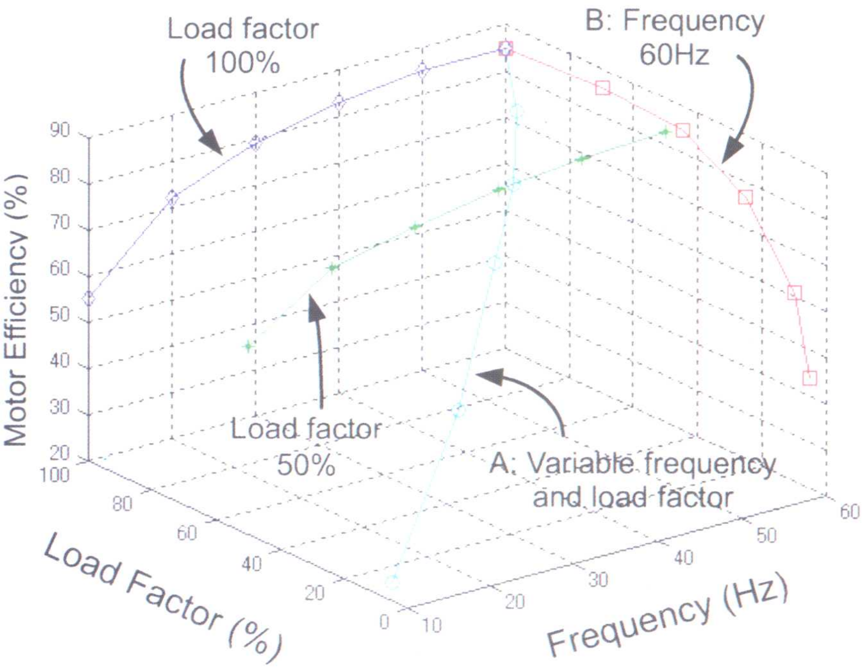
ENSURE ENERGY EFFICIENCY OF HVAC SYSTEMS

by Fulin Wang

NFOC & LCCE



上海科学普及出版社

ENSURE ENERGY EFFICIENCY
OF
HVAC SYSTEMS

by Fulin Wang

上 海 科 学 普 及 出 版 社

图书在版编目（CIP）数据

建筑热空调系统的节能方法/王福林编著. —上海. 上海科学普及出版社，2006. 4

ISBN 7-5427-3219-6

Ⅰ. 建… Ⅱ. 王… Ⅲ. ①建筑—空气调节系统—系统设计②建筑—空气调节系统—运行—管理 Ⅳ. TU831.3

中国版本图书馆CIP数据核字（2005）第136959号

责任编辑　林晓峰

ENSURE ENERGY EFFICIENCY OF HVAC SYSTEMS

by Fulin Wang

上海科学普及出版社出版发行
（上海中山北路832号 邮政编码200070）
http://www.pspsh.com

各地新华书店经销　上海市崇明裕安印刷厂印刷
开本 787 × 1092　1/16　印张 10.5　字数 363000
2006年4月第1版　2006年4月第1次印刷

ISBN 7-5427-3219-6/TK · 4　　定价：28.00元

Introduction to the author

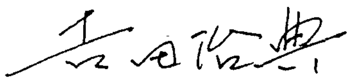
Dr. Fulin Wang was born in Yantai China in 1971. He graduated from Wuhan Urban Construction Institute, now the east campus of Huazhong University of Science and Technology, and obtained the bachelor degree in 1993. After working as a HVAC design engineer in Yantai Design and Research Institute for five years, in 1998 Mr. Wang entered Tsinghua University and studied in the Department of Thermal Engineering under the direction of Professor Yi Jiang, and got his master degree in 2001. Soon after that Mr. Wang went to Japan to study in Professor Harunori Yoshida' s laboratory in Department of Global Environment Engineering, Kyoto University, and received his Ph.D. in 2004. Then he works as an assistant professor in Kyoto University until now.

