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(I-P EDITION)

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ASHRAE Learning Institute

Fundamentals of Heating and Cooling Loads

(I-P Edition)

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Table of Contents

Chapter 1 Heat Transfer and Load Calculation

- Instructions
- Study Objectives of Chapter 1
- 1.1 Conduction
- 1.2 Convection
- 1.3 Radiation
- 1.4 Thermal Capacitance, Sensible and Latent Heat Transfer
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 1

Chapter 2 Simple Heat Loss Calculation Procedure

- Instructions
- Study Objectives of Chapter 2
- 2.1 The Basic Process
- 2.2 Example Building
- 2.3 Useful Comments
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 2

Chapter 3 Temperature Design Conditions and Weather Data

- Instructions
- Study Objectives of Chapter 3
- 3.1 Inside Design Conditions
- 3.2 Outside Design Conditions
- 3.3 Winter Outdoor Design Temperature
- 3.4 Wind and Annual Extremes Data
- 3.5 Summer Outdoor Design Conditions
- 3.6 Other Sources of Climatic Information
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 3

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Chapter 4 Thermal Properties of Materials

- Instructions
- Study Objectives of Chapter 4
- 4.1 Building Material Properties
- 4.2 U-Factors for Non-Uniform Sections
- 4.3 Surface Resistances and Dead-Air Spaces
- 4.4 Thermal Performance Among Alternatives
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 4

Chapter 5 Heat Transfer Through Walls, Roofs and Floors

- Instructions
- Study Objectives of Chapter 5
- 5.1 Building Description
- 5.2 Zoning the Design
- 5.3 Unheated Spaces
- 5.4 Slab-on-Grade
- 5.5 Basement
- 5.6 Crawlspace
- 5.7 Dormers, Gables and Overhangs
- 5.8 Building Summary
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 5

Chapter 6 Infiltration and Ventilation

- Instructions
- Study Objectives of Chapter 6
- 6.1 Infiltration Sources
- 6.2 Air Change Method
- 6.3 Effective Leakage Area Method
- 6.4 Ventilation
- 6.5 Humidification and Moisture Control
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 6

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Chapter 7 Cooling Load Calculations

- Instructions
- Study Objectives of Chapter 7
- 7.1 Introduction
- 7.2 Heat Flow Rates
- 7.3 Initial Design Considerations
- 7.4 Calculation Methods
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 7

Chapter 8 Air-Conditioning Loads on Walls, Roofs and Partitions

- Instructions
- Study Objectives of Chapter 8
- 8.1 Sol-Air Temperatures
- 8.2 CLTD for Roofs
- 8.3 CLTD for Walls
- 8.4 Interior Partitions
- 8.5 Sample Problem
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 8

Chapter 9 Cooling Loads from Windows

- Instructions
- Study Objectives of Chapter 9
- 9.1 Introduction
- 9.2 Window Gains by Conduction
- 9.3 Solar Heat Gains
- 9.4 Internal and External Shading Devices
- 9.5 Example Calculations
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 9

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Chapter 10 Internal Loads

- Instructions
- Study Objectives of Chapter 10
- 10.1 Lighting
- 10.2 Power
- 10.3 Appliances
- 10.4 People
- 10.5 Cooling System Gains
- 10.6 Examples
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 10

Chapter 11 Example Heating and Cooling Load Calculations

- Instructions
- Study Objectives of Chapter 11
- 11.1 Sample Problem Definition
- 11.2 Initial Data Collection and Assumptions
- 11.3 Heating Load
- 11.4 Cooling Load
- 11.5 Review
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 11

Chapter 12 Transfer Function Method

- Instructions
- Study Objectives of Chapter 12
- 12.1 Heat Gain by Conduction Through Exterior Walls and Roofs
- 12.2 Conversion of Cooling Load from Heat Gain
- 12.3 Use of Room Transfer Functions
- Summary
- Bibliography
- Skill Development Exercises for Chapter 12

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Appendices

- Appendix A Thermal Properties of Building and Insulating Materials
- Appendix B Wall Types
- Appendix C July CLTD for Calculating Cooling Load

Skill Development Exercises for All Chapters

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Chapter 1
Heat Transfer and Load Calculation

Contents of Chapter 1

- Instructions
- Study Objectives of Chapter 1
- 1.1 Conduction
- 1.2 Convection
- 1.3 Radiation
- 1.4 Thermal Capacitance, Sensible and Latent Heat Transfer
- The Next Step
- Summary
- Bibliography
- Skill Development Exercises for Chapter 1

Instructions

Read the material in Chapter 1. At the end of the chapter, complete the skill development exercises without consulting the text. Re-read parts of the text as needed to complete the exercises.

