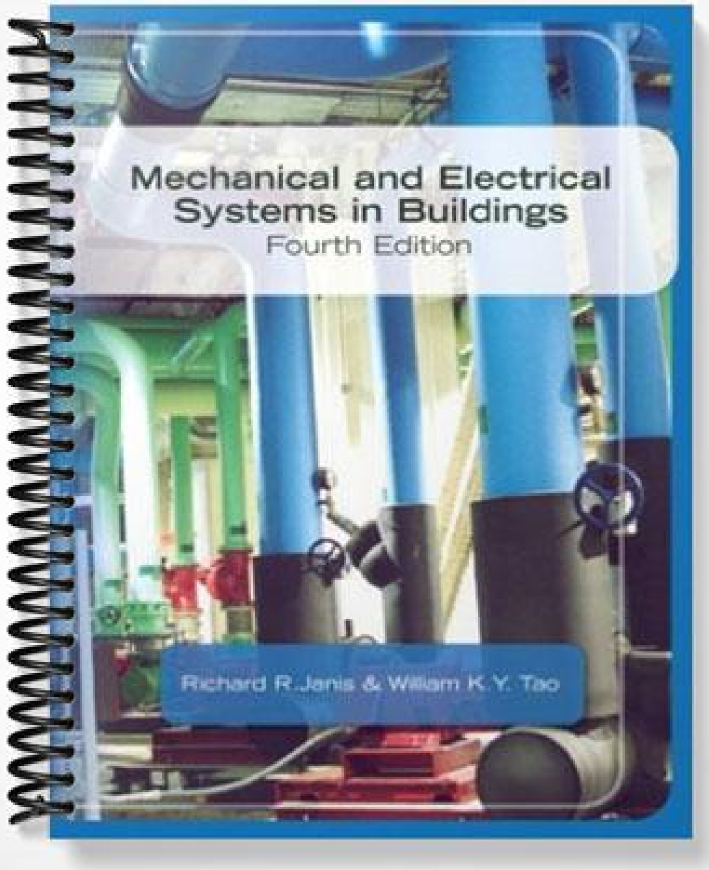
SOLUTIONS MANUAL



Online Instructor's Manual
to accompany

Mechanical and Electrical Systems in Buildings

Fourth Edition

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PEARSON
Prentice Hall

Upper Saddle River, New Jersey
Columbus, Ohio

10 9 8 7 6 5 4 3 2 1

PEARSON Prentice Hall

ISBN-13: 978-0-13-513012-4
ISBN-10: 0-13-513012-3

A MESSAGE

To colleagues and instructors,

The instructor's manual contains answers to questions that appear at the end of each chapter in the text. In addition, there is an overview page pertaining to each chapter. Hopefully, these will assist you in preparing your class lectures.

This book is arranged along five basic disciplines–HVAC, Plumbing and Fire Protection, Electrical, Illumination, and Noise and Vibration Controls. Each discipline may be taught separately or as a whole. As college courses, the entire book with supplemental references should be for a two-semester course with 3 credit-hours for each semester.

When taught separately, the following credit hours are recommended:

- As a Mechanical Course 3 credit hours
  (Chapters 1 through 9 + Chapters 18 and 19)
- As an Electrical Course 3 credit hours
  (Chapters 10 through 17 + Chapters 1 and 19)
- As an Acoustic and Vibration Course 1 credit hour
  (Chapters 18 and 19)
- As an Illumination Course 1 to 2 credit hours
  (Chapters 14 through 17 + Chapter 1)

We thank you for choosing this book for your class or in your professional practice.

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Overview and Questions/Answers

CHAPTER 1
INTRODUCTION TO MECHANICAL AND ELECTRICAL SYSTEMS: ENERGY, SUSTAINABILITY, AND ECONOMICS

OVERVIEW

Chapter 1 covers topics that are relevant for all the mechanical and electrical systems covered in subsequent chapters. These materials are essential background and context for subsequent chapters.

Mechanical systems involve the transfer of energy and fluids. Understanding the basic physics of energy is a prerequisite for building load estimating, systems selection and energy conservation. Chapter 1 describes heat, thermal properties of materials, the conversion of energy from one form to another, and the thermal values of commonly used fuels. Transfer of fluids is covered so that students understand the units of flow and pressure that are used to specify and measure the performance of systems and equipment.

Simple example problems are included, and the instructor is encouraged to work them and similar exercises on the board to insure that students are prepared to go on to subsequent chapters.

Mechanical and electrical systems affect the design of buildings. Architectural students especially should appreciate why modern buildings are different in form and dimension to older buildings. This understanding is useful if future buildings are to use less energy by using passive climate control strategies.

Resource conservation, comfort, and habitability are all part of sustainable design, and this topic is discussed in Chapter 1 as it applies to the entire building design process, including all systems. The most important message in these sections, and perhaps in the entire book, is that good building design certainly affects occupant performance. Furthermore, improved occupant performance is worth a larger investment in design and construction than is usually made.

Commissioning is another topic that applies to virtually all systems and equipments discussed in subsequent chapters, so an overview of commissioning is included in Chapter 1.

All systems present many options for design, and selecting among these options relies on evaluation tools to assess quality. Several methods are presented, including the decision matrix, which is useful in documenting subjective criteria, and various economic evaluation tools, such as payback analysis and life cycle costing.

CHAPTER 1
INTRODUCTION TO MECHANICAL AND ELECTRICAL SYSTEMS: ENERGY, SUSTAINABILITY, AND ECONOMICS

QUESTIONS AND ANSWERS

1.1 If lighting load for a 20,000 sq ft building is estimated at 2 Watts/sq ft, what will be the resulting heat generated by lighting?

