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A transient model for the thermal inertia of chilled-water systems during demand response

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ABSTRACT

Demand response (DR) of air-conditioning systems is important to shift or reduce the peak electricity demand of commercial buildings by shift or reduce the cooling load. Popular DR strategies of air-conditioning systems include zonal temperature reset and direct control of the main equipment. Many DR studies have been conducted on the thermal inertia of buildings for temperature resetting, but there are few studies on the thermal inertia of air-conditioning systems, which is relatively small but not negligible. In this paper, the thermal inertia of air-conditioning systems is defined as the character that causes the variation of the supply cooling capacity to zones lagging behind the variation of the cooling capacity from plants after DR strategies are implemented. This paper develops an inertia model of chilled-water systems with three sub-models, including chiller model, chilled-water pipe model and cooling coil model. The model describes the dynamic process from the cooling plant to terminal units when DR strategies on chillers are implemented. A new parameter $Q(t)$ named the "refrigerant cooling capacity" is introduced in this study to simplify the thermal inertia model. The $Q(t)$ patterns during the dynamic processes of two series of common chiller-side control strategies (On/Off control and resetting the chilled-water temperature) are obtained and validated using experiments and field tests. In the end, the entire transient model of air-conditioning systems is validated using experiments.

1. Introduction

Global building energy consumption has steadily increased [1]. The building sector represents over 40% of worldwide primary energy consumption [2]. The growth in energy use for heating, ventilation and air conditioning (HVAC) systems is particularly significant [3]. The energy consumed by electric air-conditioning is 30–50% of the total electric energy consumed during summer in many cities worldwide. This proportion even exceeds 50% in some commercially dense and developed cities [4]. In addition to the accumulated energy use, buildings, particularly commercial buildings, tend to simultaneously have high electricity demand under heat waves, which causes significant peak demand exertion on the grid [5]. Particularly, in extreme weather, the peak load caused by air-conditioning systems can jeopardize the grid. Recently, the demand response (DR), which is a technology that is used to flatten the peak, has become a popular solution in both the US and European electricity markets [6,7]. The DR can be defined as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."[8]

Feasible DR strategies for heating, ventilation and air-conditioning (HVAC) systems were summarized by Motegi et al. [9]. The literature indicates that HVAC-based DR strategies for a given facility are subjected to the type and condition of the building, mechanical equipment, and energy management and control systems (EMCS). Three commonly used DR strategies focus on different parts of the building and systems. They include zone temperature control, air distribution control, central-plant control strategies, and so on. Among these strategies, many researchers [10–18] have focused on the study of zone control strategies, i.e., temperature adjustment and passive thermal mass storage. In 2002, Braun et al. [10] conducted a simple temperature reset control strategy to validate the feasibility of using the thermal inertia of a building to shift the peak load of the air-conditioning system. Xu [12] studied the potential of pre-cooling and demand limiting by adjusting the zone temperature set points in heavy-mass and light-mass buildings of California and demonstrated that the strategy significantly

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Nomenclature

A	Heat transfer area, m^2
c	Specific heat, $J/(kg\cdot{}^\circ C)$
h	Enthalpy, J/kg
m	Total mass, kg
NTU	Number of heat transfer unit
n_x	Constant
R	Heat resistant, $^\circ C/W$
T	Temperature, $^\circ C$
α	Coefficient of convention heat transfer, $W/\left(m^2\cdot{}^\circ C\right)$
α'	Coefficient of convention heat transfer under dehumidification, $W/\left(m^2\cdot{}^\circ C\right)$
ε	Heat transfer effectiveness
η	the overall fin efficiency for heat transfer only
η'	the overall fin efficiency for both air-side heat and mass transfer
λ	Thermal conductivity, $W/\left(m^2\cdot{}^\circ C\right)$
C_x	Constant
d	Hydraulic diameter, m
$\dot{M}$	Mass flow rate, kg/s
N	Arbitrary number of control volumes for coil
Nu	Nusselt number
Q	Cooling capacity, W
Re	Reynolds number
t	Time, s

Superscript

ch	Chiller
co	Coil
pi	Pipe

Subscript

a	Air
c	Coil material
e	Evaporator material
in	Inlet
ins	Insulation material
out	Outlet
p	Pipe
r	Refrigerant
s	Saturation
tot	Total
w	Water

reduced the cooling load in both light- and heavy-mass buildings. Lee and Braun [14–16] developed a simple approach to estimate the building zone temperature setpoint variations to minimize the peak cooling demands.

