ASHRAE
Learning Institute

Your Source for HVAC&R Professional Development

FUNDAMENTALS OF STEAM SYSTEM DESIGN

(I-P EDITION)

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

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.



Your Source for HVAC&R Professional Development
1791 Tullie Circle, NE • Atlanta, GA 30329-2305 USA • Tel 404.636.8400 • Fax 404.321.5478 • www.ashrae.org

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

Dear Student,

Welcome to the ASHRAE Learning Institute (ALI) **Fundamentals of HVAC&R Series** of self-directed or group learning courses. 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, CEUs 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 test your comprehension of the course material. These exercises allow you to apply the principles you have learned and develop a deeper mastery of the subject matter. If you take this course for credit, please complete the exercises in the workbook and send copies from each chapter to: ASHRAE Learning Institute, 1791 Tullie Circle, Atlanta, GA 30329-2305 or edu@ashrae.org.

Please include your student ID number with each set of exercises submitted. Your student ID is the last five digits of your order number, which can be located in the top left corner of your packing slip. You can also email us for your ID at edu@ashrae.org. 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 own 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 or 3.5 CEUs of continuing education credit. **Please note:** The ALI does not award partial credit for SDLs. All exercises must be completed to receive full continuing education credit.

We hope your educational experience is satisfying and successful.

Sincerely,



Karen M. Murray
Manager of Professional Development

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

ASHRAE Learning Institute

Fundamentals of Steam System Design

(I-P Edition)

Prepared by

Dr. Ho Sung Lee
Dr. Peter Parker
Western Michigan University



ASHRAE
1791 Tullie Circle NE • Atlanta, GA 30329

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

ASHRAE Fundamentals of HVAC&R Series

Print

Fundamentals of...

Psychrometrics

Air System Design

Steam System Design

Heating and Cooling Loads

Heating Systems

Thermodynamics

Water System Design

Refrigeration

eLearning

Fundamentals of...

HVAC Control Systems

HVAC Systems

Refrigeration

Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality

Standard 90.1-2004, Energy Efficiency in New Buildings

Fundamentals of Steam System Design I-P
A Course Book for Self-Directed or Group Learning
ISBN 978-1-933742-01-4

© 2006 ASHRAE
All rights reserved.

ASHRAE Learning Institute

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 book 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

Joyce Abrams
Group Manager of Education and Certification

Karen Murray
Manager of Professional Development

Martin Kraft
Managing Editor

Vickie Warren
Secretary/ Administrative Assistant

Special Publications

Mark Owen
Editor/Group Manager of Handbook and Special Publications

Cindy Sheffield Michaels
Managing Editor

Matt Walker
Associate Editor

Elisabeth Warrick
Assistant Editor

Meaghan O'Neil
Editorial Assistant

Michshell Phillips
Editorial Coordinator

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

Any errors or omissions in the data should be brought to the attention of Special Publications via e-mail at **SDLcorrections@ashrae.org**.

Any updates/errata to this publication will be posted on the ASHRAE Web site at www.ashrae.org/publicationupdates.
Errata noted in the list dated 4/1/11 have been corrected.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Table of Contents

Chapter 1. Introduction to Steam System Design 1-1
1.1 Introduction 1-2
1.2 Review of Thermodynamic Fundamentals 1-3

Chapter 2. HVAC Steam Systems 2-1
2.1 Steam and Condensate 2-2
Sensible Heat and Latent Heat 2-2
Dry and Wet Saturated Steam 2-3
Superheated Steam 2-3
Gauge Pressure and Absolute Pressure 2-3
Specific Volume 2-3
Condensate 2-5
2.2 Advantages of Steam 2-6
2.3 Basics of Steam Systems in HVAC 2-7
Condensate Return and Steam Trap 2-7
Water Hammer 2-7
Steam Separator 2-8
Drip Leg, Dry Return and Feed water System 2-8
Air Vent 2-8
System Operation 2-11
Vacuum Breaker 2-11
Heating Load 2-12
2.4 Operating Pressures of Steam Systems 2-12
2.5 Steam Heating Systems 2-13
Steam Distribution 2-13
One-Pipe Steam Heating Systems 2-13
Two-Pipe Steam Heating Systems 2-15
2.6 Steam Condensate Systems 2-16

