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Further development of a thermal comfort based fuzzy logic controller for a direct expansion air conditioning system

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HIGHLIGHTS

- A previous developed fuzzy logic controller is simplified.
- The simplification would not reduce the control performance.
- PMV was used as regulator in the fuzzy logic controller.
- Temperature, humidity and local air velocity were considered in PMV index.
- 4–7.6% energy can be saved by introducing a local fan.

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ABSTRACT

The primary purpose of A/C is offering occupants with acceptable indoor thermal comfort levels. Thermal comfort is a complicated result of non-linear interactions between six parameters. However, many of current A/C systems solely control air temperature. Whenever anyone of the five parameters other than temperature varies significantly, an occupant may feel thermally uncomfortable. To address the issue, a comprehensive thermal comfort index should be used as regulator in A/C systems.

One fuzzy logic controller is available. However, the approach to the fuzzy logic controller is complicated. In this paper, one previous established fuzzy logic controller is simplified for its real application. Test results demonstrated that the simplification would not reduce the control performances in terms of control accuracy and sensitivity. A local fan was installed in the conditioned space to act as personalized ventilation. It is shown that at the same thermal comfort level, about 4–7.6% energy saving of the A/C system could be achieved when a higher local fan speed was used. With simplifications, the thermal comfort based fuzzy logic controller has a high potential of commercialization. It can contribute to the realization of low carbon A/C systems while improving indoor thermal comfort for building occupants.

1. Introduction

Direct expansion (DX) air conditioning (A/C) systems are widely used in small-to-medium size buildings because they are simpler, more energy efficient and generally cost less to own and maintain. However, indoor air humidity is usually assumed unchanged or left uncontrolled in the current controllers [1–3]. Most DX systems are equipped with single-speed compressors and fans, relying on on-off cycling to maintain indoor dry-bulb temperatures only [4]. This results in an uncontrolled equilibrium of indoor humidity, leading to a reduced level in the thermal comfort of occupants [5,6].

The traditional principal method for indoor humidity control used in large central HVAC systems is to overcool air to remove more moisture. Then reheat it to a suitable supply temperature. This strategy is costly and inefficient since it uses a great deal of energy to overcool air and then more energy to reheat it [7]. Because of the difficulty in humidity control, only the air temperature is set as the control objective in most DX A/C system.

However, with the development of variable speed (VS) technic, air temperature and humidity could be controlled by simultaneously varying compressor speed (Cs) and supply air fan speed (Fs) in DX A/C systems [8]. In addition to the traditional proportional-integral-differentiation control strategies [9], various advanced controllers have been designed for and employed in DX A/C systems for humidity control.

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Nomenclature

A/C	air conditioning
Cs	compressor speed
DX	direct expansion
Fs	fan speed
FLC	fuzzy logic controller
IFLC	improved fuzzy logic controller
PMV	predicted mean vote
$Q_{l,E}$	output latent cooling capacity from a DX A/C system, kW
$Q_{s,E}$	output sensible cooling capacity from a DX A/C system, kW
$Q_{t,E}$	total output cooling capacity from a DX A/C system, kW
$Q_{t,S}$	total cooling load in a conditioned space, kW
RH	relative humidity, %
SHR_E	equipment sensible heat ratio of a DX A/C system
SHR_S	application SHR in a conditioned space
T_{db}	air dry-bulb temperature, °C
T_{wb}	air wet-bulb temperature, °C
VS	variable speed
$_{set}$	set point

These include direct digital control [10], multi-input multi-out control method [11], neural network based [12–14] and fuzzy logic controller (FLC) [15]. Compared to on-off controller, improved energy efficiency of the DX A/C system can also be achieved [9,15,16]. It should be noted that, the development of these advanced controllers are usually complicated and mathematical modeling supports are usually required.

A FLC was previously established for a VS DX A/C system based on the characteristics of the system [17]. The control logic is simple and applicable to other A/C systems with different capacities. Simultaneous indoor air temperature and humidity control can also be achieved. Nevertheless, the experimental approaches to obtain the performance characteristics of the system is complex and time consuming. Simplifications are required to further develop the FLC for a DX A/C system to extend its real application.