However, the EMCS is required to support the global reset of zone temperatures to implement demand-shifting strategies based on zone temperature reset. Therefore, temperature adjustment is not a universal strategy. When EMCS does not support the global reset of zone temperatures, central-plant control strategies can be used, such as resetting the supply chilled-water temperature or shutting down some chillers [13]. The DR controls in previous temperature adjustment studies have inherent and significant delays [19]. Xue et al. [19] proposed a fast DR control strategy for commercial buildings from the chiller plant side. Keeney and Braun [20] developed and tested a control strategy for an office building to limit the peak cooling load and continue building operation if one of the four central chiller units was shut down. Through a survey of large commercial buildings, Song et al. [21] noted that most occupants did not feel the interruption of the cooling supply when the air-conditioning system shut down for 10–20 min per hour. It is observed that central-plant control strategies can effectively shift or reduce the peak load of air-conditioning systems.

An air-conditioning system can shift or reduce the peak cooling load without affecting the thermal comfort of occupants by using the thermal inertia of the building [22]. Most studies focused on developing an accuracy model of the building thermal inertia while simplified or ignored the dynamic character and thermal inertia of the air-conditioning system. However, plant-side control strategies, such as shut off the chillers, and increase the chilled-water temperature, which also take advantage of the thermal inertia character of the air-conditioning system. This inertia delays the temperature increase of the chilled water and keeps supplying cooling to zones. In this study, this character is called the “thermal inertia of air-conditioning system”, which is defined as the character that causes the variation of the supply cooling capacity to zones lagging behind the variation of the cooling capacity from plants.

Different from the existing studies on DR of the air conditioning system, this paper focuses more on the control strategies of the chiller side, concerning the thermal inertia of the air conditioning system during DR events. This study is intended to provide a thermal inertia model of the air conditioning system, combining the theoretical and experimental methods, so as to predict the dynamic variation of the cooling capacity after DR control strategies are implemented.

This paper is organized as follows: Section 2 reviews the related literatures about dynamic model air-conditioning systems, and reviews the models of the chilled water side in detail, including chiller, cooling coil and chilled-water pipe; section 3 develops the thermal inertia model of the air-conditioning system; and section 4 validates the models using experiments. Discussions and conclusions are provided in sections 5.

2. Dynamic air-conditioning system model review

Dynamic models of air-conditioning systems can be valuable tools to predict system behavior during the start-up, feedback control and shutdown [23].

Pengfei Li et al. [24,25] have reviewed the previous work on HVAC equipment modeling comprehensively, including vapor compression cycles, air-handling units, major types of chillers, cooling tower, heating systems, and renewable-energy driven systems. Shengwei Wang [26] presented a traditional component-based dynamic model to simulate the thermal, hydraulic, environmental and mechanic characteristics and energy performance of a building and VAV air-conditioning system. Chen Wu et al. [27] developed a simplified lumped parameter dynamic model for a triple evaporator air conditioner. Bourhan Tashtoush et al. [28] described a dynamic model of an HVAC system including a zone, heating coil, cooling and dehumidifying coil, humidifier, ductwork, fan, and mixing box. Mossolly et al. [29] presented a space and equipment mathematical model consisting of models for air handling unit of the HVAC system to predict energy consumption of various components in response to optimized set points of the selected control strategy. Glenn Platt [30] developed a mathematical model of the HVAC system based on physical principles and circuit theory.

The dynamic models appeared in the above literature are formulated from physical fundamentals such as mass continuity, energy conservation and heat transfer laws by using a lumped-parameter model and physical relations, which are called physical-based models or white-box models [31].

The data-based strategy or black-box model, based on mathematical rules to obtain the formulation of the system from experimental data, is also used in the dynamic model of the air conditioning systems [32–34]. Although the performance param-