Study Objectives of Chapter 1

Chapter 1 is an introductory chapter reviewing the fundamentals of heat transfer as it applies to buildings. There are three basic processes through which thermal energy is transferred within buildings: conduction, convection and radiation (see *Figure 1-1*). In this chapter, we will review these processes, and discuss where they must be considered in the calculation of the building thermal loads. The basic equations used to calculate each of these terms will be presented. We will also briefly discuss thermal capacitance and the difference between sensible and latent energy. After studying Chapter 1, you should be able to:

- Give an example of each type of heat transfer.
- Given a thickness and conductivity value, determine the coefficient of heat transfer from $U = k/L$.
- Convert a given R-value to a U factor using $U = 1/R$.
- Explain the difference between heat capacitance and heat transmission.
- Explain the difference between sensible and latent energy.

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1.1 Conduction

Conductive heat transfer is associated with heat transfer through solid materials. If one end of a material is in contact with a hot surface, the vibrating molecules (represented by a high temperature) will transfer their energy through the material to the cooler end. A classic example of conduction is when you burn your lips on a hot coffee cup. The high temperature of the coffee is quickly transported through the cup material to your mouth.

In buildings, conduction occurs easily through building materials such as metal, glass and concrete. Poor conducting materials are usually used as insulating materials. Examples include fiberglass, insulating foams and mineral wool. Some materials such as wood fall between these two extremes. The ability of a material to conduct heat is measured by a property called thermal conductivity, k, which has units of (Btu·in/h·ft²·°F). Dividing this value by the thickness of material, L, measured in inches, yields another very important term called the coefficient of heat transfer, or U-factor: $U = k / L$, in units of (Btu/h·ft²·°F).

The reciprocal of this value is called the thermal resistance, $R = 1 / U$, in units of (h·ft²·°F/Btu). This term is frequently encountered in the industry as a rating value for insulating materials. Two important characteristics of R-values are that the R-value increases directly proportionally with the thickness, L, of the material, and that R-values for different materials in a structural cross-section can be added directly.

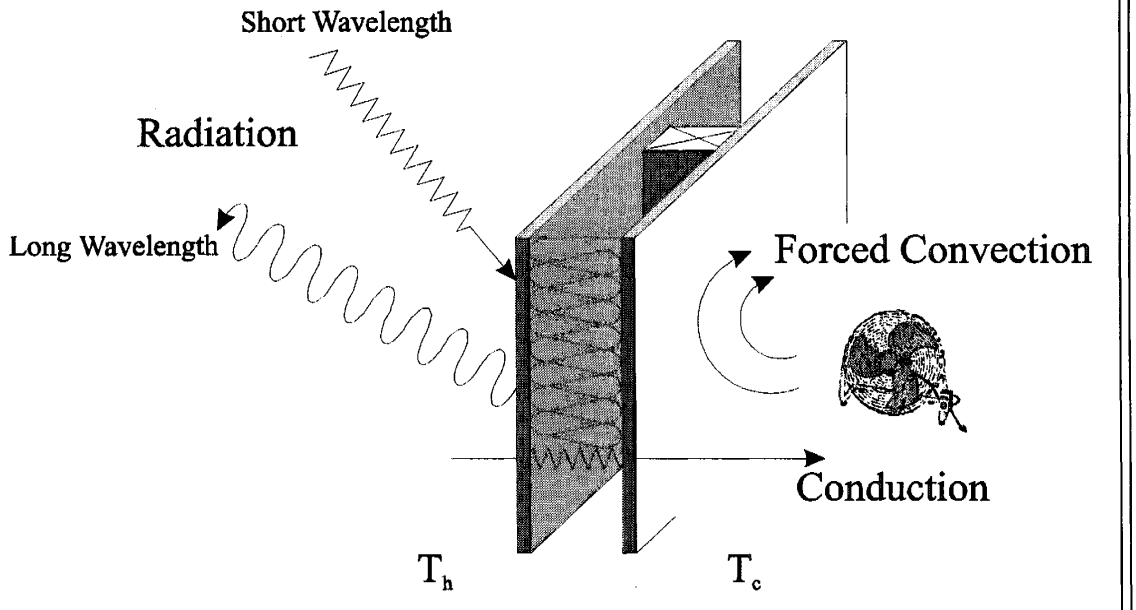


Figure 1-1. Heat Transfer Processes

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The normal sequence to solving a conduction problem would be to look up the R-values for the materials in a building cross-section, add those values, and then take the reciprocal of that answer to get the U-factor. Now you are ready to calculate the rate of conductive heat transfer.

