ASHRAE®
Learning Institute

Your Source for HVAC&R Professional Development

Fundamentals of Thermodynamics (SI Edition)

A Fundamentals of HVAC&R Series
Self-Directed Learning Course

ASHRAE®

1791 Tullie Circle NE • Atlanta, GA 30329 • www.ashrae.org

ASHRAE®
Learning Institute

Your Source for HVAC&R Professional Development

1791 Tullie Circle, NE • Atlanta, GA 30329-2305 • Phone: 678.539.1146 • Fax 678.539.2146 • www.ashrae.org

Karen M. Murray kmurray@ashrae.org
Manager of Professional Development

Dear Student,

Welcome to this ASHRAE Learning Institute (ALI) self-directed or group learning course. We look forward to working with you to help you achieve maximum results from this course.

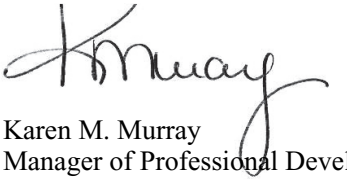
You may take this course on a self-testing basis (no continuing education credits awarded) or on an ALI-monitored basis with credits (PDHs or LUs) awarded. ALI staff will provide support and you will have access to technical experts who can answer inquiries about the course material. For questions or technical assistance, contact us at 404-636-8400 or edu@ashrae.org.

Skill Development Exercises at the end of each chapter will gauge your comprehension of the course material. If you take this course for credit, please complete the exercises and either email copies from each chapter to edu@ashrae.org (preferred method) or fax them to 678-539-2161. Be sure to include your student ID number with each set of exercises. (Your student ID can be the last five digits of your Social Security number or other unique five-digit number you create.) We will return answer sheets to the Skill Development Exercises and maintain records of your progress. Please keep copies of your completed exercises for your records.

When you finish all exercises, please submit the course evaluation, which is located at the back of your course book. Once we receive all chapter exercises and the evaluation, we will send you a Certificate of Completion indicating 35 PDHs/LUs of continuing education credit. The ALI does not award partial credit for self-directed or group learning courses. All exercises must be completed to receive full continuing education credit. You have two years from the date of purchase to complete each course.

We hope your educational experience is satisfying and successful.

Sincerely,



Karen M. Murray
Manager of Professional Development

Fundamentals of Thermodynamics

(SI Edition)

Prepared by

Douglas M. Robinson



ASHRAE
1791 Tullie Circle • Atlanta, GA 30329

Fundamentals of Thermodynamics (SI Edition)
A Course Book for Self-Directed or Group Learning
ISBN 978-1-931862-84-4

© 2005 ASHRAE
All rights reserved.

ASHRAE is a registered trademark in the U.S. Patent and Trademark Office, owned by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

No part of this publication may be reproduced without permission in writing from ASHRAE, except by a reviewer who may quote brief passages or reproduce illustrations in a review with appropriate credit, nor may any part of this publication be reproduced, stored in a retrieval system, or transmitted in any way or by any means—electronic, photocopying, recording, or other—without permission in writing from ASHRAE. Requests for permission should be submitted at www.ashrae.org/permissions.

ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user.

ASHRAE STAFF

ASHRAE Learning Institute

Karen Murray
Manager of Professional Development
Gabrielle Gaston
Assistant Manager of Professional Development
Sarah Boyle
Managing Editor of Professional Development
Kelly Arnold
Administrative Assistant
Brian Haynes
Product Support Specialist

Special Publications

Mark Owen
Editor/Group Manager of Handbook and Special Publications
Cindy Sheffield Michaels
Managing Editor of Special Pubs
James Madison Walker
Managing Editor of Standards
Lauren Ramsdell
Assistant Editor
Mary Bolton
Editorial Assistant
Michshell Phillips
Editorial Coordinator

Publishing Services

David Soltis
Group Manager of Publishing Services and Electronic Communications
Jayne Jackson
Publication Traffic Administrator

Publisher

W. Stephen Comstock

For course information or to order additional materials, please contact:

ASHRAE Learning Institute
1791 Tullie Circle, NE
Atlanta, GA 30329

Telephone: 404/636-8400
Fax: 404/321-5478
Web: www.ashrae.org/ali
E-mail: edu@ashrae.org

Errors or omissions in the data should be brought to the attention of Special Publications via **SDLcorrections@ashrae.org**.

Any updates/errata to this publication will be posted on the ASHRAE Web site at www.ashrae.org/publicationupdates.

