PRINCIPLES OF REFRIGERATION

FIFTH EDITION

ROY J. DOSSAT | THOMAS J. HORAN

Principles of Refrigeration

Fifth Edition

Roy Dossat
Thomas J. Horan, P.E.
Ferris State University

Prentice Hall
Upper Saddle River, New Jersey
Columbus, Ohio

Library of Congress Cataloging-in-Publication Data

Dossat, Roy J.
Principles of refrigeration.—5th ed. / Roy J. Dossat, Thomas J. Horan.
p. cm.
Includes index.
ISBN 0-13-027270-1
1. Refrigeration and refrigerating machinery. I. Horan, Thomas J., 1957– II. Title.

TP492 .D65 2001
621.5'6—dc21 2001026708

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This book was set in New Caledonia and Frutiger by TechBooks,
and was printed and bound by Courier Kendallville, Inc. The cover was printed by The Lehigh Press, Inc.

Pearson Education Ltd., *London*
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10 9 8 7 6 5
ISBN: 0-13-027270-1

To Kathy
When we married, God gave me a gift beyond measure . . .
Thank you for your love and friendship.

And in loving remembrance of Hazel

Preface

Principles of Refrigeration has been one of the foundation textbooks in the refrigeration field since Roy Dossat wrote the first edition in 1961. Through four additional editions, Mr. Dossat presented the fundamentals of refrigeration theory, components and systems to students who were preparing to enter an occupation rich with opportunities. I am honored that Mr. Dossat selected me to carry on his tradition of excellence by awarding me the opportunity to write the fifth edition of his textbook.

Having taught HVAC/R students at Ferris State University, I have discovered the strengths and weaknesses that students have in developing the study habits and analytical skills they need to prepare themselves as successful technicians, technologists and engineers. I know from personal experience that if students graduate without the ability to build upon their educational experience, they will be limited in their advancement and opportunities. If an instructor can teach students how processes can be broken down into the fundamental principles, they will be able to correctly analyze and troubleshoot systems and processes that were not presented in a book or classroom activities. I have used this information, along with feedback from many faculty and graduates who used the previous editions of this book, as the basis for writing the fifth edition. The following paragraphs outline some of the significant changes in the text.

- This book is intended for students of two- and four-year refrigeration programs who have previously completed a fundamental course in refrigeration systems. Although such a course is not a prerequisite, this edition was written to advance the student's knowledge of refrigeration systems by presenting more detailed information about the refrigeration cycle, component design and system operation than is normally found in an introductory text. The book presents the science behind the operation of systems as a method of building solid analytical skills that will raise the student above his or her peers when it comes to determining the cause of system malfunctions and inefficiencies and to selecting the best component to modify a system or replace a failed part.
- The first eleven chapters of the book have been significantly enhanced. The thermodynamics, heat transfer, mechanics and physics topics have been expanded. Rather than a review, these topics are now thoroughly explained in a manner that allows a student to comprehend the sciences related to refrigeration processes. The information develops the foundation needed to understand the underlying theory of refrigeration component and system operation. This part of the book may be a comprehensive review for students in programs where these subjects are taught as separate courses, but it is also an excellent presentation for those who use this book as the primary resource for this information.
- All of the information presented in Parts 1 through 3 is used throughout the remainder of the text to explain how refrigeration components function. There is no esoteric or "nice-to-know" information presented in this section, so classroom time can be used more efficiently. The refrigeration cycles show how changes in system variables are transferred through the system. This information develops the reader's analytical skills.
- The book presents the formulas, units and proofs that support the information presented in the chapters in Parts 2, 3 and 4. The mathematical material is

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intended to be a resource in developing the relationships that exist in the processes rather than as a mathematical exercise. These relationships will be applied throughout the remainder of the text; the formulas will not. The chapters can be just as effective in training a technician without the associated formulas, but they are there to show from whence the information presented in the chapter was derived. In support of this presentation method, all of the mathematics related to the chapter material is presented in the last section of the chapter labeled "Optional Analysis." This section can be skipped or assigned as extra credit material.

