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Enabling energy-efficient approaches to thermal comfort using room air motion

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A B S T R A C T

In warm environments, room fans can provide comfort using substantially less energy than air-conditioning. The savings are greater if the fans make it possible to successfully condition the building with natural ventilation or evaporative cooling systems, instead of chillers. Although there are many laboratory studies of comfort using desk fans and personalized fans, tests for ceiling fans are rare, mainly in early studies from the 1980s. This study examines the cooling effect of a low-wattage ceiling fan on occupants when air comes from different directions with different speeds. We conducted 96 human subject tests in an environmental chamber. Sixteen college students each experienced 6 air movement conditions: two different air speeds and three different air directions between fan and subject: from front, side, or right above the head (total eleven configurations). The difference in thermal comfort and thermal sensation generated by fixed and oscillating fans was also investigated. The temperature and humidity conditions for the tests were 28 °C and 50% RH.

It was found that the majority of subject (70%) perceive the thermal environment without fans comfortable. This number rise to 100% for some configuration with fans. Our subject found that the oscillating air movement had no effect in terms of improved thermal comfort or thermal sensation, but it greatly improves their air quality perception. The subjects did not report any dry eyes discomfort for any of the eleven configurations.

1. Introduction

Compressor-based air-conditioning is the second largest consumer of electricity in US commercial buildings, exceeded only by electrical lighting (141 billion kWh vs. 393 billion kWh), [1]. In office buildings compressor-based cooling constitutes roughly 15% of total electricity consumption.

The amount of energy used to condition commercial buildings is increased by the tendency of building operators to maintain buildings at too-low ambient temperatures during warm seasons [2]. The overcooling was found to significantly reduce occupant comfort and even caused health symptoms [3]. There are a number of reasons for summer overcooling, but an important one is the insufficient air movement around occupants in conventional sealed office buildings [4,5]. Sealed designs with low air movement consistently show lower occupant satisfaction than offices with operable windows [6,7]. Although buildings with operable windows tend to have warmer interior temperatures than sealed buildings, the modest increase in indoor air movement that they provide gives them comfort ratings superior to those of sealed buildings.

This suggests one can reduce cooling energy demand by allowing a building to float within an expanded indoor temperature range while maintaining the occupants' thermal comfort by providing air movement using fans. Fans of very low wattage (as low as 3 W) have been shown to yield the equivalent of 3 K offset of air temperature within an individual workstation [8]. Buildings employing such fan cooling promise substantial savings in their heating, ventilation, and air conditioning (HVAC) energy, more than 30% below that of conventionally conditioned buildings [9–11]. The energy savings may be even greater if the warmer setpoint temperatures enable the primary cooling source to be switched from a compressor-based system to one of the more efficient and lower-power approaches, such as natural ventilation or evaporative cooling. Room fans may be readily applied in both new and retrofit designs since they can be easily installed and the savings can be achieved by only changing HVAC system setpoints.

Since the1960's, the use of air movement to maintain thermal comfort in warm conditions was impeded by strict limits to air

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movements in thermal comfort standards (e.g. ASHRAE 55-1992, 2004 and ISO 7730). This has led to almost no innovation in designing interiors to use air movement, and only modest innovation in industrial products that move air. However, in recent years, the air movement requirements in these standards have been revised to permit higher indoor air speeds, following the results of extensive field and laboratory studies (ASHRAE 55-2010 [12]). The revisions pave the way for the above mentioned 30% reduction in HVAC, and also for significant reduction in their peak power demand. They also enable more individual environmental control and the good levels of occupant comfort already observed in naturally ventilated buildings with fans in warm and humid climates [9,13–17].

The ASHRAE database of comfort field studies [4,5,18,19] shows that more occupants prefer more air movement, while very few prefer less, when environments are in the range of slightly cool to slightly warm. The challenge becomes how to implement indoor air movement devices within the interior space, so that they are: highly energy efficient, comfortable and acceptable to occupants, visually attractive to building management and designers, and straightforward to design. For this purpose we integrated a head of an oscillating floor fan into an acoustical ceiling panel, and performed this study to characterize the thermal responses of occupants under different subject-fan positions, different air velocities, and fixed vs. oscillating fan settings. This is just a first step toward a new generation of ceiling integrated fans that can satisfy users' demand for comfort and reduce building energy consumption. This study proves the effectiveness of these devices and lets industry to move the next steps, especially for what concern a visually attractive design that would facilitate the use of fans in offices.