Table of Contents

Chapter 1 Introduction to HVAC

- Instructions
- Study Objectives of Chapter 1
- 1.1 Introduction 1-2
- 1.2 HVAC: Heating, Ventilating and Air-Conditioning 1-3
- 1.3 The Major Processes of Air-Conditioning 1-4
- 1.4 Thermodynamics and Psychrometrics 1-6
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 1

Chapter 2 Systems, Properties, States and Processes

- Instructions
- Study Objectives of Chapter 2
- 2.1 Introduction 2-2
- 2.2 Closed and Open Systems in Thermodynamics 2-2
- 2.3 Forms of Energy 2-6
- 2.4 Properties of a System 2-9
- 2.5 Equilibrium States 2-9
- 2.6 Processes and Cycles 2-10
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 2

Chapter 3 Property Diagrams for Pure Substances

- Instructions
- Study Objectives of Chapter 3
- 3.1 The State Postulate 3-2
- 3.2 Properties 3-2
- 3.3 Phases and Phase Changes for Pure Substances 3-9
- 3.4 Property Diagrams 3-13
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 3

Chapter 4 Thermodynamic Tables and Charts

- Instructions
- Study Objectives of Chapter 4
- 4.1 Introduction 4-2
- 4.2 Tables for Saturated Liquid and Vapor 4-4
- 4.3 Tables for Superheated Vapor and Compressed Liquid 4-10
- 4.4 Thermodynamic Liquid/Vapor Charts 4-10
- The Next Step
- Summary
- Skill Development Exercises for Chapter 4

Chapter 5 Ideal Gas Law and Air Tables

- Instructions
- Study Objectives of Chapter 5
- 5.1 Ideal Gas and the Ideal Gas Law 5-2
- 5.2 The Ideal Gas Law as an Equation of State 5-4
- 5.3 Constant Specific Heat 5-5
- 5.4 Air Tables 5-7
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 5

Chapter 6 Heat and Work

- Instructions
- Study Objectives of Chapter 6
- 6.1 Introduction 6-2
- 6.2 Heat 6-3
- 6.3 Work 6-6
- 6.4 Flow Work 6-15
- The Next Step
- Summary
- Skill Development Exercises for Chapter 6

Chapter 7 First Law of Thermodynamics Applied to Closed Systems

- Instructions
- Study Objectives of Chapter 7
- 7.1 Introduction to Controlled Mass Approach 7-2
- 7.2 The First Law of Thermodynamics for a Closed System 7-3
- 7.3 Conservation of Energy 7-4
- 7.4 First Law Applied in Example Cases 7-5
- The Next Step
- Summary
- Skill Development Exercises for Chapter 7

Chapter 8 First Law of Thermodynamics Applied to Open Systems

- Instructions
- Study Objectives of Chapter 8
- 8.1 Introduction to the Control Volume Approach 8-2
- 8.2 Conservation of Mass 8-3
- 8.3 Conservation of Energy and the First Law for Open Systems 8-4
- 8.4 Steady-Flow Processes 8-6
- 8.5 First Law Applied in Examples of Steady-Flow Processes 8-9
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 8

Chapter 9 Applications of the First Law of Thermodynamics

- Instructions
- Study Objectives of Chapter 9
- 9.1 Compressors, Turbines, Pumps and Fans 9-2
- 9.2 Throttling Valves and Metering Devices 9-7
- 9.3 Heat Exchangers, Condensers and Evaporators 9-8
- The Next Step
- Summary
- Skill Development Exercises for Chapter 9

Chapter 10 The Carnot Cycle

- Instructions
- Study Objectives of Chapter 10
- 10.1 The Second Law of Thermodynamics 10-2
- 10.2 Heat Engines, Refrigerators and Heat Pumps 10-3
- 10.3 Reversible and Irreversible Processes 10-7
- 10.4 The Carnot Cycle and the Reverse Carnot Cycle 10-8
- The Next Step
- Summary
- Skill Development Exercises for Chapter 10

Chapter 11 Refrigeration Cycles - Ideal Cycles

- Instructions
- Study Objectives of Chapter 11
- 11.1 Refrigeration Equipment 11-2
- 11.2 The Ideal Vapor-Compression Refrigeration Cycle 11-4
- 11.3 Analysis of the Components and Cycle 11-6
- 11.4 Performance of Ideal Refrigerators and Heat Pumps 11-7
- The Next Step
- Summary
- Skill Development Exercises for Chapter 11

Chapter 12 Refrigeration Cycles - Actual Cycles

- Instructions
- Study Objectives of Chapter 12
- 12.1 The Actual Vapor-Compression Refrigeration Cycle 12-2
- 12.2 Absorption Refrigeration System 12-6
- 12.3 Gas Refrigeration System 12-8
- 12.4 Modifications to the Basic Vapor Compression Cycle 12-9
- 12.5 Irreversibility 12-21
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 12

Chapter 13 Combustion and Thermochemistry

- Instructions
- Study Objectives of Chapter 13
- 13.1 Introduction to Combustion 13-2
- 13.2 Fuel Types 13-3
- 13.3 Stoichiometry of Reactions 13-4
- 13.4 Non-Stoichiometric Combustion 13-6
- 13.5 Air-Fuel Ratios 13-7
- 13.6 Carbon Monoxide 13-8
- Summary
- Bibiography
- Skill Development Exercises for Chapter 13

Appendices

- Appendix A-1 Dimensions and Units Used in Air-Conditioning Applications
- Appendix A-2 Unit Conversion Factors
- Appendix A-3 SI Unit Review
- Appendix B Thermodynamic Properties of Water at Saturation
- Appendix C-1 R-22 Properties of Saturated Liquid and Saturated Vapor
- Appendix C-2 Pressure-Enthalpy Diagram for R-22
- Appendix C-3 R-134a Properties of Saturated Liquid and Saturated Vapor
- Appendix C-4 Pressure-Enthalpy Diagram for R-134a
- Appendix D Thermodynamic Properties of Moist Air at 14.696 psia
- Appendix E ASHRAE Psychrometric Chart