The total electrical power will be 20,000 sq ft × 2 Watts/sq ft, or 40,000 Watts (40 kW). The conversion factor from electricity to heat is 3.41 Btuh/kW, so the heat generated will be 40 kW × 3.41 Btuh/kW = 136,400 Btuh.

1.2 If the lighting load were increased, what would be the effect on other building systems?

Heat from lights adds to air conditioning load. Increasing lighting load will increase the size of air conditioning equipment. Requirements for power distribution equipment will also be increased directly by increased lighting and indirectly by increased air conditioning. Heat from lights might decrease requirements for building heating, but most engineers will not factor lighting into the size of heating equipment since lights may not be on.

1.3 How much CO2 will be liberated to the atmosphere in a year's time due to lighting operation in the building of question 1?

From Table 1-4, we find data on CO2 production resulting from power generation. Assuming a coal fired plant, 2.4 lbs. of CO2 will be produced per kWh. One year is 8,760 hours. Electrical energy will be 40 kW × 8,760 hours = 350,000 kWh. CO2 generated will be 350,000 kWh × 2.4 lbs./kWh = 840,000 lbs. Lesser amounts would be generated if the lighting were operated less than continuously, or if the power generation were by gas or oil.

1.4 How much heat (Btu's) will be stored in a 100 sq ft concrete wall 1 ft thick if it is warmed from 75ºF to 85ºF by exposure to sunlight?

Use the equation Q = M × C × TD with information from Table 1-2. Mass will be 100 cu.ft. × 144 lb./cu.ft., or 14,400 lbs. Specific heat of concrete is 0.156.

Q = 14,400 × 0.156 × (85-75) = 22,500 Btu

1.5 What is the value of the heat in question 2 compared with gas at $1.00 per therms burned in a boiler at 85% efficiency?

One therm is 100,000 Btu. If the boiler is 85% efficient, one therm will produce 85,000 Btu of output for the $1.00 worth of gas. The value of 22,500 Btu is, therefore, (22,500 / 85,000) × $1.00, or $0.26.

1.6 How does "sustainable" design differ from energy effective design?

Utility, comfort, environmental impact, and appropriate use of technology are criteria for mechanical/electrical systems in a sustainable design process as well as energy conservation.

1.7 What factors should the architect and engineer consider to produce a high performance environment for building occupants?

Healthful indoor air quality, thermal comfort and individual control, good lighting, and connection with the outdoors are the main issues cited in Chapter 1.

1.8 What is the relationship between building codes and sustainable design?

Sustainable design inherently produces buildings that exceed minimum requirements of codes and standards.

1.9 How does saving energy help to protect the environment?

Using less energy reduces air pollution from burning fossil fuels.

1.10 What is the role of maintainability in sustainable buildings?

Solutions must be maintainable to last long term and perform as intended.

1.11 How could building site selection affect the environment?

Chapter 1 cites daylight, views, and natural ventilation, which are all affected by site selection. However, students may go beyond these answers and cite many other issues such as infrastructure loads, pollution due to auto traffic, and other issues related to building site.

1.12 What factors should interior designers consider in terms of indoor air quality? Architects? HVAC engineers? Design teams?

Indoor air pollution comes from finish materials and furniture, which are selected by interior designers. Architects are responsible for locating fresh air intakes appropriately to avoid bringing exhaust or polluted air into the building. Architects are also responsible for detailing to control moisture, thereby preventing mold growth. HVAC engineers are responsible for proper ventilation rates and humidity control. The activities and decisions of each member of the design team affects the others.

1.13 What design features would you suggest to allow personal climate control in a single story residence? A high rise office building? A classroom building?

A single story residence might use operable windows as well as the ability to adjust HVAC airflow. Operable windows are not advisable in high rise buildings, but personal control might be achieved by system features such as the task cooling device shown in Figure 1-9, or by adjustable floor registers. In a classroom building, personal control can be achieved by any of the means listed, plus the choice of seating location.

1.14 What sustainable design issue should architects consider in deciding window materials and locations?

Architects should consider daylight and view when selecting window materials and locations.

1.15 What is the difference between qualitative and quantitative factors in an analysis? How might we deal with each?

Qualitative factors, such as comfort, can be evaluated as better or worse, but have no standardized basis for numerical measurement. Quantitative factors, such as system cost, do have a basis for numerical measurement. Both qualitative and quantitative factors can be ranked in importance and compared using a decision matrix.

1.16 Prepare a decision matrix to decide between operable windows and fixed windows in an office building. Fill out the matrix as if you were an occupant, a maintenance staffer, the building owner.

There is no absolute correct answer for this exercise. It is meant to stimulate thought and the thought process. The following is a possible result and demonstrates the format of the answer.

How an Occupant Might Think of Operable Windows					
		Operable Windows		Fixed Sash	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**
Comfort	9	8	72	7	63
Connection with outdoors	9	9	81	3	27
Initial cost	2	4	8	6	12
Energy consumption	2	8	16	4	8
Water hazard	2	3	6	9	18
Freeze hazard	2	3	6	9	18
Security	2	3	6	9	18
Total score			**195**		**164**
% score (normalized)			**100%**		**84%**

How an Occupant Might Think of Operable Windows					
		Operable Windows		Fixed Sash	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**
Comfort	3	8	24	7	21
Connection with outdoors	2	9	18	3	6
Initial cost	2	4	8	6	12
Energy consumption	5	8	40	4	20
Water hazard	8	3	24	9	72
Freeze hazard	8	3	24	9	72
Security	8	3	24	9	72
Total score			**162**		**275**
% score (normalized)			**59%**		**100%**

How an Occupant Might Think of Operable Windows					
		Operable Windows		Fixed Sash	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**
Comfort	6	8	48	7	42
Connection with outdoors	3	9	27	3	9
Initial cost	8	4	32	6	48
Energy consumption	8	8	64	4	32
Water hazard	8	3	24	9	72
Freeze hazard	8	3	24	9	72
Security	8	3	24	9	72
Total score			**243**		**347**
% score (normalized)			**70%**		**100%**

1.17 Will a developer use a higher or lower discount rate than a building owner? Why?

Developers' profit expectation is higher than that of a building owner, so they will apply a higher discount rate in cash flow analysis.