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Table of Contents

Vented Return Systems (Dry and Wet Returns) 2-16
Nonvented Return Systems 2-16
2.7 Boiler Connections 2-17
Gravity Return 2-19
Pumped Return 2-19

Chapter 3. Terminal Units I 3-1
3.1 Natural Convection Units 3-2
Radiators 3-2
Convectors 3-5
Baseboard Units 3-7
Finned-Tube Units 3-8
3.2 Ratings of Heat –Distributing Units 3-9
3.3 Corrections for Nonstandard Conditions 3-9
3.4 Applications 3-12
Radiators 3-12
Convectors 3-13
Baseboard Radiation 3-13
Finned-Tube Radiation 3-13

Chapter 4. Terminal Units II 4-1
4.1 Unit Heaters 4-2
Type of Unit Heater 4-3
Location for Proper Heat Distribution 4-4
Rating of Unit Heaters 4-5
Piping Connections 4-9
4.2 Unit Ventilators 4-10
Heating Capacity Requirements 4-12
4.3 Fan-Coil Units 4-14
4.4 Cabinet Heaters 4-15
4.5 Induction Units 4-15
4.6 Air-Handling Units 4-16
Humidifiers 4-17
Steam Coils 4-18

Chapter 5. Boilers 5-1
5.1 Boilers 5-2

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Table of Contents

5.2 Boiler Classifications 5-3
Working Pressure and Temperature 5-3
Construction Materials 5-4
Type of Draft 5-6
Condensing or Noncondensing 5-8
5.3 Fuels and Combustion 5-8
Fuels 5-8
Combustion 5-9
5.4 Efficiency 5-13
5.5 Cost of Producing Steam 5-14
5.6 Boiler Sizing 5-15

Chapter 6. Steam Valves, Steam Traps, Flash Tanks, and Condensate Receiver Tanks 6-1
6.1 Fundamentals of Valves 6-2
6.2 Manual Valves 6-3
Globe Valves 6-3
Gate Valves 6-4
Ball Valves 6-4
Plug Valves 6-5
Check Valves 6-5
6.3 Self-Contained Valves 6-6
Pressure-Reducing Valves (PRV) 6-6
Installation 6-7
Valve Size Selection 6-9
Temperature Control Valves (Temperature Regulators) 6-10
6.4 Safety Devices 6-11
6.5 Steam Traps 6-13
Mechanical Traps 6-14
Float and Thermostatic Traps 6-14
Inverted Bucket Traps 6-15
Thermostatic Traps 6-15
Bellows Thermostatic Traps 6-16
Bimetallic Thermostatic Traps 6-16
Kinetic Traps 6-17
Thermodynamic Traps (Disc Traps) 6-17

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Table of Contents

Orifice Traps 6-17
Steam Trap Selection and Sizing 6-18
6.6 Flash Steam 6-20
6.7 Condensate Receiver Tanks 6-24

Chapter 7. Steam Piping Design 7-1
7.1 Pipe Sizing 7-2
Initial Pressure and Pressure Drop 7-3
Maximum Velocity 7-3
Equivalent Length of Run 7-4
Sizing Steam Pipes 7-7
Sizing Condensate Pipes 7-10
7.2 Piping 7-15
Supply Piping Design Considerations 7-17
Return Piping Design Considerations 7-20
Terminal Equipment Piping Design Considerations 7-21
7.3 Pipe Materials 7-21
7.4 Insulation 7-23
Types of Insulation 7-24
Forms of Insulation 7-24
Insulation Materials 7-25
Insulation Thickness 7-25
7.5 Pipe Expansion 7-27
Expansion Loops 7-27
Expansion Joints 7-27
7.6 Pipe Supporting Elements 7-29
Pipe Supports 7-31
Hangers 7-31
Roller Supports 7-31
Pipe Guides 7-32
Anchors 7-32

