Field Measurement on Skin Temperature and Thermal Comfort of the Human Body with Various Wind Directions

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Field Measurement on Skin Temperature and Thermal Comfort of the Human Body with Various Wind Directions

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Abstract: *The desk fan as a personal thermal comfort (PTC) device remains an effective thermal adaptation method for office building applications, offering indoor thermal comfort to occupants. However, there are research gaps related to its effect on the skin temperature of office occupants. This study addresses these research gaps by conducting field measurements inside an air-conditioned office room at a set point temperature of 29 °C, involving three stages of fan configurations: Stage 1 No-fan, Stage 2 Single fan, and Stage 3 Dual fan. The overall measurement outcomes noted that different configurations of air direction from desk fans successfully improved the occupant's thermal comfort from slightly comfortable to moderately comfortable by reducing the thermal sensation to 50%. Additionally, the air directions from the front and head were most preferred. The air movement lowered the skin temperature from 0.7 to 0.9 °C.*

Keywords: Personal thermal comfort; desk fan; skin temperature; air-conditioned office room; hot-humid tropical climate

1. INTRODUCTION

Excessive utilization of air conditioning (AC) in hot and humid areas results in substantial energy consumption and the discharge of detrimental gases such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), along with CO_2 emissions and depletion of energy resources [1]. Research conducted by Zaki et al. [2] and Damiati et al. [3] in Malaysia revealed that AC usage contributes to 50 to 57% of energy consumption in office buildings. This is primarily because occupants tend to set the AC temperature below the recommended comfort range of 24.6 to 26 °C. The substantial energy consumption, particularly from coal-fired power plants, leads to significant CO2 emissions and exhausts energy reserves, prompting the Malaysian government to adjust the thermostats of air conditioning systems in government offices to a temperature of 24 °C [3-5]. Research conducted in China has demonstrated that the building sector is accountable for more than 50% of the region's carbon emissions and close to 50% of its energy consumption [6-8]. In order to tackle these concerns, it is imperative to decrease energy consumption in buildings, and it is essential to design HVAC systems that are more energy-efficient without compromising on comfort. This issue is vital since the occupant's thermal preference or behavior towards HVAC usage determines the energy consumption [9, 10].

Another study conducted by Fernandes and Regnier [11] also supports this claim, emphasizing the necessity of reducing energy consumption by over 50% to achieve a reduction in carbon emissions compared to current levels. Zhai et al. [12] conducted a study that focused on the anticipated rise in energy consumption in commercial buildings. They estimated that there will be an annual increase of about 0.9 to 2.7% by 2035. Prior research has provided additional evidence supporting the aforementioned information, suggesting that carbon emissions from the building sector could rise from 12 to 37% by 2050 due to space heating and building cooling [1, 13]. As previously stated, the research indicated that it is essential to decrease energy consumption in the construction industry in order to effectively control carbon emissions and address future energy difficulties and climate emergencies. Hence, the HVAC design must employ energy-efficient methods to fulfil the thermal comfort standards and the occupants' preferences.

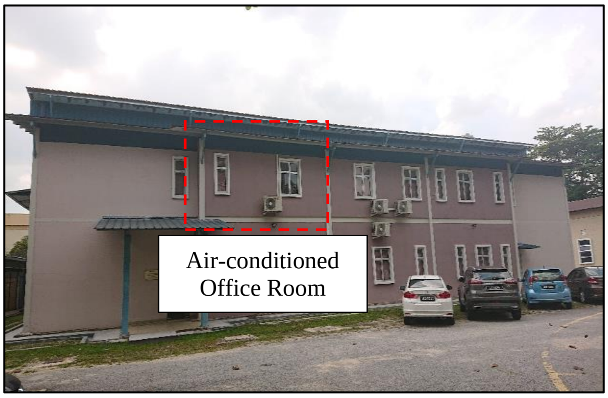
An effective strategy to decrease air conditioning usage in office buildings involves implementing the personal thermal comfort (PTC) approach, which aims to provide individualized thermal comfort [14, 15]. The PTC application proposes using air conditioning and desk fans at elevated temperature settings in an office setting. The utilization of a desk fan can effectively direct the airflow towards an individual, thereby enhancing personal comfort within their immediate vicinity. However, additional data from field experiments is needed to investigate the impact of air generated by desk fans from various directions on thermal comfort and its influence on skin temperature. Therefore, this study addresses the objectives through field measurements: to investigate the impact of additional air movement generated by desk fans from various directions on thermal comfort and its effect on skin temperature. The expected outcomes of this study highlight the importance of additional air movement from desk fan configurations for reducing thermal sensation and skin temperature to maintain the comfort level of occupants in the office room.