Current FLC only considers the temperature and humidity, however, the thermal comfort is also influenced by the other parameters, such as air velocity, mean radiation temperature, clothing factor and metabolic rate. A comprehensive thermal comfort index is therefore needed. The predicted mean vote (PMV) is such a widely recognized thermal comfort index proposed by Fanger [18,19]. It is a complicated index takes account of the non-linear interaction between two subjective parameters and four objective ones. The PMV index motivates us to develop a PMV-based fuzzy logic controller of a direct expansion (DX) A/C system for better thermal comfort.

In addition, PMV-based fuzzy logic controller provides potential energy saving because of controllable air velocity. Previous research work suggests that it is possible to reduce HVAC energy consumption without sacrificing indoor thermal comfort while using PMV as regulator [20–23]. It is reported that 6–33.7% energy could be saved by increasing PMV setting but still keeping it within the comfort range [24]. However, without an appropriate dehumidification ability and personalized ventilation strategy, increasing PMV setting can only be accomplished by increasing air temperature [25]. If humidity can be controlled and a higher air velocity can be achieved at working places, air temperature could be set a little bit higher. A smaller indoor sensible cooling load and additional energy saving can be achieved at the same thermal comfort level.

Therefore, the objectives of this paper include, (1) simplification of an available FLC to extend its application and (2) introduction of PMV index into the FLC as controlled variable, taking consideration of the variations of air temperature, humidity and local air velocity in the conditioned space. It is then organized as follows. Firstly, the previously developed FLC for a DX A/C system [17] is briefly reviewed, and the development of the thermal comfort based FLC detailed with two steps' modification. Secondly, the results of controllability tests for the thermal comfort based FLC using an experimental DX A/C system are presented. Finally, conclusions are given.

2. Controller development

In this section, a previously developed FLC [17] for a VS DX A/C system is further simplified and improved. Simultaneous control over indoor air dry-bulb temperature (T_{db}) and wet-bulb temperature (T_{wb}) can be achieved using the FLC, based on the characteristics of the system.

2.1. The FLC previously developed

The details of the FLC previously developed were reported elsewhere [17]. For the completeness of the current paper, these are briefly reproduced as follows.

The schematic diagram of the developed FLC for a VS DX A/C system is shown in Fig. 1. As seen, T_{db} and T_{wb} are inputs to the controller to estimate the required sensible capacity $Q_{s,E}$ and latent capacity $Q_{l,E}$ according to fuzzy laws in the FLC. Then, the required total cooling capacity ($Q_{t,E}$) and sensible heat ratio (SHR_E) can be evaluated using the following equations.

$$Q_{t,E} = Q_{s,E} + Q_{l,E}, \quad SHR_E = Q_{s,E}/Q_{t,E} \tag{1}$$

After obtaining $Q_{t,E}$ and SHR_E, Cs and Fs at the next time step, i.e., Cs (t + 1) and Fs (t + 1) can be determined with the aid of the performance characteristics of the A/C system. As shown in Fig. 2, the system characteristics is presented in the format of a performance map, which can describe the inherent operational characteristics of a DX A/C system at a typical indoor operating condition. It was obtained through experiments under different combinations of Cs and Fs and constant indoor operating condition of 25 °C and 50% relative humidity (RH). The map was manually divided into nine zones and nine points A to J were assigned to represent the corresponding nine zones and cover the normal operating combinations of Cs and Fs. If the estimated $Q_{t,E}$ and SHR_E were within Zone I, Cs (t + 1) and Fs (t + 1) of the DX A/C system would operate at the speed combination of Point A. If the

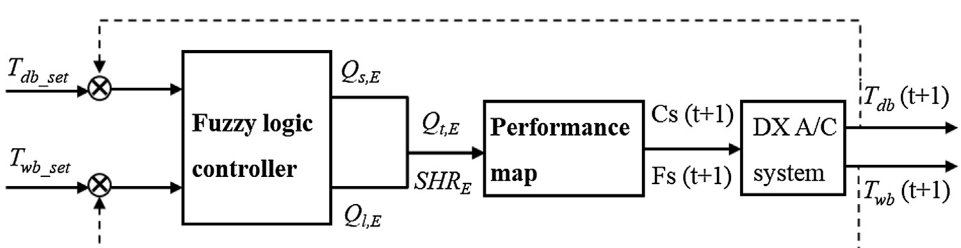

Fig. 1. Flow chart of the FLC for a DX A/C system.