Principles of Heating Ventilating and Air Conditioning

8th Edition

Based on the 2017 *ASHRAE Handbook—Fundamentals*

Ronald H. Howell

ASHRAE®

PRINCIPLES OF HEATING VENTILATING AND AIR CONDITIONING

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The following authors contributed significantly to the textbook *Principles of Heating, Ventilation, and Air Conditioning.* They recently passed away and were not part of the 2017 revisions.

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2017 *ASHRAE Handbook—Fundamentals*

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PREFACE

Principles of Heating, Ventilating, and Air Conditioning, a textbook based on the 2017 *ASHRAE Handbook—Fundamentals*, should provide an attractive text for air-conditioning courses at engineering colleges and technical institutes. The text has been developed to give broad and current coverage of the heating, ventilation, and air-conditioning field when combined with the 2017 *ASHRAE Handbook—Fundamentals*.

The book should prove most suitable as a textbook and subsequent reference book for (a) undergraduate engineering courses in the general field of HVAC, (b) similar courses at technical institutes, (c) continuing education and refresher short courses for engineers, and (d) adult education courses for nonengineers. It contains more material than can normally be covered in a one-semester course. However, several different single-semester or shorter courses can be easily planned by merely eliminating the chapters and/or parts that are least applicable to the objectives of the particular course. This text will also readily aid in self-instruction of the 2017 *ASHRAE Handbook—Fundamentals* by engineers wishing to develop their competence in the HVAC&R field.

Although numerous references are made to the other ASHRAE Handbook volumes, sufficient material has been included from these to make this text complete enough for various courses in the HVAC&R field. The material covered for various audiences in regular university courses, technical institute courses, and short courses can and will vary greatly. This textbook needed to be complete to satisfy all of these anticipated uses and needs. Toward this end, the following major sections are included:

Part I	General Concepts, Chapters 1–10
Part II	Air-Conditioning Systems, Chapters 11–16
Part III	HVAC&R Equipment, Chapters 17–20

Although the 2017 *ASHRAE Handbook—Fundamentals* is published in an SI edition, which uses international units, and an inch-pound (I-P) edition, this single version of *Principles of Heating, Ventilating, and Air Conditioning* is designed to serve the I-P edition with some SI interspersed throughout.

There are several significant changes in this edition. Chapter 4 has new values for climatic design information. Chapter 7 has been extensively revised with new design data. These changes make *Principles* compatible with the 2017 *ASHRAE Handbook—Fundamentals*. In addition, the chapters on system design and equipment have been significantly revised to reflect recent changes and concepts in contemporary heating and air-conditioning system practices. Also, the *Solutions Manual* has been extensively edited.

A particular point of confusion must be pointed out. Because this book was developed to be used with the ASHRAE Handbook's *Fundamentals* volume, a number of tables and figures have been reproduced in the original form, complete with references to material elsewhere in *Fundamentals* (not in this book). Thus, if the subheading in the table or figure indicates that it is a *Fundamentals* table or figure, then all references to other locations, equations, tables, etc., refer to those in *Fundamentals*, not in *Principles*.

Dr. Harry Sauer, Jr., one of the co-authors of this textbook, passed away in June 2008. Likewise, William J. Coad was also a co-author of this textbook and passed away in August 2014. Both Dr. Sauer and Mr. Coad made significant contributions to the book.

September 2017 Ronald H. Howell

Chapter 1

BACKGROUND

This chapter provides a brief background on the heating, ventilating, air-conditioning, and refrigeration (HVAC&R) field and industry, including the early history and some significant developments. An introduction to a few basic concepts is included along with suggestions for further reading.

1.1 Introduction

On the National Academy of Engineering's list of engineering achievements "that had the greatest impact on the quality of life in the 20th century," *air conditioning and refrigeration* came in tenth, indicating the great significance of this field in the world. With many people in the United States spending nearly 90% of their time indoors, it is hardly surprising that providing a comfortable and healthy indoor environment is a major factor in life today. In fact, over $33 billion of air-conditioning equipment was sold in the US during the year 2010 alone.

Air-conditioning systems usually provide year-round control of several air *conditions*, namely, temperature, humidity, cleanliness, and air motion. These systems may also be referred to as *environmental control systems*, although today they are usually called heating, ventilating, and air-conditioning (HVAC) systems.

The primary function of an HVAC system is either (1) the generation and maintenance of comfort for occupants in a conditioned space; or (2) the supplying of a set of environmental conditions (high temperature and high humidity, low temperature and high humidity, etc.) for a process or product within a space. Human comfort design conditions are quite different from conditions required in textile mills or for grain storage and vary with factors such as time of year and the activity and clothing levels of the occupants.