1.18 An energy conservation option has a first cost of $25,000. It requires $2,000 per year maintenance and saves $5,000 per year in utilities. What is the simple payback period for the option?

The net annual saving for the investment is $3,000, which is utility saving less maintenance cost. Simple payback is $25,000 investment divided by $3,000 savings, or about 8 years.

1.19 The system in the prior exercise will last 15 years with no salvage value. What is the 15-year life cycle cost assuming energy cost escalation of 4% annually, maintenance cost escalation 2% annually, and a 5% discount rate? What if the discount rate is 15%?

Cash Flow Analysis for a $25,000 Feature, 5% Discount Rate

First cost	25,000	over **and** above base		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Discount rate	....	....	**5.0**	**%**

	Savings or (Costs) for Year Incurred				Net Present Value		
Year	**Instl.**	**Energy**	**Maint.**		**Net annual**	**Year**	**Cumulative**
0	(25,000)	-	-		(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)		3,000	2,850	(22,150)
2	-	5,200	(2,040)		3,160	2,852	(19,298)
3	-	5,408	(2,081)		3,327	2,853	(16,445)
4	-	5,624	(2,122)		3,502	2,852	(13,593)
5	-	5,849	(2,165)		3,684	2,851	(10,742)
6	-	6,083	(2,208)		3,875	2,849	(7,894)
7	-	6,327	(2,252)		4,074	2,845	(5,048)
8	-	6,580	(2,297)		4,282	2,841	(2,207)
9	-	6,843	(2,343)		4,500	2,836	628
10	-	7,117	(2,390)		4,726	2,830	3,458
11	-	7,401	(2,438)		4,963	2,823	6,281

12	-	7,697	(2,487)		5,211	2,816	9,097
13	-	8,005	(2,536)		5,469	2,807	11,904
14	-	8,325	(2,587)		5,738	2,798	14,703
15	-	8,658	(2,639)		6,019	2,789	17,491
		Total discounted cash flow					**17,491**

Cash Flow Analysis for a $25,000 Feature, 15% Discount Rate

First cost	25,000	over and above base		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Discount rate	....	....	**15.0**	**%**

	Savings or (Costs) for Year Incurred				**Net Present Value**		
Year	**Instl.**	**Energy**	**Maint.**		**Net annual**	**Year**	**Cumulative**
0	(25,000)	-	-		(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)		3,000	2,550	(22,450)
2	-	5,200	(2,040)		3,160	2,283	(20,167)
3	-	5,408	(2,081)		3,327	2,043	(18,124)
4	-	5,624	(2,122)		3,502	1,828	(16,296)
5	-	5,849	(2,165)		3,684	1,635	(14,661)
6	-	6,083	(2,208)		3,875	1,461	(13,199)
7	-	6,327	(2,252)		4,074	1,306	(11,983)
8	-	6,580	(2,297)		4,282	1,167	(10,726)
9	-	6,843	(2,343)		4,500	1,042	(9,684)
10	-	7,117	(2,390)		4,726	931	(8,754)
11	-	7,401	(2,438)		4,963	831	(7,923)
12	-	7,697	(2,487)		5,211	741	(7,182)
13	-	8,005	(2,536)		5,469	661	(6,521)
14	-	8,325	(2,587)		5,738	590	(5,931)
15	-	8,658	(2,639)		6,019	526	(5,405)
		Total discounted cash flow					**(9,684)**

1.20 Assume the option in the prior exercise is installed in a building with 200 occupants, average personnel cost $60,000 per year. If the device interferes with temperature control, resulting in 2% decrease in productivity, what would the simple payback be?

For this exercise we include the assumed economic effect of the concept on productivity, which will be a loss of 200 × $60,000 × 2%, or -$240,000 per year.

Coupled with savings of $3,000, the net cost will be $237,000 per year. No payback. Ever.

1.21 What would the payback be if the option in the prior exercise improved temperature control and resulted in a 2% increase in productivity?

The economic effect would be a value of 200 × $60,000 × 2%, or + $240,000 per year. Coupled with savings of $3,000, the net cost will be $243,000 per year. Instant payback.

1.22 Calculate the life cycle costs for the two cases (2% decrease, 2% increase in productivity) using data from prior exercises for 5% discount rate and 15% discount rate.

Cash Flow Analysis for a $25,000 Feature, Hamper Productivity 2% **5% Discount Rate**

First cost	25,000	over and above		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Productivity effect	(240,000)	per year	2.0	% per year escalation
Discount rate	....	....	**5.0**	**%**

Year	Savings or (Costs) for Year Incurred				Net Present Value		
	Instl.	Energy	Maint.	Prod.	Net annual	Year	Cumulative
0	(25,000)	-	-	-	(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)	(240,000)	(237,000)	(225,150)	(250,150)
2	-	5,200	(2,040)	(244,800)	(241,640)	(218,080)	(468,230)
3	-	5,408	(2,081)	(249,696)	(246,369)	(211,230)	(679,461)
4	-	5,624	(2,122)	(254,690)	(251,188)	(204,594)	(884,055)
5	-	5,849	(2,165)	(259,784)	(256,099)	(198,165)	(1,082,220)
6	-	6,083	(2,208)	(264,979)	(261,104)	(191,936)	(1,274,155)
7	-	6,327	(2,252)	(270,279)	(266,205)	(185,901)	(1,460,056)
8	-	6,580	(2,297)	(275,685)	(271,402)	(180,054)	(1,640,110)
9	-	6,843	(2,343)	(281,198)	(276,699)	(174,389)	(1,814,499)
10	-	7,117	(2,390)	(286,822)	(282,096)	(168,901)	(1,983,400)

