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Decentralized optimization for vapor compression refrigeration cycle

Lei Zhao, Wen-Jian Cai*, Xu-dong Ding, Wei-chung Chang

Centre for E-City, School of Electrical and Electronic Engineering, Nanyang Technological University, BLK S2-B2a-08, Nanyang Ave, Singapore 639798, Singapore

HIGHLIGHTS

► The decentralized optimization problem of VCC is formulated.
► Decentralized optimization technique is modified and applied to the problem.
► Experiments show proposed method energy consumption is close to global optimization.
► Experiments show proposed method is much faster than global optimization.

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ABSTRACT

This paper presents a model based decentralized optimization method for vapor compression refrigeration cycle (VCC). The overall system optimization problem is formulated and separated into minimizing the energy consumption of three interactive individual subsystems subject to the constraints of hybrid model, mechanical limitations, component interactions, environment conditions and cooling load demands. Decentralized optimization method from game theory is modified and applied to VCC optimization to obtain the Perato optimal solution under different working conditions. Simulation and experiment results comparing with traditional on–off control and genetic algorithm are provided to show the satisfactory prediction accuracy and practical energy saving effect of the proposed method. For the working hours, its computation time is steeply reduced to 1% of global optimization algorithm with consuming only 1.05% more energy consumption.

1. Introduction

The refrigeration industry was firstly evolved in response to the pressing need to preserve and transport food for expanding populations. It continued to grow as human comfort and industrial applications demands. Its applications can be divided into four groups: food production and distribution, chemical and industry processes, special application and comfort air conditioning [1]. The energy consumption of refrigeration system is quite large in industry as well as domestic usage. For instance, statistical data shows air conditioner and refrigerator account for 28% of home energy consumption in US [2]. For hot and humid tropical country such as Singapore, this ratio can even rise to over 50% [3]. Among all types of cooling systems, electricity based vapor compression cooling systems are still dominant in the current market. The effort to reduce the energy consumption through system control and optimization in vapor compression refrigeration system is of practical significance due to both energy shortage and global warming concerns [4].

During earlier studies, system optimization was based on experience and intuitive analysis because simple yet reliable model of each component was not established. Stoecker claimed that to increase heat exchanging efficiency so that to achieve higher Coefficient of Performance (COP), superheat and subcool should both be minimized [5]. With the introduction of variable speed drive to the compressor and electronic expansion valve, the energy saving potential of vapor compression cycle (VCC) was further studied, theoretical comparison of various refrigeration capacity control methods in full and part-load conditions shows that both of them are efficient technique for capacity control [6,7]. Optimization scheme for whole system based on components' polynomial models was also investigated, Sanaye et al. assigned cost functions for components and used Lagrange multipliers method to minimize the objective function [8]. Jensen and Skogestad proposed to add an active charger as complementary variable for manipulation and discussed the selection of the controlled variable to improve the system efficiency [9–11]. Larsen et al. proposed a gradient method to find the suboptimal solution for condensing pressure, while keep

* Corresponding author. Tel.: +65 6790 6862; fax: +65 6793 3318.
E-mail address: ewjcai@ntu.edu.sg (W.-J. Cai).