PREFACE

Energy efficiency is of fundamental importance to the human society because of the limited amount of the fossil fuel reserve on our planet and the great impact on the global environment. For this reason, a lot of research on improving energy efficiency has been launched in many fields. Approximately one third of primary energy is consumed in non-industrial buildings, such as dwellings, offices, hospitals, and schools, where it is used for space heating and cooling, lighting and the operation of appliances. Hence the efficient energy use in building sector is an important issue to be studied.

Our laboratory, the Laboratory of Sustainable Built Environment Engineering, contributes to the research on energy efficiency of buildings since its establishment. During 2001 to 2004, we took part in an internationally cooperated research project Annex 40, which is a research project committed under the International Energy Agency and is focused on commissioning of building Heating, Ventilation and Air-conditioning (HVAC) systems to improve energy performance. Mr. Fulin Wang took part in this research project and used the research results as a part of his doctoral dissertation and received his Ph.D. in 2004.

This book is written on the basis of Fulin' s Ph.D. dissertation, which mainly consists of two parts. The first part discusses how to determine an energy efficient design scheme of buildings' HVAC systems from the view point of life cycle cost,which was carried out in Tsinghua University during his master course. The method ensures an energy efficient HVAC system to be designed from its very beginning. The second part proposes the methodology for automated commissioning of HVAC system for the purpose of ensuring the energy efficiency of HVAC systems during the operational phase,which was conducted in Kyoto University during his Ph.D.course. The method keeps HVAC systems run energy efficiently during the whole life cycle. Besides proposing the methodology to ensure energy efficient HVAC systems, this book also proposed mathematical models of several HVAC components, equipments and subsystems to achieve automated commissioning of HVAC system. An experimental study is also introduced on the feasibility of automating the commissioning process of a Variable Air Volume (VAV) HVAC system. I think this book could be a useful reference to the researchers in the field of building energy and HVAC system.



Harunori Yoshida
Professor at the Dept. of Urban and Environmental Engineering
Faculty of Engineering, Kyoto University, Japan
September, 2005

NOMENCLATURE

Roman symbols

A	Area (m^2)
A_c	Amount of chillers
a	Error of proportional band L_0
a_0, a_1, a_2, a_3, a_4	Fitted coefficients for the equation of C_h-C_f
b	Error of proportional band L_1
C_a	Influence coefficient of HVAC scheme to cost
C_{EV}	Flow rate coefficient of expansion valve
C_f	Dimensionless flow rate
C_h	Dimensionless pressure head
C_o	Influence coefficient of outside air supply scheme to cost
C_p	Specific heat (kJ/kg.k)
C_r	Dimensionless flow resistance
C_s	Influence coefficient of heating and cooling source scheme to cost
C_V	Valve resistance coefficient ($kPa/(kg/s)^2$)
C_{V0}	Valve resistance coefficient when valve is full open ($kPa/(kg/s)^2$)
CL	Total cooling load (kW)
CO_y	The cost in the y^{th} year, CO_0 is the initial investment cost
D	Diameter (m)
E	Energy consumption (kW)
EC	Electric power consumption (kW)
EP	Electric power price
e_0, e_1, e_2, e_3, e_4	Fitted coefficients for the equation of η-C_f
F	Frequency of power line (Hz)
f_0, f_1, f_2, f_3, f_4	Fitted coefficients for the equation of C_f-C_r
G	Bias when dead-band is considered (℃)
GC	Gas consumption (m^3/s)
g	Dead-band of valve control bias (℃)

g_e	Error of dead-band of valve control bias (℃)
g_o	Original dead-band of valve control bias (℃)
H	Heat produced by unit fuel (kJ/kg)
HHV	Higher heat value (kJ/Nm^3)
hr	A building's opening hours
I	Integral control output (%)
IIC	Initial investment cost (RMB, unit of Chinese currency)
INV	Invert output (%)
i	Numbering of equipments
in	Interest
i_0, i_1, i_2, i_3, i_4	Fitted coefficients for the equation of inverter efficiency equation
I_V	Valve capacity index (m^3/h at 1 bar)
K	Coefficient of proportional action (1/℃)
L	Proportional band (℃)
L_0	Proportional band when inverter output is 0 (℃)
L_1	Proportional band when inverter output is 100 (℃)
LE	Length (m)
LF	Load factor
m	Mass flow rate (kg/s)
m_0, m_1, m_2, m_3, m_4	Fitted coefficients for the equation of motor efficiency
n	Life cycle (year)
N	Rotational speed (r/m)
O	Controller output for valve opening (%)
O_V	Valve relative opening
OC	Yearly operational cost (RMB/a)
P	Pressure (Pa)
PE	Price of energy
PF	Price of fuel
PH	Pressure head (Pa)
PI	Proportional-integral control output (%)
PO	Proportional control output (%)

