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Energy-efficient HVAC systems: Simulation–empirical modelling and gradient optimization

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ABSTRACT

This paper addresses the energy saving problem of air-cooled central cooling plant systems using the model-based gradient projection optimization method. Theoretical–empirical system models including mechanistic relations between components are developed for operating variables of the system. Experimental data are collected to model an actual air-cooled mini chiller equipped with a ducted fan-coil unit of an office building located in hot and dry climate conditions. Both inputs and outputs are known and measured from field monitoring in one summer month. The development and algorithm resulting from the gradient projection, implemented on a transient simulation software package, are incorporated to solve the minimization problem of energy consumption and predict the system's optimal set-points under transient conditions. The chilled water temperature, supply air temperature and refrigerant mass flow rate are calculated based on the cooling load and ambient dry-bulb temperature profiles by using the proposed approach. The integrated simulation tool is validated by using a wide range of experimentally collected data from the chiller in operation. Simulation results are provided to show possibility of significant energy savings and comfort enhancement using the proposed strategy.

1. Introduction

As the energy needs of the world are growing with the increasing population, researchers have made great efforts to lead to energy-efficient processes and preserve the environment. About half of the total energy consumption of our modern society is consumed in buildings, in which a major proportion is for heating, ventilating and air-conditioning (HVAC). Therefore, much research has focused on energy savings in HVAC systems. Among their several types, the air-cooled chillers are responsible for 60% of the electricity used for air-conditioning which can amount to 25–40% of the total electricity consumption of an air-conditioned building [1]. Furthermore, air-cooled chillers together with their air handling units remain a popular choice for industrial and commercial air conditioning due to their easy installation, simplicity of operation and lower maintenance costs compared to water-cooled chillers. Therefore, energy efficiency improvements for these chillers can significantly reduce buildings' power consumption.

The field of energy control of central cooling plants to enhance system performance and efficiency has recently attracted much research attention [2–5]. Apart from efforts devoted to the development of eco-friendly and energy-efficient HVAC technologies using renewable energy sources such as solar energy [6–8], several studies have highlighted the potential impact of optimisation on energy and comfort of HVAC systems. Congradac and Kulic [9] described the use of genetic algorithms for optimal operation of HVAC systems. A simulation was conducted to demonstrate how much power can be saved via the suggested method. Wemhoff [10] applied a novel control method using multi-dimensional interpolation of optimised control configurations for various load distributions. The results showed the method was able to save energy by 19% as compared to an uncontrolled system. Zaheeruddin and Ning [11] developed a neural network based optimization algorithm to find the optimal set-points for a variable air volume HVAC system. Their results showed that an optimal operation strategy could offer a remarkable energy savings under partial load conditions. Ma and Wang [12] presented a model-based supervisory and optimal control strategy for central chiller plants to enhance the system performance and energy efficiency with 0.73–2.25% of daily energy savings via a reference using traditional settings. Recently, Beghi and Cecchinato [13] have designed an adaptive controller for a packaged air-cooled water chiller, using the quasi steady-state and a moving boundary model for the chiller dynamics to evaluate the effect of energy losses during the system operation time. Their algorithm could grant 3–7.3% improvement in energy savings with respect to supply water temperature control. All these studies primarily demonstrated their energy saving potential in HVAC systems associated with the use of control techniques. On the other hand, operational optimization of HVAC system components taking into account human comfort has attracted less attention, while it represents directly investments required to ensure that the system installed in buildings are operating in an optimal mode.

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Nomenclature

A	orifice area (m^2)
AU	overall heat transfer coefficient of evaporator (kW/°C)
C	mass flow coefficient
C_p	constant pressure specific heat (kJ/(kg °C))
d_i	expansion valve inlet diameter (m)
D	orifice diameter (m)
k	compression index
l	cooling coil length (m)
LMTD	logarithmic mean temperature difference (°C)
M_{ccw}	cooling coil water mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	compressor speed (rad/s)
P_{cf}	variable air volume fan power consumption of the condenser (kW)
P_{comp}	compressor power consumption (kW)
p_{dis}	discharge pressure (kPa)
P_{fcu}	variable air volume fan power consumption of the ducted fan-coil unit (kW)
p_i	upstream pressure of the expansion valve (kPa)
p_o	downstream pressure of the expansion valve (kPa)
p_{suc}	suction pressure (kPa)
P_{total}	total power consumption of central cooling plant (kW)
Q	heat capacity (kW)
Q_b	building cooling load (kW)
r	radius of the rotor (m)
s_c	stork of the cylinder (m)
T	temperature (°C)
v	velocity (m/s)
$\dot{V}_{comp}$	refrigerant flow rate of the compressor (m^3/s)
$\dot{V}_{con}$	air-cooled condenser air flow rate (m^3/s)
$\dot{V}_{sup}$	Cooling coil air volume (m^3)
w_{comp}	indicated work input to compressor(kJ/kg)
$w_{comp,t}$	isentropic work input to compressor(kJ/kg)
φ	overall displacement coefficient of the compressor
ε	relative eccentricity of the rotor
μ_r	refrigerant dynamic viscosity (Pa.s)
ρ	density (kg/m^3)
σ_i	surface tension (N/m)
η_{comp}	total efficiency of the compressor