- The formulas are presented in Inch-Pound and System International units. All variables are written with the appropriate units to show students how to properly approach problems by applying the fundamental relationships. This reduces the memorization of formulas and increases the understanding of the interrelationships between the sciences. The use of SI units also exposes students to the associated methods of measuring variables, so they become familiar with the information found on product literature and equipment nameplates. The formulas and examples are used to show relationships without making the book appear to be a engineering text.
- Most of the topics in the 4th edition remain in this edition, although they have been reorganized to improve the flow of information. The entire book was rewritten using a style that is more closely related with books, manuals and other material read by today's students.
- Some of the chapters that appeared too long have been split into two smaller chapters, so they are easier for the instructor to build lectures around and less intimidating to students. Each chapter also includes true-and-false questions along with multiple-choice questions to highlight the important information presented in the chapter.

Through these and other changes, I have taken a very important, comprehensive and effective resource and made it easier for both student and instructor to use and comprehend the information. Through the use of smaller sentences, fewer assumptions, more explanation and a logical presentation format, I believe I have succeeded in developing a new edition of the book that honors Mr. Dossat's intent to help those who have chosen the refrigeration field for their career. This edition will be more appealing to faculty who currently use the book and more inviting to those who are looking for a comprehensive textbook for their students.

Thomas Horan

Acknowledgments

I want to thank the people who helped to make the project a reality. I especially thank Mr. Roy Dossat and his family for trusting in my ability to develop this edition of his much-requested book. I also express my deep appreciation to my wife Kathy and daughters Holly, Heather, Michelle, and Kelly for their love and support through book three.

A big thank you to Eileen O'Reilly of Solve-It and to Carolyn Greene, Denise Keller, and Susan Free of TechBooks, who took a manuscript with many rough edges and finished it in a manner that makes it so much more than the original. You were an excellent team.

I also want to thank the following reviewers who helped me fine tune the text for accuracy and content: Donald Lynch, Rend Lake College; and Gorden Preiss, New England Institute of Technology.

Thanks to Ed Francis, senior editor at Prentice Hall, and his staff for their assistance.

Once again, it is my sincere hope that this text will build the talents and self-confidence of the reader so that she or he may enjoy a lifelong career in the HVAC/R field.

Contents

PART 1

Introduction to Mechanical Refrigeration and Food Preservation

The primary application of mechanical refrigeration systems is to preserve food. Secondary applications include comfort air-conditioning, medical equipment cooling and industrial process cooling. This section of the text introduces the reader to the importance of refrigeration, categories of refrigeration equipment and to the methods and equipment used to preserve food.

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CHAPTER 1

Introduction to Refrigeration

INTRODUCTION

The refrigeration industry evolved in response to the pressing need to preserve and transport food for expanding populations. It continued to grow as comfort and industrial air-conditioning applications were developed. This chapter presents an overview of the refrigeration industry and the equipment designed, installed and serviced by people employed in this field.

OBJECTIVES

Upon completion of this chapter, the student will be able to:

- *List several refrigeration and air-conditioning processes that incorporate mechanical refrigeration equipment*
- *List and describe the five classifications of refrigeration*
- *Describe the design characteristics of the equipment used in food storage*

1.1 The History and Scope of the Industry

Mechanical refrigeration has grown into an expansive industry that permits societies to grow and prosper.

The mechanical equipment used in the early days of refrigeration was bulky, inefficient and relatively expensive. The design and operating characteristics of this equipment usually required a mechanic or operating engineer to be on duty at all times. These characteristics limited the use of mechanical refrigeration to storage warehouses and large ice manufacturing and meat-packing plants.

The refrigeration industry rapidly expanded during the first half of the 20th century. The development of precision manufacturing methods, safer refrigerants and the invention of the fractional horsepower electric motor contributed to this explosive growth. These innovations made it possible to produce smaller, more efficient refrigeration equipment for commercial and residential use. That growth continues as new motor technology, refrigerants and microprocessor-based control systems are incorporated into equipment. Today, there are few homes or business establishments in the United States that do not have one or more mechanical refrigeration units being used in refrigerators, freezers, small air conditioners and dehumidifiers.

