C 1 = 1.1356 kJ/kg˚C λ 1 = 5.14 × 10 -2 w/m˚C, Pr 1 = 0.64, υ 1 = 55.30 m 2 /sec Reynolds number of flue gas in tube Inner cross-section of tube Gas velocity in tube V 1 = 10 m/sec Tube diameter d 1 = 0.05 m Correlation for Nusselt number is = + = ° 450 285 2 367 C Re 1 1 1 1 = V d u A d 1 1 2 2 2 4 0 05 4 1 96 10= = × = × − p p . . m 2 Re . . . 1 6 3 10 0 05 55 3 10 9 03 10 = × × = × − Nu Re Pr 1 1 0 8 1 0 43 3 0 8 0 43 0 021 0 021 9 03 10 0 64 25 3 = = × × = . ( ) ( ) . (.) (.) . . . . . Heat transfer coefficient from flue gas to tube (h 1) Reynolds number of air flowing over tube bank is For flow over staggered tube bank, the correlation is Nu 2 = C × (Re 2) 0.6 × (Pr 2) 0.33 where � is the correction factor. For a tube bank with x t = x l , � = 1, and C = 0.41. Hence, Nu 2 = 0.41 × (1.19 × 10 4) 0.6 × (0.684) 0.33 = 101. Heat transfer coefficient from tube surface to air is Overall heat transfer coefficient for heat transfer, Flue gas → tube → air is λ is the conductivity of steel tube. It is about 40–50 w/m°C.

Hence, the middle term is neglected. = = × × = ° − Nu 1 1 1 2 1 25 3 5 14 10 0 05 26 l d h w m C . . . / Re . . . 2 2 2 2 6 4 6 0 055 27 8 10 1 19 10 = = × × = × − V d u h Nu d 2 2 2 2 2 101 3 49 10 0 055 64= = × × = ° − l . . w/m C h h d d h = + − + 1 1 2 1 1 2 1 2 / l h h h = = = ° + + 1 1 20 7 1 1 1 26 1 101 1 2 . w/m C Mean temperature of flue gas t 1 m = 368°C Mean temperature of air t 2 m = 140°C Mean temperature difference of exchange Δt m = 368 − 140 = 220°C Heat transferred Q is Q = hAΔ t (We will assume that the correction factor ~ 1.0) Substituting The mass flow rate of flue gas is m • 1 = 2.6 kg/sec where n is the number of tubes. Substituting Adding 20% for uncertainties in heat transfer coefficient n � 287 A A Q h t = = Area of heat exchange surface (m 2) 1 Δ A 1 3 488 10 20 7 220 107= × × = . m 2 m d V n 1 1 1 2 1 4 • = × × ×r p n m d V = • 4 1 1 1 2 1 r p n = × × × × = 4 2 6 0 055 0 05 10 239 2 . . .p The height (length) of one tube (single pass) can now be

calculated as the total area is known. On the air side the mass flow rate m 2 and velocity V 2 is

known. For the tube arrangement (staggered) and equal lat

eral and longitudinal spacing 1.25 d 2

where A 2 is the total narrow clear air passage available in

a row

where n c is the number of tubes in one row (across the flow). Total number of tubes is n = 287 Number of tubes placed longitudinally (along the flow) Hence the exchanger will have a matrix of 25 × 12 tubes. A d n A d n 1 1 1 2 2 107 2 0 05 287 1 19 1 2 = · = = × × × = − p p p l lor m . . ~ . m V A • = 2 2 2 2 r A m V A d d n d c 2 2 2 2 2 2 2 2 2 14 0 854 6 0 418 0 055 1 2 = = × = = × = − × × = = • r . . .) , . . Inter tube gap tube length (1.25 m, m 2 l l n c = − × × = − 0 418 1 25 1 0 0 055 1 2 25 3 25 . (. .) . . . ~ n n n c l = = − 287 25 12 ~