Appendix A
Table 1: Temperature Table A:1
Table 2: Pressure Table A:3
Table 3: Properties of Superheated Steam A:6

Student Answer Sheets
Evaluations

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Preface

This material is designed as an introduction to the use of steam for residential and commercial heating, humidification, and, to a much lesser extent, air conditioning. Each chapter is introduced with the learning objectives for the chapter, followed by the material for the chapter. A set of bibliographic references follows the text material. These references are included as sources of further information on the material in the chapter. A set of skill exercises follows the bibliographic references.

Symbol and abbreviation usage in the inch-pound system presents some problems. For example, there is great disparity in the use of the symbol "lb". Some authors use this abbreviation to mean a measure of mass, others use it as a measure of force (due to the numeric equivalency between a pound (mass) and a pound (weight or force), and some authors let the reader determine the appropriate interpretation from the context. Similarly, "h" and "hr" are abbreviations used for "hour". In this text, we will use lb_m to indicate a pound (mass), lb_f to indicate a pound (force), and "hr" to indicate "hour". However, some of the tables and figures that we include come from older references and will use lb for either lb_m or lb_f. Likewise, "h' is occasionally used for "hour". In these cases, we believe the context is sufficiently unambiguous that the symbols are easily interpreted.

The properties of water and steam are extensively studied and tabulated. Periodically, the published tables are revised as measurement methods are refined. Major revisions occurred in 1967 and again in 1997. The steam tables in the appendix and the data used in the examples use the 1997 version of the steam tables. When compared to older tables, the properties of water and steam may differ somewhat, but the difference is normally quite small (e.g. < 0.1%) and generally insignificant for engineering purposes.

This book is the result of the efforts of many. In addition to the authors, the manuscript was reviewed by Roy Ahlgren, Richard Hegberg, Kelly Paffel, and Doug Reindl. They provided important insights and suggestions, although final responsibility for the material rests with the authors. Bruce Kimball from the ASHRAE Learning Institute was the Managing Editor.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Chapter 1
Introduction to Steam System Design

Contents of Chapter 1

Instructions
Study objectives of Chapter 1
- 1.1 Introduction
- 1.2 Thermodynamics Review

Summary
The Next Step
Bibliography
- Skill Development Exercises

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Instructions

Read the material of Chapter 1. Re-read the material emphasized in the summary. As necessary, review the material *in Fundamentals of Thermodynamics and Psychrometrics* to ensure a thorough comprehension of thermodynamics as applied to open and closed systems. At the end of the chapter, complete all of the skill development exercises.

Study Objectives of Chapter 1

Chapter 1 is intended to give an overview of steam systems used for HVAC and to review the thermodynamic principles necessary for the analysis of steam systems used in HVAC. After studying Chapter 1, you should be able to define a system, determine if it is open or closed, and write the appropriate material and energy balance for the system. You should then be able to describe the basics of HVAC steam systems and classify them (or parts thereof) as open or closed systems.

1.1 Introduction

Steam system heating is an important component of building design. Designing and specifying efficient and economic space conditioning systems takes a significant effort. Similarly, air conditioning (the control of the temperature and humidity of the air in the process or building space) may be critical for proper process operation or important for employee comfort. Steam is an ideal medium for supplying energy or moisture for many applications. The proper design of a steam HVAC system depends upon a thorough understanding of the system requirements, the properties of steam, and the ability of a source to supply that steam.