Another objective of this study is to investigate the effect of an intermittent air movement on subjects' thermal comfort and thermal sensation. There are no examples in literature of studies that considered this type of airflow.

2. Method

The experiments were carried out at the Center for the Built Environment (CBE), University of California at Berkeley, between August and September 2012.

2.1. Chamber setup and the ceiling fan

We set up 4 workstations in the chamber (Fig. 1) with two fans. One fan was set in a way to provide airflow toward heads and faces of the two subjects' (we call it "front" in this paper). The other fan provided airflow towards sides of heads of the two subjects' (we call it "side" in this paper).

For this study two prototypes of oscillating ceiling fan were made (circled in red (in the web version) in Fig. 1). The fan motor and propeller are commercially available, while the structure to integrate the fan into the ceiling panels was custom fabricated. These fans were selected due to their excellent energy efficiency, with an energy consumption that ranges from 2 W to 15 W, and because they are extremely quiet. No difference in terms of dBA was measured with the chamber ventilation system turned on between fan on and off. The average noise level was always around 33 dBA.

The fan power can be set among 7 levels. The oscillation angle is 90°, and the fan oscillation period is 28 s.

2.2. Subjects and test conditions

Human subjects were tested to evaluate comfort for warm conditions (28 ± 0.3 °C). The relative humidity of the chamber was kept at 50% ± 1%.

Four workstations were installed in the Controlled Environmental Chamber at UC Berkeley so that four subjects could be tested at the same time. The chamber size is 5.5 × 5.5 m, with windows on two sides, south and west. The windows are well shaded by fixed external shades. The windows temperature was controlled by a dedicated air system. The room air temperature is controlled by 8 floor grille diffusers, and the air is exhausted through a 0.6 × 0.6 m ceiling return grille.

Several configuration were studied, the subjects experienced two different air velocity and three different air directions, plus the oscillation feature. A schematic representation of all the different configurations and their configuration codes used in the analysis is presented in Table 1.

Sixteen subjects (8 females and 8 males) participated in each of the ten test conditions, plus one test without fans. During a single test the subjects experienced two different configurations, one in the first part of the test and one in the second, except for the configurations "2 Fixed Below", "3 Fixed Below" and "No-fan", which were tested singly. See the column "Test number" in Table 1. When two configurations have the same test number means that they were tested during the same session. The total number of tests was 112. The tests without fan (in this paper called no-fan) provided reference conditions for comparison with the tests with the fans.

Subjects were asked to wear summer clothing (0.5 clo), and their clothing were checked before every test to guarantee the right clo value.

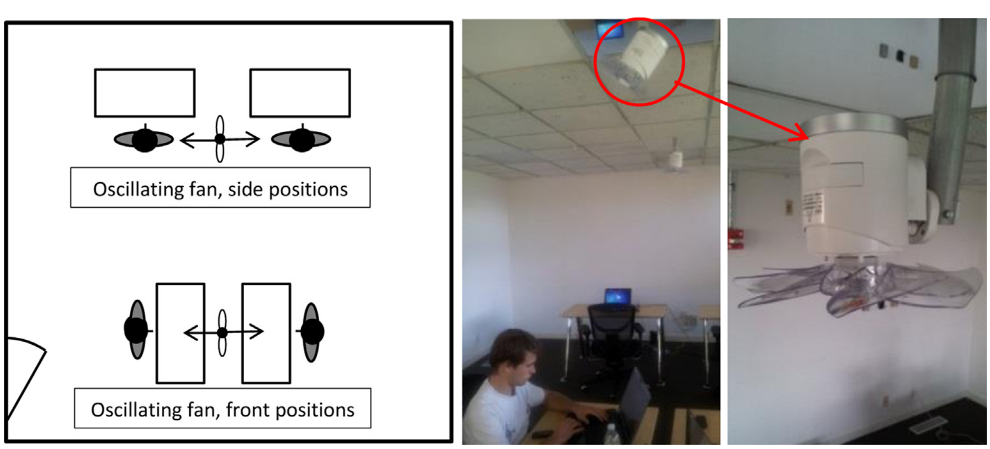

Fig. 1. Chamber set up and ceiling fan prototype.