15.5 DRYING OVENS

Drying, i.e., removal of moisture (complete or partial) from substances, is an important unit operation in a large number of processing industries. It is used in agriculture, raw vegetable preservation, processed food, paper, textile, dairy, painting, and many other processes. There are a number of drying methods available such as freeze drying, solar drying, spray drying, and heat drying. Consequently, a large variety of dryers is available in the market. The method and machinery for drying will have to be carefully chosen to suit the raw material, drying conditions, and desired quality and quantity of the product. In this book we will only consider drying by heating. For a detailed treatment of all drying treatments, refer to special literature. Consider a solid containing moisture or water at a temperature T_2 (Figure 15.14 (A)). Hot air at temperature T_1 is flowing over the interface or boundary XY. As $T_1 > T_2$ the heat will flow from air to the interface at which heat trans fer will take place by convection. From the interface the heat will flow in the solid by conduction as shown. Due to this heat, the moisture on the interface will evaporate and the vapor will be carried away by air. Moisture from the interior will then move by diffusion toward the interface. Thus, there will be a mass transfer flow set up from solid to air through the interface. This will be because of the concentration gradient between the solid (C_2) and air (C_1). As time passes, the moisture in the solid will decrease. Thus in drying, there are two opposite transfer processes taking place simultaneously. Heat will be transferred from air to solid and moisture (mass) will be transferred in the opposite direction. The typical progress of drying with time is shown in Figure 15.14(B). Water in the solid may be free, loosely bonded, or chemically bonded. Loose and free moisture will be readily removed. Chemically bonded water is difficult or sometimes impossible (uneconomical) to remove.

Figure 15.14 Heat and mass transfer in drying.

For heat transfer, the general equations are: (15.8) (15.9) Similarly, for mass transfer (15.10) (15.11) Equation (15.8) and Equation (15.9) are already introduced in Chapter 3. Equation (15.10) and Equation (15.11) are mass transfer equations which are similar to Equation (15.8) and Equation (15.9). Here, D = Diffusion coefficient m^2/sec β = Mass transfer coefficient m/sec

C 1 , C 2 , C w = Moisture concentrations in air, solid, and interface (kg/m 3) j = Mass flux kg/sec What was discussed earlier is a highly simplified version of mass transfer in a typical drying operation. Mass transfer is a separate special topic of interest to chemical engines. Our interest in this book is confined to heating design, and the discussion above should be sufficient. The process information we need is drying curves as shown in Figure 15.14(B), established at various air temperatures. This will enable us to decide the time and the temperature required. As a rule, the highest possible temperature should be chosen without damage to the quality of the dried product. There are two reasons. First, the moisture carrying capacity of air increases rapidly with temperature (see Appendix D). Secondly, the heat transfer to the interior and the interface of the solid will also increase with temperature. It is likely that at some air temperature, the q h T T c w = - ˚ ( ) 1 W m C from air to interface 2 q T T L W w = - ˚ l ( ) 2 m C from interface to interior 2 j D C C L w = - -( ) 2 from interior to interface j C C w = -■( ) 1 from interface to air interface will acquire a constant temperature due to the absorption of latent heat. The output desired (Kg/h at x% moisture) will lead to the choice and size of heating machinery. If the basic process information is not available, it can be investigated by a simple laboratory procedure. Samples of a known surface area and weight are dried in an oven for a range of temperatures and time. Assuming that only simple drying takes place (i.e., without any chemical reaction) the moisture removed can be measured by loss of weight. A commercial batch-type drying oven is shown in Figure 15.15.

The wet objects are loaded in trays which may or may not be perforated. The trays are stacked on rocks. Hot air is passed over the trays. The air is heated by passing it over heaters arranged as tube bundles. Air supply is obtained by steam, electric heaters, or radiant tubes. After passing over the trays, the air acquires the evaporated moisture but has a lot of sensible heat. In some of the exhaust, the gases may be recirculated by mixing them with fresh intake air. The rest is released into the atmosphere through a stack. The exhaust stack and intake air should be sufficiently apart so that this fresh air is relatively dry and cool.