Q	Cooling/heating production (kW)
R	Coefficient of flow resistance ($Pa/(m^3/h)^2$)
r	Ratio
s	Iterative step
T	Temperature (℃)
t	Time (s)
t_o	Original integral time (s)
t_e	Error of integral time (s)
V	Volume flow rate (m^3/h)
v	Velocity (m/s)
W	Weight vector for ADLINE neural network model
W_a	Air humidity ratio (g/kg dry air)
W_f	The weight of valve linear characteristic
X	Input vector for ADLINE neural network model
Z	Bias of supply air temperature to set point (℃)

Greek symbols

α	Learning speed for ADLINE neural network model
Δ	Difference
ε	Error between estimated value and expected value
η	Efficiency
λ	Leakage coefficient (closed flow/open flow at constant pressure)
ξ	Local loss coefficient
ρ	Density (kg/m^3)
τ	Time
ϕ	Relative humidity

Subscripts and superscripts

a	Air
atm	Atmosphere

c	Cooling
cp	Cooling plant
d	Demand valve
dl	Driveline
dp	Dew-point
EV	Expansion valve
f	Fan
ft	Filter
h	Heating
i	Inlet
id	Indoor
inv	Inverter
k	Numbering of training samples
m	Measured value
mo	Motor
max	Maximum value
n	Number
nor	Normal operational data
o	Outlet
OC	Coil etc. other components except filter and fan in the indoor unit of a room air-conditioner
od	Outdoor air
off	Offset operational
r	Rated value
re	Return air
ref	Refrigerant
s	Set point
st	Saturation
su	Summer
t	Total value
ts	Time step

w	Winter
wv	Water vapor
1,2,3,4	State points in a refrigeration cycle, defined in Figure 7.2

Abbreviations

ADLINE	Adaptive linear element
AHU	Air handling unit
BEMS	Building energy management system
CAV	Constant air volume
CMOAR	Constant minimum outside air rate
COP	Coefficient of performance
DeST	Designer' s simulation toolkits
FCU	Fan coil unit
HHV	Higher heat value
HVAC	Heating ventilation and air conditioning
IIC	Initial investment cost
LCC	Life cycle cost
LCCE	Life cycle cost estimation
LMS	Least Mean Square
NFOC	No-fault operation comparison
OC	Operational cost
PI	Proportional and integral
RMB	Unit of Chinese currency
VAV	Variable air volume
VSD	Variable speed drive
VOAR	Variable outside air rate

ABSTRACT

ENSURING ENERGY EFFICIENCY OF HVAC SYSTEMS

Fulin Wang

The most important two aspects for energy efficiency and high performance of buildings' Heating Ventilation and Air-Conditioning (HVAC) systems are the selection of proper HVAC scheme at design phase and the maintenance of proper running of the HVAC system during operational phase.

For the purpose of selecting a proper HVAC scheme, Life Cycle Cost (LCC) is a good criterion to make the decision of HVAC scheme selection at design phase. This book proposes the concept of estimating the Life Cycle Cost of a HVAC system stage-by-stage corresponding to the design progress of the HVAC system, which is gradually specified stage by stage. This book divides the economic estimation of HVAC systems into four stages: beginning of design, conceptual design, preliminary design, and detailed design. The Life Cycle Cost Estimation (LCCE) methods suitable for different design stages are analyzed and proposed. At the beginning of design stage, because there is little information that can be used to estimate the economic character of HVAC systems, neural network models are built to estimate the economic parameters of HVAC systems. At conceptual design stage, different HVAC system scheme are simulated to compare how they satisfy the demand of air conditioning. The simulation results are used to estimate the economic value of the HVAC Schemes. At preliminary design stage, parts of the HVAC systems are simulated and compared and some detailed information about the HVAC equipment can be obtained and used to accurately calculate the costs. The unknown information of the HVAC systems is estimated to calculate their economic values. At detailed design stage, every part of the HVAC systems is simulated. Accurate calculation methods are analyzed according to the detailed design information.