Key Terms and Symbols

Skill Development Exercises for All Chapters

Chapter 1
Introduction to HVAC

Contents of Chapter 1

- Instructions 1
- Study Objectives of Chapter 1 1
- 1.1 Introduction 2
- 1.2 HVAC: Heating, Ventilating and Air Conditioning 3
- 1.3 The Major Processes of Air Conditioning 4
- 1.4 Thermodynamics and Psychrometrics 6
- The Next Step 8
- Summary 8
- Bibliography 8
- Skill Development Exercises for Chapter 1 9

Instructions

Read the material of Chapter 1. Re-read the parts of the chapter that are emphasized in the summary and memorize important definitions. At the end of the chapter, complete all of the skill development exercises.

Study Objectives of Chapter 1

Chapter 1 is intended to introduce the processes of HVAC and provide substance to the assertion that it is important to study thermodynamics to gain a better understanding of HVAC. Chapter 1 concludes with a definition of thermodynamics and psychrometrics. After studying the chapter, you should be able to:

- Define air conditioning;
- Name and describe seven major air-conditioning processes;
- Provide a description of thermodynamics as the science of energy; and
- List HVAC applications where knowledge of basic thermodynamics is essential.

1.1 Introduction

Modern air-conditioning systems are part of our everyday life. Whether it is the comfort enjoyed while relaxing at home, or the freedom from discomfort that allows concentration on activities at work, we can appreciate air conditioning for making our lives healthier, more enjoyable and more productive. The benefits of air conditioning are also apparent in the wide range of high quality products that are available in the marketplace. Many products and manufacturing processes are improved by air conditioning because many goods can be produced better, faster and more economically in a properly controlled environment.

Air conditioning allows for the creation of a comfortable environment indoors no matter what the weather is like outdoors. Whether it's a sweltering hot day in August or a bitterly cold night in January, air conditioning can be a boon. However, after the first cost of the refrigeration equipment, there is a cost to air conditioning, which appears in the form of energy consumption. Systems installed in the United States prior to the energy scare of 1973 were generally designed with little attention to energy conservation because energy was perceived to be plentiful and inexpensive. Prior to 1973, there was little concern about the potentially negative environmental impact of energy consumption on a wide scale.

Times have changed. Today, energy conservation is a key component in air-conditioning design. Efficiency is the watchword. The results of energy conservation efforts have led to some interesting shifts in the air-conditioning marketplace. There are many more system configurations than ever before as designers try to take advantage of any opportunity to save energy, and there are tradeoffs to be made between energy conservation and performance. This means that it is important to know and understand how to best select components for an HVAC system.

Besides the actual redesign of components such as compressors, furnaces, refrigerators and heat exchangers for better efficiency, there has also been a dramatic expansion in the logic and sophistication of electronic controllers used in air-conditioning systems. Properly implemented changes in system control have the potential to lead to significant improvements in performance. Today, buildings often have an energy management system.

As the result of many energy conservation techniques, the issues of health and air quality have drawn a lot of recent attention in air-conditioning systems. For instance, there is a current controversy about the question of ventilation rates and air quality on board large passenger airplanes. Energy considerations call for minimizing the ratio of outside air to recirculated air. In contrast, the ventilation need is for plenty of fresh outside air to avoid the build-up of contaminant gases such as carbon dioxide. What constitutes the right balance? There are standards and guidelines for such ventilation requirements, but they must be continually reviewed because of new situations and revised health evidence.

To study the historical record of air conditioning is to take a fascinating trip through the tremendous technical and scientific record of our society. There are the pioneers such as Robert Boyle, Sadi Carnot, John Dalton, James Watt, Benjamin Franklin, John Gorrie, Lord Kelvin, Ferdinand Carré, Willis Carrier, Thomas Midgley and many others who have brought us to our current level. We can expect that there is further history still to be written. Air conditioning could not have developed the way it has were it not for all of the accomplishments of science and engineering in this century. Advances in thermodynamics, fluid mechanics, electricity, electronics, construction, materials, medicine, controls and social behavior are the building blocks to better engineered products of air conditioning.

Many of these famous names are connected to the study of thermodynamics. The term *thermodynamics* was first used by Lord Kelvin in 1849, and the first textbook on thermodynamics was written by William Rankine in 1859. Thermodynamics is the cornerstone to understanding the processes of air conditioning.

1.2 HVAC: Heating, Ventilating and Air Conditioning

For a long time, the term *air conditioning* was associated with the act of air cooling only. This has changed and the definition of air conditioning has been broadened to include all of HVAC. HVAC stands for "Heating, Ventilating and Air Conditioning."

