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A Thermal Comfort based Controller for a Direct Expansion Air Conditioning System

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Abstract

For building HVAC systems, better indoor thermal comfort control and higher energy efficiency could be achieved using a thermal comfort index as the controlled variable instead of air temperature. Although there can be various simplification approaches, indoor air humidity has been commonly assumed constant or left uncontrolled. Neglecting the importance of indoor humidity control would adversely affect the control performance of an air conditioning system. In addition, it is difficult to control local air velocity in the vicinity of a user. Therefore, either a constant local air velocity or an air velocity varying to a preset pattern was assumed in a thermal comfort model. In this paper, a thermal comfort based controller is developed and reported. Controllability tests were carried out which showed that better energy efficiency of the DX A/C system could be achieved when a higher local fan speed was used.

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Keywords: Thermal comfort; direct expansion; air conditioning; control; air velocity;

1. Introduction

Indoor thermal comfort derives from a complicated non-linear interaction between the four environment dependent variables (air temperature, velocity, humidity and mean radiant temperature) and the two person dependent variables (activity level and clothing) [1]. A large number of HVAC systems, however, only regulate air temperature, controlled by air temperature regulators (ATRs). If one of the other five parameters varies significantly, a user may feel thermally uncomfortable. Over the years, a large number of comfort index regulators (CIRs) have been developed and used for

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guiding the design of HVAC systems [1-4]. These include the PMV (predicted mean vote) index, proposed and developed by Fanger [1].

Nomenclature

A/C	Air conditioning
CIR	Comfort index regulator
DX	Direct expansion
PMV	Predicted mean vote
T_{db}	Dry-bulb temperature
T_{wb}	Wet-bulb temperature

A simplified thermal comfort model is normally necessary when designing a CIR. Although there can be various simplification approaches, variations in indoor air humidity and air velocity around occupants have always been regarded as influencing thermal comfort to only a small extent. Consequently, indoor air humidity is usually assumed constant or left uncontrolled [5-6]. However, although ASHARE Standards [7] recommend a wide comfort range of relative humidity from 30% to 60%, humidity levels above 60% do adversely affect indoor thermal comfort and indoor air quality significantly [8]. A practical reason for this is however the difficulty for building A/C systems to simultaneously control indoor air temperature and humidity. On the other hand, the increase in the air velocity around occupants would help improve comfort level, although the averaged room temperature increased. Remarkable effects could be obtained from people who had moderate activity [9]. Accordingly, the personalized ventilation resulted in an energy saving without causing occupant dissatisfaction [10].

Energy efficiency is also important in judging the performance of an HVAC system. Previous research work has shown that it is possible to reduce HVAC energy use without sacrificing indoor thermal comfort while using CIR technology [11], by increasing PMV setting but still keeping it within the comfort range. However, without an appropriate humidity control strategy, increasing PMV setting can only be accomplished by increasing air temperature. Very often, the scope for increasing air temperature is limited, particularly in hot and humid climates. If indoor humidity can be controlled to a low level and a higher air velocity was achieved at working places, however, at the same PMV setting, T_{db} could be set a little higher, leading to a smaller indoor sensible cooling load.

When applied to HVAC system control, fuzzy logic controller attracted much research interests because of its characteristics of capturing the approximate and inexact nature of a controlled process, such as human thermal comfort. [5, 12]. In this paper, an experimental study on a direct expansion (DX) A/C system with an emphasis on indoor thermal comfort is reported. Firstly, the development of a fuzzy logic controller is presented. This is followed by presenting a simplification approaches to predicted mean vote (PMV), the commonly used CIR. Finally, examples of controllability tests results are given.