Few people outside of those directly connected with the refrigeration trade are aware of the significant part that the industry has played in the development of highly

technological societies. Nor do they realize the extent to which these societies are dependent upon mechanical refrigeration for their very existence. For example, refrigeration systems make it possible to:

1. process, freeze, store, transport and display perishable products
2. preserve food in sufficient quantities to feed growing populations
3. make buildings inhabitable in the summer heat
4. develop new chemicals, plastics, synthetic rubber and other new useful materials
5. construct large water dams, roads, tunnels, foundations, mining shafts and other concrete structures
6. produce medicines, medical procedures and test equipment
7. increase the product yield from a fixed quantity of raw materials
8. increase the efficiency of textile and paper processes to reduce costs
9. improve methods of hardening steels for machine tools

This list represents only a few of the hundreds of ways that mechanical refrigeration is being used today. Many new applications in the electronic, laboratory and medical fields are found each year. Perhaps the only trend slowing the current growth of the refrigeration industry is the lack of trained technical personnel to design, build and service this equipment.

1.2 Classification of Applications

Mechanical refrigeration systems are placed in one of five categories, based upon their design function.

For convenience of study, refrigeration applications may be grouped into five general categories:

1. domestic refrigeration
2. commercial refrigeration
3. industrial refrigeration
4. marine and transportation refrigeration
5. air-conditioning

The processes and equipment in each of these categories are described in subsequent chapters. Note that the boundaries of these categories are not precisely defined, allowing some applications to be included in more than one category.

1.2.1 DOMESTIC REFRIGERATION

The *domestic refrigeration* category includes all household refrigerator and freezer applications. The food storage volume of these units is typically less than 25 cubic feet, to permit the unit to fit in a typical home. These units are small in size, having power ratings of between one-twentieth and one-half horsepower. Their general design incorporates an induction motor that is hermetically sealed within a steel compressor dome. Domestic refrigeration represents a significant portion of the refrigeration industry because of the substantial number of units in service.

1.2.2 COMMERCIAL REFRIGERATION

Commercial refrigeration focuses on the design, installation and maintenance of refrigerated fixtures of the types used in retail stores, restaurants, hotels, laboratories, hospitals and other institutions. These units are used to store, display, process and dispense perishable commodities. Large reach-in and walk-in refrigerators and freezers including those used in scientific, manufacturing, medical and computer laboratories are the more common commercial refrigeration equipment currently found in service.

1.2.3 INDUSTRIAL REFRIGERATION

Industrial refrigeration applications are often confused with those in the commercial refrigeration category because the division between these two areas is not clearly defined. As a general rule, industrial applications are generally much larger than their commercial counterparts. They also have the distinguishing requirement of needing an attendant on duty while the equipment is operating. This person is usually an operating engineer licensed by the municipality where the equipment is located. Typical industrial applications include ice-manufacturing plants, large food-packing plants (meat, fish, poultry and frozen foods), breweries and creameries. Other industrial applications include refrigeration requirements for oil refineries, chemical and rubber plants. Industrial applications are also used to supply the cooling requirements of large medical, office and university campuses.

1.2.4 MARINE AND TRANSPORTATION REFRIGERATION

Marine refrigeration refers to cooling and freezing systems aboard large ocean vessels. It includes requirements for fishing boats, vessels transporting perishable cargo and for the ship's stores on vessels of all kinds. *Transportation refrigeration* refers to equipment used in long distance and local delivery trucks and refrigerated railway cars. Transportation refrigeration does not include comfort air-conditioning applications found in automobiles, trains, airplanes, trucks and other vehicles and vessels. These applications fall into the air-conditioning category.

1.2.5 AIR-CONDITIONING

Air-conditioning is concerned with the characteristics of the air within a particular area called a zone. A zone may be one or more rooms having the same conditioning requirements or an entire building or facility. In addition to dry bulb temperature, air-conditioning characteristics may include:

1. humidity
2. air motion
3. air cleanliness
4. air purity

Air-conditioning applications are classified as either comfort or industrial processes, based upon their design intent. Any application whose primary function is the conditioning of air for human comfort is classified as *comfort air-conditioning*. Typical comfort air-conditioning applications are found in homes, schools, offices, houses of worship, hotels, retail stores, public buildings, factories, automobiles, buses, trains, planes and ships. The remaining noncomfort applications are called *industrial air-conditioning*. Industrial air-conditioning processes are used to:

1. control the moisture content of hygroscopic (moisture absorbing) materials
2. control the rate of chemical and biochemical reactions
3. limit the variations in size due to thermal expansion and contraction of precision manufactured articles
4. provide clean, filtered air essential for trouble-free operation of equipment and instrumentation
5. provide clean, filtered air essential to the production of quality products

In addition to their primary design function, industrial air-conditioning systems may also provide some comfort air-conditioning. Under these circumstances, the equipment is operated to maintain the requirements of the industrial process with the secondary function of comfort air-conditioning as an accepted outcome. It is not an essential part of the industrial system's design.

