Applied Thermal Engineering 29 (2009) 2187–2193

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Indoor thermal comfort characteristics under the control of a direct expansion air conditioning unit having a variable-speed compressor and a supply air fan

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ARTICLE INFO

Article history:
Received 27 August 2008
Accepted 31 October 2008
Available online 8 November 2008

Keywords:
Thermal comfort
DX A/C unit
Variable-speed

ABSTRACT

Indoor thermal environment is important as it affects the health and productivity of building occupants. Direct expansion (DX) air conditioning (A/C) units are commonly used for environmental control in small- to medium-scaled buildings. This paper reports on an experimental study to investigate the indoor thermal comfort characteristics under the control of a DX A/C unit having variable-speed compressor and supply fan at a fixed space cooling load but having three different ratios between its sensible part and latent part. The experimental results suggested that under a fixed indoor total cooling load with three different space sensible heat ratios (SHRs) of 0.92, 0.72 and 0.62, varying both speeds of compressor and supply fan in the DX A/C unit would influence indoor thermal comfort. Furthermore, when a DX A/C unit having variable-speed compressor and supply fan is used for indoor thermal comfort control under abnormal indoor load conditions, its ability of indoor thermal comfort control through varying compressor speed and supply fan speed may be duly restricted.

1. Introduction

Direct expansion (DX) Air conditioning (A/C) units, such as rooftop, split-type and window-type air conditioners, are commonly used in small- to medium-scaled buildings. When compared to chilled water-based A/C installations, the use of DX A/C units is more advantageous because they are simpler, more flexible, more energy efficient and generally cost less to own and maintain.

With the rapid development of technology, the use of variable-speed compressor and supply fan in DX A/C units has become more and more prevalent and practical. Li and Deng [1] carried out an experimental study on the inherent operational characteristics of a DX A/C unit at fixed inlet air temperature and humidity when the speeds of its compressor and supply fan were varied. The experimental results demonstrated that varying both compressor and supply fan speeds could lead to varying equipment sensible heat ratio (SHR), or the varying ability to dehumidify of the DX A/C unit. Therefore, it could be understood that simultaneously varying compressor and supply fan speeds of a DX A/C unit, would directly and indirectly affect indoor air temperature, relative humidity (RH), air velocity and mean radiant temperature (MRT) and consequently indoor thermal comfort level. However, previously studies such as those by Andrade et al. [2] and Krakow et al. [3] only considered the effects of varying compressor and fan speed on indoor environmental conditions, i.e., air temperature and humidity only, rather than indoor thermal comfort characteristics.

On the other hand, an optimal comfort control concept for variable-speed heat pumps and air conditioners was proposed in a simulation-based study [4]. The control objective was to maximize the system efficiency while simultaneously satisfying comfort requirements. A multi-dimensional search technique was employed to find the optimum compressor speed, indoor airflow rate and evaporator superheat at a given ambient condition. Simulation results indicated that although there existed an infinite number of combinations of compressor speed and indoor airflow rate that could satisfy the comfort requirements as measured by using Fanger's comfort index, only one speed combination resulted in the maximum efficiency. Nevertheless, this study was only based on simulation and no experimental evidences were presented.

There have been recent developments in using thermal comfort index, rather than a single environmental parameter such as air temperature or humidity for controlling the operation of A/C systems. Simulation and experimental studies have been reported that thermal comfort control can help achieve better thermal comfort, and a higher energy efficiency and system reliability [5–7].

This paper reports on an experimental investigation of indoor thermal comfort characteristics under the control of a DX A/C unit having variable-speed compressor and supply fan at a fixed space cooling load condition. Firstly, the well-known Fanger's thermal comfort model was simplified for the current experimental investigation. This is followed by reporting the experimental results of indoor thermal comfort characteristics under the control of a DX

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doi:10.1016/j.applthermaleng.2008.10.011

Nomenclature

C_{pa}	air specific heat at constant pressure, kJ/kg °C
h_c	convective heat transfer coefficient, W/m^2 °C
L	thermal load on A human body, met, W/m^2
m_a	air mass flow rate, kg/s
M	actively level, met, W/m^2
p_{av}	water vapor partial pressure, kPa
PMV	predicted mean vote
PPD	predicted percentage dissatisfied, %
Q_{fgh}	supply fan heat gain, kW
RH	air relative humidity level, %
SHR	sensible heat ratio
t_{adb}	air dry-bulb temperature, °C
$\bar{t}_r$	mean radiant temperature, °C
W	external work done by muscles, met, W/m^2

Subscripts

db	dry-bulb
fi	supply fan inlet
fo	supply fan outlet

A/C unit under a given space cooling load, with three different space SHRs, namely, 0.92, 0.72 and 0.62, respectively. Finally, a discussion on indoor thermal comfort control with through varying compressor and supply fan speed is given.