The proportion of recirculation is adjusted by using dampers. The operation will benefit by using dry air. However, large scale drying of intake air is not economical. The same design can be modified for continuous operation by providing entry and exit doors at positions X and Y, respectively (Figure 15.15). Another type of drier known as drum drier is shown in

Figure 15.16. Here the raw material is a liquid or paste, or dough. It is dried by passing over a pair of heated rollers. These driers are used for milk, purees, mashes, etc. Note that the product is heated from the bottom while moisture is evolved at the top surface.

15.6 BAKING OVENS

Baking is defined as heating to a low temperature in an enclosure. Traditionally, “baking” refers to cooking certain food items such as bread and cakes in an oven. Technically, baking is used in a large number of nonfood related processes such as foundry (core baking), adhesive joining (curing), surface coating (vitreous enameling), paint drying and so on. Bread making requires baking at about 200-250°C. Core baking (CO_2) is done at a similar temperature range. Porcelain enamel baking requires 800-850°C. Baking temperatures for painted articles are in the range 120-180°C depending upon the type of paint. In the baking of bread and similar items, a mixture of CO_2 and steam is evolved which is harmless. In some processes such as paint drying or adhesive curing, solvents and other gases are evolved which are likely to be harmful and combustible. Consequently, in industrial ovens, arrangements to safely dispose of the evolved gases is required. As the temperatures in baking are low (except enamel

Figure 15.15 Batch Type Drying Oven.

Figure 15.16 Drum drier.

ling) a large number of heat sources are available to the designer. Paint drying can be done by using high intensity or infrared bulbs. Baking can be done with wood, electricity, or indirect heating by gas or oil. Radiant tubes with gas or steam are also suitable for many applications. Microwave heating is already discussed in Chapter 10. Due to the diversity of processes and heating techniques, a large variety of ovens is available. Some designs are shown in Figure 15.17. A simple oven using wood or coal is shown in Figure 15.17 (A).

It is built of ordinary brick masonary and consists of two chambers. The lower chamber is for burning the fuel. It may have a grate and an ash pit in the bottom. The upper chamber is used for baking. The hot combustion gases rise above and circulate around the baking chamber before exhausting at the top. There may or may not be a door to the baking chamber. Heat transfer is by conduction through the walls and convection around the chamber. Because of the brick work construction, the oven holds a lot of heat. The same design with a few modifications can be adapted for oil burning by installing a burner in the lower chamber. A cabinet-type oven is shown in Figure 15.17(B). The articles are kept in trays which are stacked on a rollout rack. The oven may operate on an electrical heater of sealed radiant tubes or gaseous fuel (natural gas). In both cases, the heaters or burners may be installed inside the cabinet. If oil burning is used, the burner is located outside the cabinet and combustion gases are circulated around the cabinet on the outer side. Thus heating is by convection .This avoids exposure of articles to combustion gases which may give an objectionable odor. Food baking produces moisture, air, or carbon dioxide. Many times, additional steam is injected to improve the crust of the baked item. There is a separate exhaust for cabinet gases. Many baking ovens for food have a rotating tray arrangements as shown in Figure 15.17 (C). This arrangement gives a better quality. The temperature and rotational speed is so adjusted that baking is completed in one revolution. Baking ovens for high volume production such as breads, cakes, and biscuits are of the continuous type. They use a moving metal band or woven mesh through the oven. The general construction is similar to a continuous furnace discussed in Section 15.2.4 (Figure 15.4). The muffle and belts are made of stainless steel or monel (Ni-Cu) alloys. A paint drying oven is shown in Figure 15.17. It is heated

Figure 15.17 Examples of typical baking ovens.

by arrays of lamps with reflectors. Tungsten, carbon filament, or quartz lamps are used. The article to be dried is suspended by hooks that are moved through the oven by an overhead chain. The lamps have a limited life. The glass bulbs and reflectors are tarnished or blackened by the solvent vapors. However, the construction and maintenance is easy. Similar designs are used for enameling, with heating accomplished by radiant tubes. In both the cases, it is necessary to dispose of the solvent fumes through an exhaust fan and stack.

