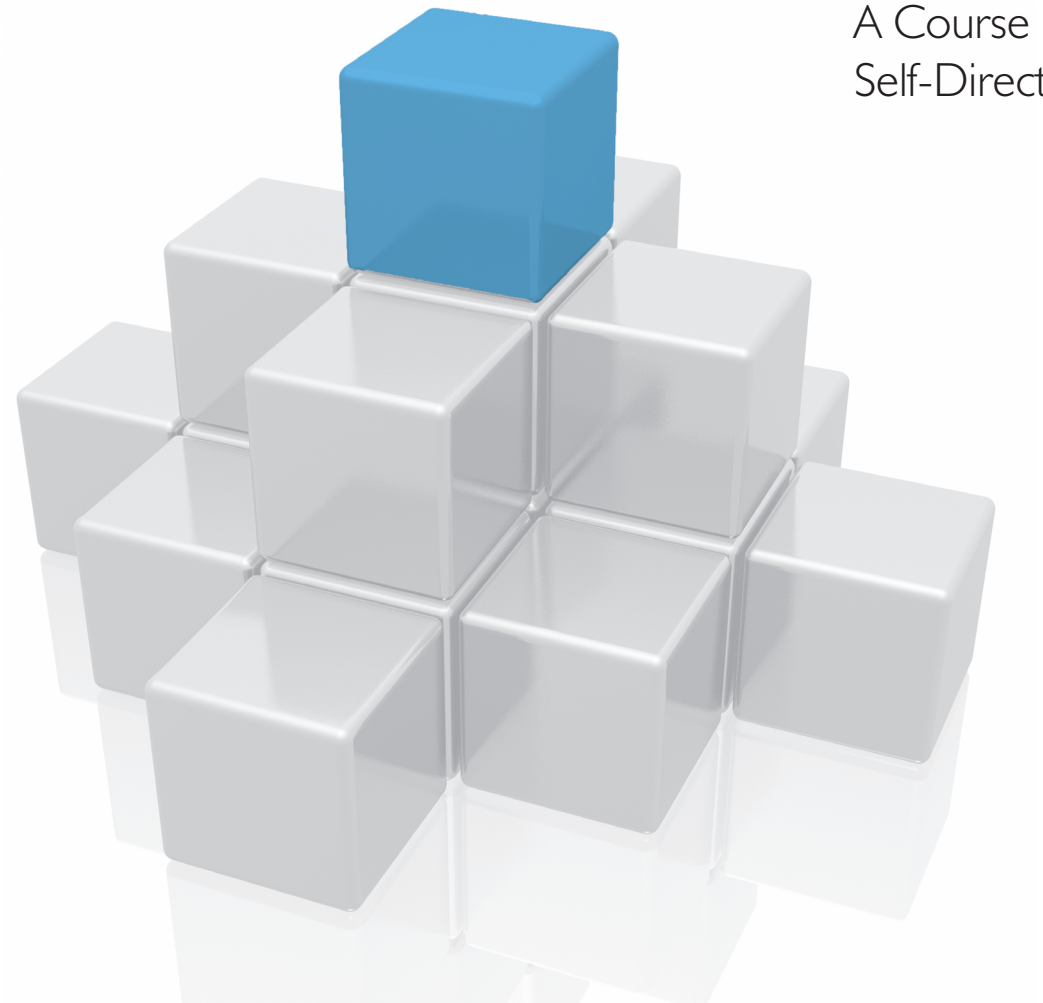
Fundamentals of Design and Control of Central Chilled-Water Plants

Steven T. Taylor, PE

SI

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Steven T. Taylor, PE

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ASHRAE Learning Institute

Atlanta

Fundamentals of Design and Control of Central Chilled-Water Plants (SI)
A Course Book for Self-Directed or Group Learning
ISBN 978-1-939200-68-6 (paperback)
ISBN 978-1-939200-69-3 (PDF)
SDL Number: 00686

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Steven T. Taylor, PE, Fellow ASHRAE, is the founding principal of Taylor Engineering, Alameda, CA. He is a registered mechanical engineer specializing in HVAC system design, control system design, indoor air quality engineering, computerized building energy analysis, and HVAC system commissioning. Mr. Taylor graduated from Stanford University with a BS in Physics and a MS in Mechanical Engineering and has 40 years of commercial HVAC system design and construction experience. He was one of the primary authors of the HVAC sections of ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings* and California's Title 24 energy standards and ventilation standards. Other ASHRAE projects and technical committees Mr. Taylor has participated in include ASHRAE Standard 62.1 on indoor air quality (chair), ASHRAE Standard 55 on thermal comfort (member), Guideline 13 on specifying DDC (chair), Guideline 16 on economizer dampers (chair), Guideline 36 on advanced control sequences (founder and member), the TC 1.4 on controls (chair), and the TC 4.3 on ventilation (chair). He is past vice-chair of the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Indoor Environmental Quality Technical Advisory Group, a member of the CSU Mechanical Review Board, and a 16-year member of the International Association of Plumbing and Mechanical Officials (IAPMO) Mechanical Technical Committee administering the Uniform Mechanical Code.

