COMBINED COOLING, HEATING, AND POWER SYSTEMS

WILEY-ASME PRESS SERIES LIST

Combined Cooling, Heating, and Power Systems: Modeling, Optimization, and Operation	Shi	August 2017
Applications of Mathematical Heat Transfer and Fluid Flow Models in Engineering and Medicine	Dorfman	February 2017
Bioprocessing Piping and Equipment Design: A Companion Guide for the ASME BPE Standard	Huitt	December 2016
Nonlinear Regression Modeling for Engineering Applications	Rhinehart	September 2016
Fundamentals of Mechanical Vibrations	Cai	May 2016
Introduction to Dynamics and Control of Mechanical Engineering Systems	To	March 2016

COMBINED COOLING, HEATING, AND POWER SYSTEMS

MODELING, OPTIMIZATION, AND OPERATION

Yang Shi
University of Victoria, Canada

Mingxi Liu
University of Victoria, Canada

Fang Fang
North China Electric Power University, China

This Work is a co-publication between ASME Press and John Wiley & Sons Ltd.

WILEY

ASME PRESS

This edition first published 2017

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Shi, Yang, 1972- author. | Liu, Mingxi, 1988- author. | Fang, Fang, 1976- author.
Title: Combined cooling, heating, and power systems : modeling, optimization, and operation / Yang Shi, Mingxi Liu, Fang Fang.
Description: Singapore ; Hoboken, NJ : John Wiley & Sons, 2017. | Includes bibliographical references and index. | Description based on print version record and CIP data provided by publisher; resource not viewed.
Identifiers: LCCN 2017004053 (print) | LCCN 2017012538 (ebook) | ISBN 9781119283379 (Adobe PDF) | ISBN 9781119283423 (ePub) | ISBN 9781119283355 (cloth)
Subjects: LCSH: Cogeneration of electric power and heat. | Cooling systems. | Heating.
Classification: LCC TK1041 (ebook) | LCC TK1041 .S55 2017 (print) | DDC 621.1/99–dc23
LC record available at https://lccn.loc.gov/2017004053

Cover image: © artJazz/Gettyimages
Cover design by Wiley

Set in 10/12pt, TimesLTStd by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

To my beloved parents and family
–Yang Shi

To my beloved parents and Jingwen
–Mingxi Liu

To my beloved parents and family
–Fang Fang

Contents in Brief

Contents

List of Figures

List of Tables

Series Preface

The Wiley-ASME Press Series in Mechanical Engineering brings together two established leaders in mechanical engineering publishing to deliver high-quality, peer-reviewed books covering topics of current interest to engineers and researchers worldwide. The series publishes across the breadth of mechanical engineering, comprising research, design and development, and manufacturing. It includes monographs, references and course texts.

Prospective topics include emerging and advanced technologies in Engineering Design; Computer-Aided Design; Energy Conversion & Resources; Heat Transfer; Manufacturing & Processing; Systems & Devices; Renewable Energy; Robotics; and Biotechnology.

Preface

Combined cooling, heating and power (CCHP) is a feature of trigeneration systems able to supply cooling, heating, and electricity simultaneously. CCHP systems can be employed to provide buildings with cooling, heating, electricity, hot water and other uses of thermal energy. CCHP features with the great potential of dramatically increasing resource energy efficiency and reducing carbon dioxide emissions. Our intention through this book is to provide a timely account as well as an introductory exposure to the main developments in modeling, optimization, and operation of CCHP systems. At the time of conceiving this project, we believed that the development of a systematic framework on modeling and optimal operation design of CCHP systems was of paramount importance. A concise overview of the research area is presented in Chapter 1. We hope it will help readers arrive at a broader and more balanced view of CCHP systems. The remainder of the book presents the core contents, which are divided into five chapters. In Chapter 2, based on two conventional operation strategies, that is, following electric load (FEL) and following thermal load (FTL), a novel optimal switching operation strategy is presented. Chapter 3 presents a configuration with hybrid chillers and design of the optimal operation strategy. In Chapter 4, based on the concept of energy hub, a system matrix-based model is proposed to systematically facilitate the design of optimal operation strategies. Chapter 5 discusses the load prediction problem which plays an instrumental role in designing CCHP operation schemes. In Chapter 6, a complementary CCHP-organic Rankine cycle (CCHP-ORC) system is introduced.

