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Experimental comparison between set-point based and satisfaction based indoor thermal environment control

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ABSTRACT

Current indoor thermal environment is usually automatically controlled based on a temperature set-point given by room occupants or building managers. However, investigation shows that many temperature set-points are far from the comfortable temperature range recommended by design handbooks. Such unreasonable temperature set-points will result in not only uncomfortable indoor thermal environment, but also waste of cooling or heating energy. The authors have proposed a methodology of satisfaction based control to take place of the traditional set-point based control. This paper describes the experimental comparison results between satisfaction based indoor thermal environment control and set-point based control. Two test-beds were set up and a series of experiments was conducted to compare control performances, user acceptances, user work performances and system energy consumptions of the set-point based and satisfaction based control. The comparison results show that the satisfaction based control can achieve more stable thermal environment. Both of the two control methods can get relatively high scores regarding user acceptance and work performance. There are no statistically significant differences for user acceptance and work performance between two control methods. However, satisfaction based control consumed 15.3% and 11.9% less energy at two test-beds respectively than set-point based control due to more reasonable temperature settings given by the satisfaction based control.

1. Introduction

Current indoor thermal environment is usually automatically controlled based on temperature set-points, which are commonly given by building managers through building automation system (BAS) or the occupants themselves through local thermostats. The temperature set-points given by building managers might not reflect the building occupants' personalized thermal preferences. And the temperature set-points given by room occupants might deviate far from the comfort range recommended by design handbooks. Unreasonable temperature settings, such as 15 °C for cooling and 30 °C for heating, can be seen frequently. Field investment [1] of the thermostat temperature settings in an office building shows that only 50% of the thermostat temperature settings located in the summer comfort temperature range of 23.5–27 °C recommended by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) [2]. Further, 22% of thermostats temperature settings were lower than 16 °C. It could imagine that the occupants' purpose of setting thermostats at extremely low or high set-points should be intending to rapidly cool down or heat up the room. However, after they focus on their work, they usually forget to adjust the temperature settings back to a comfortable range until the overcooled or overheated environment causes uncomfortable sensations. These unreasonable temperature settings can not only result in uncomfortable over-cooled or over-heated indoor thermal environments, but also lead to waste of cooling or heating energy.

Researchers have noticed this phenomenon and tried to solve this problem. Marc Fountain et al. [3] developed a kind of human machine interface (HMI) with only "cooling room" and "heating room" buttons for the purpose of preventing people from giving unreasonable set-points. Henderson et al. [4] attempted to use comfort control strategy instead of set-point control to save energy and enhance comfort. Simmonds [5] had studied the relationship between energy consumption of air-conditioning system

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Table 1
Meteorological data of the two cities where the test-beds are located.

	North latitude	East longitude	Winter dry-bulb temperature (°C)	Winter relative humidity (%)	Summer dry-bulb temperature (°C)	Summer relative humidity (%)	Winter enthalpy (kJ/kgDA)	Summer enthalpy (kJ/kgDA)
Guangzhou	23°10′	113°20′	5.2	72	34.2	62	15.1	88.7
Lanzhou	36°03′	103°53′	−11. 5	54	31.2	36	−9.1	57.7

Table 2
Main envelop thermal properties of the office rooms where the test-beds located.

	Wall		Window	
	Composition	U value (W/m^2K)	Composition	U value (W/m^2K)
Guangzhou	Lime mortar 20 mm Aerated concrete 150 mm Cement mortar 20 mm	1.081	Plastic steel frame, double-layer glazing	2.9
Lanzhou	Lime mortar 20 mm Sintered clay hollow brick 300 mm Cement mortar 20 mm	0.609	Aluminum alloy frame, single-layer glazing	5.7

and indoor thermal comfort to find an optimal rule to control the system.