The design of a building's steam heating systems first requires determining the heating load. The heating load is a result of many factors including the building's construction, the local weather distribution, the building occupancy patterns, and indoor environmental requirements. The heating load determines the size of the required heating source. In determining the heating load, reference should be made to chapters 28 (Residential Heating Loads) and 29 (Load Calculation Procedures) of ASHRAE's *2005 Fundamentals Handbook* and to ASHRAE's *Cooling and Heating Load Principles*. Typical examples of heating loads are:

Solar Radiation

Infiltration

Ventilation Air

People

Appliances

Lighting

Water, in both its liquid and vapor form, is a rather unique substance that makes it particularly suitable for HVAC uses. It is abundant and thus relatively cheap. The conden-

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

sation of the vapor liberates a rather large amount of energy on a per unit mass basis, which makes it ideal for transporting heat energy from a source to a destination. It changes from the liquid to the vapor state at relatively low temperatures (e.g. 212°F at 1 atmosphere). The liquid form is relatively easy to pump. Both the vapor and liquid forms are non-toxic, non-corrosive, and non-flammable. Thus, systems that utilize steam have been developed to heat work spaces, humidify air, and provide an energy source for heat-driven refrigeration.

A simple schematic of a steam heating system is shown in Figure 1.1:

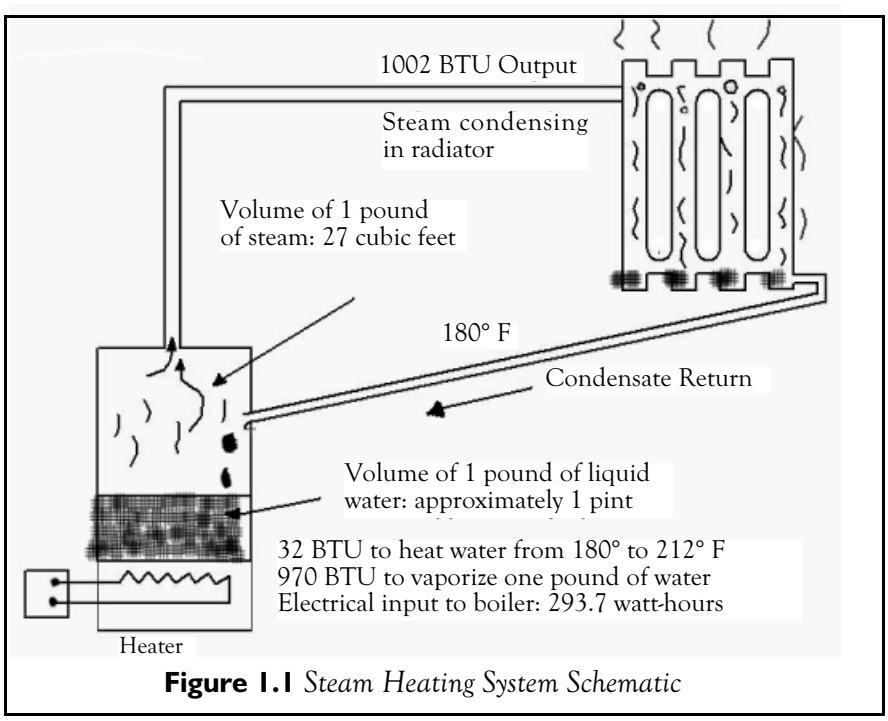


Figure 1.1 *Steam Heating System Schematic*

1.2 Thermodynamics Review

In the previous paragraphs, we have used the "system" rather loosely. To ensure proper analysis, it is important to properly define what is in a "system" and what is not in a system. A "system" is that collection of components and processes that is identified for study. Everything else is the "surroundings" or the "environment". Consider the old-fashion radiator used for space heating. As shown in Figure 1.2, a relatively complete collection of components consists of the radiator, the inlet and return piping, the boiler, and a steam storage drum. If we were interested in studying the performance of this group of components for space heating, we might consider the entire collection as the system. However, if we were more interested in the heat transfer processes in the radiator, we might single out the radiator for study. Identifying single or multiple components for inclusion in the system is normally done by drawing a circle around the components to be included in the scope of the system.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