The writing of this monograph has benefitted greatly from discussions with many colleagues. We wish to express our heartfelt gratitude to Professor Jizhen Liu who shared many of his ideas and visions with us. Others who contributed directly by means of joint research on the subject include Le Wei, Qinghua Wang, Hui Zhang, and Huiping Li, with whom we have enjoyed many collaborations. We have also benefitted from constructive and enlightening discussions with Jianhua Zhang, Guolian Hou, Jian Wu, Ji Huang, Xiaotao Liu, Chao Shen, Yuanye Chen, Bingxian Mu, Jicheng Chen, and Kunwu Zhang, among others. Support from the Natural Sciences and Engineering Research Council of Canada, from the National Natural Science Foundation of China (under grant 61473116 and 51676068) has been very helpful and is gratefully acknowledged. Finally, as a way of expressing our deep

gratitude and indebtedness, the first author dedicates this book to his wife Jing, and Eric and Adam, the second author to his wife Jingwen, and the third author to his wife Le, and Bowen and Yihe, for their great support and encouragement on this project.

Yang Shi, Mingxi Liu, Fang Fang
Victoria, BC, Canada

Acknowledgment

The authors would like to thank all those who have helped in accomplishing this book.

Acronyms

AFC	Alkaline Fuel Cell
ANN	Artificial Neural Network
AR	AutoRegressive
ARIMA	AutoRegressive Integrated Moving Average
ARMA	AutoRegressive Moving Average
ARMAX	AutoRegressive Moving Average with eXogenous inputs
ATC	Annual Total Cost
ATCS	Annual Total Cost Saving
ATD	Aggregate Thermal Demand
BFGS	Broyden–Fletcher–Goldfarb–Shanno
CCHP	Combined Cooling, Heating, and Power
CDE	Carbon Dioxide Emissions
CDER	Carbon Dioxide Emissions Reductions
CHP	Combined Heating and Power
CITHR	Cooling-side Incremental Trigeneration Heat Rate
COP	Coefficient of Performance
DHC	District Heating and Cooling
DOE	Department of Energy
EA	Evolutionary-Algorithmic
EBMUD	East Bay Municipal Utility District
EC	Evaluation Criteria
EDM	Electric Demand Management
EITHR	Electrical-side Incremental Trigeneration Heat Rate
EPA	Environmental Protection Agency
EUETS	European Union Emissions Trading Scheme
ec	Electric Chiller
FCL	Following Constant Load
FEL	Following the Electric Load
FTL	Following the Thermal Load
GA	Genetic Algorithm
GHG	GreenHouse Gas
GRG	Generalized Reduced Gradient
GRU	Gainsville Regional Utilities

HETL	Hybrid Electric-Thermal Load
hrc	Recovered Heat for Cooling
hrh	Recovered Heat for Heating
HRSG	Heat Recovery Steam Generator
hrs	Heat Recovery System
HTC	Hourly Total Cost
HTCS	Hourly Total Cost Savings
HVAC	Heating, Ventilation, and Air Conditioning
IC	Internal Combustion
IV	Instrument Variable
KKT	Karush–Kuhn–Tucker
LP	Linear Programming
LS	Least Squares
MA	Moving Average
MAE	Mean Absolute Error
MAFC	Magnesium-Air Fuel Cell
MAPE	Mean Absolute Percentage Error
MCFC	Molten Carbonate Fuel Cell
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MSPE	Mean Square Prediction Error
MPC	Model Predictive Control
OLS	Ordinary Least Squares
ORC	Organic Rankine Cycle
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PEC	Primary Energy Consumption
PES	Primary Energy Savings
PGU	Power Generation Unit
PURPA	Public Utility Regulatory Policy Act
PV	PhotoVoltaic
QP	Quadratic Programming
SNPV	System Net Present Value
SOFC	Solid Oxide Fuel Cell
SP	Separation Production
SQP	Sequential Quadratic Programming
TDM	Thermal Demand Management
TITHR	Thermal-side Incremental Trigeneration Heat Rate
TPES	Trigeneration Primary Energy Saving
TRR	Total Revenue Requirement
TSLS	Two-Stage Least Squares
TSRLS	Two-Stage Recursive Least Squares
WADE	World Alliance for Decentralized Energy