If improperly sized equipment or the wrong type of equipment is used, the desired environmental conditions usually will not be met. Furthermore, improperly selected and/or sized equipment normally requires excess power and/or energy and may have a higher initial cost. The design of an HVAC system includes calculation of the maximum heating and cooling loads for the spaces to be served, selection of the type of system to be used, calculation of piping and/or duct sizes, selection of the type and size of equipment (heat exchangers, boilers, chillers, fans, etc.), and a layout of the system, with cost, indoor air quality, and energy conservation being considered along the way. Some criteria to be considered are

- Temperature, humidity, and space pressure requirements
- Capacity requirements
- Equipment redundancy
- Spatial requirements
- First cost
- Operating cost
- Maintenance cost
- Reliability
- Flexibility
- Life-cycle cost analysis

The following details should be considered to properly design an air-conditioning system:

1. The location, elevation, and orientation of the structure so that the effects of the weather (wind, sun, and precipitation) on the building heating and cooling loads can be anticipated.
2. The building size (wall area, roof area, glass area, floor area, and so forth).
3. The building shape (L-shaped, A-shaped, rectangular, etc.), which influences equipment location, type of heating and cooling system used, and duct or piping locations.
4. The space use characteristics. Will there be different users (office, bank, school, dance studios, etc.) of the space from year to year? Will there be different concurrent requirements from the tenants? Will there be night setback of the temperature controller or intermittent use of the building's facilities?
5. The type of material (wood, masonry, metal, and so forth) used in the construction of the building. What is the expected quality of the construction?
6. The type of fenestration (light transmitting partition) used, its location in the building, and how it might be shaded. Is glass heat absorbing, reflective, colored, etc.?
7. The types of doors (sliding, swinging, revolving) and windows (sealed, wood or metal frames, etc.) used. What is their expected use? This will affect the amount of infiltration air.
8. The expected occupancy for the space and the time schedule of this occupancy.
9. Type and location of lighting. Types of appliances and electrical machinery in the space and their expected use.
10. Location of electric, gas, and water services. These services should be integrated with the locations of the heating and air-conditioning duct, piping, and equipment.

11. Ventilation requirements for the structure. Does it require 100% outdoor air, a given number of CFM per person, or a given number of CFM per square foot of floor area?
12. Local and/or national codes relating to ventilation, gas, and/or electric piping.
13. Outside design temperatures and wind velocities for the location.
14. The environmental conditions that are maintained. Will fluctuations of these conditions with load be detrimental to the purpose served by the structure?
15. The heating and cooling loads (also consider the moisture load, air contaminants, and noise).
16. The type of heating and cooling system to be used in the structure. Is it forced air, circulated water, or direct expansion? Will it be a multizone, single zone, reheat, variable air volume, or another type of system? What method of control will be used? Will a dedicated outdoor air system be considered?
17. The heating and cooling equipment size that will maintain the inside design conditions for the selected outside design condition. Electric heat or fossil fuel? Mechanical vapor compression or absorption chiller?
18. The advantages and disadvantages of oversizing and undersizing the equipment as applied to the structure. Survey any economic tradeoffs to be made. Should a different type of unit be installed in order to reduce operating costs? Should a more sophisticated control system be used to give more exact control of humidity and temperature or should an on-off cycle be used? Fuel economy as related to design will become an even more important factor in system selection and operation.
19. What is the estimated annual energy usage?

In general, no absolute rules dictate correct selections or specifications for each of the above items, so only engineering estimates or educated guesses can be made. However, estimates must be based on sound fundamental principles and concepts. This book presents a basic philosophy of environmental control as well as the basic concepts of design. These ideas relate directly to the *ASHRAE Handbook* series: 2014 *Refrigeration*, 2015 *HVAC Applications*, 2016 *HVAC Systems and Equipment*, and most directly to 2017 *Fundamentals*.

1.2 Historical Notes

Knowing something of the past helps in understanding current design criteria and trends. As in other fields of technology, the accomplishments and failures of the past affect current and future design concepts. The following paragraphs consist mainly of edited excerpts from *ASHRAE Journal* articles: "A History of Heating" by John W. James, "The History of Refrigeration" by Willis R. Woolrich, and "Milestones in Air Conditioning" by Walter A. Grant, with additional information obtained from ASHRAE's Historical Committee. These excerpts provide a synopsis of the history of environmental control.

Obviously, the earliest form of heating was the open fire. The addition of a chimney to carry away combustion byproducts was the first important step in the evolution of heating systems. By the time of the Romans, there was sufficient knowledge of ventilation to allow for the installation of ventilating and panel heating in baths. Leonardo da Vinci had invented a ventilating fan by the end of the 15th century. Robert Boyle's law was established in 1659; John Dalton's in 1800. In 1775, Dr. William Cullen made ice by pumping a vacuum in a vessel of water. A few years later, Benjamin Franklin wrote his treatise on Pennsylvania fireplaces, detailing their construction, installation, and operation.

Although warming and ventilating techniques had greatly improved by the 19th century, manufacturers were unable to exploit these techniques because

- Data available on such subjects as transmission coefficients, air and water friction in pipes, and brine and ammonia properties were sparse and unreliable.
- Neither set design conditions nor reliable psychrometric charts existed.
- A definitive rational theory that would permit performance calculation and prediction of results had not yet been developed.
- Little was known about physical, thermodynamic, and fluid dynamic properties of air, water, brines, and refrigerants.
- No authoritative information existed on heat transmission involving combustion, conduction, convection, radiation, evaporation, and condensation.
- No credible performance information for manufactured equipment was available.

Thanks to Thomas Edison, the first electric power plant opened in New York in 1882, making it possible for the first time to have an inexpensive source of energy for residential and commercial buildings.

1.1.1 Furnaces

By 1894, the year the American Society of Heating and Ventilating Engineers (ASH&VE) was born, central heating was fairly well developed. The basic heat sources were warm air furnaces and boilers. The combustion chambers of the first warm air furnaces were made of cast iron. Circulation in a gravity warm air furnace system is caused by the difference in air density in the many parts of the system. As the force of combustion is small, the system was designed to allow air to circulate freely. The addition of fans (circa 1899) to furnace systems provided a mechanical means of air circulation. Other additions to the modern furnace include cooling systems, humidification apparatuses, air distributors, and air filters. Another important step for the modern heating industry was the conversion of furnaces from coal to oil and gas, and from manual to automatic firing.

