Building and Environment 65 (2013) 109–117

Contents lists available at SciVerse ScienceDirect

Building and Environment

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

Comfort under personally controlled air movement in warm and humid environments

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ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form
24 March 2013
Accepted 27 March 2013

Keywords:
Thermal comfort
Perceived air quality
Warm-humid
Air movement
Personal control
Low energy

ABSTRACT

This study examined the effects of personally controlled air movement on human thermal comfort and perceived air quality (PAQ) in warm-humid environments. At temperatures 26, 28, and 30 °C, and relative humidity (RH) 60% and 80%, sixteen human subjects were exposed to personally controlled air movement provided by floor fans in an environmental chamber. The subjects reported their thermal sensation, thermal comfort, and PAQ during the tests. Two breaks periods with elevated metabolic levels were used to simulate normal office activities. Results show that with personally controlled air movement, thermal comfort could be maintained up to 30 °C and 60% RH, and acceptable PAQ could be maintained up to 30 °C 80% RH, without discomfort from humidity, air movement or eye-dryness. Thermal comfort and PAQ were resumed within 5 min after the breaks. The 80% acceptable limit implicit in comfort standards could be extended to 30 °C and 60% RH. The average energy consumed by the fans for maintaining comfort was lower than 10 W per person, making air movement a very energy-efficient way to deliver comfort in warm-humid environments.

1. Introduction

Compressor cooling in buildings is already the main contributor to peak load in long tropical or sub-tropical summers, affecting both energy use and electrical grid safety, and this trend is going to accelerate in the coming decades with the cooling demand growth in South China, South-east and South Asia. In the face of the huge energy impacts that this increase is causing, one must examine alternative ways of achieving comfort in warm-humid environments.

In warm environments, air movement has the potential to conserve energy while maintaining occupants' comfort. Field studies in warm-humid climates have shown that occupants remained comfortable in naturally ventilated buildings with natural wind and fans [1–7]. In air-conditioned buildings, a reanalysis of ASHRAE field study database also shows that a majority of occupants preferred more air movement when their thermal sensations are slightly warm or warmer [8].

Recently, ASHRAE Standard 55 "Thermal environmental conditions for human occupancy" increased allowable air movement for comfort in warm environments [9], providing more opportunities for air movement design for cooling [10]. Air movement has long been shown to be effective at increasing convective and evaporative heat loss in warm environments [11–14]. Laboratory studies have found that thermal comfort can be well maintained by personally controlled horizontal air movement in ambient temperatures as high as 27.8 °C and 30 °C [15,16]. Recent studies have shown that a 3 W personal fan maintains a neutral thermal sensation up to 30 °C and 50% RH [17].

Of such studies, relatively few have combined high temperatures and high humidity. One of these, by Tanabe and Kimura [18] tested horizontal air movement provided by an array of box fans on sedentary subjects wearing 0.6clo, and found that comfort could be maintained at 31 °C, 50% RH with 1.6 m/s air speed, and at 29 °C, 80% RH with 1.4 m/s air speed. Kubo et al. [19] tested self-selected frontal airflow with subjects wearing 0.35 clo at 30 °C and 80% RH. Subjects chose a cooler-than-neutral thermal sensation by selecting an average air speed of 1.27 m/s at 30 °C and 80% RH. Even higher air speeds (up to 3 m/s) has been preferred by subjects in Thailand

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http://dx.doi.org/10.1016/j.buildenv.2013.03.022

[20] and Hong Kong [21] at temperatures higher than 30 °C and at RH values as high as 85%.

Studies have also shown that air movement significantly improves people's PAQ in warm temperature and moderate humidity conditions up to 30 °C [17,22,23], and in humid environment up to 28 °C [24–26], although the causal mechanism behind this is not well understood.

However, the cited research has mainly focused on overall thermal sensation, paying less attention to general acceptability of thermal environment, PAQ, humidity and air movement, and possible eye discomfort due to high air speeds. Previous studies used large fan-box or personalized ventilation systems; less has been done with regular room fans, which are easier and cheaper to implement in buildings. Another issue is human reaction to thermal transients, because air movement, unlike temperature and humidity, is almost never uniform across space, and the ability of air movement to restore comfort after periods of time spent in still air is important. These issues are of great importance because answers to these questions might impact the wide adoption of air movement devices.

The aims of the study were to: (1) examine the ability of personally controlled low-energy fans to maintain thermal comfort and PAQ in warm-humid environments; (2) examine the ability of air movement to restore thermal comfort and PAQ after a short burst of activity; (3) determine the threshold values for temperature and humidity under which acceptable comfort can be maintained with personally controlled air movement.

2. Methods

The experiments were carried out at the environmental chamber at the Center for the Built Environment (CBE), University of California, Berkeley in June 2012.

2.1. Facilities

2.1.1. Climate chamber

The CBE climate chamber measures 5.5 m × 5.5 m × 2.5 m, controlling temperature to an accuracy of ±0.5 °C, and RH ±3%. The chamber has windows on two sides, South and West. The windows are well shaded by fixed external shades. The windows temperature is controlled by a dedicated air system. The room air temperature is controlled and ventilated by 8 floor grill diffusers, and the air is exhausted through a ceiling return grill. The outdoor flow rate in this study was around 85–104 L/s. Since the maximum number of occupants was 5 (four subjects and one experimenter), the minimum outdoor air supply rate was between 17.0 and 20.8 L/s person, much higher than the current requirement for office buildings (4.3 L/s person) [27].

Fig. 1 shows the experimental set up. The chamber was set up to simulate a typical open plan office without partitions. Four workstations (WS) were set up so that four subjects could be tested at the same time. Each workstation was assigned a floor fan, a laptop and a mesh chair. The fans were placed in the middle of the room, blowing air toward the corners in order to minimize interaction between the airflows.

2.1.2. The fans

The commercially available fan is very energy efficient and consumes only 2–14 W for fan speed settings 1 to7 (Table 1). Each fan was placed 1.5 m away from the position of the subject. The subjects controlled the fan speeds with a remote controller. Mean air speeds (1.1 m height at where the subjects sat) ranged from 0.4 m/s to 1.7 m/s from level 1 to level 7 (Table 1).

a. Chamber configuration

b. Air speed measurement

Fig. 1. Layout of the test chamber and air speed measurement.

2.1.3. Physical measurements

Room temperature and RH were measured continuously with HOBO Temperature and RH data loggers attached to the back of each table during all the tests. The accuracy of temperature measurement was ±0.35 °C, and RH accuracy was ±2.5%.

Air speed was measured with omnidirectional hotwire anemometers (Sensor Inc., with a response time of 2 s and an accuracy of 0.02 m/s ± 1.5% of reading). Measurements were made before and after the experiment to characterize the air speed at each workstation, at the 0.1 m, 0.6 m, and 1.1 m levels. Air speeds were

Table 1
Fan power and measured air speed at each setting.

Level	Power (W)	Air speed (m/s)				
		ws 1	ws 2	ws 3	ws 4	Mean
0	1[a]	0.05	0.05	0.05	0.05	0.05
1	2	0.49	0.46	0.45	0.41	0.44
2	3	0.54	0.58	0.56	0.61	0.57
3	4	0.65	0.72	0.66	0.71	0.69
4	7	1.19	1.30	1.25	1.34	1.27
5	9	1.28	1.42	1.44	1.40	1.39
6	11	1.54	1.55	1.62	1.63	1.59
7	14	1.72	1.70	1.73	1.74	1.72

[a] Plug load.