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A direct optimal control strategy of variable speed pumps in heat exchanger networks and experimental validations

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ABSTRACT

Energy conservation of HENs (heat exchanger networks) has been attaching more and more attentions with all kinds of methods for operation optimization. Several methods optimize the temperature and/or pressure differential set points for HENs, but cannot control the components directly, which has to seek the help of some control strategies. This paper introduces a direct optimal control strategy of VSPs (variable speed pumps) based on the newly proposed thermal resistance-based optimization method together with the physical models of each component in HENs, which can directly calculate the optimal rotation frequencies of each VSP for optimal operation. To illustrate this method, a series of experiments are performed with a VWV (variable water volume) HEN, including a group of experiments to determine the characteristic parameters in the physical models of each component, and the others to test the HEN performances with the optimal operating parameters and other alternative ones. The results show that the newly proposed direct control strategy can directly get the optimal rotation frequencies of each VSP with the least total power consumption under specific system requirements and constraints. On this basis, for different system requirements, different operating frequencies of VSPs are optimized to demonstrate the universality of the direct optimal control strategy.

1. Introduction

HENs (heat exchanger networks) perform significant roles in many engineering fields, such as power plants, chemical industries, and spacecraft thermal control systems. Optimization of HENs is of great significance to energy conservation and has attracted more and more attentions, where many excellent optimization models [1–6] have been developed ranging from single parameter to multiple parameters methods. Single parameter methods contribute to the industry applications extensively by analyzing the system performances with only a single parameter [7–10], ignoring some other secondary factors. For instance, Kaya [7] analyzed and optimized the capability of a chiller with the chilled water temperature, Thielman [8] offered an energy management control system with the condenser water temperature, Wang et al. [9] proposed a pressure set point control method for an indirect water-cooled chilling system, and Lu et al. [10] raised a optimization method for a HVAC (heat, ventilation and air condition) system with the duct differential pressure set point. On the other hand, in order to obtain a higher energy efficiency by considering the system with more detail factors, researchers propose some multi parameters optimization methods [4,5,11–14]. For example, the combination of the set points of supply air temperature and static pressure in an air handling unit benefits the energy conservation of the corresponding HVAC system [4]. The control strategy integrated with the chilled water temperature and the secondary pump head helps the optimization of a central VWV (variable water volume) chiller system [14]. These models and methods have been made great contributions to energy conservation of HENs. Here, it is worth noting that most optimized variables in these methods are temperatures [7,8,14–16] and pressure differentials [9,14,15,17] in some part of the system, such as the chilled water temperature [7,14,16], the condenser water temperature [8], the discharge air temperature [15], the pressure differential of secondary pump [14,17], the fan static pressure [15], and the pressure drop through the heat exchanger [9].

However, the direct control parameters in a HEN are the rotation frequencies of pumps, fans and compressors and/or the opening of valves, rather than the set points of temperatures and pressure differentials. Therefore, with these optimal set points, it is

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Nomenclatures

A	area, m^2
a	characteristic parameter of VSP
b	dynamic coefficient of head loss
c_p	specific heat at constant pressure, J/(kg K)
d	diameter, m
f	Darcy friction-factor
H	head loss, m
h	installation height, m
h_f	Moody-type friction loss, m
h_m	minor loss, m
K	minor loss coefficient
k	heat transfer coefficient, W/(m^2 K)
L	length, m
m	mass flow rate, kg/s
P	energy consumption, W
Q	heat transfer rate, W
R	thermal resistance, K/W; uncertainty function
R^2	coefficient of determination
S	cross-sectional areas of the pipe, m^2
T	temperature, K
t	temperature, K
V	volume flow rate, L/min
v	fluid velocity, m/s
w	uncertainty
x	independent parameter
α, β, γ	Lagrange multipliers
δ	deviation
ξ	heat exchanger effectiveness
Π	Lagrange function
ρ	density, kg/m^3
ω	rotation frequency, Hz

Subscripts

c	cold fluid
cal	calculated value
d	dynamic
e	evaporator
exp	experiment value
fit	fitted value
h	hot fluid
hx	heat exchanger
i	inlet
m	mixing process
max	maximum
min	minimum
o	outlet
p	pressure differential
r	refrigerant
ref	the referenced value for calculation
s	static head
T	temperature
t	total
V	volume flow rate
w	water

unavoidable to control the corresponding components by seeking the help of some control strategies, such as the PID (proportion, integration, and differentiation) controllers [10,14,18], the DDC (direct digital control) strategies [19], the online control strategies [20], and the feedback [21] or self-turning control strategies [22,23].

The aforementioned methods with the optimal set points and the control strategies divide the optimization into two sequential steps virtually. One is to get the optimal set points to satisfy the requirements, and the other is to achieve these set points by regulating the running components and/or the valves through some control strategies. However, these two sequential steps separate the influences of the pumps and pipelines characteristics out of the global system performance, and consequently narrow down the range of the optimization results artificially. What's more, the control strategies require more or less setting time [24,25]. The set points are only controlled close to but not indeed the optimal values, and incessantly varied within a range, which is influenced by the controller [26,27].

In order to directly obtain the optimal control parameters for each operating component, Chen et al. [28] provide a thermal resistance-based method for HEN optimization, which links the operating parameters, i.e. the rotation frequencies of VSPs (variable speed pumps), directly to the requirements, such as the required heat transfer rate and the surrounding temperature, and the performance of each component, including the heat exchanger thermal conductances, the pump characteristics, and the pipeline characteristics.

In order to avoid the inconveniency of the control strategies with intermediate parameters, this contribution provides a general approach to obtain the optimal direct control parameters for global optimization of HENs. On this basis, a simple VWV system is optimal controlled to illustrate the applications and validate the approach experimentally. Based on the physical models of heat exchangers, VSPs (variable speed pumps), and pipelines, we first fit the thermal conductances of heat exchangers and the characteristic parameters of VSPs and pipelines in a VWV HEN by a series of experiments. With these fitted physical models, utilization of the thermal resistance-based optimization method directly offers different optimal rotation frequencies of each VSP under different operating conditions. Experimental measurements of the HEN performance illustrate that the optimized VSP rotation frequencies indeed lead to the lowest total energy consumptions of the HEN under different operating conditions.

2. Experiment facilities and measurement instruments

Fig. 1 is the sketch of an experimental VWV HEN, consisting of two counter-flow plate heat exchangers, three VSPs, three MV (magnetic valves), a thermostatic hot water tank, a chiller, and pipelines wrapped up with thermal insulating materials. The working fluids in Loop 1 and 3 are water, and that in Loop 2 is a refrigerant R142b. The VSPs drive the working fluids to circulate in each loop, transferring heat in the thermostatic hot water tank through Heat exchanger 1, Heat exchanger 2, finally to the evaporator of the chiller.

Three turbine VFM (volume flow-meters) with an accuracy ±0.5% of the full scale 20 L/min are utilized to measure the fluid flow rates in three loops. Three DPT (differential pressure transducers) with an accuracy ±0.2% of the full scale 350 kPa are employed to measure the pressure differentials of each VSP. A PG (pressure gauge) with the full scale 1.8 Mpa is equipped in Loop 2 to monitor the refrigerant absolute pressure. T type copper-constantan thermocouples (Produced by Omega Engineering) with an accuracy ±0.2 °C serve to test the working fluid temperatures in each measurement points shown in Fig. 1, where two