Subscripts

a	air
cc	cooling coil
chw	chilled-water
con	condenser, condensing
db	dry-bulb
eva	evaporator, evaporative
i	inlet
o	outlet
r	refrigerant
ret	return
sup	supply
w	water

More importantly, reports on practical optimal control strategies for chilled water systems seem to be still sparse in the literature.

The objective of this research is to obtain valid models for operational components of central cooling plant HVAC systems, to develop an optimal strategy for their control variables for minimizing the energy consumption while satisfying comfort conditions, and to evaluate the implementation of the developed algorithm on a real-world office building. Here, a physical–empirical approach is used to obtain the system models, from which the proposed optimal control strategy is formulated. The system's control variables are continuously updated online by using the gradient projection method to search for global and local minima. A numerical algorithm is then developed to obtain optimal settings from the minimization of an objective function. Furthermore, energy efficiency and performance of the proposed strategy are verified and evaluated with data collected from an actual air-cooled chiller, installed in a building as a case study. In order to quantify and determine optimal control variables of the cooling plant, several field tests were conducted. A linear constraint, formulated by using experimentally collected data and empirically based regression, is incorporated to impose the required range limits for the control variables. To deal with complexity of the heat transfer process, building-dependency of the HVAC system, and the increased cumbersome computation, a transient simulation software package [14], is used to predict the HVAC system performance under optimizing control variable set-points in the presence of transient loads. The cooling plant models, experimental data and proposed optimization algorithm are coded and implemented within the TRNSYS-16 environment so that dynamic predictions of all main equipment in the whole system can be performed simultaneously. To show effectiveness of the proposed control strategy, a predicted mean vote (PMV) index is computed for the building under investigation. The results obtained show a significant energy saving potential when using the proposed approach while maintaining the building indoor comfort conditions. As of a generic nature, this optimization technique can be applied to any central cooling plant.

The paper is organized as follows. After the introduction, Section 2 describes the mathematical models using the proposed simulation–empirical modelling approach. Section 3 presents the formulation of the gradient projection method of the HVAC system together with its optimization algorithm. The set-up and uncertainty analysis are described in Section 4. The results and discussion are included in Section 5. Finally, a conclusion is drawn in Section 6.

2. Mathematical models

The schematic of the central cooling plant is shown in Fig. 1(a) while the log pressure–enthalpy (p–h) diagram for the air-cooled chiller using the R134a refrigerant in steady-state conditions is shown in Fig. 1(b). The system comprises an air-cooled scroll chiller, a ducted fan-coil as the air-handling unit, chilled water pumps, valves and connection tubes. Efficiency of vapour compression chillers depends strongly on the system variable set-points. Furthermore, nonlinearity and complexity inherently existing in the dynamic process of a central cooling plant make it difficult to be represented accurately by using only thermodynamic and heat transfer models. Fortunately, these models can be developed empirically from the experimental monitored data for application in optimal operations of the system in consideration. Adopting the method reported in [15], this section presents the physical–empirical models for the system components by using real-world data experimentally collected. These models then are implemented in the simulation tool TRNSYS-16 to extract the right system dynamics and examine the optimization approach, taking the advantage of the versatile software, wherein heat transfer and thermodynamic laws are incorporated for reliable transient analysis.

2.1. Air-cooled chiller

Many models for chillers have been developed using various principles, see [16–18]. To target the system's energy efficiency, our objective is to predict the air-cooled scroll chiller's power consumption in relation to the supply chilled water temperature and the refrigerant mass flow rate, while its thermodynamic transient performance is analysed by