1.3 Commercial Refrigerators

The term commercial refrigerator is usually applied to the ready-built and custom-built refrigerated fixtures of the type used by retail stores and markets, hotels, restaurants and institutions.

Commercial equipment is used for processing, storing, displaying and dispensing perishable commodities. Although there are a number of special-purpose refrigerated fixtures which defy classification, most commercial fixtures can be grouped into three principal categories:

1. reach-in refrigerators
2. walk-in coolers
3. display cases

1.3.1 REACH-IN REFRIGERATORS

The reach-in refrigerator is probably the most versatile and the most widely used of all commercial fixtures. Applications are found in institutions of all kinds, including grocery stores, meat markets, bakeries, drug stores, lunch counters, restaurants, florists and hotels. Whereas some reach-in refrigerators serve only a storage function, others are used for both storage and display. Figure 1-1 depicts a side view of a glass door, frozen food reach-in unit. The glass door suggests that the unit will be used for display and storage purposes because units that are only used for storage typically have solid doors. A solid door has a lower overall heat transfer coefficient, making the unit efficient for nondisplaying applications.

1.3.2 WALK-IN COOLERS

Walk-in coolers are primarily storage fixtures. They are available in a wide variety of sizes to fit almost any need. Nearly all retail stores, markets, hotels, restaurants and institutions employ one or more walk-in coolers for the storage of perishables. Walk-in coolers are designed to

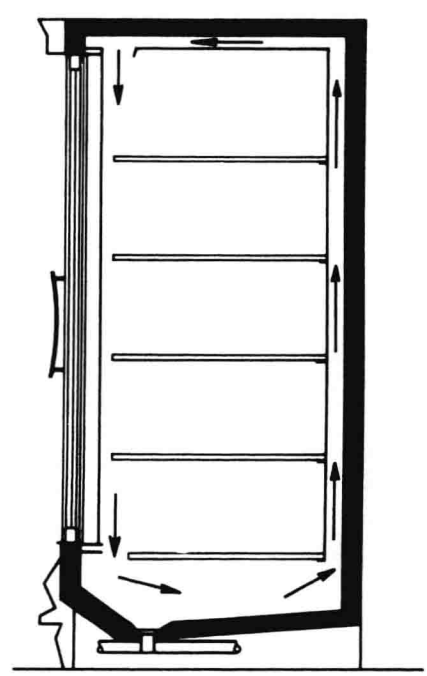

Fig. 1-1 Glass door, frozen food reach-in. (Reprinted by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, from the 1994 *ASHRAE Handbook—Refrigeration.*)

allow two- or four-wheel carts to move freely through the door, permitting the loading of large boxes and cartons of product.

For short-term storage some walk-in coolers also function as display units. These units are equipped with glazed reach-in doors along one or more of their sides. This feature is especially convenient for storing, displaying and dispensing dairy products, eggs, beverages and floral arrangements. Walk-in coolers with reach-in doors are widely used in grocery stores, convenience stores, florists and shopping clubs.

1.3.3 DISPLAY CASES

The principal function of any kind of display fixture is to exhibit the product or commodity as attractively as possible in order to stimulate sales. Therefore, in the design of these refrigerated fixtures, first consideration is given to the displaying of the product. Consequently, the final design of the unit is not necessarily compatible with providing optimum storage conditions for the products being displayed. As a result, the storage life of a product is compromised in order to increase potential sales. The storage life for typical products in a display case ranges from a few hours (fresh salads) to several weeks depending on the type of product, its packaging and the fixture's characteristics.