1.1.2 Steam Systems

James Watt developed the first steam heating system in 1770. However, the first real breakthrough in design did not occur until the early 1900s when circulation problems in these systems were improved with the introduction of a fluid-operated thermostatic trap.

From 1900 to 1925, two-pipe steam systems with thermostatic traps at the outlet of each radiator and at drip points in the piping gained wide acceptance. In smaller buildings, gravity systems were commonly installed to remove condensate. For larger systems, boiler return traps and condensate pumps with receivers were used. By 1926, the vacuum return line system was perfected for installation in large and moderate-sized buildings.

Hot water heating systems were developed in parallel with steam systems. As mentioned before, the first hot water heating system was the gravity system. In 1927, the circulator, which forced water through the system, was added to two-pipe heating systems. A few years later, a diverting tee was added to the one-pipe system, allowing for forced circulation.

During the 1930s, radiators and convectors were commonly concealed by enclosures, shields, and cabinets. In 1944, the baseboard radiator was developed. Baseboard heating improved comfort conditions as it reduced floor-to-ceiling temperature stratification.

Unit heaters and unit ventilators are two other forms of convection heating developed in the 1920s. Unit heaters were available in suspended and floor types and were classified according to the heating medium used (e.g., steam, hot water, electricity, gas, oil, or coal combustion). In addition to the heating element and fan, unit ventilators were often equipped with an air filter. Many designs provided air recirculation and were equipped with a separate outdoor air connection.

Panel heating, another form of heat distribution, was developed in the 1920s. In panel heating, a fluid such as hot water, steam, air, or electricity, circulates through distribution units embedded in the building components.

1.1.3 Early Refrigeration

Early forms of refrigeration included the use of snow, pond and lake ice, chemical mixture cooling to form freezing baths, and the manufacture of ice by evaporative and radiation cooling of water on clear nights.

By the 18th century, certain mixtures were known to lower temperatures. One such mixture, calcium chloride and snow, was introduced for commercial use. This particular mixture made possible a temperature down to –27°F (–33°C). In Great Britain, machines using chemical mixtures to produce low temperatures were introduced. However, by the time these machines were ready for commercial exploitation, mechanical ice-making processes had been perfected to such an extent that chemical mixture freezing was rendered obsolete except for such batch processes as ice cream making.

1.1.4 Mechanical and Chemical Refrigeration

In 1748, in Scotland, Dr. William Cullen and Joseph Black lectured on the latent heat of fusion and evaporation and “fixed air” (later identified as carbon dioxide). These discoveries served as the foundation on which modern refrigeration is based.

In 1851, Dr. John Gorrie, was granted US Patent No. 8080 for a refrigeration machine that produced ice and refrigerated air with compressed air in an open cycle. Also in 1851, Ferdinand Carre designed the first ammonia absorption unit.

In 1853, Professor Alexander Twining of New Haven, Connecticut, produced 1600 lb of ice a day with a doubleacting vacuum and compression pump that used sulfuric ether as the refrigerant.

Daniel L. Holden improved the Carre machine by designing and building reciprocating compressors. These compressors were applied to ice making, brewing, and meat packing. In 1872, David Boyle developed an ammonia compression machine that produced ice.

Until 1880, mechanical refrigeration was primarily used to make ice and preserve meat and fish. Notable exceptions were the use of these machines in the United States, Europe, and Australia for beer making, oil dewaxing, and wine cooling. At this time, comfort air cooling was obtained by ice or by chilling machines that used either lake or manufactured ice.

1.1.5 History of ASHRAE

The American Society of Heating and Ventilating Engineers (ASHVE) was formed in New York City in 1894 to conduct research, develop standards, hold technical meetings, and publish technical articles in journals and handbooks. Its scope was limited to the fields of heating and ventilating for commercial and industrial applications, with secondary emphasis on residential heating. Years later the Society’s name was changed to the American Society of Heating and Air-Conditioning Engineers (ASHAE) to recognize the increasing importance of air conditioning.

In 1904, the American Society of Refrigerating Engineers (ASRE) was organized and headquartered at the American Society of Mechanical Engineers (ASME). The new Society had 70 charter members and was the only engineering group in the world that confined its activities to refrigeration, which at that time consisted mainly of ammonia systems.

In 1905, ASME established 288,000 Btu in 24 hrs as the commercial ton of refrigeration (within the United States). In the same year, the New York Stock Exchange was cooled by refrigeration. In 1906, Stuart W. Cramer coined the term “air conditioning.”

The First International Congress on Refrigeration was organized in Paris in 1908 and a delegation of 26 was sent from the United States. Most of the participants were members of ASRE.

ASHAE and ASRE merged in 1959, creating the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Figure 1-1 depicts ASHRAE's history. ASHRAE celebrated its Centennial Year during society year 1994-1995. In commemoration of the centennial, two books on the history of ASHRAE and of the HVAC industry were published, *Proclaiming the Truth* and *Heat and Cold: Mastering the Great Indoors*.

1.1.6 Willis H. Carrier

Willis H. Carrier (1876-1950) has often been referred to as the "Father of Air Conditioning." His analytical and practical accomplishments contributed greatly to the development of the refrigeration industry.