For the operational phase, the on-going commissioning is considered to be the method that can maintain the high performance of a HVAC system. This book proposes an on-going commissioning methodology of No-Fault Operation Comparison (NFOC). The no-fault operation data of a HVAC system can be obtained from simulation or past no-fault operational data records. The data obtained from the simulation using the design conditions represent the no-fault performance. The simulation analysis realizes on-going commissioning through continuously comparing the HVAC sys-

tems real-time operational data with simulated data. This approach suits for the air or water processing components or subsystems, such as fan subsystems, valves, VAV boxes, and coils etc., whose processing results or outputs can be both simulated and measured. Past no-fault operation that are under the almost same heat conditions as current operation can be used to continuously compare with the real-time current operation during operational phase to check whether current operation has faults or not. This approach suits for commissioning components whose simulation models are not suitable for commissioning, such as temperature sensors, air flow rate sensors etc.

The main new points of this book can be summarized as follows:

1) Develops a methodology for determining an optimal HVAC scheme from valid candidates using Life Cycle Cost Estimation at design stages.

2) Gives different economic estimation methods suitable for different design stages corresponding to the characteristics of different design stages: neural network method for the beginning of design and empirical estimations for conceptual design, preliminary design and detailed cost calculation method for detailed design phase.

3) Proposes the No-Fault Operation Comparison methodology for on-going commissioning of HVAC systems during operational phase through comparing real-time operational data with no-fault operational data that are obtained from simulation and past no-fault operational data records.

4) Develops a total energy consumption model of fan subsystems that can estimate the measurement-easy total energy consumption of fan subsystems and is suitable for on-going commissioning.

5) Experimentally studies the on-going commissioning characteristics of a real VAV system. The experimental study reveals the feasibility of automated on-going commissioning of HVAC systems through comparing real time operational data with no-fault operational data obtained from simulation or past no-fault operational data records.

6) Develops a filter resistance estimation model that can estimate filter resistance without pressure sensor only using thermal or energy performance data of air-conditioners and is suitable for on-going commissioning filters in room air-conditioners.

Keywords: HVAC, Design, Life cycle cost, Commissioning, Operation, Energy efficiency

CONTENTS

CONTENTS i
LIST OF TABLES vi
LIST OF FIGURES vii
NOMENCLATURE xi
ABSTRACT xvii
INTRODUCTION 1
0.1 Background 1
0.2 Objectives 2
0.3 Structure 2
0.3.1 Part 1: design phase 2
0.3.2 Part 2: operational phase 3

CHAPTER 1

LIFE CYCLE COST ESTIMATION METHOD FOR HVAC SYSTEMS AT DESIGN PHASE 9
1.1 Concept 9
1.2 Methodology 11

CHAPTER 2

LIFE CYCLE COST ESTIMATION USING NEURAL NETWORK AT BEGINNING OF DESIGN 15
2.1 Introduction 15
2.2 Influence factors 16
2.3 Sensitivity analysis 17
2.3.1 Sensitivity analysis of initial investment cost 17
2.3.2 Sensitivity analysis of operational cost 19
2.4 Cost estimation 19
2.4.1 Selection of neural network model 20
2.4.2 Training of neural network model 22
2.4.3 Estimation using neural network model 31
2.5 Summary 33

CHAPTER 3

LIFE CYCLE COST ESTIMATION FOR THE OTHER THREE DESIGN STAGES 35

3.1 Introduction 35
3.2 Conceptual design stage 35
3.2.1 Influence factors 35
3.2.2 Sensitivity analysis 36
3.2.2.1 Sensitivity analysis of initial investment cost 36
3.2.2.2 Sensitivity analysis of operational cost 37
3.2.3 Cost estimation 39
3.2.3.1 Estimation of initial investment cost 39
3.2.3.2 Estimation of operational cost 39
3.3 Preliminary design stage 40
3.3.1 Cost estimation of terminal systems 40
3.3.1.1 Initial investment cost 40
3.3.1.2 Operational cost 43
3.3.2 Cost estimation of heating/cooling source systems 43
3.3.2.1 Initial investment cost 43
3.3.2.2 Operational cost 45
3.4 Detailed design stage 46
3.4.1 Initial investment cost 46
3.4.2 Operational cost 47
3.5 Summary 47