2. Development of a fuzzy logic controller

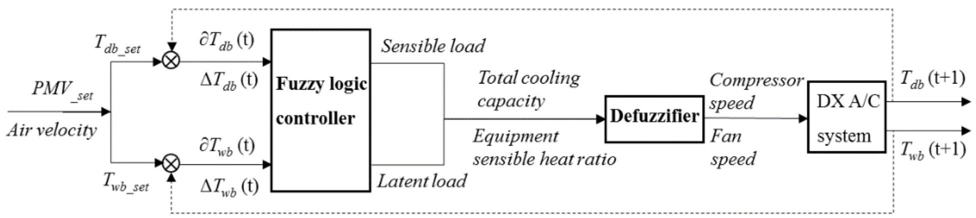

Fig. 1 Flow chart of the fuzzy logic controller for a DX A/C system

Fig. 1 shows the complete flow chart of the fuzzy logic controller which was developed based on a previous work [13]. In [13], a novel control principle was developed to decouple the temperature and humidity control loops by introducing two interim variables, i.e., the sensible and latent output cooling capacity of the DX A/C system. Then, a defuzzifier was applied to convert the calculated sensible/ latent load obtained from the fuzzy logic controller to the speeds of compressor and supply fan, as shown in Fig. 1. An artificial neural network model for a variable speed DX A/C system was trained and used as a defuzzifier [13]. The training progress for the artificial neural network model is complicated. Therefore, in this paper, the defuzzifier was replaced by an experimental figure, i.e., Fig. 2, obtained through an experimental DX A/C system.

Fig. 2 was obtained under different speed combinations of compressor and supply air fan at a constant indoor air condition of 25 ºC and 50% relative humidity. It was plotted as a trapezoid shape with the total output cooling capacity and the equipment sensible heat ratio, i.e., the ratio of the sensible cooling capacity to the total cooling capacity, directly showing the relation between cooling capacity and the speeds of compressor and fan. In order to simplify the use of the trapezoid, it was divided into nine zones, each with a representative point. The nearest representative point to the calculated point of total cooling capacity and sensible heat ratio would be chosen to determine the speeds operation of compressor and fan in the experimental DX A/C system.

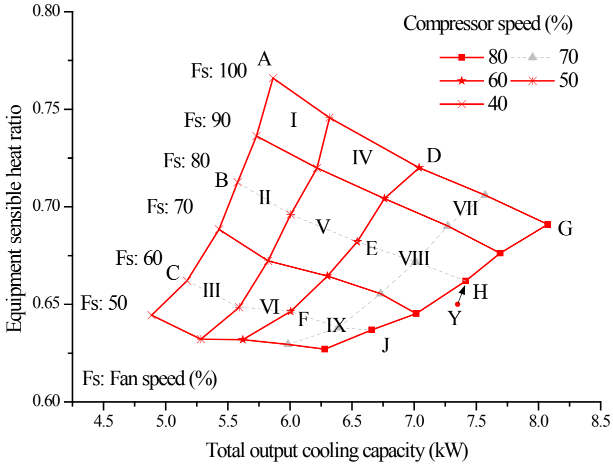

Fig. 2 Proposed zoning with nine representative points in the trapezoid

3. Simplification to the comfort index regulator

The CIR have two functions, the set-point establishment and thermal comfort evaluation. The set-point establishment module will generate an appropriate PMV setting, where the actual required settings for indoor dry-bulb temperature (T_{db}) and wet-bulb temperature (T_{wb}) will be determined. These settings will be input to the fuzzy logic controller to simultaneously control T_{db} & T_{wb} by varying compressor and supply fan speeds in the DX A/C system.

4. Experimental rig and controllability test results

4.1 Experimental rig

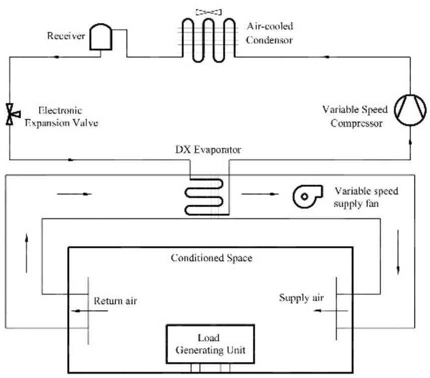

Fig. 3 The schematic diagram of the experimental rig

As shown in Fig. 3, an experimental rig was established to resemble a typical DX A/C system. It mainly consisted of two parts, a DX refrigeration plant and an air distribution sub-system. The nominal output cooling capacity from the DX refrigeration plant 7.5 kW. The refrigerant was R410a, with a total charge of 5.8 kg. A load generating unit was placed in the indoor space to simulate both sensible and latent loads. A two-speed fan was placed 0.8 cm away from an occupant, which could be manually controlled. When the local fan was switched off, the measured air velocity around working place was measured at about 0.15 m/s. The averaged measured air velocity were 0.21 m/s and 0.34 m/s when the fan was low and high speed operated, respectively.