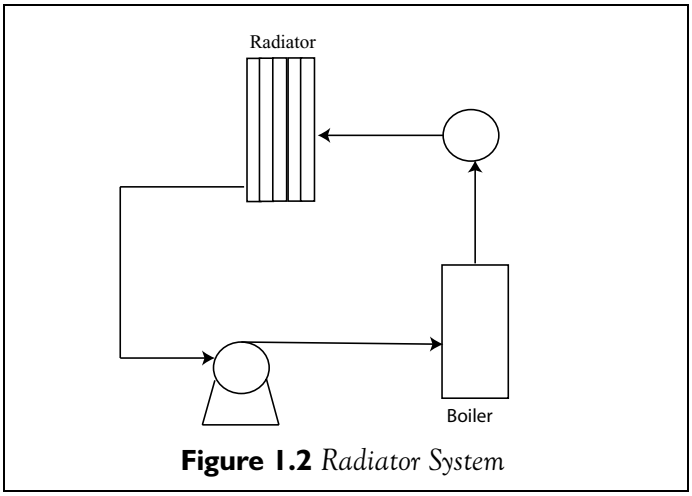


Figure 1.2 *Radiator System*

Figure 1.3a includes all the components as the system, while Figure 1.3b isolates the radiator as the system. In the case of Figure 1.3b, everything except the radiator is included in the surroundings; only the radiator is in the system.

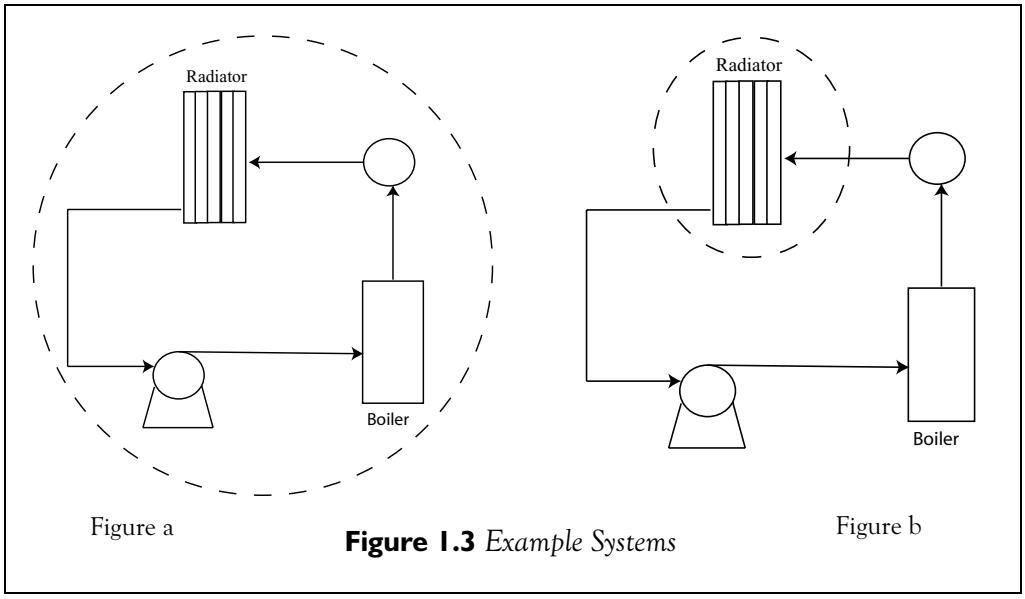


Figure 1.3 *Example Systems*

Figure 1.3 also serves to illustrate the difference between "closed" and "open" systems. A system is closed when there is no exchange of **mass** with the surroundings. As is shown in Figure 1.3a, there is no flow of steam across the system boundary, so the system is closed. An open system, on the other hand, can exchange mass with the surrounding. In Figure 1.3b, the heating fluid enters and leaves the system (the radiator), so the system is open. Energy flows, such as heat, can cross the system boundaries for both open and closed systems. Steam HVAC systems are normally “closed” since supply steam should not be allowed to “leak” into the building structure and condensate must be collected and returned to the boiler to conserve energy and minimize water treatment costs.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

It is important to properly define a system for study. Too narrow a definition leaves out critical parts for the analysis; too inclusive a definition may add unnecessary complexity and hide the important components or processes.