11	-	7,401	(2,438)	(292,559)	(287,595)	(163,584)	(2,146,984)
12	-	7,697	(2,487)	(298,410)	(293,199)	(158,433)	(2,305,418)
13	-	8,005	(2,536)	(304,378)	(298,909)	(153,443)	(2,458,860)
14	-	8,325	(2,587)	(310,466)	(304,727)	(148,608)	(2,607,468)
15	-	8,658	(2,639)	(316,675)	(310,655)	(143,924)	(2,751,392)
Total discounted cash flow							**(2,751,392)**

Cash Flow Analysis for a $25,000 Feature, Improve Productivity 2% **5% Discount Rate**

First cost	25,000	over and above		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Productivity effect	240,000	per year	2.0	% per year escalation
Discount rate	....	....	**5.0**	**%**

Year	Savings or (Costs) for Year Incurred				Net Present Value		
	Instl.	Energy	Maint.	Prod.	Net annual	Year	Cumulative
0	(25,000)	-	-	-	(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)	240,000	243,000	230,850	205,850
2	-	5,200	(2,040)	244,800	247,960	223,784	429,634
3	-	5,408	(2,081)	249,696	253,023	216,936	646,570
4	-	5,624	(2,122)	254,690	258,192	210,299	856,869
5	-	5,849	(2,165)	259,784	263,468	203,867	1,060,735
6	-	6,083	(2,208)	264,979	268,854	197,633	1,258,368
7	-	6,327	(2,252)	270,279	274,353	191,591	1,449,959
8	-	6,580	(2,297)	275,685	279,967	185,736	1,635,695
9	-	6,843	(2,343)	281,198	285,698	180,061	1,815,756
10	-	7,117	(2,390)	286,822	291,549	174,561	1,990,317
11	-	7,401	(2,438)	292,559	297,522	169,230	2,159,547

12	-	7,697	(2,487)	298,410	303,620	164,064	2,323,611
13	-	8,005	(2,536)	304,378	309,847	159,057	2,482,669
14	-	8,325	(2,587)	310,466	316,204	154,205	2,636,873
15	-	8,658	(2,639)	316,675	322,694	149,501	2,786,375
				Total discounted cash flow			**1,815,756**

Cash Flow Analysis for a $25,000 Feature, Hamper Productivity 2% **15% Discount Rate**

First cost	25,000	over and above		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Productivity effect	240,000	per year	2.0	% per year escalation
Discount rate	....	....	**15.0**	**%**

	Savings or (Costs) for Year Incurred				**Net Present Value**		
Year	**Instl.**	**Energy**	**Maint.**	**Prod.**	**Net annual**	**Year**	**Cumulative**
0	(25,000)	-	-	-	(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)	(240,000)	(237,000)	(201,450)	(226,450)
2	-	5,200	(2,040)	(244,800)	(241,640)	(174,585)	(401,035)
3	-	5,408	(2,081)	(249,696)	(246,369)	(151,301)	(552,336)
4	-	5,624	(2,122)	(254,690)	(251,188)	(131,122)	(683,458)
5	-	5,849	(2,165)	(259,784)	(256,099)	(113,633)	(797,090)
6	-	6,083	(2,208)	(264,979)	(261,104)	(98,475)	(895,566)
7	-	6,327	(2,252)	(270,279)	(266,205)	(85,339)	(980,905)
8	-	6,580	(2,297)	(275,685)	(271,402)	(73,955)	(1,054,860)
9	-	6,843	(2,343)	(281,198)	(276,699)	(64,088)	(1,118,948)
10	-	7,117	(2,390)	(286,822)	(282,096)	(55,537)	(1,174,485)
11	-	7,401	(2,438)	(292,559)	(287,595)	(48,127)	(1,222,612)
12	-	7,697	(2,487)	(298,410)	(293,199)	(41,705)	(1,264,317)

13	-	8,005	(2,536)	(304,378)	(298,909)	(36,140)	(1,300,457)
14	-	8,325	(2,587)	(310,466)	(304,727)	(31,317)	(1,331,774)
15	-	8,658	(2,639)	(316,675)	(310,655)	(27,137)	(1,358,911)
				Total discounted cash flow			**(1,358,911)**

Cash Flow Analysis for a $25,000 Feature, Improve Productivity 2% **15% Discount Rate**

First cost	25,000	over and above		
Equipment life	15	years		
Salvage value	-	(demolition)		
Energy savings	5,000	per year	4.0	% per year escalation
Maintenance	2,000	per year	2.0	% per year escalation
Productivity effect	240,000	per year	2.0	% per year escalation
Discount rate	....	....	**15.0**	**%**

	Savings or (Costs) for Year Incurred				Net Present Value		
Year	**Instl.**	**Energy**	**Maint.**	**Prod.**	**Net annual**	**Year**	**Cumulative**
0	(25,000)	-	-	-	(25,000)	(25,000)	(25,000)
1	-	5,000	(2,000)	240,000	243,000	206,550	181,550
2	-	5,200	(2,040)	244,800	247,960	179,151	360,701
3	-	5,408	(2,081)	249,696	253,023	155,388	516,089
4	-	5,624	(2,122)	254,690	258,192	134,778	650,867
5	-	5,849	(2,165)	259,784	263,468	116,902	767,769
6	-	6,083	(2,208)	264,979	268,854	101,398	869,167
7	-	6,327	(2,252)	270,279	274,353	87,951	957,119
8	-	6,580	(2,297)	275,685	279,967	76,288	1,033,407
9	-	6,843	(2,343)	281,198	285,698	66,172	1,099,579
10	-	7,117	(2,390)	286,822	291,549	57,398	1,156,978
11	-	7,401	(2,438)	292,559	297,522	49,788	1,206,766
12	-	7,697	(2,487)	298,410	303,620	43,187	1,249,954
13	-	8,005	(2,536)	304,378	309,847	37,462	1,287,416