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Nomenclatures

A_v	opening percentage of electronic expansion valve
c	coefficients of hybrid models
d	coefficients of cost functions
f	function
F	frequency of compressor
K	penalty
H	enthalpy
$H_{c,fg}$	enthalpy difference of gas and liquid saturated refrigerant in condenser
$H_{c,r,i}$	condenser inlet refrigerant enthalpy
$H_{c,r,o}$	condenser outlet refrigerant enthalpy
$H_{com,r,i}$	compressor inlet refrigerant enthalpy
$H_{com,r,o}$	compressor outlet refrigerant enthalpy
$H_{e,g}$	enthalpy of saturated refrigerant in evaporator
$H_{e,r,i}$	evaporator inlet refrigerant enthalpy
$H_{e,r,o}$	evaporator outlet refrigerant enthalpy
$H_{i,s}$	compressor outlet refrigerant enthalpy under isentropic compression
H_k	Cholesky factorization of Hessian Matrix of the cost function in step k
M	Cholesky factorization of Hessian Matrix of the cost function
$\dot{m}_{c,air}$	air flow rate of condenser
$\dot{m}_{c,air,max}$	upper bound of air flow rate of condenser
$\dot{m}_{c,air,min}$	lower bound of air flow rate of condenser
$\dot{m}_{c,air,nom}$	nominal air flow rate of condenser
$\dot{m}_{e,air}$	air flow rate of evaporator
$\dot{m}_{e,air,max}$	upper bound of air flow rate of evaporator
$\dot{m}_{e,air,min}$	lower bound of air flow rate of evaporator
$\dot{m}_{e,air,nom}$	nominal air flow rate of evaporator
$\dot{m}_r$	refrigerant mass flow rate
$\dot{m}_{r,max}$	maximal refrigerant mass flow rate
$\dot{m}_{r,min}$	minimal refrigerant mass flow rate
P_c	refrigerant saturated pressure in condenser
$P_{c,max}$	maximal condenser saturated pressure allowed
$P_{c,min}$	minimal condenser saturated pressure allowed
P_e	refrigerant saturated pressure in evaporator
$P_{e,max}$	maximal evaporator saturated pressure allowed
$P_{e,min}$	minimal evaporator saturated pressure allowed
$\dot{Q}_c$	heat transfer rate in condenser
$\dot{Q}_e$	heat transfer rate in evaporator
$\dot{Q}_{com}$	heat transfer rate in compressor
$\dot{Q}_{req}$	cooling load requirement
$T_{c,air,i}$	condenser inlet air temperature
$T_{c,max}$	maximal refrigerant saturation temperature in condenser
$T_{c,min}$	minimum refrigerant saturation temperature in condenser
$T_{c,r,i}$	condenser inlet refrigerant temperature
$T_{c,r,o}$	condenser outlet refrigerant temperature
$T_{c,sc}$	condenser subcool temperature
$T_{c,r,sat}$	condenser refrigerant saturated temperature
$T_{com,r,i}$	compressor inlet refrigerant temperature
$T_{com,r,o}$	compressor outlet refrigerant temperature
$T_{e,air,i}$	evaporator inlet air temperature
$T_{e,r,i}$	evaporator refrigerant inlet temperature
$T_{e,r,o}$	evaporator refrigerant outlet temperature
$T_{e,r,sat}$	refrigerant saturated temperature in evaporator
$T_{e,max}$	maximal refrigerant saturation temperature in evaporator
$T_{e,min}$	minimal refrigerant saturation temperature in evaporator
$T_{e,sh}$	evaporator superheat temperature
$T_{e,max}$	upper bound of superheat
$T_{e,min}$	lower bound of superheat
$\dot{W}_{c,fan}$	condenser fan power
$\dot{W}_{c,fan,nom}$	condenser fan power when air flow rate is $m_{c,air,nom}$
$\dot{W}_{com}$	electricity power consumption of compressor
$\dot{W}_{c,fan}$	evaporator fan power
$\dot{W}_{e,fan,nom}$	evaporator fan power when air flow rate is $m_{e,air,nom}$
$\dot{W}_{total}$	total power
x	state vector of subsystem
η_{com}	enthalpy delivery efficiency of compressor
ρ	inlet refrigerant density
β	coefficients of energy consumption terms
γ	updating coefficient of β

Subscripts

air	feature of air
c	condenser
com	compressor
e	evaporator
ev	expansion valve
fan	evaporator or condenser fan
i	inlet
k	number of current cycle
m	mass flow rate
r	refrigerant
o	outlet
η	enthalpy delivery efficiency

the superheat and evaporating pressure constant [12]. Recently, Barreira et al. optimized the split type residential air conditioner based on thermoeconomic analysis [13]. Zhou et al. employed theoretical model of air conditioning cycle components, formulated and solved a multi-objective optimization problem for high heat flux removal [14].

Unfortunately, few research papers have been published through the view of systematic optimization of VCC, because components of vapor compression refrigeration cycle are severely interacted, these interactions complicate the optimization problem as well as the solving procedures. The optimization problem discussed in similar system (HVAC) includes the work of Kusiak et al. They proposed series of data driven system optimization techniques for commercial HVAC systems. Simulation results based on experiment conducted showed that system level optimization can improve overall system operating performance significantly [15–17]. Fong et al. utilized robust evolutionary method to obtain appropriate energy management measure for HVAC system [18]. Ning proposed a neural network based optimal supervisory operation strategy to find the optimal set points [19]. To minimize HVAC system energy consumption, Yao et al. developed a global optimization model based on decomposition–coordination algorithm [20].

Although these methods have been proved effective, the computation burden of the existed algorithm based on centralized formulation is too large for online optimization. The convergence time, though can be neglected in academic research, is an important factor in practice. Recently, a relatively novel optimization method called decentralized optimization has been proposed in Refs. [21,22] by Inalhan. In the decentralized optimization algorithm, the original problem can be separated into several subsystem optimizations with constraints updating. It has been