4.2 Experimental test conditions

Using the developed fuzzy logic controller, two examples of experiments were conducted to test its control performances. During the experiments, PMV was used as regulator. Each test lasted for 3 hours with local fan disabled in the first hour, low speed operation in the second hour and high speed in the last hour. Detailed experimental conditions were listed in Table 1. During each test, sensible and latent loads were kept constant through adjusting the inputs to the load generating unit.

Table 1 Experimental test conditions

<table>
<tr><th rowspan="2">Test No.</th><th colspan="4">Fixed setting</th><th colspan="3">Altered local fan speed/ air velocity
--/ m/s</th></tr>
<tr><th>PMV</th><th>Relative humidity (%)</th><th>Sensible load (kW)</th><th>Latent load (kW)</th><th></th><th></th><th></th></tr>
<tr><td>1</td><td>0</td><td>50</td><td>4.40</td><td>2.18</td><td rowspan="2">Off/ 0.15</td><td rowspan="2">Low speed/ 0.21</td><td rowspan="2">High speed/ 0.34</td></tr>
<tr><td>2</td><td>-0.3</td><td>50</td><td>4.53</td><td>2.09</td></tr>
</table>

4.3 Experimental test results

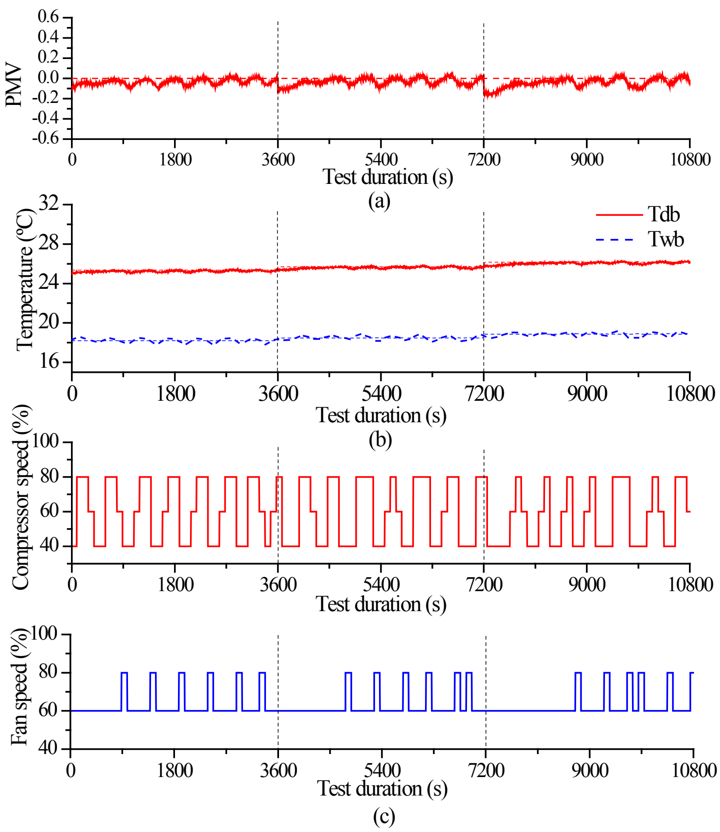

Fig. 4 Variation profiles of indoor air status and compressor/ supply fan speed in Test 1

In the first test, PMV was set as 0, which is neutral for most of people's sensation. When the local fan speed was increased from 0 to low speed between 3600 s and 7200 s, and further high speed in the rest of experiments, the air velocity around occupants was increased form 0.15 m/s to 0.21 m/s and further 0.34 m/s in the last operation hour. The PMV setting was kept constant, but that for T_{db} / T_{wb} were increased, from 25.36 °C/ 18.19 °C to 25.69 °C/ 18.47 °C in the second hour and 26.16 °C/ 18.85 °C in the last hour, respectively.

As seen in Fig. 4 (a), the calculated PMV in the indoor space of the DX A/C system were oscillated around 0, within acceptable range of [-0.10, 0.03]. When the local fan was switched on or turned to a higher speed, a sudden drop in PMV value would be observed, due to the increase in air velocity.

In Fig. 4 (b), the variation profiles of T_{db} / T_{wb} were plotted. Before the local fan was enabled, T_{db} and T_{wb} were varied with small ranges. In 3600 s, a low speed for the local fan was introduced. Settings for T_{db} and T_{wb} were increased. It took about 400 s for T_{db} and T_{wb} reaching their new settings. During the experiments, the space sensible and latent cooling loads were kept at fixed values through using the indoor load-generating unit. Therefore, when the variation rages and cycles were similar in the three periods.