2. METHODOLOGY

2.1 Investigated Office Room

The field study was the air-conditioned office room of Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM), located in Kuala Lumpur. The study was conducted in a 26 m² office room equipped with desk fans to replicate real-life office conditions accurately. As depicted in Fig. 1 and specified in Table 1, the room featured a cassette-type air conditioner and two vertical windows facing the outside, a south-facing facade with a combined area of 1.9 m².

The study focused on a single-person office setup to create a localized thermal environment tailored to individual preferences, avoiding influence from other individuals. The main objective was to examine the impact of various air directions on a single person.



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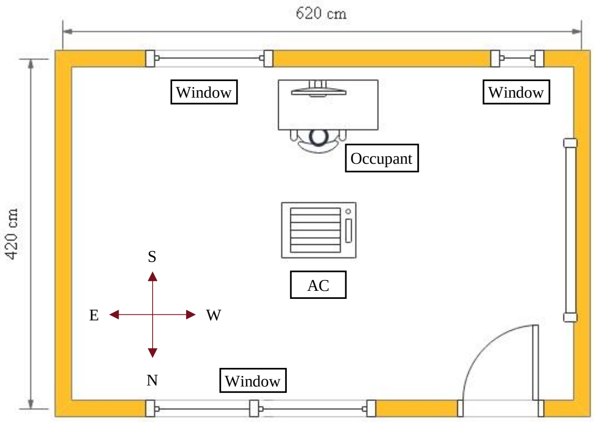


(b)

Fig. 1. (a) Front façade and (b) Floor plan of the air-conditioned office room

Table 1. Specification of air-conditioned office room

Components	Details
Office area (m^2)	26.04
Type of office room	Single occupant
Type of air-conditioner	Cassette
Orientation	South
Building material	Brick, cement plaster, plasterboard

2.2 Occupant Details

Occupants in this field measurement were healthy university students, 10 males and 10 females, aged 21 to 39. The occupants' body mass index (BMI) was recorded around 17.9 to 37.8 kg/m^2. Since the field measurement was conducted in the office, the occupant activities were limited to reading, typing, writing, utilizing phone and computer and sitting quietly, with an average metabolic rate of 1.1 met based on the ASHRAE standard. Furthermore, the average clothing value of male occupants was 0.37 clo and 0.57 clo for females.

2.3 Case Studies

The study involved ten case studies, divided into three stages, to examine the effect of different air direction configurations on occupants' thermal comfort and skin temperature in an air-conditioned office setting. Detailed information on these case studies and their average air speeds can be found in Table 2. In the first stage, the office was conditioned solely by an air conditioner set at 29.0 °C, without fans. The subsequent stages introduced single-fan and dual-fan setups, with desk fans placed 0.5 meters from the occupant to avoid thermal discomfort, as recommended by previous research. The fans used had a power rating of 15 Watts and a diameter of 15 cm.

Table 2. Case studies for field measurement

Stage	Configuration	Air Speed (m/s)
Stage 1	No-fan (Nf)	0.10
Stage 2	Front fan (Fr)	1.52
	Left fan (Lf)	1.54
	Right fan (Rf)	1.56
	Overhead fan (Hf)	1.52
	Leg fan (Lg)	1.51
Stage 3	Front and left fans (FL)	1.77
	Front and right fan (FR)	1.78
	Front and overhead fan (FH)	1.74
	Front and leg fan (FLg)	1.51

2.4 Instrument Setup

The actual condition during the field measurement is shown in Fig. 2. The field measurements were partially regulated by an air conditioner set to 29.0 °C. Four key indoor thermal parameters were recorded every 10 seconds: indoor temperature (T_i), globe temperature (T_g), relative humidity (*RH*), and air speed (V_a). The air speed data referred to that produced by desk fans placed around the occupant. To study the impact of air on skin temperature, the skin temperature (T_{skin}) was also measured using iButtons at a 3-minute interval.