While the transient (time-varying) behavior of systems is often of interest, the steady state behavior of the system is usually used as the design basis. Thus, the mass and energy balances for steady flow are critical steps in the analysis. The mass balance for a closed or open system is:

$$\text{Mass: } 0 = \sum_{in} \dot{m} - \sum_{out} \dot{m} \tag{1-1}$$

Where $\dot{m}$ represents the flow rate.

Note that flows into the system are considered positive and flows leaving the system are considered negative.

Explicitly showing the heat and work energy flows in Figure 1.2, we have Figure 1.4.

The closed system energy balance[1] for the system of Figure 1.4 is:

$$\left(\frac{dE}{dt}\right)_{sys} = \dot{Q} - \dot{W} \tag{1-2}$$

where

E = energy of the system

$\dot{Q}$ = flows of heat energy into (or out of) the system

$\dot{W}$ = rate of work applied to the system

The open system, steady-state energy balance is similar to the closed system energy balance, but has additional terms related to the flow of energy through the system:

$$\sum_{out} \dot{m}\left(h + \frac{\upsilon^2}{2} + gz\right) - \sum_{in} \dot{m}\left(h + \frac{\upsilon^2}{2} + gz\right) = \dot{Q} - \dot{W} \tag{1-3}$$

where

h = specific enthalpy of the material in stream

υ = velocity of material in stream

z = elevation above a common reference plane

1. The sign of the work term in the energy balance must be considered carefully. ASHRAE and other mechanical engineering societies consider work done by the system as positive, while chemical engineers and the International Union of Pure and Applied Chemistry consider work done by the system as being negative. When consulting multiple references, always check for the sign convention for the work term.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

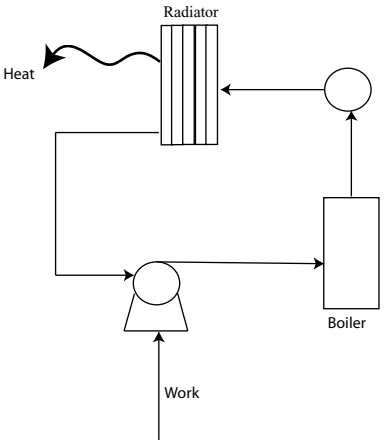


Figure 1.4 *Energy Flows*

g = acceleration due to gravity

The energy term E on the left hand side of Equation (1-2) includes the internal energy as well as kinetic and potential energy terms:

$$E = m\left(u + \frac{\upsilon^2}{2} + gz\right) \tag{1-4}$$

where:

m = mass of the system

u = specific internal energy

A variety of other energy terms, such as chemical and nuclear energies have been neglected.

For most HVAC systems, changes in kinetic and potential energy are negligible compared to the changes in the other energy forms and can be neglected. The closed and open system energy balance generally reduce to equations (1-5) (closed system) and (1-6) (open system)

$$m(u_2 - u_1) = Q - W \tag{1-5}$$

$$\sum_{out} \dot{m}h - \sum_{in} \dot{m}h = \dot{Q} - \dot{W} \tag{1-6}$$

where the subscripts on the internal energy terms in (1-5) represent two points in time and Q and W are the total amounts of energy and work supplied in the time interval under study.

The signs on both work and heat flow are critical, as they show the direction of flow. Universally, the flow of heat, $\dot{Q}$ is considered positive when flowing from the surround-

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

ing into the system. Thus, in Figure 1.4, the flow of heat to the boiler is positive and the flow of heat from the radiator is negative.

As noted in the footnote above, there are two conventions for the sign of the work term. This text will use the ASHRAE convention that work done by a system is positive, while work done on the system is negative. Thus, in Figure 1.4, the work supplied to the pump (in the form of electrical energy) is considered negative.

The specific internal energy, u, and the specific enthalpy, h, are properties of the material. These two energy terms are related to each other by (1-7)

$$h \equiv u + (P \cdot v) \tag{1-7}$$

where

P = pressure of the system
u = internal energy per unit mass
v = specific volume of the material.