14	-	8,325	(2,587)	310,466	316,204	32,496	1,319,912
15	-	8,658	(2,639)	316,675	322,694	28,189	1,348,101
Total discounted cash flow							**1,099,579**

CHAPTER 2
HVAC FUNDAMENTALS

OVERVIEW

The HVAC Section of this book is organized into six chapters addressing the four elements of HVAC systems:

- Fundamentals (Chapter 2)
- Overall Systems (Chapter 3)
- Heating and Cooling Production (Chapters 4 and 5)
- Delivery Systems (Chapters 6 and 7)

Heat transfer and fluid flow are the governing principles for the design of HVAC systems. Other information required in design includes the selection of weather date, properties of materials, and performance of equipment and its components. Essentials of these are included in these chapters to illustrate the design process. These data are by no means complete, and should not be used in actual design of construction projects. The Handbooks published by the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) should be used when designing actual construction projects. ASHRAE is located at 1791 Tullie Circle, N.E., Atlanta, GA 30329.

HVAC Fundamentals is an introduction to criteria for HVAC system design and basics of load calculations.

Section 2.1, "Environmental Comfort," emphasizes the fact that temperature control, while essential, is only one of many factors that affect human comfort in the built environment. Some of the factors involve political and economic issues, such as energy prices, making comfort criteria somewhat less than scientific.

Section 2.2 covers the essential topic of psychrometrics, or the study of air-water mixtures. In teaching this material, the author has found that constructing a psychrometric chart on the board is an effective way to present the material. Consider starting with the concept that warm air holds more moisture than cold air and drawing the saturation curve, then drawing curves of various relative humidity percentages, finally introducing other parameters on the chart.

Section 2.3 covers basics of Energy Transport. All the flow equations presented in this section can be derived from the basic physics that change in heat (or heat flow) is the product of mass (or mass flow), specific heat, and temperature difference. All the equations in this section are similar except for the constants, which are specific to the material under consideration.

Sections 2.4 through 2.7 cover basic heating and cooling load calculations. The method presented is much less complicated than the algorithms used in modern computer programs for load calculations. This is intentional so as to focus on concepts of how heat flows through buildings rather than the complex calculations needed for high precision. Nonetheless, the methods presented can be used in practice and will render conservative results.

Section 2.8 covers load control strategies. This section applies knowledge from earlier in the chapter so that architects and engineers can collaborate to reduce loads, reduce the size and cost of mechanical systems, and save energy.

CHAPTER 2
HVAC FUNDAMENTALS

QUESTIONS AND ANSWERS

2.1 State the factors that affect environmental comfort and their general ranges of values, where applicable.

Temperature and humidity - low limit values for comfort are 68°F, 30% RH; high limit values for comfort are 79°F, 55% RH. Air motion should be between 10 feet per minute and 50 feet per minute. Radiant effects from cold and warm surfaces can also affect comfort.

2.2 Briefly describe the difference between sensible and latent heat.

Sensible heat produces temperature change. Latent heat affects the amount of water vapor in the air.

2.3 For air at 75°F, 50% relative humidity, what will happen to relative humidity if the air is cooled to 65°F? Cooled to 50°F?

At 65°F relative humidity would increase to 70%. At 50°F relative humidity would increase to 100%.

2.4 How much water is present in 1 pound of air at 75°F, 50% relative humidity? How much water is present in 1 pound of air at 95°F DB (dry bulb), 78°F WB (wet bulb)?

One pound of air at 75°F, 50% relative humidity contains 0.0093 pounds (65 grains) of water. One pound of air at 95°F DB, 78°F WB contains 0.017 pounds (118 grains) of water.

2.5 What is the rate of removal of moisture required to reduce a 1,000-cfm airstream from the higher to the lower conditions in problem 2.4?

Mass flow rate of 1,000 cfm can be determined from specific volume on the psychrometric chart. At 95°F DB, 78°F WB, specific volume is approximately 14.4 cu. ft. per pound of dry air. Thus, 1,000 cfm will equate to about 70 pounds of air per minute. Difference in moisture content is about 0.0077 pounds water per pound air (from Question 2.4). The rate of moisture removal is 70×0.0077, or 0.54 pounds of water per minute.

2.6 If 40 lbs. per hour of water is allowed to evaporate into an airstream, what will be the effect on the dry bulb temperature? What will be the effect on the wet bulb temperature?

Dry bulb temperature will decrease; wet bulb temperature will remain approximately constant.

2.7 How much heat is required to warm 1,000 gallons of water from 60°F to 130°F?

Specific heat of water is 1.0. One thousand gallons of water weighs 8,350 pounds. Temperature rise is 70°F. Heat requirement will be 8,350 × 70, or 585,000 Btu.

2.8 How much heat is liberated when 1,000 gallons of water cools from 160°F to 140°F?

Heat liberated is 167,000 Btu. (Procedure similar to Question 2.7.)

2.9 What is the heat liberation rate for a 500-gpm water flow cooling from 140°F to 110°F?

Use equation 2-2. Q = 500 × 500 × (140-110), or 7,500,000 Btuh.

2.10 A heating system load is 300,000 Btuh. How much heating water flow is required to satisfy the load if the system is designed for a 20°F temperature drop? How much flow for a 30°F drop?

Use equation 2-5. GPM = 300,000 / (500 × 20), or 30 GPM for 20 ° drop. GPM = 300,000 / (500 × 30), or 20 GPM for 30 ° drop.