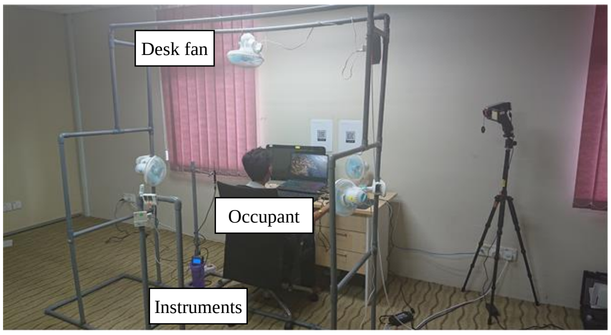


Fig. 2. Actual condition of field measurement involving occupant, desk fans and instruments

The indoor temperature (T_i) was measured using a TnD TR77-ui with an HHA-3151 sensor, which has a range of -30 to 80 °C and an accuracy of ±0.3 to 0.5 °C. Globe temperature (T_g) and relative humidity *(RH)* were recorded with a HOBO logger, equipped with a TMC1-HD sensor, capable of measuring temperatures from -40 to 100 °C with an accuracy of ±0.25 °C, and humidity from 10 to 90% with an accuracy of ±2.5%. Air speed (V_a) was measured using a Kanomax 6501-0G with a needle probe 6542-2G, which can detect speeds from 0.01 to 50 m/s with an accuracy of ±2% or 0.015 m/s. Skin temperature (T_{skin}) was compiled using an iButton D1923 embedded data logger, with a range of -20 to 85 °C and an accuracy of ±0.5 to 1.4 °C.

2.5 Field Measurement Procedure

The field measurement session consisted of two main sections: the initial conditioning process and the field measurements accompanied by case studies. Each occupant took part in two sessions conducted in an air-conditioned office room, with a gap of 3 to 4 weeks between the sessions. For example, if the initial session occurred in early September, the subsequent session was planned for either the third or fourth week of September. The purpose of this interval was to monitor the occupant's comfort reaction in different weather conditions. Appointments were arranged from 09:00 to 17:00, each lasting around 2.5 to 3 hours. The session commenced by adjusting the room temperature to 29.0 °C using an air conditioner, installing sensors such as the iButton, and conducting a compulsory briefing process.

During a compulsory briefing, the occupant was provided information regarding the field measurement procedure, case studies, and allowable actions, which also aided their adjustment to the surroundings. Since the occupant was involved in activities that required little physical movement and was wearing light clothing, they did not feel any additional discomfort caused by their clothing, dampness of their skin, or their metabolic rate. Following a 15-minute briefing and adjustment period, Stage 1 of the field measurement commenced. After 15 minutes of Stage 1, the occupant completed a thermal questionnaire, which assessed their responses to the thermal conditions (thermal sensation vote, TSV; and thermal preference vote, TP), air movement (air movement acceptability vote, WMA), and overall comfort (overall comfort vote, OC). Next, the experiment progressed to Stage 2, during which the occupant activated a single fan in accordance with the predetermined configurations outlined in the case study.

Following Stage 2, the occupant could take a 15-minute break, during which they could either rest or proceed immediately to the subsequent stage. During Stage 3, the occupant activated two fans using a procedure like the previous stages.

3. RESULTS AND DISCUSSION

3.1 Thermal Sensation and Preference with the Presence of Air from Different Directions

Fig. 3 displays the results of the thermal sensation vote (TSV) and thermal preference vote (TP) based on a 7-point TSV scale and a 5-point TP scale, respectively. The data includes responses from all occupants for two measurement sessions. The results of this study demonstrate a strong correlation between fan configurations and indoor temperature, as evidenced by a p-value of less than 0.001. The no-fan configuration had an overall TSV of 0.6. Approximately 48% of the respondents voted neutral on the TSV questionnaire, while 45% voted slightly hot (+1). Conversely, 55% and 20% of votes in TP indicate a preference for cooler (-1) and much cooler (-2) thermal conditions, respectively. This outcome indicates that even if the respondent has already voted Neutral (0), they still desire a cooler environment. This implies that the neutral vote does not truly reflect acceptance of the thermal sensation.