In its modern sense, air conditioning is the control of temperature, moisture content, cleanliness, sound, air quality and air circulation as required by occupants, a process or a product in the space. This is a definition attributed to Willis Carrier (1876-1950) in the book, *Father of Air Conditioning*.[1] Embedded in this definition of air conditioning are many ideas that have been shaped over time about our perceived need for air conditioning and the changing technology that makes air conditioning possible. This is a wide ranging definition that gives interpretation to the idea of conditioning the air in a given space for some specific purpose.

Air conditioning is more than an occasional luxury. It is important to our everyday comfort, health and well-being whether we are at home, in the workplace, out shopping or traveling from one place to another. It includes heating, cooling, humidifying, dehumidifying, ventilating and control of air quality year-round. Besides being important for humans and animals, air conditioning is also essential to many manufacturing processes. For example, precision-engineered products are often made under closely controlled conditions that can only be produced in an air-conditioned environment.

1.3 The Major Processes of Air Conditioning

The seven major processes of air conditioning are heating, cooling, humidifying, dehumidifying, cleaning, ventilating and air movement.

- *Heating* is the process of adding thermal energy (heat) to the air in the conditioned space for the purposes of raising or maintaining the temperature of the air.
- *Cooling* is the process of removing thermal energy (heat) from the air in the conditioned space for the purposes of lowering or maintaining the temperature of the air.
- *Humidifying* is the process of adding water vapor (moisture) to the air in the conditioned space for the purposes of raising or maintaining the moisture content of the air.
- *Dehumidifying* is the process of removing water vapor (moisture) from the air in the conditioned space for the purposes of lowering or maintaining the moisture content of the air.
- *Cleaning (often referred to as filtration)* is the process of removing particulate, chemical and biological contaminants from the air in the conditioned space for the purposes of improving or maintaining the air quality.
- *Ventilating* is the process of exchanging air between the outdoors and the conditioned space for the purposes of diluting the gaseous and particulate contaminants in the air and improving or maintaining air quality, composition and purity.
- *Air Movement* (circulation and mixing) is the process of moving air through conditioned spaces in the building for the purposes of achieving the proper ventilation and facilitating the thermal energy transfer, humidification (or dehumidification) and cleaning processes outlined above.

These are the seven major air-conditioning processes used in HVAC systems. Heating and cooling are the most basic and probably the most recognized. If the space is too hot or too cold, then the occupants are unlikely to be comfortable or productive and there is a need to adjust the temperature by adding or removing thermal energy. Heating has been around for a long time and may utilize a variety of heat sources such as the burning of a fuel, electricity or chemical reaction to supply the heat. Cooling is more complicated. It requires a means for removing energy from the air and usually involves a refrigeration cycle or evaporative cooling technique. It takes work energy to drive the refrigeration cycle.

The term *air* is used to mean a mixture of dry air and water vapor. Strictly speaking, the term *moist air* should be used, but it is common in air-conditioning terminology to use *air* when referring to *moist air*. There are several standard measures used to describe the proportions of this mixture

such as humidity ratio and moisture content. It is important to understand that there is only a limited range of mixture proportions that are considered to be comfortable by humans. The range is also dependent on temperature. The proportion of water vapor to dry air in the mixture is changed by adding water vapor (humidification) or removing water vapor (dehumidification). The study of the properties and processes of moist air at atmospheric pressures is known as psychrometrics and will be discussed further in a separate Self-Directed Learning course.

Humidification may be accomplished by allowing the air to blow over water on a wet porous surface, by spraying small droplets into the air stream, by misting with an ultrasonic mister, or by steam injection. On the other hand, dehumidification is most commonly accomplished by cooling. Cooling removes the energy from the water vapor, causing it to convert to liquid water. There is a limit to the amount of water vapor that can be held by the air. This limit is known as the saturation condition and it decreases with decreasing temperature. If the temperature of saturated air is decreased, then the vapor condenses into water droplets and drips (or rains) out of the mixture. The result is that the air contains less water vapor.

The change of state from water vapor to liquid water (condensation), or from liquid water to water vapor (evaporation) involves transfer of substantial amounts of thermal energy known as latent heat. Because heating and cooling are about the management of thermal energy to control temperature, it is clear that the effects of humidification and dehumidification will be interrelated with heating and cooling in air conditioning.

There are many types of airborne pollutants. Particulates such as pollen, dust and smoke are common items that must be removed from a typical space. Microscopic organisms such as bacteria, fungi and viruses may be important for health reasons. Some pollutants are just irritating, but others may be deadly. The removal of these pollutants is often achieved by filtering or treating the air stream. Heating and dehumidification are powerful deterrents to many small organisms.

Air exchange between the outdoors and the conditioned space is either by ventilation (intentional) or by infiltration (unintentional and normally undesirable). It is important because the outdoor air is often used to dilute pollutants (such as carbon dioxide) and replenish oxygen to the indoor air. Forced ventilation provides for the best control of air exchange rate and air distribution in a building and is usually mandatory in larger buildings where a minimum outdoor air exchange rate is required. On the other hand, natural ventilation is driven by wind pressure, indoor-outdoor temperature differences or the opening of a window, and it is not closely controlled. Infiltration refers to air that leaks in through cracks, incomplete seals and unintentional openings.