2.11 Approximately how much steam flow would be required for a 300,000 Btuh heating load?

Use equation 2-7. Steam flow = 300,000/1000, or 300 pounds per hour. Most practitioners assume a value of 1000 Btu per pound of low-pressure steam.

2.12 Cooling system load is 48,000 Btuh sensible. How much chilled air is required to satisfy the load if the system is designed for a 20°F temperature rise? How much flow is required for 15°F rise?

Use equation 2-6. CFM = 48,000/(1.1 × 20), or 2,180 CFM for 20° temperature rise. CFM = 48,000/(1.1 × 15), or 2,910 CFM for 15° temperature rise.

2.13 Your client desires an interior temperature of 72°F for the design of his HVAC system in St. Louis (close to the airport weather station). Assuming

that a 97.5% design will be satisfactory, what is the design temperature difference?

From Table 2-1A, 97.5% design temperature is 6°F. Temperature difference is 72 minus 6, or 66°F for heating load estimate.

2.14 Your client desires an interior temperature of 78°F for the design of her HVAC system in St. Louis (close to the airport weather station). Assuming that a 5% design will be satisfactory, what is the design temperature difference?

From Table 2-1A, 5% design temperature is 91°F. Temperature difference is 91 minus 78, or 13°F for cooling load estimate.

2.15 What will be the U-factor for a wall constructed as follows?

- 6" thick concrete wall.
- The wall is finished on the interior with 1/2" drywall, adhesively applied to the surface.
- The drywall is applied over 1.5" furring.
- The furring space is filled with insulation at R-4 per inch.

Use Tables 2-2, 2-3, and 2-4 for this exercise.

U-factor, 6" concrete wall:

Construction	r	
Outside air film	0.15	
6" concrete	0.48	
Inside air film	0.68	
Total R	1.31	U = 1/1.31 = 0.76

Add 1/2" drywall @ r = .45. Total R increases to 1.76; U = 0.57.
Add furred air space @ 1.12. Total R increases to 2.88; U = 0.35.
Fill air space with R4 per inch insulation (delete air space, add insulation). Total R increases to 7.76; U = 0.13.

2.16 What will be the heating load for a wall 10' high by 500' long that is constructed as per the last description in Question 15 under conditions specified in Question 13?

Use equation 2-9. Q = 0.13 × (10 × 500) × 66 = 43,000 Btuh.

2.17 What will be the cooling load if the wall in Question 16 faces south? North? West?

The wall is most similar to type C wall in Table 2-13. From Table 2-12, maximum TETD's are 36, 25, and 52 for south, north and west. Using equation 2-11, $Q = 0.13 \times (10 \times 50) \times 36$, or 2,340 Btuh for the south wall. Similarly, 1,630 Btuh for north and 3,380 for west.

2.18 What will be the heating load for a 5' × 5' window constructed of single-pane clear glass according to the criteria in Question 13? Assume U = 1.05. Double-pane clear glass, U = 0.55?

Use equation 2-9. $Q = 1.05 \times (5 \times 5) \times 66 =$ 1,730 Btuh for single glass. Similarly, 910 Btuh for double glass.

2.19 What will be the July cooling load for a 5' × 5' west-facing window constructed of single-pane clear glass according to the criteria in Question 13? Double-pane clear glass? Double-pane tinted glass with a shading coefficient of 0.75?

Use equation 2-11. From Table 2-14, the maximum SHGF is 216. From Table 2-12, SC is 1.0. Other values are found in questions 13 and 18.

$$Q = 1.05 \times (5 \times 5) \times 13 + 1.0 \times (5 \times 5) \times 216 = 5{,}740 \text{ Btuh}$$

Double-pane glass reduces U-factor to 0.55 and SC to 0.85; Q = 4,770 Btuh. For double pane tinted glass, Q = 4,390 Btuh.

2.20 What internal heat gain will result from each of the following in an office?

- Ten people, moderate activity
- Four copy machines, 500 watts each
- Twelve suspended light fixtures, two 60-watt lamps each

From Table 2-13, sensible heat gain is 250 Btuh per person, total 450. Total heat gain from occupants will be 2,500 sensible, 4,500 total Btuh. For electrical loads, use equation 2-16.

Copy machines $Q = 10 \times 500 \times 3.41 = 17{,}050$ Btuh
Lights $Q = 12 \times 2 \times 60 \times 3.41 = 4{,}910$ Btuh

2.21 What minimum outside air quantity would be required for the room in Question 2.20?

From Table 2-8, outdoor air requirement is 20 CFM per person. Total requirement will be 100-CFM minimum.

2.22 What heating load would result from the minimum outside air in Question 2.21 under the criteria of Question 2.13? What cooling load for inside conditions of 75 ° F, 50% RH?

For heating load, use equation 2-10. Q = 1.1 × 100 × 66 = 7,260 Btuh

For sensible cooling load, use equation 2-10. Q = 1.1 × 100 × 13 = 1,430 Btuh
For latent cooling load, use equation 2-11. From psychrometric chart, outside condition results in absolute humidity of 0.0141 pounds (99 grains) water per pound air; inside condition, .0093 (65 grains). Q = 0.68 × 100 × (99 - 65) = 2,310 Btuh.

2.23 What is the Wind Chill Factor of an outdoor environment if the measured dry bulb temperature is 40°F with a wind velocity of 50 mph?

From Table 2-15A, the WCF of an outdoor environment at 40°F and 40 mph is 10°F. According to paragraph 2.8, wind velocity greater than 43 mph has little added chilling effect. Thus, the WCF at 40°F and 50 mph is approximately the same as shown for 40°F, which is the rounded value for 43°F.

2.24 If the Wind Chill Factor of the outdoor is said to be (-)20°C and the dry bulb temperature is 0°C, what is the expected wind velocity?

