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Evaluation of operation and control in HVAC (heating, ventilation and air conditioning) system using exergy analysis method

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ABSTRACT

The optimal control strategy proposed for HVAC (heating, ventilation and air conditioning) systems was usually compared with the original one, in which the disparity with perfect operation was seldom discussed. Based on the exergy analysis models developed, this paper presents a *CPI* (control-perfect index) method to evaluate control of HVAC systems as well as obtain the disparity of candidate strategy with ideal operation. Through minimizing the exergy loss in HVAC system, the limited-ideal operation corresponding to specific operation condition is obtained. With DEA (data envelopment analysis) method, the optimization frontier is trended by sets of limited-ideal operation points and viewed as ideal operation. With the benchmark of ideal operation, the *CPI* scores of various control strategies can be evaluated. An airport HVAC system is selected as a case study and its simulation is validated using the real operation data. Six control strategies used in the HVAC system are evaluated. The results show that the original strategy has the lowest efficiency. Other five optimal strategies have the higher efficiencies because of their higher *CPI* scores. The disparity of each strategy with ideal operation is also estimated, which points to the inherent challenge of developing global optimal algorithm.

1. Introduction

For the higher energy efficiency, the optimal control strategies have been developed in HVAC (heating, ventilation and air conditioning) systems. From the component control to system-level optimization, the control strategies have been designed better and better. IEA (International Energy Agency) conducted the systematic research of simulation and optimization for building and HVAC systems in 1990s [1]. Then the studies on optimal control and management for buildings became more active. More detailed optimal control strategies have been developed for building and HVAC systems. Zaheer-Uddin [2] presented the optimal control strategies for the time-scheduled operation of an HVAC system. Braun [3] developed a near-optimal method for the cooling storage system with the real time pricing. Ma and Wang [4] presented several optimal strategies applied in a high-rise building, which saved more energy compared with the original strategy used in real system. Nassif [5] used the genetic algorithm to optimize the supply chilled water temperature, supply air temperature and supply air static pressure in a VAV (variable air volume) system. Sun and Reddy [6] presented a CSB-SQP (complete simulation-based sequential quadratic programming) method to optimize the operation and control of building HVAC systems. Dodier and Henze [7] developed general nonlinear regression models using ANN (artificial neural network) for HVAC systems. To evaluate the optimal control strategies proposed, the widely used method is to compare the energy consumption of optimal strategy with that of original one.

Recently, assessing the operation performance for HVAC system is becoming an attractive topic. Engwerda [8] evaluated different optimal strategies applied in an existing HVAC system at a school campus, in which the energy consumptions of different solutions were compared. Henze [9] evaluated the reinforcement learning control strategy that can find the optimal solutions for the control problem in a thermal energy storage system. Ardehali [10] analyzed the operation performance of HVAC system under various control strategies. The energy management and control system was believed to be an efficient analysis tool for improving the system operation level. Holder [11] presented an evaluation method for HVAC system based on the energy consumption analysis. The operation performances of components were evaluated firstly and then they were combined to assess the system operation. Lee [12] employed the simplified energy analysis procedure to evaluate

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Nomenclature

CPI	control-perfect index
IPI	improving potential index
E	exergy
EL	exergy loss
T	temperature (°C)
PLR	part load ratio
LR	cooling load ratio
Q	cooling capacity (kW)
W	power (kW)
m	mass flow rate (kg/s)
OS	operation status
a_0–a_2	coefficient
R^2	coefficients of determination
DMU	decision making unit
COP	coefficient of performance
AHU	air handling unit
HVAC	heating, ventilation and air conditioning
CS1–CS6	control strategy 1–6

Greek symbols

$\eta_{overall}$	overall efficiency
η_{tech}	technical efficiency
η_{scale}	scale efficiency