CHAPTER 4

ON-GOING COMMISSIONING METHODOLOGY FOR OPERATIONAL PHASE 51

4.1 Introduction 51
4.2 Introduction to commissioning 51
4.2.1 Definition of commissioning 51
4.2.2 Historical development of commissioning 53
4.2.3 Current research on building commissioning 54
4.3 On-going commissioning methodology 55
4.3.1 Simulation comparison approach 58

4.3.1.1 Coil 58
4.3.1.2 Valve and damper 59
4.3.1.3 VAV box 63
4.3.1.4 Fan subsystem 63
4.3.2 No-fault operational data comparison approach 66
4.3.2.1 Malfunctioning supply air temperature sensor 67
4.3.2.2 Malfunctioning room air temperature sensor 69
4.4 Summary 71

CHAPTER 5

TOTAL ENERGY CONSUMPTION MODEL OF FAN SUBSYSTEM SUITABLE FOR ON-GOING COMMISSIONING 73

5.1 Introduction 73
5.2 Models 73
5.2.1 Fan efficiency model 77
5.2.2 Driveline efficiency 79
5.2.3 Motor efficiency 79
5.2.4 Inverter efficiency 81
5.3 Model parameters, inputs, and output 82
5.3.1 Parameters 82
5.3.2 Inputs 83
5.3.3 Output 83
5.4 Experimental validation 83
5.4.1 Validation using normal fan subsystem 84
5.4.1.1 Coefficients fitting for fan model 85
5.4.1.2 Coefficients fitting for motor model 87
5.4.1.3 Coefficients fitting for inverter model 88
5.5 Application for automated on-going commissioning 90
5.6 Application case study 91
5.7 Summary 94

CHAPTER 6

EXPERIMENT STUDY ON THE ON-GOING COMMISSIONING OF A REAL VAV SYSTEM 97

6.1 Introduction 97

6.2 Low efficiency fan subsystem 100
6.2.1 Experimental method 100
6.2.2 Results, discussion and conclusions 103
6.3 Malfunctioning supply air and room air temperature sensor 104
6.3.1 Experimental method 104
6.3.2 Results, discussion and conclusions 105
6.4 Stuck AHU outdoor air damper 106
6.4.1 Experimental method 106
6.4.2 Results, discussion and conclusions 106
6.5 Stuck AHU water valve 108
6.5.1 Experimental method 108
6.5.2 Results, discussion and conclusions 108
6.6 Summary 108

CHAPTER 7

MODEL-BASED COMMISSIONING FOR FILTERS IN ROOM AIR-CONDITIONERS 111

7.1 Introduction 111
7.2 Models 113
7.2.1 Estimation using fan energy consumption data 116
7.2.2 Estimation using thermal performance data 116
7.3 Model parameters, inputs, and output 123
7.3.1 Parameters 123
7.3.2 Inputs 123
7.3.3 Output 124
7.4 Model validation 124
7.4.1 Validation results of estimating using fan power consumption data 129
7.4.2 Validation results of estimating using thermal performance data 129
7.5 Model-based commissioning methodology 132
7.6 Summary 133

CHAPTER 8

CONCLUSIONS 135

8.1 Efficiency should be ensured from very beginning using economic estimation method at design phase 135

8.1.1 Neural network method suits for economic estimation at beginning of design 135
8.1.2 Empirical equations suit for economic estimation at other design stages 136
8.2 No-fault operation comparison methodology for operational phase ensures system efficiency during whole life cycle 136
8.2.1 Simulation using suitable models automates on-going commissioning 136
8.2.2 Past no-fault operational data records suits for continuously commissioning sensors 137
8.3 Summary 137
REFERENCES 139