15.7 FANS

We use fans for agitating or moving air or gases. In furnaces or ovens, they serve as circulators, moving the atmosphere in the enclosure. In heat exchangers or drying there are used as a heat transfer medium. In some applications, ejectors or exhaust fans help remove the confined or slow moving gases. In all such applications it is necessary to choose the correct fan for satisfactory and economical operation. In this section we will take a limited review of fans suitable in heating applications. For more information consult special books or literature by manufacturers. There are two basic types of fans. The classification is based on the flow of air through the fan. In “axial flow” fans (Figure 15.18(A)), the air enters and leaves along the axis or the shaft. The fans are made as propellers with a number of blades (usually 2–6) attached symmetrically around a hub fixed to a shaft. In passing through the blades, the air, gas, or steam acquires a velocity and pressure head.

Figure 15.18 Axial or propeller fan.

Radial flow or “centrifugal” fans (Figure 15.19(A)) have a rotating cage or scroll with blades or slots at the outer periphery. The blades may be straight or inclined in, or opposite to, the direction of rotation. Air is admitted at the center. It flows toward the beds under centrifugal force and exits through the slots. The cage rotates in a volute housing which collects the existing air and discharges through a tangential outlet.

For circulation in confined places such as furnace enclosures, axial fans are used. Here circulation and velocity are more important than the volume. These fans help to homogenize the atmosphere and assist natural convection. In applications such as waste heat exchangers, cooling beds, or drying, the volume required to be moved is large and the pressure requirements are also applicable. Here we use centrifugal fans. The main performance requirements are volume, pressure, and velocity of discharge. One more criteria of considerable interest to our purpose is the aerodynamic shape of the discharge. This defines the extent or spread of the discharge stream. This shape is very important in the choice of an axial fan to be used as a circulator. The aerodynamic cone shape depends on the profile of the impeller blades (Figure 15.18(B)).

The mechanical efficiency of fans is not very important to us as the fans usually consume only a small fraction of the total power of the furnace. Fans of all types display typical characteristics and are governed by the “fan laws.” These characteristics are shown by the manufacturer on performance curves. They show the behavior of pressure, power, and efficiency against percent rated delivery (m). If the fan is delivering to an open atmosphere without any restriction, the air delivered is 100% rated. If the fan outlet is closed the delivery is 0%. The air delivered at any delivery has a pressure (static) p and a velocity v. We have seen in Chapter 2 that the velocity can also be converted to pressure (Bernoulli’s principle), hence the total pressure of a fan at output is Static pressure velocity pressure Pa)+ = +p Vr 2 2 (Figure 15.19 Centrifugal fans or blowers.

where p is the air density. The fan characteristics usually show total and static pressures. The volume handled Q (m^3) is measured at the inlet and velocity is measured at the outlet by dividing Q by the outlet area. The typical characteristics of axial and centrifugal fans are shown in Figure 15.18(C), Figure 15.19(C). Note that these curves are not standard and will show some variation with the manufacturer's design. An important fact displayed by all fans is that they can be used over a wide range of delivery and pressure. We will have to carefully choose the desired combination. Manufacturers usually produce a range of fans with various sizes. It will be worth noting the influence of some parameters on the characteristics. The effects are roughly the same for both types of fans.

Effect of Rotational Speed (N rpm)

Increasing the design speed will increase the swept volume and hence, the discharge Q. The total pressure and power will also increase (power $\propto N^3$, pressure $\propto N^2$). Change in fan size (wheel or propeller diameter) D will also increase discharge Q, pressure ($P \propto N^2$), and power

(power $\propto N^5$). This assumes the speed to be same, i.e., design speed. For an axial fan to be used in an enclosure, the size of the latter will limit the maximum wheel diameter that can be accommodated. In the case of a centrifugal fan, the fan’s main requirements are delivery and enough pressure to overcome ducting resistance. Axial fans to be used at high temperatures (> 500 as in heat treatment furnaces) must be constructed from heat resistant materials such as inconel. They are usually operated at slow speeds as their main purpose is atmosphere circulation. Similar fans used in food or other ovens, can be fabricated from stainless steels. Axial fans for high temperatures are not standardized and will have to be designed by considering creep and corrosion. Their drive motor and gear are located outside, and the entry of the shaft and its bearings have to be sealed and cooled. Centrifugal fans usually operate at ambient temperature and are available in standard size.