Subscripts

LI	limited-ideal operation
Act	actual operation
sys	system
I	subsystem of cooling tower
II–V	subsystem of chiller 1–4
VI	subsystem of air handling units
CT	cooling tower
CH	chiller
OD	outdoor
ID	indoor
out	outlet
db	dry-bulb
wb	wet-bulb
chw	chilled water
SA	supply air
OA	outdoor air

the fault level that can represent operation situation of HVAC system. Calvino [13] compared the energy consumption under various thermal comfort control strategies. The evaluation logic aimed to optimize energy consumption and thermal comfort properly. Roulet [14] employed the ELECTRE method to evaluate the energy consumption and indoor air quality for HVAC system. Blondeau [15] compared the various ventilation strategies for the HVAC system. Pantelic [16] presented the RR-PARETO2 method to assess the design and operation of HVAC system, which concerned the energy consumption, thermal comfort, indoor air healthy index and AHU (air handling unit) heat transfer efficiency.

As a concept that stems from both the first and second law of thermodynamics, exergy is more suitable to be used as the evaluating parameter for HVAC systems. Actually, exergy analysis that provides an effective tool to improve the energy use has been widely used in the buildings [17]. IEA projected on the exergy conservation in buildings with the achievements of Annex 37 [18] and Annex 49 [19]. In these studies, the low exergy systems for building and HVAC systems were investigated and some examples of best practice buildings were provided. Utlu [20] evaluated the exergy consumption in the Turkish residential and commercial buildings. Similar studies on the exergy consumption in the residential and commercial buildings were also illustrated by Kondo [21] and Xydis [22]. In addition, there were some investigations about the exergy optimization for HVAC systems [23,24], which focused on the whole thermal generation chain and its exergy efficiency. Reducing exergy losses in the buildings usually means to use energy in a more rational way. Consequently, exergy analysis can be used as a tool to evaluate the optimal control strategies proposed in HVAC systems.

As to the evaluation of optimal control strategies in HVAC systems, generally, there are still some aspects that need to be further investigated. Firstly, the selection of comparison benchmark needs to be discussed. The original mediocre strategy used in buildings, which was usually selected as the evaluating benchmark, is hard to rank various optimal strategies completely but simply show their energy saving ratios. Actually, it is difficult to unify the scoring criteria for the HVAC systems using randomly selected comparison benchmarks. In addition, it is not known the disparity of proposed control strategy with the system ideal operation. It is necessary to find out the “perfect operation” as an impartial benchmark so as to assess the improving potential of candidate strategy.

In this paper, an evaluation method based on exergy analysis is presented to assess the operation and control of HVAC system. The exergy is used as a characteristic variable in the evaluating process. The *CPI* (control-perfect index) is presented as the ranking factor for the HVAC system. Ideal operation level of HVAC system is obtained using the DEA (data envelopment analysis) method. The *CPI* scores and improving potentials of six control strategies are evaluated in an airport HVAC system.

2. Evaluation methodology for the HVAC system

2.1. Exergy analysis models for HVAC system

For the HVAC system, the exergy balance can be expressed as equation (1).

$$F_i = \xi(x_i, P_i) \tag{1}$$

where x_i is the internal variables of component *i*. F_i is the fuel entering into the *i*th component, P_i is its product.

The unit exergy consumption coefficient k_i can be denoted as

$$F_i = k_i \cdot P_i \tag{2}$$

Consequently, the exergy balance in the cooling towers can be expressed as equations (3) and (4).

$$E^{CD}_{out,i} - E^{CD}_{in,i} = m_{CD,i} \cdot \left[\left(h^{CD}_{out,i} - h^{CD}_{in,i} \right) - T_0 \left(s^{CD}_{out,i} - s^{CD}_{in,i} \right) \right] \tag{3}$$

$$E_{CT} = \sum_{i=1}^{5} \tilde{m}_{CD,i} \cdot \left(e^{Che} - e^{Phy} \right) \tag{4}$$

where the superscript *CD* means the condenser of chiller. The subscripts *in* and *out* refer to the inlet and outlet. *E*, *h* and *s* represent the exergy, enthalpy and entropy. $m_{CD,i}$ means the flow