Older residential homes depended on infiltration for an adequate air exchange rate. However, this has become a concern in many modern houses which are purposefully tightly sealed as an energy conservation measure.

Air movement, circulation and mixing are all fluid mechanics processes that involve moving the air between and through the conditioned spaces and to places where the other processes of heating, cooling, humidifying, cleaning and ventilating can occur. Air movement may be forced or free (natural convection). Forced air movement as produced by fans may be carefully controlled. However, free air movement is often driven by temperature (density) gradients in the conditioned space and occurs without control. Mixing is an important process that occurs when outdoor air is mixed with indoor air as part of ventilation or when newly conditioned air mixes with air already in the conditioned space.

1.4 Thermodynamics and Psychrometrics

To better understand and analyze each of the HVAC processes, it is essential to study and develop an appreciation of thermodynamics and psychrometrics. The terms *thermodynamics* and *psychrometrics* may sound quite formidable at first, but as we shall see, they are descriptive terms for some common-sense ideas. Studying thermodynamics will provide the tools for quantifying, analyzing and interpreting the very practical matters of HVAC.

Thermodynamics may be defined as the science of energy. Everybody has some feeling for what is generally meant by energy, but a precise definition takes some development. In the next chapter, some specific definitions and derivations will make it clear how thermodynamics describes the relationships between the different forms of energy and the conversion of one form of energy to another. These relationships occur in almost every aspect of our daily lives. For example, how is it possible to convert the electrical energy of the power supply into a cooling effect in an air-conditioned room? How can solar energy be effectively captured and put to good use? How are the heating needs for a house calculated for the middle of winter? These and many other questions may be answered by conducting an energy, or thermodynamic, analysis.

You may be familiar with the conservation of energy principle. It states that, during an interaction, energy can change from one form to another, but that the total amount of energy remains constant. Said another way, it means that energy is neither destroyed nor created, but only changes from one form to another. Forms of energy include internal (such as chemical, thermal, nuclear and electrical), potential and kinetic. To effectively use this principle, it is essential to understand the different forms of energy, the conversion of one energy form to another, the flow of energy across boundaries, and the ability to store energy.

Thermodynamics is about the conversion of one form of energy to another. Energy conversions are described in terms of the various properties of substances and the changes of the properties that occur as a result of energy transformations. Thermodynamics is based on experimental

observations. The observations are then expressed in terms of some basic laws. For example, the First Law of Thermodynamics is an expression of the conservation of energy principle. The observation that some processes occur in one direction, but not the reverse (for example, the flow of heat from a hot object to a cold one, or the generation of heat by friction) is embodied in the Second Law of Thermodynamics.

On the other hand, psychrometrics is the branch of thermodynamics that deals with the thermodynamic properties and processes of moist air. It is important to study psychrometrics because, in HVAC, we are interested in controlling humidity as well as temperature. The study of psychrometrics is aided by a chart of moist air properties known as the psychrometric chart. Psychrometrics is a field of study for which there is a separate Self-Directed Learning course offered by the ASHRAE Learning Institute.

The applications for thermodynamics are numerous. In HVAC, the study of thermodynamics is particularly applied to:

- Refrigeration and heat pumps
- Heat exchangers
- Cooling and heating coils
- Radiators
- Furnaces
- Fans
- Pumps
- Water and air distribution systems
- Building load calculations
- Human occupation and activity levels

Both thermodynamic and psychrometric principles are applied to these processes:

- Air flow over cooling and heating coils
- Humidifiers and dehumidifiers
- Outdoor weather conditions
- Air in conditioned spaces (with interest in the comfort envelope)
- Breathing by humans and animals

The following chapters of this course will explain the basics of thermodynamics and then consider the practical applications to many of the areas listed above.

The Next Step

This first chapter provided an introduction to HVAC and the importance of thermodynamics. In the next chapter, we will begin to build an understanding of thermodynamics by starting with the basics. In Chapter 2, we will introduce the concepts of open and closed systems, forms of energy, equilibrium and property definition. Chapter 2 will also include explanations of the state of a substance, and the process of state change shown on a property diagram.

Summary

Chapter 1 has been an introductory chapter. Following an introduction and a definition of air-conditioning, the seven main processes of HVAC were listed as heating, cooling, humidifying, dehumidifying, cleaning, ventilating and air movement. Each of these processes involves equipment for implementation and transfer of energy. The study of thermodynamics (or the science of energy) is all about the relationship between different forms of energy, and is essential to fully understand the processes of HVAC. The First Law of Thermodynamics was introduced as a statement of the conservation of energy principle. The Second Law of Thermodynamics was said to embody the idea of irreversibility of some naturally occurring events. After studying this chapter, you should be able to:

- Define air conditioning;
- Name and describe the seven major air-conditioning processes;
- Provide a description of thermodynamics as the science of energy; and
- List HVAC applications where knowledge of basic thermodynamics is essential.

Bibliography

1. Ingels, Margaret. *Father of Air Conditioning.* Garden City: Country Life Press, 1952.

Skill Development Exercises for Chapter 1

Complete these questions by writing your answers on the worksheets at the back of this book.

