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Cooling efficiency of a brushless direct current stand fan

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ABSTRACT

In warm environments, isothermal cooling by deliberately enhanced air movement can maintain thermal comfort using less energy than compressor-based air conditioning. To evaluate the performance of a brushless direct current (DC) stand fan, the cooling fan efficiency (CFE) index was measured in a climatic chamber under four dry-bulb temperatures (24, 26, 28, and 30 °C), six speed settings (corresponding to centreline speeds in the range 0.6–2.5 m/s at 1 m distance), two fan-manikin distances (1 and 2 m) and two orientations (front, side). The CFE index is defined as the ratio of the whole-body cooling effect generated by non-uniform airflow from the fan to its power consumption (°C/W). The CFE index overcomes the limitations of assessing the cooling effect based just on a few air speed measurements. The results show that the CFE index is influenced by dry-bulb temperature, fan speed setting, and fan-manikin distance, but not by fan-manikin orientation. The lower the temperature and the closer the fan, the higher is the CFE index. Increasing fan speed setting simultaneously enhances whole-body cooling and increases power use. Consequently, the CFE has a non-monotonic relationship with fan speed setting and the peak value is reached for an intermediate speed. As compared with previous testing results using an alternating current stand fan, the CFE index of the DC fan we tested is three times higher. As a complement to air-conditioning, the tested stand fan is a suitable energy-efficient technology for providing thermal comfort in warm environments.

1. Introduction

Elevated air speed is an effective method of cooling people in moderately warm indoor environments. An electrically powered mechanical fan can be used to enhance air speed near people to cool them. Cooling fans can be used instead of, or to augment, compressor-based air-conditioning systems to contribute to occupant thermal comfort by means of isothermal cooling [1–3]. Furthermore, personal control over one's thermal environment can increase comfort, satisfaction and self-reported productivity [4–6]. Cooling fans are well-suited to provide personal control. Cooling the human body by means of elevated air movement under high dry-bulb temperature conditions contributes to substantial energy savings [7–9]. In cold environments, elevated air movement causes draft, defined as unwanted local cooling [10]. However, elevated air movement can enhance thermal comfort in warm environments [3,11–19]. The use of fans for cooling may be more feasible in tropical than in temperate climates because tropically acclimatized people prefer slightly higher air movement and slightly cool thermal sensation [7,20]. A comprehensive literature review on thermal comfort research conducted over the past twenty years has documented the theoretical and empirical support for using cooling fans [21]. Thermal comfort standards [22–24] allow for an increased indoor temperature to be offset by elevated air movement. Although perceived air quality is negatively affected by elevated temperature and relative humidity [25,26], perceived air quality is improved by elevated air speed [26–29].

Appearance, control options, and price are important parameters to be considered when purchasing cooling fans. However, little quantitative information is available regarding the cooling capacity

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and energy efficiency of fans. Comparing the performance of cooling fans from the point of view of cooling capacity and energy consumption is important for their application in practice, including their implementation as a means of providing thermal comfort in an energy-efficient manner. To address this issue, Schiavon and Melikov [30] introduced the cooling fan efficiency (CFE) index, defined as the ratio between the fan-generated whole-body cooling effect (as measured with a thermal manikin) and fan power consumption. The CFE index allows one to objectively compare cooling fans in terms of their ability to cool people in an energy efficient manner. Schiavon and Melikov measured the CFE index for four fans (ceiling, desk, stand, and tower) in a real office at three dry-bulb temperatures and at different fan speed settings. The results revealed that the CFE index is sensitive enough to identify differences in the performance of the cooling devices and that the cooling fans generate a non-uniform velocity field around occupants, which cannot be described with a single air speed. Schiavon and Melikov did not test either the effect of fan-manikin distance or the effect of fan-manikin orientation on the CFE index; therefore, the influence of these parameters on the CFE index is unknown. This knowledge gap is pertinent, because cooling fans that are under the direct control of people, such as desk fans and stand fans, can be used at different distances and with different orientations.

Fans that use brushless direct current (DC) motors are more energy-efficient than fans that use alternating current (AC) motors [31–33]. Motor operation depends on electromagnetic force, which is induced by rotor winding. Electromagnetic force has to be kept in the same direction. For AC motors, the direction of the stator's magnetic field is changed; for brushed DC motors, the current is reversed. In a brushed DC motor, a brush commutator is needed to reverse the current. In brushless DC motors, an electronic device, such as a semiconductor inverter, replaces the commutator. Brushless DC motors last longer, have low electromagnetic noise and are energy efficient. Brushless DC motors also can modulate speed easily and smoothly [33].