Carrier graduated from Cornell University in 1901 and was employed by the Buffalo Forge Company. He realized that satisfactory refrigeration could not be installed due to the inaccurate data that were available. By 1902, he developed formulas to optimize forced-draft boiler fans, conducted tests and developed multirating performance tables on indirect pipe coil heaters, and set up the first research laboratory in the heating and ventilating industry.

In 1902, Carrier was asked to solve the problem faced by the lithographic industry of poor color register caused by weather changes. Carrier's solution was to design, test, and install at the Sackett-Wilhelms Lithographing Company of Brooklyn a scientifically engineered, year-round air-conditioning system that provided heating, cooling, humidifying, and dehumidifying.

By 1904, Carrier had adapted atomizing nozzles and developed eliminators for air washers to control dew-point temperature by heating or cooling a system's recirculated water. Soon after this development, over 200 industries were using year-round air conditioning.

At the 1911 ASME meeting, Carrier presented his paper, "Rational Psychrometric Formulae," which related dry-bulb, wet-bulb, and dew-point temperatures of air, as well as its sensible, latent, and total heat load, and set forth the theory of adiabatic saturation. The formulas and psychrometric chart presented in this paper became the basis for all fundamental calculations used by the air-conditioning industry.

By 1922, Carrier's centrifugal refrigeration machine, together with the development of nonhazardous, low-pressure refrigerants, made water chilling for large and medium-size commercial and industrial applications both economical and practical. A conduit induction system for multiroom buildings, was invented in 1937 by Carrier and his associate, Carlyle Ashley.

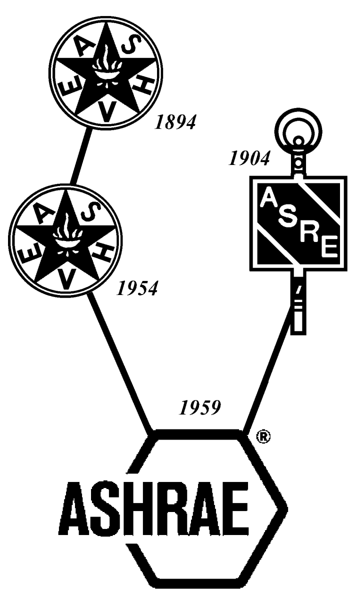

Fig. 1-1 Background of ASHRAE

1.1.7 Comfort Cooling

Although comfort air-cooling systems had been built as of the 1890s, no real progress was made in mechanical air cooling until after the turn of the century. At that time, several scientifically designed air-conditioning plants were installed in buildings. One such installation included a theater in Cologne, Germany. In 1902, Alfred Wolff designed a 400-ton system for the New York Stock Exchange. Installed in 1902, this system was in operation for 20 years. The Boston Floating Hospital, in 1908, was the first hospital to be equipped with modern air conditioning. Mechanical air cooling was installed in a Texas church in 1914. In 1922, Grauman's Metropolitan Theater, the first air-conditioned movie theater, opened in Los Angeles. The first office building designed with and built for comfort air-conditioning specifications was the Milam Building, in San Antonio, Texas, which was completed in 1928. Also in 1928, the Chamber of the House of Representatives became air conditioned. The Senate became air conditioned the following year and in 1930, the White House and the Executive Office Building were air-conditioned.

The system of air bypass control, invented in 1924 by L. Logan Lewis, solved the difficult problem of humidity control under varying load. By the end of the 1920s, the first room air conditioner was introduced by Frigidaire. Other important inventions of the 1920s include lightweight extended surface coils and the first unit heater and cold diffuser.

Thomas Midgley, Jr. developed the halocarbon refrigerants in 1930. These refrigerants were found to be safe and economical for the small reciprocating compressors used in commercial and residential markets. Manufacturers were soon producing mass market room air conditioners that used Refrigerant 12.

Fluorinated refrigerants were also applied to centrifugal compression, which required only half the number of impellers for the same head as chlorinated hydrocarbons. Space and materials were saved when pressure-formed extended-surface tubes in shell-and-tube exchangers were introduced by Walter Jones. This invention was an important advance for centrifugal and reciprocating equipment.

Other achievements of the 1930s included

- The first residential lithium bromide absorption machine was introduced in 1931 by Servel.

- In 1931, Carrier marketed steam ejector cooling units for railroad passenger cars.
- As of the mid-1930s, General Electric introduced the heat pump; the electrostatic air cleaner was put out by Westinghouse; Charles Neeson of Airtemp invented the high-speed radial compressor; and W.B. Connor discovered that odors could be removed by using activated carbon.

With the end of World War II, air-conditioning technology advanced rapidly. Among the advances were air-source heat pumps, large lithium-bromide water chillers, automobile air conditioners, rooftop heating and cooling units, small, outdoor-installed ammonia absorption chillers, air purifiers, a vapor cycle aircraft cabin cooling unit, and a large-capacity Lysholm rotary compressor.

Improvements on and expansions of products that already existed include

- Dual-duct central systems for office buildings
- Change from open to hermetic compressors from the smallest reciprocating units to large-capacity centrifugals
- Resurgence of electric heating in all kinds of applications
- Use of heat pumps to reclaim heat in large buildings
- Application of electrostatic cleaners to residences
- Self-contained variable volume air terminals for multiple interior rooms
- Increasing use of total energy systems for large buildings and clusters of buildings
- Larger sizes of centrifugals, now over 5000 tons in a single unit
- Central heating and cooling plants for shopping centers, colleges, and apartment and office building complexes

In the late 1940s and into the early 1950s, development work continued on unitary heat pumps for residential and small commercial installations. These factory-engineered and assembled units, like conventional domestic boilers, could be easily and cheaply installed in the home or small commercial businesses by engineers. In 1952, heat pumps were placed on the market for mass consumption. Early heat pumps lacked the durability needed to withstand winter temperatures. Low winter temperatures placed severe stress on the components of these heat pumps (compressors, outdoor fans, reversing valves, and control hardware). Improvements in the design of heat pumps has continued, resulting in more-reliable compressors and lubricating systems, improved reversing valves, and refined control systems.