Symbols

$a_i(\star)$	The ith equality constraint of variable $\star$
ATC	Annual total cost
$ATCS$	Annual total cost savings
C_{ac}	Unit price of the absorption chiller
C_b	Unit price of the boiler
C_{ca}	Carbon tax rate
C_e	Electricity rate
C_{ec}	Unit price of the electric chiller
C_f	Natural gas rate
C_h	Unit price of the heating unit
$c_j(\star)$	The jth inequality constraint of variable $\star$
C_{pgu}	Unit price of the PGU
C_s	Electricity sold-back rates
CDE	Carbon dioxide emissions
CDE^{CCHP}	Carbon dioxide emissions of the CCHP system
CDE^{CCHP}_{FEL}	Carbon dioxide emissions of the CCHP system under FEL
CDE^{CCHP}_{FTL}	Carbon dioxide emissions of the CCHP system under FTL
CDE^{SP}	Carbon dioxide emissions of the SP system
$CDER$	Carbon dioxide emissions reductions
COP_{ac}	Coefficient of performance of the absorption chiller
COP_{ec}	Coefficient of performance of the electric chiller
$COST$	Operational cost
$COST^{CCHP}_{FEL}$	Operational cost of the CCHP system under FEL
$COST^{CCHP}_{FTL}$	Operational cost of the CCHP system under FTL
$COST^{SP}$	Operational cost of the SP system
$\mathrm{Cov}[\bullet, \star]$	Covariance of variables $\bullet$ and $\star$

E[⋆]	Expectation of variable ⋆
E_{ec}	Electricity consumed by the electric chiller in the CCHP system
E_{ec}^{SP}	Electricity consumed by the electric chiller in the SP system
E_{excess}	Excess electricity
E_{grid}	Purchased electricity from the grid by the CCHP system
$\check{E}_{grid}(t)$	Purchased electricity for compensating for the cooling gap
E_{grid}^{SP}	Purchased electricity from the grid by the SP system
e_i	Standard basis vector with the ith element being 1
E_i^{ℓ}	Electricity input of component ℓ
E_o^{ℓ}	Electricity output of component ℓ
$\bar{E}_o^{pgu}$	Maximum electricity generated by the PGU
E_{orc}	Electricity output of the ORC
E_p	Parasitic electricity
E_{pgu}	Electricity generated from the PGU
$\bar{E}_{pgu}$	Maximum electricity generated by the PGU
$E_{pgu-FEL}$	Electricity generated from the PGU under FEL
$E_{pgu-FTL}$	Electricity generated from the PGU under FTL
E_{pro}	Electricity generated by the PGU
E_{req}	Electricity required by building users and the electric chiller
E_{user}	Electricity required by building users
E_{userl}	Lower bound of electricity required by building users
E_{useru}	Upper bound of electricity required by building users
EC	Evaluation criteria function value
EC_{annual}	Annual evaluation criteria function value
EC_{FEL}	Evaluation criteria function value of the CCHP system under FEL
EC_{FTL}	Evaluation criteria function value of the CCHP system under FTL
EC_{hour}	Hourly evaluation criteria function value
$EC_{hour,ij}$	Hourly evaluation criteria function value of day i, hour j
F_b	Fuel consumed by the boiler in the CCHP system
F_b^{SP}	Fuel consumed by the boiler in the SP system
F_{b-FEL}	Fuel consumed by the boiler in the CCHP system under FEL
F_{b-FTL}	Fuel consumed by the boiler in the CCHP system under FTL
F^{CCHP}	Fuel consumed by the CCHP system
F_i^{ℓ}	Fuel input of component ℓ
F_m	Total fuel consumption
$\check{F}_m$	Additionally purchased fuel

F_{m-FEL}	Total fuel consumption of the CCHP system under FEL
F_{m-FTL}	Total fuel consumption of the CCHP system under FTL
F_o^ℓ	Fuel output of component ℓ
F_{pgu}	Fuel consumed by the PGU
$F_{pgu-FEL}$	Fuel consumed by the PGU in the CCHP system under FEL
$F_{pgu-FTL}$	Fuel consumed by the PGU in the CCHP system under FTL
F_{pgum}	Maximum fuel consumption of the PGU
$F_{pgumopt}$	Optimal PGU capacity
F_{red}	Reduced fuel consumption
F^{SP}	Fuel consumed by the SP system
$\mathcal{H}^\ell$	Energy conversion matrix of component ℓ
h_1	Enthalpy of organic fluid at the inlet of pump
h_2	Enthalpy of organic fluid at the outlet of pump
h_{2s}	Enthalpy at the outlet of pump for the isentropic case
h_3	Enthalpy of organic fluid at the outlet of the evaporator
h_4	Enthalpy of organic fluid at the outlet of the pump
h_{4s}	Enthalpy of organic fluid at the outlet of the turbine for the isentropic case
HTC	Hourly total cost
HTC^{CCHP}	Hourly total cost of the CCHP system
HTC^{SP}	Hourly total cost of the SP system
$HTCS$	Hourly total cost savings
K	Power to heat ratio
k_e	Site-to-primary energy conversion factor for electricity
k_f	Site-to-primary energy conversion factor for natural gas
L	Facility's life
$\max f(\bullet)$	Maximize the function value of $f(\bullet)$
$\min f(\bullet)$	Minimize the function value of $f(\bullet)$
$\max\{\bullet, \star\}$	Maximum value between $\bullet$ and $\star$
$\min\{\bullet, \star\}$	Minimum value between $\bullet$ and $\star$
m_{orc}	Organic fluid mass flow rate
PEC	Primary energy consumption
PEC^{CCHP}	Primary energy consumption of the CCHP system
PEC^{CCHP}_{FEL}	Primary energy consumption of the CCHP system under FEL
PEC^{CCHP}_{FTL}	Primary energy consumption of the CCHP system under FTL
PEC^{SP}	Primary energy consumption of the SP system