1-01. List the seven main air-conditioning processes, give a one-sentence description of each process, and give another one-sentence reason why the process is likely to be found in a hospital.

1-02. Define what is meant by *air conditioning*.

1-03. Name five pieces of normal HVAC equipment for which the application of thermodynamic principles is essential to predict performance.

1-04. Explain what is meant by the conservation of energy principle.

1-05. Provide two examples of a process that goes in one direction but will not go in the reverse direction without applying an external energy source.

1-06. What is the difference between dry air and moist air?

Chapter 2
Systems, Properties, States and Processes

Contents of Chapter 2

- Instructions 1
- Study Objectives of Chapter 2 1
- 2.1 Introduction 2
- 2.2 Closed and Open Systems in Thermodynamics 2
- 2.3 Forms of Energy 6
- 2.4 Properties of a System 9
- 2.5 Equilibrium States 9
- 2.6 Processes and Cycles 10
- The Next Step 15
- Summary 15
- Bibliography 15
- Skill Development Exercises for Chapter 2 16

Instructions

Read the material of Chapter 2. Re-read the parts of the chapter that are emphasized in the summary and memorize important definitions. At the end of the chapter, complete all of the skill development exercises.

Study Objectives of Chapter 2

The building blocks of thermodynamics (such as systems, properties, states, processes and cycles) will be introduced in this chapter. Many new terms will be introduced and defined. The definitions may seem far removed from the applications of interest, but this development of a terminology and logic is essential to understanding how to apply the laws of thermodynamics.

After studying Chapter 2, you will be able to:

- Define and describe open and closed systems;
- Define and describe the different forms of energy;
- Define and describe properties and states; and
- Define and describe processes and cycles.

2.1 Introduction

Thermodynamics is about the conversion of one form of energy to another. Energy conversions, in turn, are described in terms of the various properties of substances and the changes of the properties that occur as a result of energy transformations. Thermodynamics is based on experimental observations. The observations are then expressed in terms of basic laws.

For example, the First Law of Thermodynamics is an expression of the conservation of energy principle. The observation that some processes occur in one direction, but not in the reverse direction (for example, the flow of heat from a hot object to a cold one, or the generation of heat by friction) is embodied in the Second Law of Thermodynamics. However, before we can apply these laws as analysis tools to solve practical applications, we must develop a methodology of analysis. This methodology starts with the definitions of systems, properties, states, processes and cycles.

The study of thermodynamics is framed around a system identified for analysis, and the interactions between that system and its surroundings. The condition, or equilibrium state, of a system is defined in terms of the values of the system's properties when at that condition. Properties are any characteristics of the system. The "dynamics" part of thermodynamics suggests the idea of change, and so changes of state are described in terms of processes and paths. Each of these ideas will be more fully explained.

2.2 Closed and Open Systems in Thermodynamics

In thermodynamics, the first step in analyzing and finding a solution is identifying the system to be analyzed. The term *thermodynamic system* has a special meaning in this context as any quantity of matter, or any region in space, selected for study. The system is contained within an imagined system boundary, and everything outside the boundary is known as the surroundings. Heat and work (to be defined later) can cross the boundary in a form of interaction between the system and its surroundings, but it depends on the type of system as to whether mass can cross the boundary. There are two types of systems: closed and open.

A closed system is one in which a quantity of matter is identified for study. A closed system definition is often called the "control mass" approach. A quantity of matter means that the amount of mass to be studied will remain the same throughout the analysis. The matter in the system may change form, phase or location in space, but the system is identified as that matter that was originally targeted for study. There is an imaginary boundary drawn to contain the matter. The location of the matter, and therefore the shape of the boundary, may change with time; but to remain a closed system, no mass enters or leaves the system through the boundary. Everything outside the boundary is known as the surroundings. Although there is no mass exchange across the boundary in closed systems, there may still be work and heat crossing the boundary as the system interacts with its surroundings.

The other type of system is the open system. An open system is one in which a region in space is identified for study rather than a quantity of matter. An open system definition is often called the "control volume" approach. In an open system, mass can cross the imaginary boundary between the system and its surroundings. This is important because, as we shall see later, the mass crossing the boundary can also be a vehicle for carrying energy across the boundary. The region in space does not have to be fixed in time, although it is often chosen that way for convenience. In a way, the closed system is a special case of an open system, for which there is no mass flow across the boundary.