In the 1950s came the rooftop unit for commercial buildings. Multizone packaged rooftop units were popular during the 1960s; however, most were very energy inefficient and lost favor during the 1970s. Beginning with the oil embargo of 1973, the air-conditioning field could no longer conduct "business as usual," with concern mainly for the initial cost of the building and its conditioning equipment. The use of crude rules of thumb, which significantly oversized equipment and wasted energy, was largely replaced with reliance upon more scientifically sound, and often computer-assisted, design, sizing, and selection procedures. Variable air volume (VAV) designs rapidly became the most popular type of HVAC system for offices, hospitals, and some school buildings. Although energy-efficient, VAV systems proved to have their own set of problems related to indoor air quality (IAQ), sick building syndrome (SBS), and building related illness (BRI). Solutions to these problems are only now being realized.

In 1987, the United Nations Montreal Protocol for protecting the earth's ozone layer was signed, establishing the phase-out schedule for the production of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. Contemporary buildings and their air-conditioning equipment must now provide improved indoor air quality as well as comfort, while consuming less energy and using alternative refrigerants.

1.3 Building Energy Use

Energy is generally used in buildings to perform functions of heating, lighting, mechanical drives, cooling, and special applications. A typical breakdown of the relative energy use in a commercial building is given as Figure 1-2.

Energy is available in limited forms, such as electricity, fossil fuels, and solar energy, and these energy forms must be converted within a building to serve the end use of the various functions. A degradation of energy is associated with any conversion process. In energy conservation efforts, two avenues of approach were taken: (1) reducing the amount of use and/or (2) reducing conversion losses. For example, the furnace that heats a building produces unusable and toxic flue gas that must be vented to the outside and in this process some of the energy is lost. Table 1-1 presents typical values for building heat losses and gains at design conditions for a mid-America climate. Actual values will vary significantly with climate and building construction.

The projected total U.S. energy consumption by end-user sector: transportation, industrial, commercial, and residential is shown in Figure 1-3. The per capita energy consumption for the U.S. and the world is shown in Figure 1-4, showing that in 2007 the U.S. consumption was the same as in 1965. This has

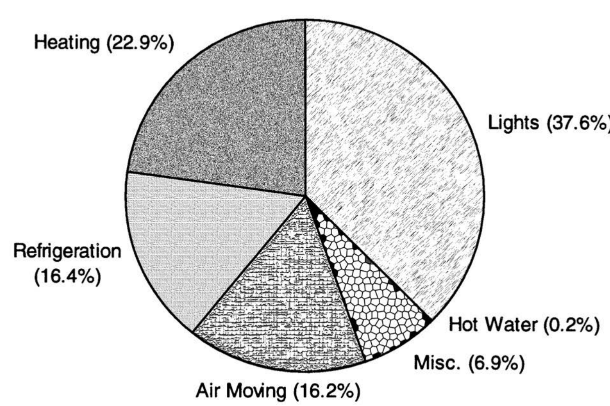

Fig. 1-2 Energy Use in a Commercial Building

been achieved through application of energy conservation principles as well as increased energy costs and changes in the economy.

The efficient use of energy in buildings can be achieved by implementing (1) optimum energy designs, (2) well-developed energy use policies, and (3) dedicated management backed up by a properly trained and motivated operating staff. Optimum energy conservation is attained when the least amount of energy is used to achieve a desired result. If this is not fully realizable, the next best method is to move excess energy from where it is not wanted to where it can be used or stored for future use, which generally results in a minimum expenditure of new energy. A system should be designed so that it cannot heat and cool the same locations simultaneously.

ASHRAE Standard 90.1-2013, "Energy Standard for Buildings Except Low-Rise Residential Buildings," and the 100-2015 series standards, "Energy Conservation in Existing Buildings," provide minimum guidelines for energy conservation design and operation. They incorporate these types of energy standards: (1) prescriptive, which specifies the materials and methods for design and construction of buildings; (2) system performance, which sets requirements for each component, system, or subsystem within a building; and (3) building energy, which considers the performance of the building as a whole. In this last type, a design goal is set for the annual energy requirements of the entire building on basis such as Btu/ft^2 per year (GJ/m^2 per year). Any combination of materials, systems, and operating procedures can be applied, as long as design energy usage does not exceed the building's annual energy budget goal. "Standard 90.1-2013 User's Manual" is extremely helpful in understanding and applying the requirements of ASHRAE Standard 90.1

This approach allows greater flexibility while promoting the goals of energy efficiency. It also allows and encourages the use of innovative techniques and the development of new methods for saving energy. Means for its implementation are still being developed. They are different for new and for existing buildings; in both cases, an accurate data base is required as well as an accurate, verifiable means of measuring consumption.

As energy prices have risen, more sophisticated schemes for reducing energy consumption have been conceived. Included in such schemes are cogeneration, energy management systems (EMS), direct digital control (DDS), daylighting, closed water-loop heat pumps, variable air volume (VAV) systems, variable frequency drives, thermal storage, dessicant dehumidication, and heat recovery in commercial and institutional buildings and industrial plants.