The basic equation for calculating conductive heat transfer is given by:

$$Q = UA(T_h - T_c) \tag{1-1}$$

where,

Q = rate of conductive heat transfer, Btu/h

U = coefficient of heat transfer (material property), Btu/h·ft²·°F

A = area of heat transfer perpendicular to the direction of heat flow, ft²

T_h = temperature at the hot side of the material, °F

T_c = temperature at the cold side of the material, °F

Note that the temperature difference (T_h -T_c) is often written in equations as (ΔT). Both terms will be used interchangeably throughout this course because both indicate the same meaning. Standard convention also dictates that thermal energy always flows from high temperature to low temperature. Thus, when a hot cup of coffee cools on the counter, it is experiencing a negative heat gain. This is also referred to as a heat loss. Buildings normally experience a heat gain in summer when it is warmer outside, and a heat loss in winter when it is warmer inside.

EXAMPLE 1-1

Problem: A material rated at R-11 is added to a wall rated at R-3. The wall dimensions are 8 ft high by 20 ft wide. The inside and outside surface temperatures are 70°F and 5°F, respectively. Find the rate of heat transfer through the wall.

Solution: First determine the total R-value by adding the two given values: R_{total} = 11+3 = 14. Next find the U-factor by taking the reciprocal: $U = 1/R = 1/14 = 0.071$. Finally, substitute the values into the conduction heat transfer equation:

$$\begin{aligned} Q &= UA(T_h - T_c) \\ &= \left(0.071 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}\right)\left(8 \times 20 \text{ ft}^2\right)\left([70-5]^\circ\text{F}\right) \\ &= 738 \text{ Btu/h} \end{aligned}$$

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1.2 Convection

Convective heat transfer occurs when fluids at different temperatures move around within the space. A baseboard convection heater is a good example of convective heat transfer. The air is heated by direct contact with the hot surface within the heater. The buoyancy of the air then lifts the heated air upwards, creating enough negative pressure to draw cooler air into the bottom of the heater.

There are two types of convective heat transfer processes: free and forced. Free or natural convection uses only the natural buoyancy of the fluid to drive the convective flow (hot air rises). In the wintertime, cold air cascades down windows, creating unpleasant drafts. In a good design, these drafts are countered by rising currents of heated air from a register or radiator located below the window.

Forced convection depends on a pump or fan to force the flow of heated fluid. A ceiling fan in winter is one example of forced ventilation; the natural thermal stratification of hot air rising to the ceiling is counteracted by the fan pushing the warmer air back down to the living zone. Wind is another example of forced convection. While it is a natural phenomenon, the thermal energy flows that wind creates as it passes over a structure are far greater than those caused by free convection into still air. This difference is what makes wind breaks and screens so valuable.

Calculating convective heat transfer is more complicated than for conduction, so usually the problems are restructured to look like a conduction problem. The key to this transformation is a term called the convective heat transfer coefficient, h_c, which replaces the U term in the conduction equation:

$$Q = h_c A(T_h - T_c) \tag{1-2}$$

In most cases, the value of h_c will be presented in a table, although it can be calculated. The convective heat transfer coefficient is determined from the Nusselt number ($Nu = h_c \cdot x / k$) which can also be expressed as a function of both the Prandtl number ($Pr = \mu \cdot c_p / k$) and either the Reynolds number ($Re = VD\rho / \mu$) for forced convection or the Grashof number ($Gr = L^3 \cdot \rho^2 \cdot ß \cdot g \cdot \Delta T / \mu^2$) for free convection.

If you have taken a heat transfer course, these relationships should look familiar to you. If you would like more information on how to calculate convective heat transfer coefficients, refer to Chapter 3 of the *ASHRAE Handbook–Fundamentals* for more details.[1] If these equations look foreign to you, do not worry. For the purposes of this course, any needed convective heat transfer coefficients will be given in the text or in a table.

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1.3 Radiation

Radiant heat transfer occurs through electromagnetic waves. This spectrum ranges continuously from very short wavelengths for x-rays and ultraviolet rays, through the visible and infrared portion to the very long wavelengths used for radio and television communications. Only the visible portion and the near-infrared wavelengths are of primary interest in HVAC work. The visible portion is represented by the sunlight streaming through the window, and near-infrared radiation is exchanged among all objects around us.