Display fixtures are of two general types: the *service case* from which the customer is usually served by an attendant and the *self-service case* from which customers serve themselves. The service case is used in smaller groceries, meat markets and bakeries. Side views of typical service cases are shown in Figures 1-2 and 1-3.

Self-service cases are very popular in supermarkets and similar self-service establishments. They are

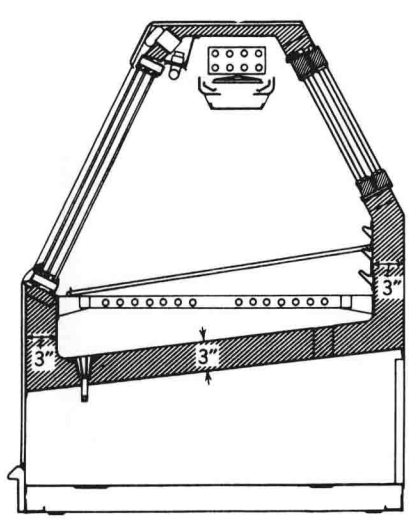

Fig. 1-2 Conventional single-duty service case for displaying meats. (Courtesy of Tyler Refrigeration Corporation.)

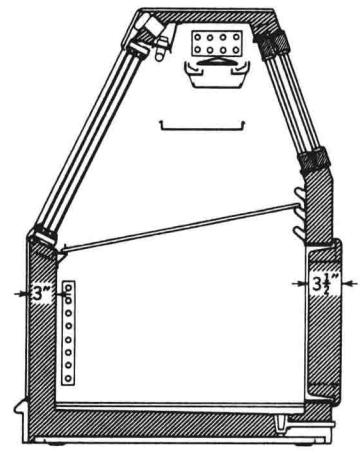

Fig. 1-3 Double-duty service case for the display and storage of meats. (Courtesy of Tyler Refrigeration Corporation.)

available as either open or closed units. These units are used to display meat, vegetables, fruit, frozen foods, ice cream, dairy products, salads and delicatessen items. Designs are available for both wall and island installation. Some units provide additional storage space under the display section. The choice of case varies with the particular type of product being displayed. Several of the more popular types of open self-service cases are shown in Figures 1-4 through 1-7.

1.3.4 SPECIAL PURPOSE FIXTURES

Although all of the refrigeration fixtures highlighted in the preceding subsections are available in a variety of designs to satisfy the specific requirements of individual products and applications, a number of special purpose

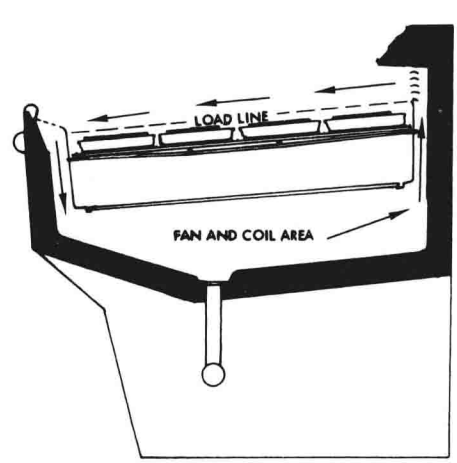

Fig. 1-4 Single-deck meat display refrigerator. (Reprinted by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, from the 1994 *ASHRAE Handbook—Refrigeration.*)

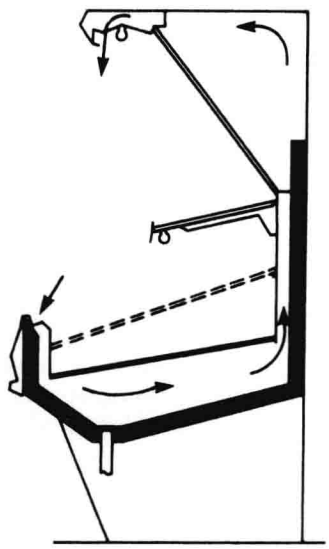

Fig. 1-5 Multiple-deck fruit and produce refrigerator. (Reprinted by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, from the *ASHRAE Handbook—Refrigeration.*)

fixtures are manufactured that may or may not fall into one of the three general categories already mentioned. Some of the more common special purpose fixtures are beverage and dairy farm milk coolers, countertop milk