For most fluids of interest, these properties are tabulated as functions of temperature and pressure. The values for h and u do not have a true zero; rather a zero value is assigned at some arbitrary temperature and pressure. For example, the **steam tables**[2] assign a value of 0 Btu/lb_m to the internal energy of liquid water at the triple point (the point where ice, liquid, and water vapor coexist: 32.02°F, 0.089 psia) For most applications, we will be concerned about the difference between two states, so the arbitrary zero value state is of no concern.

To illustrate this relation between h, u, P, and υ, consider saturated steam at 212°F and 1 atm. At these conditions, the steam tables list the properties as:

$$u = 1077.4\ Btu/lb_m$$
$$P = 1\ atm$$
$$v = 26.78\ ft^3/lb_m$$

Applying equation (1-7), we would compute

$$h = 1077.4\ Btu/lb_m + 1\ atm \cdot 26.78\ ft^3/lb_m = 1150.3\ Btu/lb_m$$

and the steam table gives an identical value. (The conversion factor for the $P \cdot v$ term is: 2.7195 $Btu/atm \cdot ft^3$.)

Changes between two states are simply the difference between the properties at the two states:

2. **Steam tables** are tabulated properties of water and water vapor. Properties normally include the specific volume, enthalpy, and entropy of both the vapor and the liquid states as functions of temperature and pressure. Appendix A is an abbreviated copy of the steam tables.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

$$\Delta u = u_2 - u_1 \qquad \Delta h = h_2 - h_1$$

Using the steam tables, the enthalpy difference between steam at 212°F and 1 atm and water at the same conditions is:

$$h_{fg} = \Delta h = 1150.3\ Btu/lb_m - 180.2\ Btu/lb_m = 970.1\ Btu/lb_m$$

This enthalpy change from the liquid state to the vapor state is also called the heat of vaporization[3] and is usually given the symbol h_{fg}.

The heat of vaporization for water is large compared to other materials. Water is also abundant, non-toxic, and relatively non-corrosive. This makes it ideal for transporting energy from high temperature sources (e.g. a boiler) to spaces that need heat, such as rooms, buildings, or processes.

Example 1-1:

Consider the radiator in Figure 1.4. Let's assume that this radiator must heat a room and calculations show that the heating demand is 10,000 Btu/hr. How much steam (available at 20 psi, saturation) must be condensed (and returned to the boiler) in the radiator to supply this energy flow?

Solution:

A picture of our system is given in Figure 1.5. We assume that there is a steady flow of steam to the radiator and that changes in kinetic energy and potential energy are negligible, especially compared to the energy given up by the condensing steam. Thus the open system energy balance (Equation 3) becomes:

$$\sum_{out} \dot{m}h - \sum_{in} \dot{m}h = \dot{Q} - \dot{W}$$

There is no work done by or to the system, so

$$\dot{W} = 0$$

As is evident from the picture of the system there is only a single input and a single output, reducing Equation 6 to:

$$\dot{m}(h_{water} - h_{steam}) = \dot{Q}$$

3. The energy required to vaporize liquid water at constant temperature and pressure is variously called the latent heat of vaporization, enthalpy of vaporization, latent heat of evaporation, and enthalpy of evaporation. These terms all refer to the same thing – the energy required to vaporize a unit mass of water at constant temperature and pressure.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

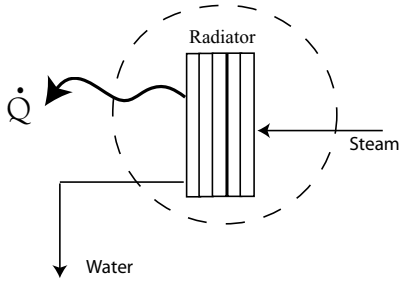


Figure 1.5 *Example Problem*

where the outlet flow is identified as "water" and the inlet flow identified as "steam". From the problem statement, $\dot{Q} = -10,000\ Btu/h$, where the negative sign indicates that the energy is leaving the system (the radiator).