From Table 2-15B, a (-)20°C WCF of an outdoor environment with its dry bulb temperature at 0°C corresponds to a wind speed of 70 Km/h.

2.25 Absolute humidity can be expressed in grains of water per lb. of air, or lbs. of water per lb. of air. Write the equation relating the following variables using both units for absolute humidity: airflow (cfm), heat flow (Btuh), absolute humidity (grains water per lb. air), and lbs. water per lb. air.

With W expressed in grains of water per lb. of air,
$Q = 0.68 \times CFM \times (W_{final} - W_{initial})$
With W expressed in lbs. of water per lb. of air,
$Q = 4800 \times CFM \times (W_{final} - W_{initial})$.

2.26 For St. Louis, Missouri, what will the percentage difference be in heating load between 99% design dry bulb and 97.5% design dry bulb heating criteria? Assume an interior space criteria of 72°F.

Heating loads are proportional to the difference between indoor and outdoor temperatures. St. Louis 99% design outdoor temperature is 2°F. At an interior temperature of 72°F, this results in a temperature difference of 70°F. St. Louis 97.5% design outdoor temperature is 6°F. At an interior temperature of 72°F, this results in a temperature difference of 66°F. The ratio of 66°F to 70°F is 94.3%. Thus, heating load for 97.5% design will be about 6% lower than 99% design.

2.27 Referring to the prior question, will the percent difference in cooling load be the same for 1% summer design condition vs. 2.5%? Explain why, or why not.

Cooling loads are due not only to outdoor temperature conditions, but also to solar heat gains and sources of heat within the building, such as people, lighting, and appliances. For this reason, cooling loads are not proportional to percentage design condition.

2.28 How much more air conditioning supply air will be needed in a room with a 50 sq ft single strength, clear window facing north compared with an identical room facing west? Assume supply air temperature of 55°F; room temperature 75°F.

The solar load for single strength clear glass can be found in SHGF Table 2-14. Peak western solar gain is 214 Btu/sq ft at 4:00 p.m. in July or August. Room heat gain for 50 sq ft of glass will be 214 × 50, or 10,700 Btuh. The air required to absorb this heat going from 55°F to 75°F can be found by the equation $Q = 1.1 \times CFM \times TD$, where TD will be 20°F (75 – 55). Solving for CFM with a heat gain (Q) of 10,700 Btuh, the air required is 486 CFM. If the window were facing north, the peak solar heat gain would be 38 Btuh at noon in June or July. With the same procedure used above, room heat gain will be 1,900 Btuh. Air requirement will be 86 CFM. The west window will require (486 – 86), or 400 CFM more air.

2.29 How much more air conditioning supply air will be needed in a room with a 50 sq ft single strength, clear window facing east compared with an identical room facing west? Ignore conducted load. Assume supply air temperature of 55°F; room temperature 75°F.

Ignoring conducted load, both rooms will require the same amount of air. Solar heat gain for east facing windows in the morning is equal to solar heat gain for west facing windows in the afternoon. The only difference in load to the room will be conducted load, which will be higher in the afternoon, due to higher outside air temperature.

2.30 How will the orientation (east vs. west) of the room in the previous question affect the overall building load?

Most buildings' overall peak load occurs in the afternoon when outside air temperatures are highest. The high load on an east-facing window in the morning will not contribute to the peak of the building. The high load of a west-facing window in the afternoon will contribute to the peak load of the building.

2.31 How much moisture will a supply air quantity of 500 CFM absorb in warming from 55°F, saturated to 75°F, 50% relative humidity? How many people would liberate this amount of humidity?

Absolute humidity at 55°F, saturated, is 65 grains per lb. At 75°F, 60% RH, absolute humidity is 78 grains per lb. Using the equation QL = 0.68 × CFM × (W_{final} – $W_{initial}$), the moisture change will be 4,420 Btuh. Moisture, or latent, loads represent the latent heat of vaporization of water, which is approximately 1000 Btu per lb. A moisture change of 4,420 Btuh represents the air absorbing about 4.4 lbs. of water per hour. Load from a single person is approximately 250 sensible, 250 latent, or 500 Btuh total. The 250 Btuh latent load represents about 0.25 lbs. per hour of moisture to the air from perspiration and breath of each person. The 4.4 lbs. of water absorbed by the air from 55°F saturated to 75°F 60% RH would equal the latent load of 4.4/0.25, or about 18 people.

2.32 If there is no latent load for the supply air in the previous question, what will be the room humidity? If there are 15 people in the room, what will be the relative humidity? (Assume that the sensible load still results in a 75°F room.)

If there is no latent load in the room, the absolute humidity of the 75°F air will be the same as for the 55°F saturated air, or 65 grains per lb. Air at 75°F, 65 grains per lb. has a relative humidity of about 50%. If there were 15 people in the room, their latent load would be 15 × 250 Btuh, or 3,750 Btuh. Using the equation QL = 0.68 × CFM × (W_{final} – $W_{initial}$) and solving for W_{final}, the absolute humidity in the room will be 76 grains per lb. From the psychrometric chart, we find that the relative humidity at 75°F will be 55%.

2.33 How much heating load (Btu per year) would be saved by changing from R-4 to R-12 insulation to a 10,000 sq ft wall with original U-factor of 0.15? Assume the wall is located in a region with four months of winter, average outside temperature 30°F, inside temperature 70°F.

The original wall's average load for the winter would be U × A × TD, or 0.15 × 10,000 × (70 – 30) = 60,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 60,000 Btuh × 3,000 hours, or 180,000,000 Btu per year. The original wall resistance was 1/0.15, or 6.7. Changing the insulation from R-4 to R-12 would increase the wall resistance by R-8 for a new resistance of R-14.7.