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Preface

Chilled-water plants are typically the most costly part of large building or campus HVAC systems and the largest energy user. Optimizing the design and control of chilled water plants can therefore have a large reduction in HVAC system life-cycle costs. But true optimization requires extensive analysis, for which few system designers have the time or funding. This course is intended to improve on the state of the art by providing updated design techniques based on rigorous life-cycle cost analysis that can provide near-optimum chilled-water plant life-cycle costs with little or no more engineering time than current practice. Recommended control sequences, also based on rigorous analysis, can improve plant performance with no more complexity than typical current practice. In addition to these design techniques, this course includes practical tips for laying out and piping chilled-water plants. The guidance applies to small plants serving small buildings as well as to district cooling plants.

This SDL is accompanied by Microsoft® Excel® spreadsheets, which can be found at [illegible] These files include a chiller bid form, a simplified chiller bid form, and a pipe size optimization tool. If the files or information at the link are not accessible, please contact the publisher.

Acknowledgments

The author would like to thank Pacific Gas and Electric Company for allowing ASHRAE to use its 1999 *CoolTools™ Chilled Water Plant Design Guide* as the basis of this course. The CoolTools™ guide was co-authored by Steve Taylor (author of this course), Mark Hydeman, Paul DuPont, and Tom Hartman.

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September 6, 2017

SI

Fundamentals of Design and Control of Central Chilled-Water Plants

Acronyms

A/D	=	analog to digital
AFLV	=	automatic flow-limiting valve
AHU	=	air-handling unit
ATS	=	automatic transfer switch
BAS	=	building automation system
BEP	=	best efficiency point
CAD	=	computer-aided design and drafting
CBV	=	calibrated balancing valve
CFC	=	chlorofluorocarbon
CHW	=	chilled water
CHWST	=	chilled-water supply temperature
COP	=	coefficient of performance
COV	=	change of value
CS	=	constant speed
CT	=	current transformer
CVRMSE	=	coefficient of variation of root mean squared error
CW	=	condenser water
CWF_d	=	design CW flow rate
CWFR	=	condenser water flow ratio
CWFSP	=	condenser water flow set point
CWRT	=	condenser return temperature
Cx	=	commissioning
CxA	=	commissioning authority
D/A	=	digital to analog
DDC	=	direct digital control
DI	=	digital input
DO	=	digital output
DP	=	differential pressure
DV/DT	=	derivative of voltage with respect to time
DX	=	direct expansion
EMI	=	electromagnetic interference
EMT	=	electrical metallic tubing
EOR	=	engineer of record
EPDM	=	ethylene propylene diene monomer
FCU	=	fan-coil unit

GWP	=	global warming potential
HBM	=	heat balance method
HCFC	=	hydrochlorofluorocarbon
HFC	=	hydrofluorocarbon
HFO	=	hydrofluoroolefin
HGBP	=	hot-gas bypass
HOA	=	hand-off-auto
HX	=	heat exchanger
HXLWT	=	heat exchanger leaving water temperature
I/O	=	input/output
IPLV	=	integrated part-load value
LCCA	=	life-cycle cost analysis
LOT	=	lockout temperature
MBE	=	mean bias error
NPLV	=	nonstandard part-load value
NPSHA	=	net positive suction head available
NPSHR	=	net positive suction head required
OAT	=	outdoor air temperature
ODP	=	ozone depletion potential
OEM	=	original equipment manufacturer
PHXLWT	=	predicted heat exchanger leaving water temperature
PICCV	=	pressure-independent characterized control valve
PID	=	proportional integral differential
PLC	=	programmable logic controller
PLR	=	part-load ratio
PVC	=	polyvinyl chloride
PWM	=	pulse width modulation
RFI	=	radio frequency interference
RMS	=	root mean square
RTD	=	resistance temperature detector
RTS	=	radiant time series
SAT	=	supply air temperature
SOO	=	sequence of operation
SPLR	=	staging part-load ratio
TAB	=	testing, adjusting, and balancing
TDH	=	total dynamic head
TES	=	thermal energy storage
THHN	=	thermoplastic high heat resistant nylon coated
TOPP	=	theoretical optimum plant performance
TXV	=	thermal expansion valve
UPS	=	uninterruptible power source
VAV	=	variable air volume
VFD	=	variable-frequency drive