Using the steam tables, we find the enthalpy of steam and water at 20 psia as:

$$h_{steam} = 1156.2\ Btu/lb_m$$
$$h_{water} = 196.3\ Btu/lb_m$$

Substituting these values into the energy balance and solving for the flow rate of steam gives:

$$\dot{m} = \frac{10,000\ Btu/h}{1156.2\ Btu/lb_m - 196.3\ Btu/lb_m} = 10.4\ lb_m/h$$

Thus, the radiator must condense 10.4 pounds of steam per hour to supply the necessary heat to the room.

Summary

This introductory chapter reviewed material in previous courses. Open systems have a material transport across the system boundary, while closed systems do not. Open systems and closed systems are defined with respect to the material flows. Energy flows across the system boundary can occur in either open or closed systems. Any analysis should begin by drawing a picture of the system under study and clearly identifying what is (and what is not) in the system. Once the system is defined, the appropriate material and/or energy balances are written. Closed systems will typically be non-steady state, while open systems are typically analyzed at steady state.

For steam HVAC systems, material flows are normally steam or hot water. The thermodynamic properties of water and steam are given in the steam tables, which are tabular values of enthalpy, entropy and volume as a function of temperature and pressure. The

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution,
or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

large heat of vaporization of water (and its large heat capacity) makes steam an ideal medium for transferring thermal energy from point to point.

You should now be able to:

- From a written problem, draw a picture of a system and show the system boundaries.
- Write the appropriate material and energy balances for a given system.
- Extract the necessary properties of steam from a steam table, given the system temperature and pressure.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Bibliography

ASHRAE Handbook. 2004. *HVAC Systems and Equipment*. ASHRAE, Atlanta, GA.

Clifford, G. F. 1997. *Modern Heating and Ventilating Systems Design*. Prentice Hall, Upper Saddle River, NJ.

Himmelblau, D., J. B. Riggs. 2003. *Basic Principles and Calculations in Chemical Engineering*. Prentice Hall, Upper Saddle River, NJ.

Howell, R., H. Sauer, and W. Coad. 2005. *Principles of Heating, Ventilating and Air Conditioning*. ASHRAE, Atlanta, GA.

Johnson, R. 2004. *Fundamentals of Thermodynamics*. ASHRAE, Atlanta, GA.

McQuiston, F. C., J. D. Parker and J. D. Spitler. 2005. *Heating, Ventilating, and Air Conditioning: Analysis and Design*. John Wiley & Sons, New York, NY.

Pedersen, et. al. 1998. *Cooling and Heating Load Calculation Principles.* ASHRAE, Atlanta, GA.

Sonntag, R., C. Borgnakke, and G. Van Wylen. 2002. *Fundamentals of Thermodynamics*. John Wiley & Sons, New York, NY.

© 2006 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Skill Development Exercises For Chapter 1

Please write you answers on the sheets provided in the back section of this book, and submit the answers to the ASHRAE Learning Institute.

Use the following scenario to answer all of the questions:



A teakettle is sitting on a stove burner. The stove burner is currently turned off and the teakettle is approximately ¾ full of water.

1-1. Neglecting movement of water by evaporation, is the system open or closed?

1-2. Is the system at steady state?

1-3. The burner is turned on, but the water has not yet begun to boil. Is the system at steady state with respect to material flow?

1-4. The burner is turned on, but the water has not yet begun to boil. Is the system at steady state with respect to energy flow?

1-5. The teakettle is boiling vigorously. Is the system open or closed?

1-6. The teakettle is boiling vigorously. Is the system at steady state with respect to mass flow?

1-7. The teakettle is boiling vigorously. Is the system at steady state with respect to energy flow?

1-8. The teakettle, boiling vigorously, boils off 1 cup (approximately ½ pound) of water in 20 minutes. What is the rate of heating energy applied to the teakettle in BTU/h?