PES	Primary energy savings
Q_{ac}	Cooling energy provided by the absorption chiller
Q_c	Total cooling demand
Q_{cd}	Heat exchange of the condenser
Q_{ec}	Cooling energy provided by the electric chiller
Q_{ep}	Obtained heat by evaporator
Q_{eq}	Equivalent total thermal requirement at the output of the heat recovery system
Q_b	Thermal energy provided by the boiler in the CCHP system
Q_b^{SP}	Thermal energy provided by the boiler in the SP system
Q_{gap}	Thermal energy gap
Q_h	Total heating demand
Q_{hi}^{ℓ}	Heating input of component ℓ
Q_{ho}^{ℓ}	Heating output of component ℓ
Q_{hrc}	Thermal energy from the heat recovery system for the use of cooling
Q_{hrh}	Thermal energy from the heat recovery system for the use of heating
Q_{pro}	Thermal energy provided by the PGU
Q_r	Thermal energy provided by the heat recovery system
Q_{req}	Thermal energy required by building users and the electric chiller
Q_{r-FEL}	Thermal energy provided by the heat recovery system under FEL
Q_{r-FTL}	Thermal energy provided by the heat recovery system under FTL
Q_{ro}	Thermal input of the ORC
Q_{user}	Total thermal demand by building users
R	Capital recovery factor
T_{dew}	Dew-point temperature
T_{dew}^{o}	Observation of the dew-point temperature
T_{dry}	Dry-bulb temperature
T_{dry}^{o}	Observation of the dry-bulb temperature
$\hat{T}_{dry}$	Estimation of the dry-bulb temperature
$\mathcal{V}_i^{\ell}$	Energy input vector of component ℓ
$\mathcal{V}_o^{\ell}$	Energy output vector of component ℓ
$\hat{\mathcal{V}}_o$	Forecasted load vector
$\bar{\mathcal{V}}_o^{\ell}$	Upper bound of the output of component ℓ
$\underline{\mathcal{V}}_o^{\ell}$	Lower bound of the output of component ℓ
$\mathrm{Var}[\star]$	Variance of variable $\star$
W_p	Pump power

x	Electric cooling to cool load ratio
y_c	Variable of cooling load
$\hat{y}_c$	Variable of forecasted cooling load
$\tilde{y}_c$	Variable of remained cooling to be provided
y_e	Variable of electric load
$\hat{y}_e$	Variable of forecasted electric load
y_h	Variable of heating load
$\hat{y}_h$	Variable of forecasted heating load
$\tilde{y}_h$	Variable of remained heating to be provided
$z^{-\star}$	$\star$ time lags from the current time instant
Γ_ℓ	Dispatch matrix of component ℓ
η_h	Efficiency of the heating unit
η_{pgu}	Efficiency of the PGU
η_{hrs}	Efficiency of the heat recovery system
η_b	Efficiency of the boiler
η_e^{SP}	Generation efficiency of the SP system
η_{grid}	Transmission efficiency of local grid
η_p	Isentropic efficiency
η_{orc}	Efficiency of the ORC
η_{gen}	Efficiency of the electric generator
μ_e	Carbon dioxide emissions conversion factor of electricity
μ_f	Carbon dioxide emissions conversion factor of natural gas
ξ	Evaporator effectiveness
ω_i	Weighting coefficient of the *i*th criterion
∇	Gradient
°C	Centigrade
$\exists$	Exists
$\in$	In
$\triangleq$	Define
$\sum$	Sum
$\forall$	For all
s.t.	Subject to
$\top$	Matrix/vector transpose
$\mathbb{R}^n$	Real vector space of dimension n
$\mathbb{R}^{n\times m}$	Real matrix space of dimension $n \times m$
$\bullet^*$	The optimal value of variable $\bullet$
O	Complexity

Introduction

Combined cooling, heating, and power (CCHP) systems are known as trigeneration systems. They are designed to supply cooling, heating, and electricity simultaneously. The CCHP system has become a hot topic for its high system efficiency, high economic efficiency, and low greenhouse gas (GHG) emissions in recent years. The efficiency of the CCHP system depends on the appropriate system configuration, operation strategy, and facility selection. Due to the inherent and inevitable energy waste of traditional operation strategies, high-efficiency operation strategies are urged. To achieve the highest system efficiency, facilities in the system should be appropriately sized to match with the corresponding operation strategy.