All objects give off electromagnetic waves based on their temperature. The hotter the object, the shorter the wavelength, and the greater the intensity of radiation, as shown in *Figure 1-2*. For example, the sun is at 10,000°R and radiates visible light at wavelengths from about 0.4 to about 0.7 μm (microns). When you open the door on a hot oven (about 400°F or 860°R), the typical wavelength is about 6 microns. The wavelengths from objects near room temperature are between 9 and 10 microns.

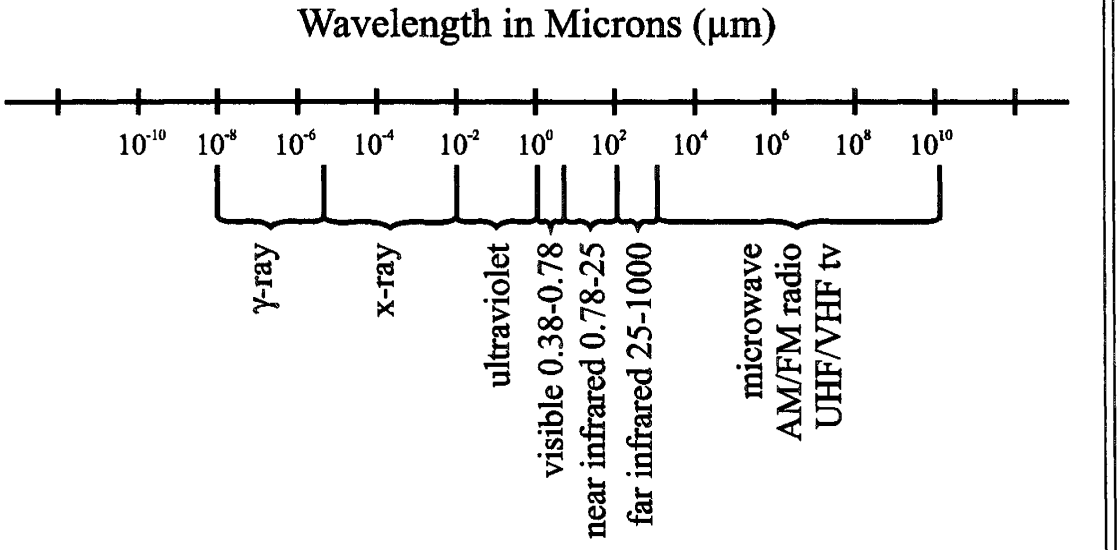


Figure 1-2. Electromagnetic Spectrum

The characteristic wavelength is determined by Wein's Displacement Law, which is given by:

$$\lambda = 5216 / T \tag{1-3}$$

where T is the absolute temperature measured in degrees Rankine (°R = °F + 460°).

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The intensity of radiation is determined by using Planck's Law:

$$I = \sigma \cdot T^4 \tag{1-4}$$

where,

I = intensity, Btu/h·ft^2

σ = Stefan-Boltzmann Constant = 0.1714×10^{-8}, Btu/h·ft^2·°R^4

T = surface temperature, °R

Note that this equation is for a black body, which is defined as an ideal emitter/absorber. When real surfaces are assumed, the equations become more complex, because they must include the surface properties as a function of the wavelength and also the view angle between the two surfaces.

How materials react to different wavelengths is given by the absorptivity, α. This quantity is equal to the emissivity, ε, of the material at the same temperature. Both of these values range between zero and one. Some references provide this data in table form, while others present it graphically. In either case, the two regions of greatest interest are the visible portion (wavelengths of around 0.5 μm) and the infrared portion (usually around 10 μm for surfaces under 100°F).

The first value determines how the surface will react to sunlight. Dark surfaces (α near 0.9) will absorb most solar radiation, while lighter or shinier surfaces (α near 0.1) tend to reflect the sun's rays. The color of the roof surface and the other outside surfaces of a structure can have a significant impact on how much solar energy is absorbed. Accounting for this gain and modeling the intensity and timing of its effect on the building cooling load are very complicated.

In the infrared range, surfaces with high absorptivity will permit more radiant heat transfer than surfaces with low absorptivity. Remember that the value of absorptivity at any given wavelength is equal to its emissivity at that same wavelength. This property can be used to our advantage in low-e glass. By not allowing thermal radiation to emit from the glass, the rate of heat transfer through the glass due to radiation is decreased.