New U-factor would be 1/14.7, or 0.068 (use 0.07). The new average load will be 0.07 × 10,000 × (70 – 30) = 28,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 28,000 Btuh × 3,000 hours, or 84,000,000 Btu per year.
Savings will be 180,000,000 – 84,000,000 = 96,000,000 Btu per year.

2.34 If the net cost of heating energy is $6.00 per million Btu, what will the utility cost saving be for the wall change in the prior problem?

Utility cost saving will be $6.00 per million Btu × 96 million Btu = $576

2.35 How much heating load (Btu per year) would be saved by changing from R-4 to R-20 insulation in a 10,000 sq ft wall with an original U-factor of 0.15? Assume the wall is located in a region with four months of winter, average outside temperature 30°F, inside temperature 70°F.

The original wall's average load for the winter would be U × A × TD, or 0.15 × 10,000 × (70 – 30) = 60,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 60,000 Btuh × 3,000 hours, or 180,000,000 Btu per year (same as Q 2.33).
The original wall resistance was 1/0.15, or 6.7. Changing the insulation from R-4 to R-20 would increase the wall resistance by R-16 for a new resistance of R-22.7. New U-factor would be 1/22.7, or 0.044 (use 0.05). The new average load will be 0.05 × 10,000 × (70-30) = 20,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 20,000 Btuh × 3,000 hours, or 60,000,000 Btu per year.
Savings will be 180,000,000 – 60,000,000 = 120,000,000 Btu per year.

2.36 If the net cost of heating energy is $6.00 per million Btu, what will the utility cost saving be for the wall change in the prior problem?

Utility cost saving will be $6.00 per million Btu × 120 million Btu = $720

2.37 What would heating load savings be for problem 2.33 in a different location with average winter temperature of 40°F? What would annual heating savings be at $6.00 per million Btu?

The original wall's average load for the winter would be U × A × TD, or 0.15 × 10,000 × (70 – 40) = 45,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 45,000 Btuh × 3,000 hours, or 135,000,000 Btu per year.
The original wall resistance was 1/0.15, or 6.7. Changing the insulation from R-4 to R-12 would increase the wall resistance by R-8 for a new resistance of R-14.7.

New U-factor would be 1/14.7, or 0.068 (use 0.07). The new average load will be 0.07 × 10,000 × (70-40) = 21,000 Btuh. The four month winter is 1/3 of a year, or (8,760 hours/year)/3 = approx. 3,000 hours. Using the equation Energy = Power × Time, the annual energy will be 21,000 Btuh × 3,000 hours, or 63,000,000 Btu per year. Savings will be 135,000,000 – 63,000,000 = 72,000,000 Btu per year. Utility cost saving will be $6.00 per million Btu × 72 million Btu = $432

2.38 Would savings in problem 2.33 be higher or lower if the facility were operated round the clock, rather than regular business hours? Why?

Savings would be lower. Running a facility round the clock means that internal heat from lights, appliances, and people is available to offset heat losses through the wall, resulting in less heating load.

2.39 A proposed building design has 10,000 sq ft of glass with shading coefficient 0.7, equally distributed north, south, east, and west. What is the total solar load in tons July 21 at 4:00 pm?

Glass areas for the four orientations will be 10,000/4 sq ft, or 2,500 sq ft in each direction. The following calculations are based on the equation Q_{solar} = A × SC × SHGF. SC is 0.7, SHGF are found in Table 2-15.
North Q_{solar} = 2,500 × 0.7 × 28 = 49,000 Btuh
South Q_{solar} = 2,500 × 0.7 × 29 = 50,800 Btuh
East Q_{solar} = 2,500 × 0.7 × 26 = 45,500 Btuh
East Q_{solar} = 2,500 × 0.7 × 216 = 378,000 Btuh
Total solar load = (49,000 + 50,800 + 45,500 + 378,000) = 524,000 Btuh, which is 524,000 Btuh / (12,000 Btuh/ton), or 44 tons.

2.40 What would the solar load in tons for the building in 2.39 be if the glass were oriented 40% north, 40% south, 10% east, and 10% west?

Glass areas for the four orientations will be as follows:
North area = 40% × 10,000 = 4,000 sq ft
South area = 40% × 10,000 = 4,000 sq ft
East area = 10% × 10,000 = 1,000 sq ft
West area = 10% × 10,000 = 1,000 sq ft

The following calculations are based on the equation Q_{solar} = A × SC × SHGF. SC is 0.7, SHGF are found in Table 2-15.
North Q_{solar} = 4,000 × 0.7 × 28 = 78,400 Btuh
South Q_{solar} = 4,000 × 0.7 × 29 = 81,200 Btuh
East Q_{solar} = 1,000 × 0.7 × 26 = 18,200 Btuh
East Q_{solar} = 1,000 × 0.7 × 216 = 151,000 Btuh
Total solar load = (78,400 + 81,200 + 18,200 + 151,000) = 329,000 Btuh, which is 329,000 Btuh / (12,000 Btuh/ton), or 27 tons.

2.41 What would the solar load in tons for the building in 2.39 be if all the glass faced north? How could this be accomplished while maintaining views in all four directions?

The following calculation is based on the equation $Q_{solar} = A \times SC \times SHGF$. SC is 0.7, SHGF is found in Table 2-15.
North $Q_{solar} = 10{,}000 \times 0.7 \times 28 = 196{,}000$ Btuh, which is 196,000 Btuh / (12,000 Btuh/ton), or 16 tons.
This could be accomplished by externally shading glass exposed to direct sun.

2.42 If the initial, incremental cost of air conditioning equipment is $2,000 per ton, how much less would the case in 2.41 cost, compared with the case in 2.39?

Savings in air conditioning load would be (56 – 21), or 35 tons. At $2,500 per ton, this is $87,500.