2. Assumptions and simplifications of the thermal comfort model

Thermal comfort has a great influence on the health and productivity of building occupants. A person's sense of thermal comfort is primarily a result of the body' heat exchange with environment, which is influenced by two personal and four environmental parameters: metabolic rate, clothing insulation, and air temperature, mean radiant temperature (MRT), air speed and humidity. Two indexes proposed by Fanger [8–9] have been extensively used and accepted in assessing indoor thermal comfort. The first one is predicted mean vote (PMV) [8] that expresses the quality of thermal environment as a mean value of votes of a large group of persons according to the ASHRAE thermal sensation scale. The other is the predicted percentage dissatisfied (PPD) [9] which expresses the thermal comfort level as a percentage of thermally dissatisfied people, and is directly determinable by PMV. The two indexes can be evaluated by

$$\mathrm{PMV} = [0.303\exp(-0.036M) + 0.028]L \tag{1}$$

$$\mathrm{PPD} = 100 - 95\exp[-(0.03353\mathrm{PMV}^4 + 0.2179\mathrm{PMV}^2)] \tag{2}$$

According to Fanger, a PPD of 10% corresponds to the PMV range of ±0.5, and even with PMV = 0, there are still about 5% of the people who are dissatisfied.

Fanger's PMV–PPD thermal comfort model has been widely used and accepted for design and field assessment of thermal comfort [10–14]. Standards for maintaining comfortable indoor thermal environments have been developed by ASHRAE [15] and ISO [16]. ASHRAE [15] defines the recommended PPD and PMV range for typical applications. The acceptable thermal environment for general comfort is PPD < 10% or $-0.5 < \mathrm{PMV} < 0.5$, which may be applied to a space where occupants have activity levels with metabolic rates between 1.0 and 1.3 met and where clothing is worn providing between 0.5 and 1.0 clo of thermal insulation.

Fanger's PMV–PPD thermal comfort model is normally applicable to sedentary or near sedentary physical activity levels. In this experimental study, occupants were assumed to sit quietly or relax in an air conditioned space served by a DX A/C unit, which could be considered as being in a sedentary physical activity level, therefore, Fanger's PMV–PPD thermal comfort model could be adopted as a base model.

The metabolic rate for quietly seated occupants was 1.0 met. It was further assumed that occupants were immobile, therefore,

$$M = 60\ \mathrm{W/m^2} \tag{3}$$

$$W = 0\ \mathrm{W/m^2} \tag{4}$$

According to ANSI/ASHRAE Standard 55 [15], in hot and humid subtropical summer, the clothing normally worn by occupants provided a thermal insulation of 0.5 clo. This clothing value was used in the current experimental study.

With the above assumptions, both PMV and PPD may be evaluated by following the calculating procedures specified in ANSI/ASHRAE Standard 55 [15]. There were four parameters, $\bar{t}_r$, $t_{adb,r}$, p_{av} and h_c, required for evaluating PMV and PPD. There may be directly measured or calculated following ANSI/ASHRAE Standard 55 [15].

3. Experimental conditions

The experimental work has been carried out using an experimental DX A/C system whose schematic diagram is shown in Fig. 1.

The experimental DX A/C system was mainly composed of two parts, i.e., a DX A/C unit and an air conditioned room served by the DX A/C unit. The size of the room was 7.6 m (L) × 3.8 m (W) × 2.8 m (H). There were electrical heaters and humidifiers, or heat and moisture load generating units (LGUs) placed inside the conditioned room to simulate both internal and external space cooling loads. The total heating capacity of the sensible load generating units, i.e., electrical heaters, was 24 kW and that for moisture load generating units, i.e., humidifiers, was 9.6 kW. The outputs from the LGUs were controlled by a computer which operated the whole experimental system. Therefore, different experimental conditions of total space cooling load and the ratios between its sensible and latent components, i.e., SHRs, may be simulated.

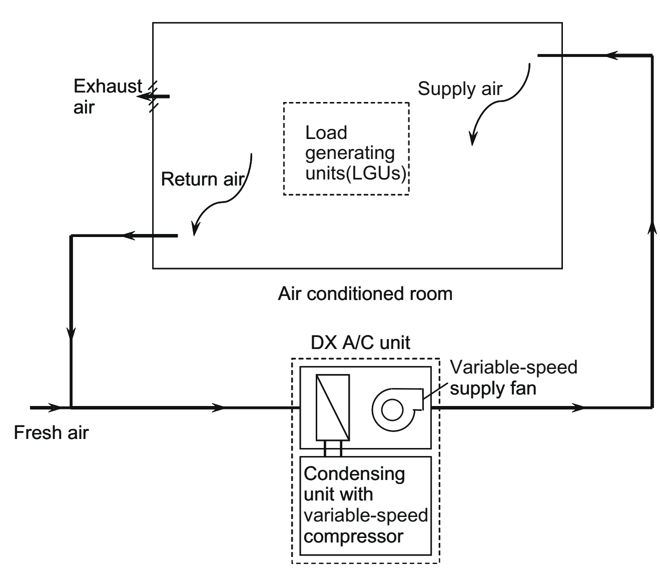

Fig. 1. Schematic diagram of the experimental DX A/C system.