VS	=	variable speed
VSD	=	variable-speed drive
WSE	=	water-side economizer
XHHW-2	=	cross-linked polyethylene high heat-resistant water-resistant
XLPE	=	cross-linked polyethylene

Overview

How to Use This Course

The purpose of this course is to provide guidance to designers and operators of new and existing central chilled-water (CHW) plants ranging from small, single-chiller plants to large, district-cooling plants. While design engineers are the primary audience, the guide also provides useful information for operation and maintenance personnel, mechanical contractors, and building managers. Upon completion of this course, the student should have a thorough understanding of CHW plant fundamentals and principles that will be useful in conjunction with plant design or operation.

The course is divided into chapters, each addressing a specific topic. It is important that you understand each topic before going on. At the end of each chapter there are questions that are intended to reinforce certain topics and to test your level of understanding. Your responses should be given to ASHRAE at www.ashrae.org/sdlonline in order to receive credit and to obtain the answer sheets.

Introduction

Many large buildings, campuses, and other facilities have plants that make chilled water and distribute it to air-handling units (AHUs) and other cooling equipment. The design, operation, and maintenance of these CHW plants has a very large impact on building energy use and energy operating cost. The intent of this course is to provide tools and guidance to engineers so that the plants they design have a near optimum balance of first costs and future operating costs. The course can also be used by plant operators to understand and resolve operational problems and improve energy efficiency through controls optimization.

Organization of Material

The course is organized in eight chapters. The first chapter is this overview.

Loads. Chapter 2 discusses the nature of CHW loads and how they should be considered in the design of CHW plants. In the past, most engineers have only estimated the peak or maximum load. However, accounting for the time pattern of loads can be just as important. Methods of calculating peak loads

and hourly loads are reviewed. These include site measurements (for existing facilities), computer simulations, rules of thumb, and prototype buildings.

Equipment. Chapter 3 reviews some basics on chillers, cooling towers, pumps, and other plant equipment. This chapter discusses the basic refrigeration cycle, water chillers, cooling towers, air-cooled condensers, pumps, and variable-speed drives.

Distribution Systems. Chapter 4 discusses different ways of arranging CHW equipment in the system to meet loads while achieving energy efficiency and operational simplicity. The pros and cons of constant-flow and variable-flow systems are discussed along with different primary-only and primary/secondary pumping systems.

Optimizing Design. Chapter 5 provides procedures and analysis techniques for optimizing CHW plant design. Topics include optimizing the selection of distribution systems and optimizing the selection of CHW and condenser water design temperatures and pipe sizes. A spreadsheet for sizing piping and calculating pump head is provided at ashrae.org/CHWSDL (Pipe Size Optimization Tool spreadsheet). Recommendations were developed from in-depth life-cycle cost analysis of typical chiller plants and are provided as easy-to-use rules of thumb and procedures to simplify plant design while still achieving near-optimum life-cycle performance.

Chiller Procurement. Chapter 6 discusses strategies for evaluating chiller options and selecting and procuring an energy-efficient and cost-effective chiller. Case studies of the chiller selection process are provided. Sample chiller bid forms are also provided (Chiller Bid Form and Simplified Chiller Bid Form).

Controls. Chapter 7 explores the many design and performance issues related to controls and instrumentation of CHW plants. Topics include types of flow and temperature sensors, styles of and selection criteria for control valves, controller requirements and interfacing issues, performance monitoring, and recommended near-optimum control sequences for CHW plants, including all-variable-speed plants where all components have variable-speed drives.

Commissioning. Chapter 8 discusses key elements of the commissioning process, addressing in detail sequence of operation review, point-to-point checkout, functional testing, and trend reviews.

Supplemental Files. Supplemental material for this SDL is available at ashrae.org/CHWSDL. These files include a chiller bid form, a simplified chiller bid form, and a pipe size optimization tool.

2 Chilled-Water Plant Loads

Instructions

Read the material in Chapter 2. Verify the examples presented in the chapter with your own calculations. At the end of the chapter, complete the Skill Development Exercises without referring to the text. Review those sections of the chapter as needed to complete the exercises.

Introduction

This chapter discusses CHW plant peak loads and annual cooling load profiles and how they affect plant design and equipment capacity. Fundamental to the design process is a keen understanding of the chiller plant cooling loads and how they vary with time. If an existing plant is being modified or expanded, it is possible to monitor the cooling load and obtain an accurate estimate of both the peak load and the cooling load profile. A great many plants, however, are designed with only preliminary information available about the building's design and function. Getting accurate peak load and cooling load profile information for these plants is much more difficult. This chapter discusses the uncertainties involved with predicting chiller plant loads and the impact of these uncertainties on the design process.