The effect of view angle between the energy source and receiver is shown in *Figure 1-3*. As the angle between the hot surface and cold surface decreases, more of the available energy is transferred between the two plates. The maximum radiant heat transfer occurs when the two plates are parallel. This geometry frequently occurs in buildings (double-pane glazings,

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hollow core walls, suspended ceilings and roofs, etc.). Neglecting edge effects, the view factor, $F_{1\text{-}2}$, is given by:

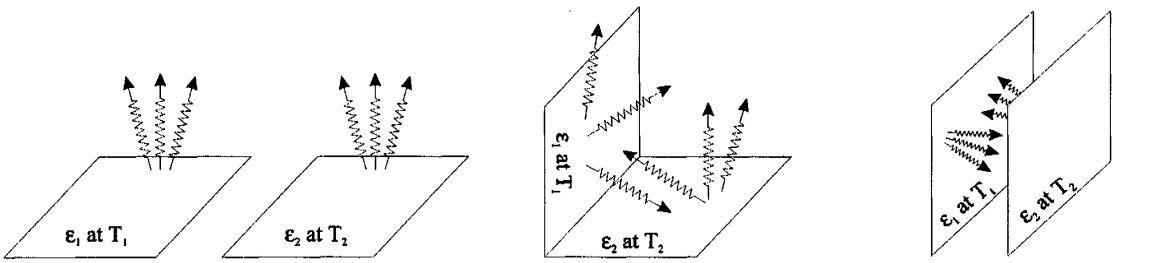
$$F_{1-2} = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} \tag{1-5}$$

where,

$F_{1\text{-}2}$ = view factor between surfaces 1 and 2

ε_1 = emissivity of surface 1 at temperature 1

ε_2 = emissivity of surface 2 at temperature 2



No Radiant Transfer (Surfaces are in same plane)

Some Radiant Transfer (Surfaces intersect)

Maximum Radiant Transfer (Surfaces are parallel)

Figure 1-3. View Angle Effects on Radiant Heat Transfer

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1.4 Thermal Capacitance, Sensible and Latent Heat Transfer

Three terms that will be used throughout this course are thermal capacitance, sensible energy transfer and latent energy transfer. This section will provide you with some background on each one.

So far, the heat transfer equations have been written assuming steady-state conditions (when both temperatures are constant). Steady-state conditions are usually used for determining the R-value of insulation, the U-factors for doors and windows, and the peak design loads for equipment sizing. However, it is occasionally necessary to consider variable temperature conditions. For example, when a night setback thermostat is used, it is necessary each morning to raise the space temperature back up to the daytime setting. How fast this temperature comes up depends on a concept called thermal capacitance.

Thermal capacitance is the ability of objects to store thermal energy. For example, if a candle is placed under a beaker full of water, it will take a long time (and a lot of energy from the candle) to raise the temperature of the beaker and the water in it. If the beaker is empty (full of air), it would not take nearly as long to see an increase in temperature of the beaker. In fact, most of the energy would be absorbed by the beaker material itself. This is because solids have a higher heat capacitance than gases.

Heat capacitance is the product of two material properties: density (ρ, measured in lb_m/ft^3) and specific heat (C_p, measured in $Btu/lb_m \cdot °F$). Water has a specific heat of 1.0 $Btu/lb_m \cdot °F$, and air has a specific heat of about 0.241 $Btu/lb_m \cdot °F$. Most common building materials have a specific heat in the range of 0.2-0.3 $Btu/lb_m \cdot °F$. The value that varies significantly is density. Insulating materials can be as light as 0.5 lb_m/ft^3, while brick and concrete products can exceed 150 lb_m/ft^3. Materials for wood frame buildings are typically around 25 to 50 lb_m/ft^3. Specific values for materials will be presented in Chapter 4.

The basic equation used to calculate thermal capacitance is:

$$Q = m \cdot C_p \cdot \Delta T \qquad (1\text{-}6)$$

where,

Q = heat transfer, Btu

m = mass of the material, lb_m

C_p = specific heat, $Btu/lb_m \cdot °F$

ΔT = temperature change in the material as a result of the heat transfer, °F

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EXAMPLE 1-2

Problem: Calculate the energy required to raise a 3-in.-thick concrete floor slab from 60°F to 70°F in a 15×20 ft room. Density is 120 lb_m/ft^3 and specific heat is 0.2 $Btu/lb_m \cdot °F$.