15.8 SOME NEW MATERIALS

15.8.1 Carbon Foams

Foams made from basic materials like pitch or tar have recently been made available in both graphite (crystalline) or carbon (amorphous) forms. Presently, carbon foams are available at a

competitive price. Typical properties of these foams are:
Density 0.27
(2.2) gm/cm Thermal conductivity
0.25–25 Electrical resistivity
– Maximum temperature 650 air, 3000˚C
inert Tensile strength > 200
N/mm 2 The foams are available in several grades of strength and density. Presently, they are being explored for applications requiring adequate strength with low weight. Their heat resisting properties should find them suitable for high temperature applications. They can be easily machined and coated or sandwiched with metallic or ceramic materials. Incidentally, metal foams are also available. These foams the characteristic metal properties such as electrical and thermal conductivity but have low densities. Presently, aluminium and stainless steel foams are marketed.

15.8.2 Alumina Refractory Adhesive

Ceramic fiber materials are already discussed in Chapter 7. Boards and other shapes of these materials are extensively used in the construction of furnaces for walls and roofs. The boards are anchored to each other or the furnace structure by using metallic fasteners such as hooks, staples, or wires. However, these fasteners are costly as they are made from heat resistant alloys. They also act as thermal short circuits by providing a highly conducting path in an insulating matrix. Recently, an alumina adhesive has been made available.

This is a single-part water-based adhesive. It can be used for bonding low density (fiber) insulating materials. Thus, metallic anchors can be eliminated from wall or roof constructions.

15.8.3 Cast Basalt

Basalt is an igneous (volcanic origin) rock commonly occurring all over the world. It has a greenish-gray color. Its main constituents are silicates of Ca, Mg, Fe, Al (feldspars). Some varieties of basalt can be melted and cast into a number of shapes such as tiles and pipes. This material is very hard and wear resistant. It can withstand temperatures up to 1000–1200°C and is corrosion-resistant. It is extensively used in the lining of exhaust and flue ducts of fuel burning furnaces. They resist abrasion by ash particles in the gases. The material is also available as ready-mix concrete and can be used for masonary work of ducts.

Bibliography

CHAPTER 1 INTRODUCTION

Dryden, I.G.C., *The Efficient Use of Energy*. 2nd Ed., Butterworth Scientific, Oxford, 1982.

Glinkov, M.A. and Glinkov, G.M., *A General Theory of Furnaces*. Mir Publishers, Moscow, 1980.

Krivandin, V. and Markov, B., *Metallurgical Furnaces*. Mir Publishers, Moscow, 1980.

Trinks, W. and Mawhinney, M.H., *Industrial Furnaces*. 5th Ed., Vols. I and II, John Wiley & Sons, New York, 1953.

CHAPTER 2 FLUID DYNAMICS

Allen, J.E., *Aerodynamics*: *The Science of Air in Motion*. 3rd Ed., Allen Brothers and Father, Blythburgh, Suffolk, 1986.

Kazantsev, E.I., *Industrial Furnaces*. Mir Publishers, Moscow, 1977.

Nekrasov, B., *Hydraulics* (*For Aeronautical Engineers*). Mir Publishers, Moscow, 1971.

Stampar, E. and Koral, R., (Ed.). *Handbook of Air Conditioning, Heating & Ventilation*, 3rd Ed., Industrial Press, New York, 1979.

CHAPTERS 3 AND 4 STEADY STATE HEAT TRANSFER AND TRANSIENT CONDUCTION

Bejan, A., *Heat Transfer.* John Wiley & Sons, New York, 1993.