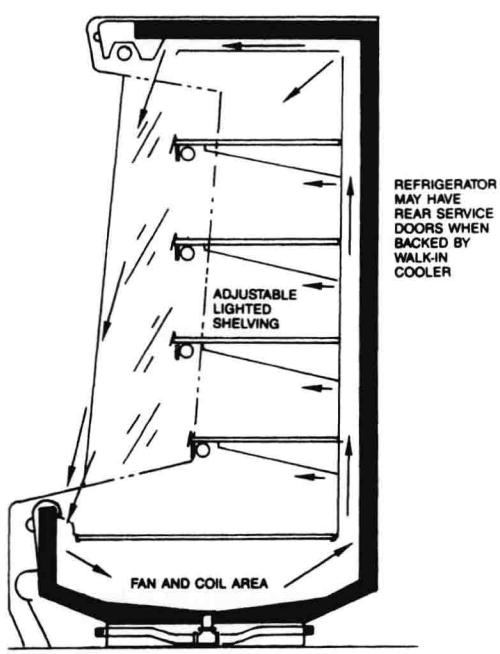

Fig. 1-6 Multi-deck dairy refrigerator. (Reprinted by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, from the 1994 *ASHRAE Handbook—Refrigeration.*)

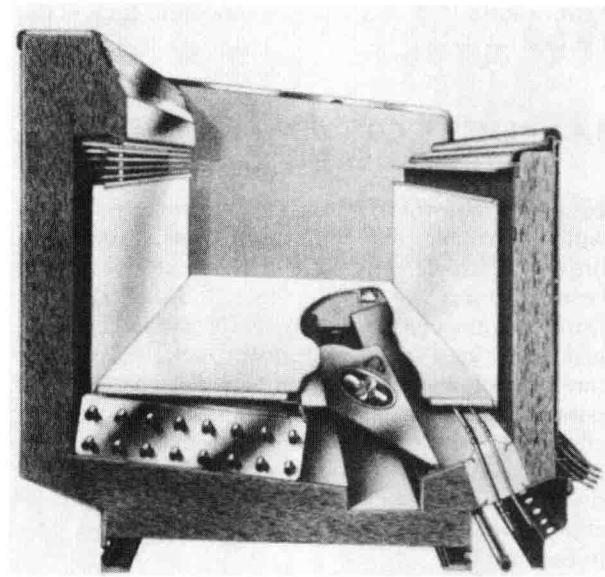

Fig. 1-7 Open-type display case for frozen foods and ice cream. (Courtesy of Tyler Refrigeration Corporation.)

and beverage dispensers, salad bars, ice-cream makers, water coolers, ice makers, back-bar refrigerators, florist boxes, dough retarders, candy cases, canned product dispensers and mortuary refrigerators.

1.4 Condensing Equipment

Each commercial refrigerated fixture has a condensing unit that is located either in the case or at a remote location.

Condensing equipment is used to transfer the heat absorbed from the product to a location outside of the refrigerated space. The condensing unit consists of a compressor that circulates the refrigerant through the system and a heat exchanger that transfers the heat to a cooler ambient. The capacity of these compressors and condensing heat exchangers range in size from one-half to 30 horsepower. The heat exchangers are typically air-cooled although some water-cooled and evaporative condensers are still being specified.

The condensers used may be an integral part of a condensing unit, located adjacent to the compressor, or they may be located in a place that is remote from the compressors. Fixtures having integral condensing units are installed in a manner that allows for sufficient air flow through the condenser and access to the coils for periodic cleaning. Increases in water and sewer costs, along with the need for water treatment systems and chemicals, limit water-cooled condenser applications. In either case, condensers are generously sized so that they are as energy-efficient as is practical. Recommended sizing for remote air-cooled condensers is a 10°F (5.5°C) temperature difference (TD) for low-temperature

fixtures and a 15°F (8.3°C) TD for medium-temperature fixtures.

1.4.1 REMOTE CONDENSING UNIT APPLICATIONS

In applications where a number of fixtures are operating with comparable temperature set points, a single compressor rack located in a basement or exterior zone can be used to service all of the cases. In this design, each fixture is connected to the remote suction and liquid line headers located at the compressor rack. Individual fixture controls allow for different cabinet operating temperatures. The condensers for these systems are generally air-cooled and located remote from the compressor rack. These systems are designed to operate in a manner that reduces the initial cost, maintenance cost and operating costs of the fixtures. A multiple unit rack is shown in Figure 1-8.