As seen from Fig. 4 (c), speeds of compressor and the supply air fan in the DX A/C system were continuously adjusted according to the output of the fuzzy logic controller. This could also explain the variation trends of T_{db} / T_{wb}. It is assumed that the variation in supply air speed had small impact on the air velocity near an occupant. Therefore, the value of air velocity for calculating PMV would be changed when there was adjustment to the local fan speed.

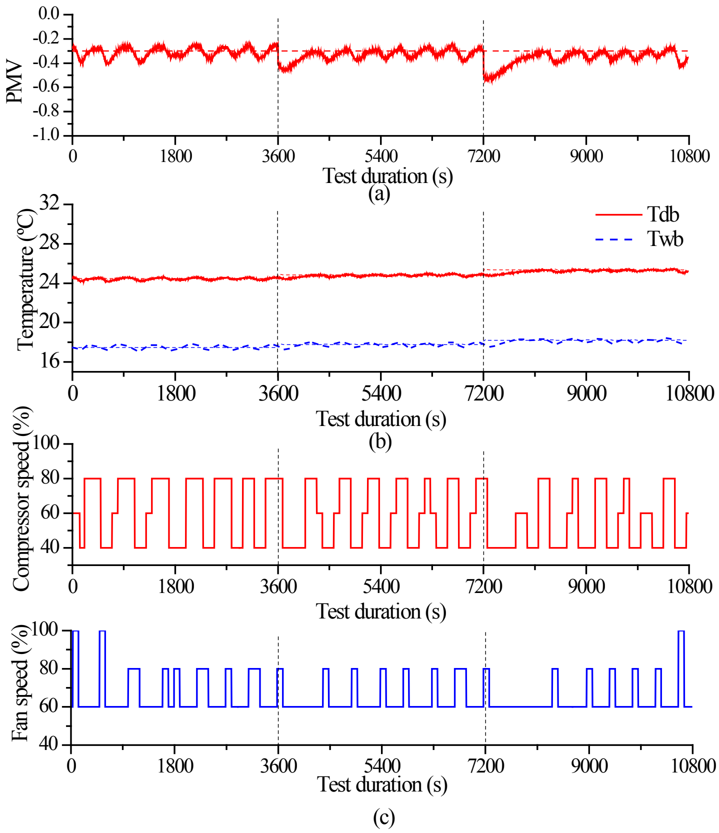

Fig. 5 Variation profiles of indoor air status and compressor/ supply fan speed in Test 2

In the second test, a lower PMV value was set and similar results as that in test 1 were observed.

Energy efficiency is also important in judging the performance of an A/C system. The energy performance of the experimental DX A/C system in each test was also monitored as detailed in Table 2. The power input to the supply fan and the local fan were also taken into account in comparing the energy performance. Under a constant indoor thermal loads and control strategies, the total power input to the DX A/C system in the last two hours are 6.2% and 7.1%, respectively, lower than that during the first hour, where the local fan was disabled. Similar, 4.0% and 7.6%

energy would be saved when a low-speed and a high-speed local fan were adopted in Test 2.

Table 2 Performance data during the three hours' operation in each test

Test	Period (Hour)	Air velocity (m/s)	Energy consumption (kWh)				Saving (%)
			Compressor	Fan	Local fan	Total	
1	0-1	0	2.108	1.460	0	3.568	--
	1-2	0.21	1.891	1.451	0.015	3.548	6.2%
	2-3	0.34	1.824	1.458	0.035	3.489	7.1%
2	0-1	0	2.205	1.526	0	3.731	--
	1-2	0.21	2.074	1.492	0.015	3.581	4.0%
	2-3	0.34	1.936	1.475	0.035	3.446	7.6%

5. Conclusion

A fuzzy logic controller was developed for a DX A/C system based on previous work. PMV was used as a comfort regular to determine the settings for indoor air temperature and humidity. A higher air velocity around working places can be achieved through using a local fan. Therefore, increasing air dry-bulb temperature setting was achieved at a constant PMV value. Experiments have been conducted, and the experimental results have demonstrated that the fuzzy logic controller can result in smooth control over PMV and 4.0% to 7.6% energy consumption of the DX A/C system could be saved when a higher local fan speed was used.

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