Carlslaw, H.S. and Jaeger, C., *Conduction of Heat in Solids.* Oxford University Press, Oxford, 1959.

Heisler, M.P., *Temperature Charts for Induction and Constant Temperature Heating.* Trans ASME, Vol. 6.9, 1947.

Incropera, F. and Dewitt, D.P., *Fundamentals of Heat and Mass Transfer.* 4th Ed., John Wiley & Sons, New York, 1996.

Isachenko, V.P., Osipova, V.A., and Sukomel, A.S., *Heat Transfer.* 3rd Ed., Mir Publishers, Moscow, 1977.

CHAPTERS 5 AND 6 FUELS AND THEIR PROPERTIES AND FUEL BURNING DEVICES

Francis, W., *Fuel Technology.* Vols. 1 and 2, Pergamon Press, Oxford, 1964.

Kazantsev, E.I., *Industrial Furnaces.* Mir Publishers, Moscow, 1977.

Roddan, M., *The Use of Fuel Oil in Furnaces for Iron and Steel Fabrication Industries*, Shell B.P.-Fuel Oil Dept., U.K., 1950.

Saxon, F., Sedgewick, G., and Proffitt, R., *Industrial and Commercial Gas Installation Practice.* Vol. 3. Butterworth, Tolley Croydon, U.K., 2000.

Technical Literature (*Burners*), Hauck Manufacturing Company, Lebanon PA, 1990.

Technical Literature (*Packaged Burners*), ECOFLAM Company, Resana, Italy, 1999.

CHAPTER 7 REFRACTORIES

Brandes E.A. and Brook, G.B., *Smithells Metal Reference Book.* 7th Ed., Butterworth-Heinemann, Oxford, 1998.

Fanzott, S.M., *Modern Refractory Technique.* Springer-Verlag, Modern Industries AG & Co., Landsburgh, Germany, 1991.

Kazantsev, E.I., *Industrial Furnaces.* Mir Publishers, Moscow, 1977.

Technical Literature, Didier-Werke AG, Wiesbaden, Germany.

Technical Literature, Harbinson Walker Co.

CHAPTER 8 METALS AND ALLOYS FOR HIGH TEMPERATURE APPLICATIONS

Brandes, E.A. and Brook, G.B., *Smithells Metal Reference Book*. 7th Ed., Butterworth-Heinemann, Oxford, 1998.

Metals Handbook, Vol. I, 9th Ed., American Society for Metals, Metals Park, Ohio 1961.

Robert E. Reed Hill, *Physical Metallurgy Principles*, D. Van Nostrand Reinhold, Princeton, NJ, 1964.

Shrier, I.L., Jarman, R.A., and Burnsteirn, G.T., Ed., *Corrosion*, Vols. I & II, 3rd Ed., Butterworth-Heinemann, Oxford, 1994.

Wiggin Nickel Alloy, Wiggin Heat Resisting Alloys, Wiggin Nickel Alloys for Heat Treatment Equipment, Henry Wiggin & Co. Ltd., Hereford, U.K.

CHAPTER 9 ELECTRIC RESISTANCE HEATING

Davies, E.J., *Conduction and Induction Heating*. IEE Power Engineering Series II, Peter Peregrinus Ltd., London, 1990.

Kanthal Handbook, Resistance Heating Alloys for Appliances and Heaters, Kanthal Heating Technology, Hallstahammar, Sweden, 1986.

Kanthal Super Handbook, Kanthal Furnace Products, Hallstahammar, Sweden, 1986.

Paschkis, V. and Presson, J., *Industrial Electric Furnaces and Appliances*. 2nd Ed., Interscience, New York, 1960.

CHAPTER 10 HIGH FREQUENCY HEATING

Aguilar, J. and Rodriguey, J., Microwave as an Energy Source for Production of B-Sic *Journal of Microwave Power and Electromagnetic Energy*. Vol. 36, No. 3, 2001.