Most of the cooling fans available in today's markets use AC motors because the manufacturing cost is currently lower than for brushless DC motors. To focus on the potential energy efficiency of fan-enhanced cooling, the present study evaluates a commercial cooling fan (Airmate S35113R) that employs a three-phase brushless DC motor. The fan has 24 speed settings and its peak power use is 17.3 W, which is less than half that of comparable AC fans. To our knowledge there have been no prior assessments of the cooling effect and the CFE index of brushless DC fans.

The aims of this research are to test the performance of a brushless DC fan utilizing the manikin-based equivalent temperature, fan power consumption and CFE index and to assess the effect of input parameters including fan-manikin distance and orientation on the CFE index. The CFE index for the brushless DC fan is quantitatively analysed and compared with values for the AC fans previously tested.

2. Methods

2.1. Experimental facilities

The experiments were carried out in the Field Environmental Chamber (FEC) at National University of Singapore (NUS). The dimensions of the FEC are 11.0 × 7.8 × 2.6 m (volume = 223 m^3). It provides accurate control of dry-bulb temperature, t_a (±0.5 °C), and relative humidity, RH (±3%). The FEC has an east-facing wall consisting of glass panels, which are attached with solar block film and equipped with internal blinds to reduce heat gain from solar radiation. The outdoor air temperature was between 31 °C and 32.5 °C during the period of study. Room air temperature was controlled by a variable air volume (VAV) air conditioning system. Relative humidity does not affect the thermal manikin measurements described below, and therefore it was not controlled, but it was continuously measured. One workstation was located at the centre of the chamber, which is far from the windows and supply air diffusers, so as to minimize their effect on measurements. Based on previous experiments performed in this room, the mean radiant temperature could be assumed equal to the dry-bulb temperature since the workstation is far from windows and there are no other significant radiant sources.

A three-phase brushless DC stand fan was used. The fan was situated in one of four positions: at 1 or 2 m distance (corresponding to 3 or 6 times the fan diameter) either in front of (zero degrees) or to the right of (ninety degrees) a dry-heat-loss thermal manikin. These distances and orientations were selected to correspond to common choices of users. The axis of the fan blades and motor are at 1.1 m height, equal to the breathing zone of a seated person. The fan consumes from 1.9 W (min speed) to 17.3 W (max speed), which generates air speeds from 0.05 m/s to 2.5 m/s at 1 m distance and 0.05 m/s to 1.3 m/s at 2 m distance, respectively (Fig. 1). The detailed relationship between fan speed setting, fan power, and air speeds measured at 1.1 m height at the target location for the two tested distances (1 and 2 m) are reported in the Supplemental Information (Table A). Turbulence intensities varied between 19% and 27% with a median value of 24%. Air speeds and turbulence intensities at the target point (breathing area) were measured without the presence of the thermal manikin.

2.2. Measuring instruments

Dry-bulb temperature and RH were measured with TSI (Shoreview, MN, USA) indoor air quality meter model 7545, with 0–60 °C measuring range, ±0.4 °C uncertainty for temperature, and 5–95% measuring range, ±3% uncertainty for RH. Air speed was measured using Dantec (Skovlunde, Denmark) Dynamics' ComfortSense System, with a response time of 0.5 s and uncertainty of 0.01 m/s ± 1% of reading. Fan power was measured by Yokogawa (Tokyo, Japan) digital power meter model 2534 with 0–5 kW measuring range and 0.1 W uncertainty. Uncertainty for measured and derived

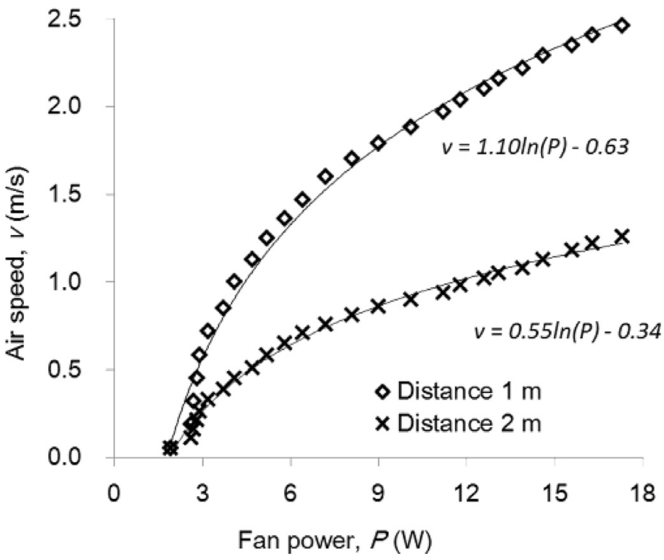

Fig. 1. Air speed (v) measured at 1.1 m height at the target location as a function of fan power (P) for the two tested distances between the fan and the target location (1 and 2 m).