An example of a closed system is shown in *Figure 2-1*. The object chosen for demonstration is a piston and cylinder combination with air in the cylinder. The air is trapped in the cylinder and there is no way for the air to escape, or for new air to come into the cylinder. The system is chosen to be

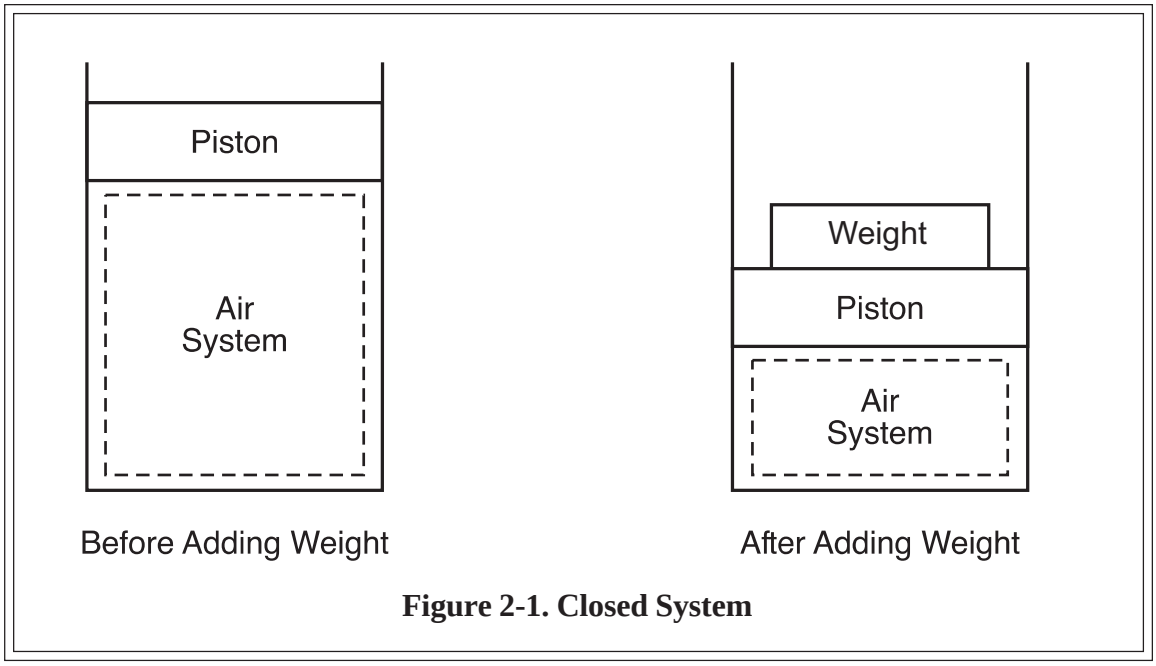


Figure 2-1. Closed System

the matter (mass of air) that is trapped in the cylinder. The system boundary is shown by the dotted line. The surroundings are then the piston itself, the cylinder wall, the cylinder head and everything else outside the dotted line. As weights are added to the piston and the piston moves to reduce the volume in the cylinder, the system (air in the cylinder) is compressed and changes shape, but it still maintains the same air that was originally targeted as the system.

Open systems are shown in *Figures 2-2* and *2-3*. *Figure 2-2* shows a piston and cylinder arrangement like before, only now there is an open valve connecting the cylinder head to a storage tank. Once again, the system is identified as the matter (mass of air) that is in the cylinder at any instant in time. However, with the open system, the amount of air in the cylinder will change when a weight is placed on the piston and the piston moves. Some of the mass initially in the system is pushed across the system boundary and into the storage tank that is part of the surroundings. There is mass flow across the boundary. Although the open system analysis is also called a control volume analysis, the volume does not have to remain fixed in time or space. As can be seen in this case, the control volume changes shape and size during the change.

Before leaving *Figure 2-2*, it is worthwhile to note that the case of the cylinder and the storage