Solution: To get the mass of concrete, first calculate the volume, then multiply by the density:

$$\begin{aligned} Q &= m \cdot C_p \cdot \Delta T \\ &= (V \cdot \rho) \cdot C_p \cdot \Delta T \\ &= (3/12 \text{ ft})(15 \cdot 20 \text{ ft}^2) \cdot (120 \text{ lb}_m / \text{ft}^3)(0.2 \text{ Btu/lb}_m \cdot °\text{F})(70 - 60°\text{F}) \\ &= 18{,}000 \text{ Btu} \end{aligned}$$

The key concept to understand at this point is that two structures of identical size but different materials (such as wood frame and concrete block) can react quite differently to temperature variations. The lighter frame building will warm up much faster than the heavy block building and will require the addition of less energy input in the process. However, the massive structure will remain warmer longer after the furnace shuts off. The same effects are true during the cooling season. In fact, we will find out that this storage effect is even more evident in the calculation of the cooling loads.

Sensible heat refers to energy stored in the form of a temperature change of the material. Two very useful equations for sensible-only energy changes in water and air flows are:

$Q = 500 \cdot \text{gpm} \cdot \Delta T$ for water flow rates measured in gpm

$Q = 1.10 \cdot \text{cfm} \cdot \Delta T$ for air flow rates measured in cfm (heating only)

In both equations, the coefficient includes all the required unit conversions and physical properties to convert from the volumetric flow rate to the heat transfer rate in (Btu/h). For example, the value 500 is equal to the average water density (8.3 lb/gal) times the specific heat of water (1.0 Btu/lb·°F) times 60 minutes per hour. The value 1.10 for air is equal to the average air density (0.075 lb/ft^3) times the average specific heat (0.242 Btu/lb·°F) times 60 (minutes per hour). Note that these equations are most accurate only near room temperature and should be used with caution at all other conditions.

Latent heat is energy stored in the form of a change of phase of matter. Most latent energy changes encountered in HVAC load calculations are related to changes in the moisture level of the air. The latent heat of vaporization is a function of temperature as shown in Table 6.3 of the 1997 *ASHRAE Handbook–Fundamentals*.[2] But a reasonable value to remember is that it takes approximately 1,050 Btu to boil 1 pound of water at 74°F.

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The Next Step

The next chapter will present the basic steps required to calculate the rate of heat loss from a simple structure. The succeeding chapters will then examine each step of the basic process in more detail. We will start with the heating load calculation because it has fewer variables to consider than cooling load calculations. But once you have mastered the heating load calculation method, you will be ready to learn how to make cooling load calculations.

Summary

This chapter has introduced the basic concepts of heat transfer, the three methods of heat transfer (conduction, convection and radiation) and some fundamental equations. In addition, the concept of thermal capacitance and its relationship to heat transfer have been explained. Finally, the concepts of sensible and latent heat transfer have been introduced.

After studying Chapter 1, you should be able to:

- Give an example of each of the three types of heat transfer.
- Given a thickness and conductivity value, determine the coefficient of heat transfer from ($U = k / L$).
- Convert a given R-value to a U-factor ($U = 1 / R$).
- Explain the difference between heat capacitance and heat transmission.
- Explain the difference between sensible and latent energy.

Bibliography

1. ASHRAE. 1997. "Heat transfer." *ASHRAE Handbook–Fundamentals*. Atlanta, GA: ASHRAE. Chapter 3.

2. ASHRAE. 1997. "Psychrometrics." *ASHRAE Handbook–Fundamentals*. Atlanta, GA: ASHRAE. Chapter 6.

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Skill Development Exercises for Chapter 1

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

1-01. Explain the type of heat transfer in each of the following situations: a gas water heater; the wall of an oven; a whistling teakettle; a light bulb; a hair dryer; a sealed thermos bottle; and an electric baseboard heater.

1-02. If fiberglass insulation has a thermal conductivity of 0.33 (Btu·in/h·ft^2·°F), find the R-value of a 5.5-in.-thick batt.

1-03. A building has a roof with continuous rigid insulation rated at R-26. Neglecting air films and the roof structure, what is the approximate U-factor of this roof?

1-04. A water heater measures 24 in. in diameter and 48 in. high. The outside wall is covered with fiberglass insulation rated at R-3. The shell of the water heater is 130°F and the outside is 75°F. Find the rate of heat loss through the wall of the unit.

1-05. Some people argue that night setback thermostats are worthless, because the furnace has to run so long in the morning to make up the difference in temperature for the space. With your knowledge of heat capacitance and heat conduction as a function of temperature, how would you answer that argument?