Understanding Loads and Their Impact on Design

To provide an optimum CHW plant design, the designer must determine both a design (peak) load and a cooling load profile that describes how the load varies over time. The design load defines the overall installed plant capacity including the chillers, pumps, piping, and towers. The cooling load profile is required to design the plant to handle often widely variable loads stably and efficiently. This includes design decisions such as the unloading mechanisms of the chillers; the application of variable-frequency drives (VFDs) on the chillers, towers, and pumps; and the relative sizes of each piece of equipment.

Certain key load parameters affect the cooling load profile and consequently the nature of the plant design. These parameters include the following:

- The use of outdoor air economizers and 100% outdoor air units
- The climate in which the plant is located
- Hours of building or facility operation
- Base (24/7) loads such as computer rooms

For example, the cooling load profile of a San Francisco office building that operates five days per week was analyzed with and without economizers. As Figure 2-1 shows, the number of hours that the plant operates increases dramatically when an economizer is not used. Additionally, the shape of the profile changes dramatically. The profile influences the optimum selection of the number and capacity of the chillers as well as the full-load and part-load energy efficiency of the machines.

What happens if this same CHW plant serving the office with economizers must also serve a relatively small data center without an economizer? Figure 2-2 shows the resulting load profile. This profile is also typical of district and campus cooling plants that serve relatively small 24/7 loads continuously, along with much larger peak summer loads. The plant clearly will need to operate efficiently at low loads. The plant must be designed very differently than the one serving the office building alone.

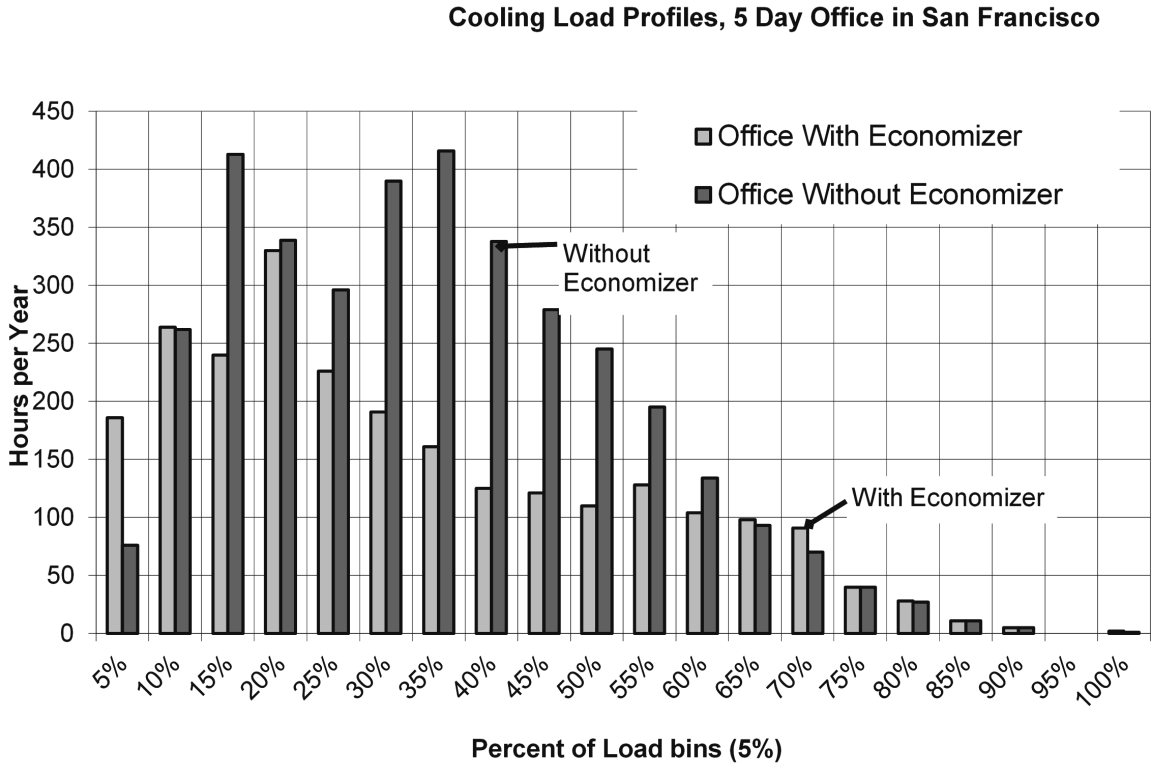


Figure 2-1 Cooling load profiles, five-day office in San Francisco.