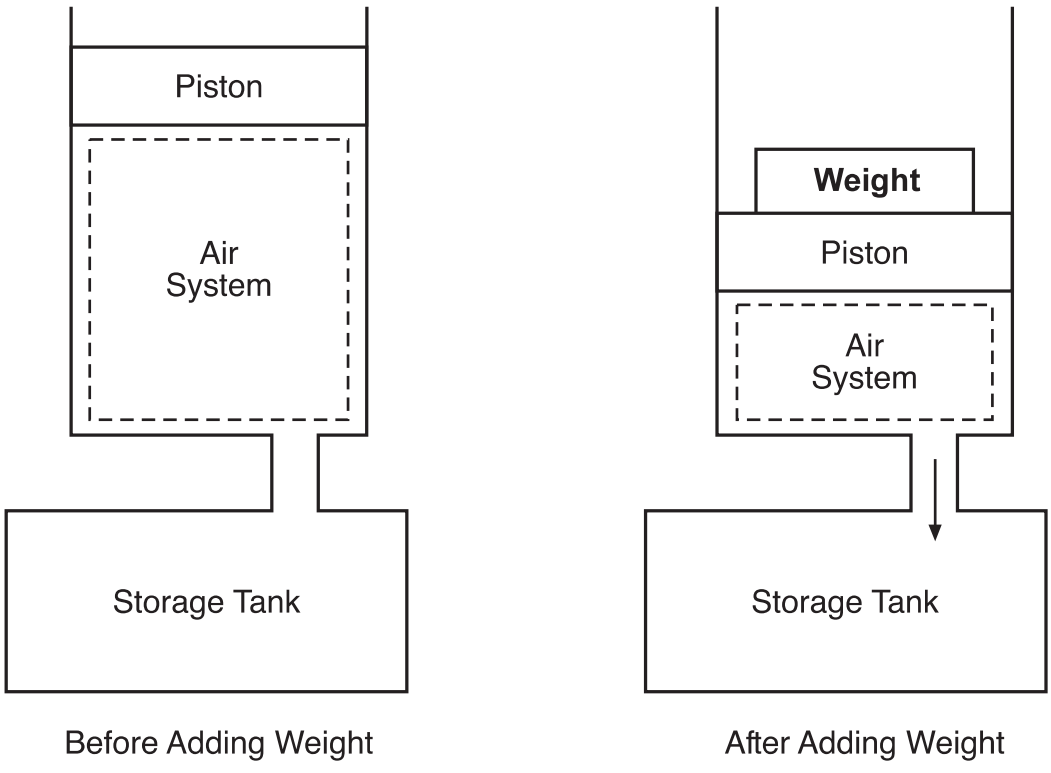


Figure 2-2. Open System

tank could have been treated as a closed system if the matter in the system had included both the air in the cylinder and the air in the storage tank. It may also be noted that a different choice of open system could have been to draw a boundary to include the piston and the weights in addition to the air. Which boundary is better depends on what is known, what is sought and what processes are occurring during the change.

Figure 2-3 depicts another example of an open system - in this case, a reciprocating compressor. The system boundary is drawn to include both the compressor and the air inside the compressor. Mass flows in across the boundary at the inlet, and out across the boundary at the outlet. In this open system, the control volume remains the same in time and space.

There are many choices when it comes to selecting the system and system boundary. The skill is in choosing a system that allows the most convenient analysis and calculation of the unknowns. We will return to the topic of system selection once we have introduced the First Law of Thermodynamics.

The conceptual model of system, system boundary and surroundings will be used later to apply the laws of thermodynamics in a way that will permit calculation of practical and useful results. There is only one set of laws, but the thermodynamic relations (equations) that are applicable to closed and open systems are different, making it important to be able to recognize the type of system before starting the analysis. Before applying laws (such as the conservation of energy), we must be able to describe the condition of the system, and define what we mean by energy.

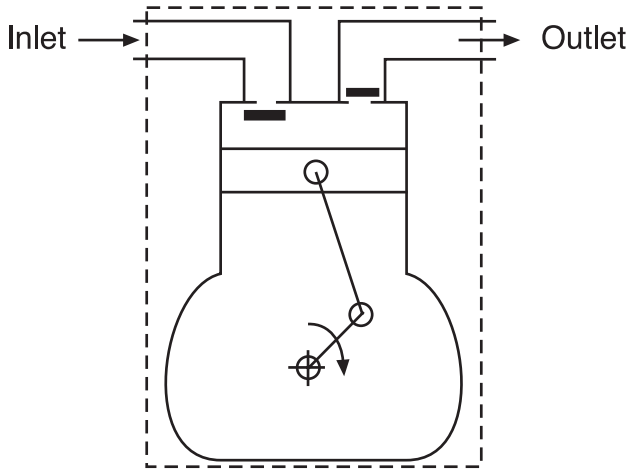


Figure 2-3. Open System Reciprocating Compressor

2.3 Forms of Energy

The different forms of energy (such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical and nuclear) add together to give the total energy of a system, *E*. The magnetic, electric, nuclear and surface tension effects are important in some cases, but are usually not significant in HVAC&R problems and will not be dealt with here. The total energy, *E*, and the total energy per unit mass, *e*, may be written as the sum of the internal, potential and kinetic energies:

$$E = U + \text{PE} + \text{KE} = U + mgz + mV^2/2$$

$$e = u + \text{pe} + \text{ke} = u + gz + V^2/2$$

The total energy on a unit mass basis, *e*, is defined as:

$$e = E/m \qquad \text{(kJ/kg)}$$

In thermodynamic analysis, it is common to group the forms of energy into two broad categories: macroscopic and microscopic. The macroscopic forms of energy are those that a system possesses as a whole with respect to some outside reference frame. Kinetic and potential energies are examples of macroscopic forms of energy because, as we shall see later, they are defined in terms of an outside reference frame. The microscopic forms of energy are those related to the molecular structure of a system and the degree of molecular activity. Microscopic forms are independent of an outside reference frame. The sum of all microscopic forms of energy is known as the internal energy of the system, *U*. On a unit mass basis, the specific internal energy is:

$$u = U/m \qquad \text{(kJ/kg)}$$

Internal energy is measured at the molecular level. The individual molecules of a system are in continuous motion and the motion contributes to translational, rotational and vibrational molecular energy. The portion of the internal energy associated with this molecular motion is known as sensible energy. The degree of molecular activity increases with temperature; therefore, the sensible energy is higher at higher temperatures.

The internal energy is also related to the intermolecular forces between molecules of the system. The forces that bind molecules are strongest in solids and weakest in gases. If sufficient energy is added to a solid or liquid, it will change phase and become a gas. The three *states* or *phases* of a substance are solid, liquid and gas. The energy added to make a substance change state is known as latent energy. Latent energy is part of the internal energy of a substance. Sensible and latent energy changes involve no chemical change in the substance of the system.