As detailed in a 1992 Department of Energy Report, "Commercial Buildings Consumption and Expenditures, 1989," more than seventy percent of the commercial-industrial-institutional (C-I-I) buildings recently built in the United States made use of energy conservation measures for heating and cooling.

The type of building and its use strongly affects the energy use as shown in Table 1-2.

Heating and air-conditioning systems that are simple in design and of the proper size for a given building generally have relatively low maintenance and operating costs. For optimum results, as much inherent thermal control as is economically possible should be built into the basic structure. Such

Table 1-1 Typical Building Design Heat Losses or Gains

	Air Conditioning		Heating	
Building Type	**ft^2/ton**	**m^2/kW**	**Btu/h·ft^3**	**W/m^3**
Apartment	450	12	4.5	45
Bank	250	7	3.0	30
Department Store	250	7	1.0	10
Dormitories	450	12	4.5	45
House	700	18	3.0	30
Medical Center	300	8	4.5	45
Night Club	250	7	3.0	30
Office Interior	350	9	3.0	30
Exterior	275	7	3.0	30
Post Office	250	7	3.0	30
Restaurant	250	7	3.0	30
Schools	275	7	3.0	30
Shopping Center	250	7	3.0	30

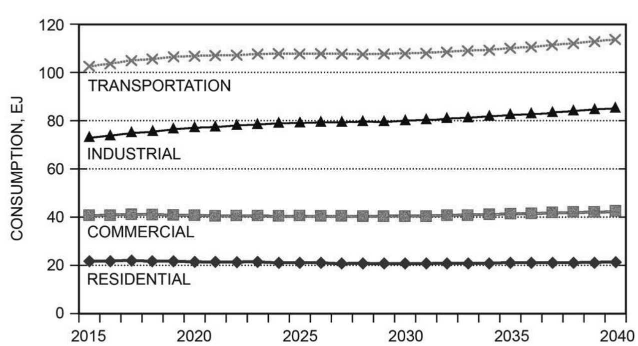

Fig. 1-3 Projected total U.S. Energy Consumption by End-User Sector
(EIA 2016)

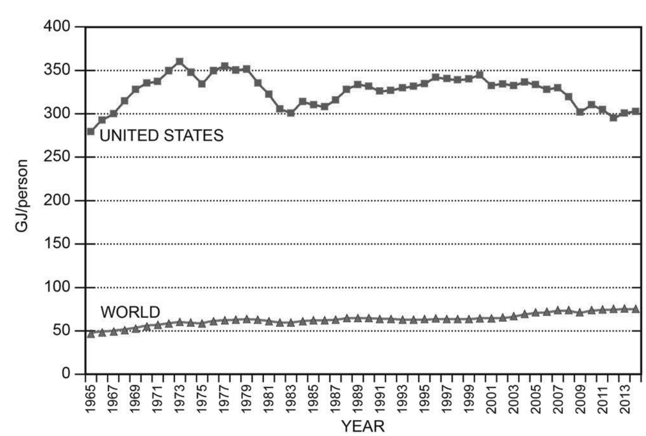

Fig. 1-4 U.S Per Capita Energy Consumption
(BP 2015)

control might include materials with high thermal properties, insulation, and multiple or special glazing and shading devices. The relationship between the shape, orientation, and air-conditioning requirement of a building should also be considered. Since the exterior load may vary from 30 to 60% of the total air-conditioning load when the fenestration (light transmitting) area ranges from 25 to 75% of the floor area, it may be desirable to minimize the perimeter area. For example, a rectangular building with a 4-to-1 aspect ratio requires substantially more refrigeration than a square building with the same floor area.

When a structure is characterized by several exposures and multipurpose use, especially with wide load swings and noncoincident energy use in certain areas, multiunit or unitary systems may be considered for such areas, but not necessarily for the entire building. The benefits of transferring heat absorbed by cooling from one area to other areas, processes, or services that require heat may enhance the selection of such systems.

Buildings in the US consume significant quantities of energy each year. According to the US Department of Energy (DOE), buildings account for 36% of all the energy used in the US, and 66% of all the electricity used. Beyond economics, energy use in the buildings sector has significant implications for our environment. Emissions related to building energy use account for 35% of carbon dioxide emissions, 47% of sulfur dioxide emissions, and 22% of nitrogen oxide emissions.

1.4 Conceptualizing an HVAC System

An important tool for the HVAC design engineer is the ability to develop a quick overview or "concept" of the magnitude of the project at hand. Toward this goal, the industry has developed a number of "rules of thumb," some more accurate than others. As handy as they might be, these approximations must be treated as just that—approximations. Don't use them as "rules of dumb."

Tables 1-1 and 1-2 are examples of such rules-of-thumb, providing data for a quick estimate of heating and cooling equipment sizes and of building energy use, requiring knowledge only of the size and intended use of the building. Other rules-of-thumb include using a face velocity of 500 fpm in determining the face area for a cooling coil, the use of 400 cfm/ton for estimating the required cooling airflow rate, the use of 2.5 gpm/ton for determining the water flow rate through the cooling coil and chiller unit, using 1.2 cfm/sq ft of gross floor area for estimating the required conditioned airflow rate for comfort cooling, and the estimation of 0.6 kW/ton as the power requirement for air conditioning. Table 1-3 provides very approximate data related to the cost of HVAC equipment and systems.