In Chapter 1, the state-of-the-art of CCHP research is surveyed. First, the development and working scheme of the CCHP system is presented. Some analyses of the advantages of this system and a brief introduction to the related components are then given. In the second part of Chapter 1, we elaborately introduce various types of prime movers and thermally activated facilities. Recent research progress on the management, control, system optimization, and facility selection is summarized in the third part. The development of the CCHP system in representative countries and the development barriers are also discussed in Chapter 1.

The operation strategy has a direct impact on the CCHP system performance. To improve the operational performance, in Chapter 2, based on two conventional operation strategies, that is, following electric load (FEL) and following thermal load (FTL), a novel optimal switching operation strategy is proposed. Using this strategy, the whole operating space of the CCHP system is divided into several regions by one to three border surfaces determined by energy requirements and the evaluation criteria (EC). Then the operating point of the CCHP system is located in a corresponding operating mode region to achieve improved EC. The EC simultaneously considers the primary energy consumption, the operational cost, and the carbon dioxide emissions. The proposed strategy can reflect and balance the influences of energy requirements, energy prices, and emissions effectively.

Most of the improved operation strategies in the literature are based on the "balance" plane, matching of the electric demands with the thermal demands. However, in more than 95% energy demand patterns, the demands cannot match with each other on this exact "balance" plane. To continuously use the "balance" concept, in Chapter 3, the system configuration is modified from the one with a single absorption chiller to be the one with hybrid chillers, thus expanding the “balance” plane to a “balance” space by tuning the electric cooling to cool load ratio. With this new “balance” space, an operation strategy is designed and the power generation unit (PGU) capacity is optimized according to the proposed operation strategy to reduce the energy waste and improve the system efficiency. A case study is conducted to verify the feasibility and effectiveness of the proposed operation strategy.

In Chapter 4, a more mathematical approach to scheduling the energy input and power flow is proposed. By using the concept of *energy hub*, the CCHP system is modeled in a matrix form. As a result, the whole CCHP system is an input–output model. Setting the objective function to be a weighted summation of primary energy savings (PES), hourly total cost savings (HTC), and carbon dioxide emissions reductions (CDER), the optimization problem, constrained by equality and inequality constraints, is solved to obtain the optimal operation strategy. The PGU capacity is also sized under the proposed optimal operation strategy. In the case study, compared with FEL and FTL, the proposed optimal operation strategy saves more primary energy and annual total cost, and can be more environmentally friendly.

Most of the current operation strategies are designed by assuming that accurate loads during the next time interval are already known. In Chapter 5, in order to solve the problem of unknown loads in practical applications, by using an AutoRegressive Moving Average with eXogenous inputs (ARMAX) model, whose parameters are identified by a proposed Ordinary Least Squares–Two-Stage Recursive Least Squares (OLS-TSRLS) algorithm, cooling, heating, and electrical loads in the future time intervals are forecasted. The identification procedure uses the dew-point temperature as the instrumental variable (IV) for the exogenous variable (dry-bulb temperature) to better explain the relation between exogenous and endogenous variables. TSRLS at the second stage helps to reduce the time complexity. A post-strategy is also proposed to compensate for the inaccurate forecasting. A case study is conducted to verify the feasibility and effectiveness of the proposed methods.

The electricity to thermal energy output ratio is an important impact factor for the operation strategy and performance of CCHP systems. If the energy requirements of users are managed to just match this ratio, the system efficiency would reach the maximum. However, due to the randomness of users’ demand, this situation is rarely achieved in practice. To solve this problem, a complementary CCHP-organic Rankine cycle (CCHP-ORC) system is configured in Chapter 6. The salient feature of this system is that its electricity to thermal energy output ratio can be adjusted by changing the loads of the electric chiller and the ORC dynamically. For such a system, an optimal operation strategy and a corresponding implemented decision-making process are presented within a wide load range. Case studies are conducted to verify the efficacy of the developed CCHP-ORC system.