However, these researches consider comfort mainly using Predicted Mean Vote (PMV) model, which is a statistical model and cannot reflect individual thermal comfort. For the purpose of achieving personalized comfortable and energy efficient indoor thermal environment, the authors [1] have proposed a novel satisfaction based control method to control the thermal environment according to the room occupants' thermal sensations of "hot", "cold", "humid", "dry", etc., which are input by room occupants through HMIs. This paper describes the experimental comparisons between the satisfaction based control and the conventional set-point based control. Control performances, user acceptances, work performances and energy consumptions under satisfaction based control and set-point based control are compared to verify the advantages of the proposed satisfaction based control.

2. Methodology

The comparison of the performances of the two control methods was conducted through experiments at two test-beds. The two test-beds were set up in a building located Guangzhou and Lanzhou in China respectively. The two locations represent the typical meteorological conditions of hot and humid summer area and cold winter area respectively. The experiments of cooling operation were conducted at Guangzhou test-bed and the experiments of heating operation were conducted at Lanzhou test-bed.

2.1. Test-bed

The test-beds were located in two cities of Guangzhou and Lanzhou respectively, which represent two typical climate zone in China. Guangzhou is located in South China and has hot and humid summer and warm winter with subtropical monsoon climate. Guangzhou is a typical city for cooling in summer and without heating in winter. By contrast, Lanzhou is located in Northwest China and has hot and dry summer and cold winter with mid-temperature continental climate. Lanzhou is a typical city for heating in winter and with very shot cooling period in summer. The detailed weather data used for air-conditioning system design of the two cities are shown in Table 1.

Both the Guangzhou and Lanzhou test-beds were constructed in an ordinary office room. The room floor areas are 58 and 59 m^2 respectively. The two test-bed rooms' layouts and field photos are shown in Figs. 1 and 2. The main envelop thermal properties of the office rooms are shown in Table 2. Each test-bed was equipped with indoor environment control systems which can be operated under set-point based or satisfaction based control. A set of sensors was installed at each test-bed to measure outdoor air temperature and humidity and indoor environmental parameters including dry-bulb temperature, globe temperature, humidity, air speed, CO_2 concentration, and sound level. The sensor boxes are placed on the occupant working desk (No. 4 and No. 9 in Fig. 1) with the height of 1.5m. The measurement range and accuracy of the sensors are shown in Table 3. Room temperature, humidity and indoor air quality were controlled by a multi-split type air conditioner (with two 1.5-horsepower indoor units serving the test-bed room), a fresh air handling unit (FAHU) and a dehumidifier at Guangzhou test-bed. The indoor thermal environment at Lanzhou test-bed was controlled by a 3-horsepower split type air conditioner, four sets of radiators (heaters), one humidifier, and two ventilation fans.

Table 3
Measurement range and accuracy of the sensors.

Measured parameter	Range	Accuracy
Temperature (indoor t_i, outdoor t_o)	−40 to 60 °C	±0.4 °C
Relative humidity (indoor RH_i, outdoor RH_o)	0–100%	±3%
CO_2 concentration (indoor C_i)	0–5000 ppm	±75 ppm
Globe temperature (indoor t_g)	−50 to 100 °C	±0.4 °C
Air speed (indoor v_i)	0–10 m	5%

2.2. Control logic

The concept of satisfaction based control system is shown in Fig. 3. The control system consists of the following three modules:

(1) HMI, which is used for room occupants to express their thermal discomfort sensations, such as hot, cold, dry, humid, draft, etc. In this experiment, the smart phone application was used to provide the HMI for the users to set temperature set-point or to input their thermal sensations. For the purpose of conducting comparison experiment, the HMI includes set-point input interface and thermal discomfort sensation input interface, as shown in Fig. 4.
(2) Controller, which is used to give action commands to the air-conditioner, ventilation fan, humidifier, dehumidifier, and FAHU. The action commands are generated using Proportional-Integral-Derivative (PID) logic according to the deviations of the controlled parameters from set-points, as shown in Eq. (1). Where $Q(\tau)$ is the PID controller output, K is the proportional coefficient, t_{set} is the temperature set-point, $t(\tau)$ is the air tem-