Table 1.4 provides approximate energy costs for commercial consumers in the United States for 2015. Keep in mind that these energy costs are very volatile at this time.

Table 1.5 gives approximate total building costs for offices and medical offices averaged for twenty U.S. locations in 2007.

The material presented in this book will enable the reader to validate appropriate rules as well as to improve upon these approximations for the final design.

Table 1-2 Annual Energy Use Per Unit Floor Area

Building Type	Annual Energy Use kWh/ft^2
Assembly	18.7
Education	25.5
Food Sales	51.5
Health Care	64.0
Lodging	38.8
Mercantile	24.8
Office	30.5
Warehouse	16.9
Vacant	6.9
All Buildings	26.7

1.5 Sustainability and Green Buildings

The following discussion concerning sustainable design and green buildings has been extracted from Chapters 34 and 35 of the 2017 *ASHRAE Handbook—Fundamentals*.

Pollution, toxic waste creation, waste disposal, global climate change, ozone depletion, deforestation, and resource depletion are recognized as results of uncontrolled technological and population growth. Without mitigation, current trends will adversely affect the ability of the earth's ecosystem to regenerate and remain viable for future generations.

The built environment contributes significantly to these effects, accounting for one-sixth of the world's fresh water use, one-quarter of its wood harvest, and two-fifths of its material and energy flows. Air quality, transportation patterns, and watersheds are also affected. The resources required to serve this sector are considerable and many of them are diminishing.

Table 1-3 Capital Cost Estimating Factors

Cooling Systems
- $1675/installed ton of cooling

Heating Systems
- $2.92/cfm of installed heating

Fans/Ducting/Coils/Dampers/Filters
- $7.84/cfm all-system

Table 1-4 Approximate Energy Costs to Commercial Consumers (2015)

Electricity ($/kWh)	0.090
Natural Gas ($/therm)	0.84
LPG ($/gal)	2.95
No. 2 Fuel Oil ($/gas)	3.46

Table 1-5 Approximate Total Building Costs ($/sq. ft.)
(Adapted from RSMeans Costs Comparisons 2007)

	2–4-Story Office Building	5–10-Story Office Building	11–20-Story Office Building	Medical Office Building
High	194	181	167	219
Average	149	130	121	169
Low	117	110	98	132

Recognition of how the building industry affects the environment is changing the approach to design, construction, operation, maintenance, reuse, and demolition of buildings and focusing on environmental and long-term economic consequences. Although this sustainable design ethic—*sustainability*—covers things beyond the HVAC industry alone, efficient use of energy resources is certainly a key element of any sustainable design and is very much under the control of the HVAC designer.

Research over the years has shown that new commercial construction can reduce annual energy consumption by about 50% using integrated design procedures and energy conservation techniques. In the past few years several programs promoting energy efficiency in building design and operation have been developed. One of these is Energy Star Label (www.energystar.gov) and another one, which is becoming well known, is Leadership in Energy and Environmental Design (LEED) (www.usgbc.org/leed).

In 1999 the Environmental Protection Agency of the US government introduced the Energy Star Label for buildings. This is a set of performance standards that compare a building's adjusted energy use to that of similar buildings nationwide. The buildings that perform in the top 25%, while conforming to standards for temperature, humidity, illumination, outdoor air requirements, and air cleanliness, earn the Energy Star Label.

LEED is a voluntary points-based national standard for developing a high-performance building using an integrated design process. LEED evaluates "greenness" in five categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, and the indoor air environmental quality.

In the energy and atmosphere category, building systems commissioning and minimum energy usages are necessary requirements. The latter requires meeting the requirements *ANSI/ASHRAE/IESNA Standard 90.1-2013, Energy Standard for Buildings Except Low-Rise Residential Buildings*, or the local energy code, whichever is more stringent.

Basically LEED defines what makes a building "green" while the Energy Star Label is concerned only with energy performance. Both of these programs require adherence to ASHRAE standards. Chapter 35 of the 2017 *ASHRAE Handbook—Fundamentals* provides guidance in achieving sustainable designs.

The basic approach to energy-efficient design is reducing loads (power), improving transport systems, and providing efficient components and "intelligent" controls. Important design concepts include understanding the relationship between energy and power, maintaining simplicity, using self-imposed budgets, and applying energy-smart design practices.

Just as an engineer must work to a cost budget with most designs, self-imposed power budgets can be similarly helpful in achieving energy-efficient design. For example, the following are possible goals for mid-rise to high-rise office buildings in a typical midwestern or northeastern temperature climate:

• Installed lighting (overall)	0.8 W/ft^2
• Space sensible cooling	15 Btu/h·ft^2
• Space heating load	10 Btu/h·ft^2
• Electric power (overall)	3 W/ft^2
• Thermal power (overall)	20 Btu/h·ft^2
• Hydronic system head	70 ft of water
• Water chiller (water-cooled)	0.5 kW/ton
• Chilled-water system auxiliaries	0.15 kW/ton
• Unitary air-conditioning systems	1.0 kW/ton
• Annual electric energy	15 kWh/ft^2·yr
• Annual thermal energy	5 Btu/ft^2·yr·°F·day

These goals, however, may not be realistic for all projects.

As the building and systems are designed, all decisions become interactive as the result of each subsystem's power or energy performance being continually compared to the "budget."