Davies, E.J., *Conduction and Induction Heating*. IEE Power Engineering Series II, Peter Peregrinus Ltd., London, 1990.

Meredith, R., *Engineering Handbook of Industrial Microwave Heating*. Institute of Electrical Engineers, London, 1998.

Paschkis, V. and Presson, J., *Industrial Electric Furnaces and Applications*. 2nd Ed., Interscience, New York, 1960.

Ryder, J.D., *Engineering Electronics*. 2nd Ed., McGraw-Hill, New York, 1967.

CHAPTER 11 CONCENTRATED HEAT SOURCES

Electron Beam Welding. Commercial Literature, Leybold Heraeus Gmbh, Hanau, Germany.

Ready, J.F., *Engineering Application of Lasers*. 2nd Ed., Academic Press, New York, 1977.

Rykalin, N., Uglov, A., Zuev, I., and Kokora, A., *Laser and Electron Beam. Material Processing Handbook*, Mir Publishers, Moscow, 1988.

Silfvast, W.T., *Laser Fundamentals*. Cambridge University Press, Cambridge, 1998.

CHAPTER 12 VACUUM ENGINEERING

Chamers, A., Fitch, R.K., and Halliday, B.S., *Basic Vacuum Technology*. 2nd Ed., Industrial and Physical Publishing, Bristol, 1998.

Roth, A., *Vacuum Technology*. 3rd Ed., Elsevier, Amsterdam, The Netherlands, 1990.

Steinherz, H.A., *Handbook of High Vacuum Engineering*. Reinhold Publishing Corporation, New York, 1963.

CHAPTER 13 PROTECTIVE ATMOSPHERES

Hotchkiss, A.G. and Weber, H.M., *Protective Atmospheres*. John Wiley & Sons, New York, 1953.

Metals Handbook. Vol. 2, 9th Ed., Metals Park, Ohio, 1980.

Trinks, W. and Mawhinny, M.H., *Industrial Furnaces*. Vol. II, 4th Ed., John Wiley & Sons, New York, 1967.

CHAPTER 14 TEMPERATURE MEASUREMENT

IR Answers and Solutions Handbook. IRCON Inc, Niles, IL, 1999.

Knight, J.R. and Rhys., D.W., *The Platinum Metals in Thermometry.* Publication No. 2244, Engelhard Industries Ltd., London, 1961.

Leigh, J.R., *Temperature Measurement and Control*. Peter Peregrinus, London, 1991.

Lide, D.R., (Editor-in-Chief), *CRC Handbook of Chemistry and Physics.* 80th Ed., CRC Press, Boca Raton, FL, 2000.

McGee, T.D., *Principles and Methods of Temperature Measurement*. Wiley Interscience, New York, 1988.

Quinn, J.J., *Temperature*. Academic Press, London, 1993.

CHAPTER 15 MISCELLANY AND FURTHER

Bird, R.B., Stewart, W.E., and Lightfoot, E.N., *Transport Phenomena*. 2nd Ed., John Wiley & Sons, Singapore, 2000.

Charms, S.E., *The Fundamentals of Food Engineering*. AVI Publishing, Westport, CT, 1998.

Perry, J.N., (Ed.), Chemical Engineers Handbook. 3rd Ed., McGraw Hill, New York, 1950.

Potter, N.N. and Hotchkiss, J.M., *Food Science*. 5th Ed., Chapman & Hall, New York, 1995.

HANDBOOKS FOR GENERAL REFERENCE AND DATA

Brands, E.A. and Brook, G.B. (Ed.), *Smithells Metals Reference Book*. 7th Ed., Butterworth-Heinemann, Oxford, 1998.

Kazanstev, E.I., *Industrial Furnaces*. Mir Publishers, Moscow, 1977.

Lide, D.R. (Ed.), *Handbook of Chemistry and Physics*. 80th Ed., CRC Press, Boca Raton, FL, 1999.

American Society for Metals, *Metals Handbook*. 9th Ed., Vols. I & II, Metals Park, Ohio, 1980.