In applications where each fixture has its own remotely located condensing unit, a refrigerant line set (suction and liquid piping) connects the fixture with its compressor. These condensing units are often mounted on racks stacked two or three high and located in a well ventilated machine room. They can also be installed outdoors if they are adequately protected against the effects of the sun and weather.

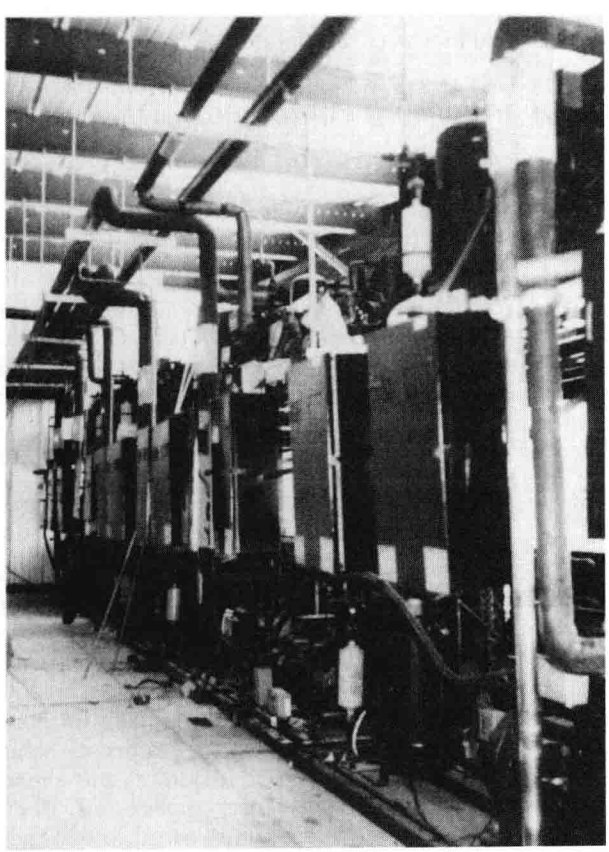

Fig. 1-8 Condensing units connected to various supermarket refrigerated display and storage fixtures are mounted two high on an outdoor sheltered rack.

1.5 Summary

The material in this chapter constitutes a brief survey of a few of the many applications of mechanical refrigeration, with special emphasis given to the area of commercial refrigeration. The applications of mechanical refrigeration are too many and too varied to permit detailed consideration of each and every type. Fortunately, this is neither necessary nor desirable since methods of system design and equipment selection are practically the same for all types of applications. Commercial refrigeration was selected for emphasis because this area embraces a wide range of applications and because the problems encountered in this area are representative of those in the other areas. Therefore, even though the discussion in this chapter and in those that follow deals chiefly with commercial refrigeration, the principles of system design and the methods of equipment selection developed therein may be applied to all types of mechanical refrigeration applications. Most commercial refrigeration applications, particularly those concerned with product storage, involve air-conditioning in that they ordinarily include tight control of the temperature, humidity, motion and cleanliness of the air in the refrigerated space.

1.6 Exercises

Determine if the following statements are true or false. Circle T if the statement is TRUE and F if the statement is FALSE. If any part of the statement is false, the entire statement is false.

1. T F Mechanical refrigeration has played a fundamental role in the development of societies throughout the world.

2. T F Auto air-conditioning processes are classified as Transportation Refrigeration.

3. T F Industrial air-conditioning processes can maintain control of temperature, humidity and the air motion within a zone.

4. T F Walk-in coolers are a residential refrigeration application.

5. T F A service display case is typically found in self-service facilities.

6. T F Condensers are used to absorb heat from the food product in a display case.

7. T F The reach-in refrigerator is the most versatile commercial fixture.

8. T F Remote air-cooled condensers used for low-temperature fixtures are selected to operate with a 10°F (5.5°C) TD.

9. T F Several fixtures operating with similar temperature set points can employ a single compressor rack.

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