Energy efficiency should be considered at the beginning of building design because energy-efficient features are most easily and effectively incorporated at that time. Active participation of all members of the design team (including owner, architect, engineer, and often the contractor) should be sought early. Consider building attributes such as building function, form, orientation, window/wall ratio, and HVAC system types early because each has major energy implications.

1.6 Problems

1.1 Estimate whether ice will form on a clear night when ambient air temperature is 45°F (7.2°C), if the water is placed in a shallow pan in a sheltered location where the convective heat transfer coefficient is 0.5 Btu/h·ft^2·°F [2.8 W/(m^2·K)].

1.2 Obtain a sketch or drawing of Gorrie's refrigeration machine and describe its operation.

1.3 Plot the history of the annual energy use per square foot of floor space for nonresidential buildings and predict the values for the years 2014 and 2015.

1.4 Estimate the size of cooling and heating equipment that is needed for a new bank building in middle America that is 140 ft by 220 ft by 12 ft high (42.7 m by 67 m by 3.7 m high). [Answer: 123 tons cooling, 11,109,000 Btu/h heating]

1.5 Estimate the size of heating and cooling equipment that will be needed for a residence in middle America that is 28 ft by 78 ft by 8 ft high (8.5 m by 23.8 m by 2.4 m high).

1.6 Estimate the initial cost of the complete HVAC system (heating, cooling, and air moving) for an office building, 40 ft by 150 ft by 10 ft high (12.2 m by 45.7 m by 3.1 m high).

1.7 Estimate the annual operating cost for the building in Problem 1.6 if it is all-electric. [Answer: $14,640]

1.8 Conceptualize, as completely as possible, using information only from Sections 1.3, 1.4, and 1.5, the building of Project 8 Two-Story Building, Appendix B, Systems Design Problems.

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Chapter 2

THERMODYNAMICS AND PSYCHROMETRICS

This chapter reviews the principles of thermodynamics, evaluates thermodynamic properties, and applies thermodynamics and psychrometrics to air-conditioning and refrigeration processes and systems. Greater detail on thermodynamics, particularly relating to the Second Law and irreversibility, is found in Chapter 2, 2017 *ASHRAE Handbook—Fundamentals*. Details on psychrometric properties can be found in Chapter 1 of the 2017 *ASHRAE Handbook—Fundamentals*.

2.1 Fundamental Concepts and Principles

2.1.1 Thermodynamics

Thermodynamics is the science devoted to the study of energy, its transformations, and its relation to status of matter. Since every engineering operation involves an interaction between energy and materials, the principles of thermodynamics can be found in all engineering activities.

Thermodynamics may be considered the description of the behavior of matter in equilibrium and its changes from one equilibrium state to another. The important concepts of thermodynamics are energy and entropy; the two major principles of thermodynamics are called the first and second laws of thermodynamics. The first law of thermodynamics deals with energy. The idea of energy represents the attempt to find an invariant in the physical universe, something that remains constant in the midst of change. The second law of thermodynamics explains the concept of entropy; e.g., every naturally occurring transformation of energy is accompanied somewhere by a loss in the availability of energy for future performance of work.

The German physicist, Rudolf Clausius (1822–1888), devised the concept of entropy to quantitatively describe the loss of available energy in all naturally occurring transformations. Although the natural tendency is for heat to flow from a hot to a colder body with which it is in contact, corresponding to an increase in entropy, it is possible to make heat flow from a colder body to a hot body, as is done every day in a refrigerator. However, this does not take place naturally or without effort exerted somewhere.

According to the fundamental principles of thermodynamics, the energy of the world stays constant and the entropy of the world increases without limit. If the essence of the first principle in everyday life is that one cannot get something for nothing, the second principle emphasizes that every time one does get something, the opportunity to get that something in the future is reduced by a measurable amount, until ultimately, there will be no more "getting." This "heat death," envisioned by Clausius, will be a time when the universe reaches a level temperature; and though the total amount of energy will be the same as ever, there will be no means of making it available, as entropy will have reached its maximum value.

Like all sciences, the basis of thermodynamics is experimental observation. Findings from these experimental observations have been formalized into basic laws. In the sections that follow, these laws and their related thermodynamic properties will be presented and applied to various examples. These examples should give the student an understanding of the basic concepts and an ability to apply these fundamentals to thermodynamic problems. It is not necessary to memorize numerous equations, for problems are best solved by applying the definitions and laws of thermodynamics.

Thermodynamic reasoning is always from the general law to the specific case; that is, the reasoning is deductive rather than inductive. To illustrate the elements of thermodynamic reasoning, the analytical processes may be divided into two steps:

1. The idealization or substitution of an analytical model for a real system. This step is taken in all engineering sciences. Therefore, skill in making idealizations is an essential part of the engineering art.
2. The second step, unique to thermodynamics, is the deductive reasoning from the first and second laws of thermodynamics.

These steps involve (a) an energy balance, (b) a suitable properties relation, and (c) accounting for entropy changes.

2.1.2 System and Surroundings

Most applications of thermodynamics require the definition of a system and its surroundings. A system can be an object, any quantity of matter, or any region of space selected for study and set apart (mentally) from everything else, which then becomes the surroundings. The systems of interest in thermodynamics are finite, and the point of view taken is macroscopic rather than microscopic. No account is taken of the detailed structure of matter, and only the coarse characteristics of the system, such as its temperature and pressure, are regarded as thermodynamic coordinates.

Everything external to the system is the surroundings, and the system is separated from the surroundings by the system boundaries. These boundaries may be either movable or fixed; either real or imaginary.