In terms of thermal acceptability, an additional finding revealed that 48% of the votes expressed dissatisfaction with the presence of air movement in the absence of a desk fan. Nevertheless, the participants demonstrated the ability to accept the thermal conditions in this particular setup. This fact underscores the significance of air circulation in preserving comfort, as shown in the earlier studies conducted by Yu et al. [7], Zhai et al. [16], and Zhang et al. [17]. According to the findings above, most respondents reported feeling slightly comfortable (rated as 3 on the scale) during the no-fan configuration. Nevertheless, the respondents also express a desire for increased air circulation. This finding supports the need for increased air circulation in response to a higher temperature in office rooms.

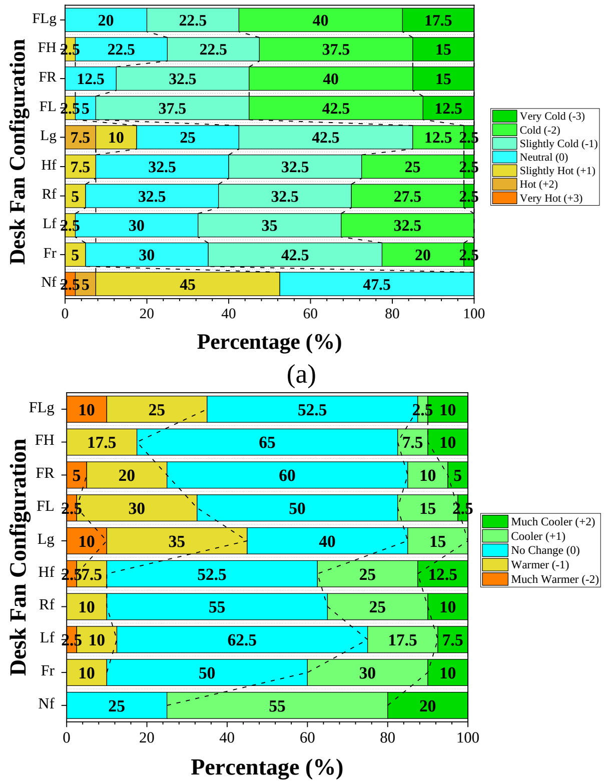


Fig. 3. Result of (a) thermal sensation vote (TSV), and (b) thermal preference vote (TP) compiled from thermal comfort survey

Figure 4 displays the percentage of votes for air movement acceptability (AMA) for each fan configuration throughout the entire measurement session. Most votes are concentrated within the blue bars for the fan configurations, except for the no-fan configuration. During the no-fan configurations, 48% of votes disapproved of the air circulation. These findings suggest that nearly 50% of occupants desired increased air circulation in the air-conditioned office space, maintaining an average indoor temperature of 28.6 °C.

Specifically, the respondents express strong satisfaction with the air movement in the fan configuration. This is evident from Figure 4, which indicates that the acceptability vote for air movement ranges from 65% to 95%. Specifically, the level of dissatisfaction decreased by approximately 28% when transitioning from the configuration without a fan to the configuration with a desk fan in front. The acceptability percentage for Stage 1 configurations ranges from 65% to 95%, with the highest percentage observed during the head fan configuration. Moreover, the acceptability of air movement in dual fan configurations varies from 73 to 90%, with the highest acceptability observed when using the front and leg fan configurations. This study's findings align with previous research by Zhou et al. [18] and Zaki et al. [2], which also noted that participants desired more air movement, particularly in office buildings located in hot-humid tropical climates. Additionally, the previous study also showed that the air movements from front and overhead were most preferred by participants [19, 20].

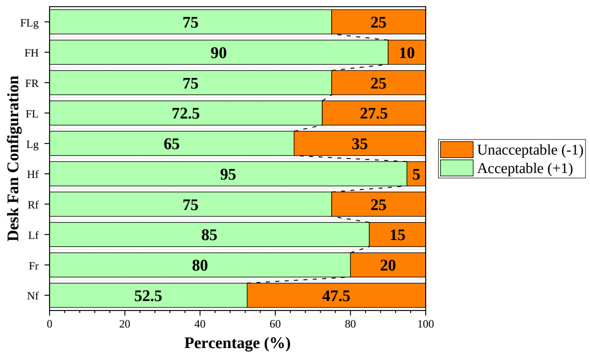


Fig. 4. Result of air movement acceptability vote (AMA) compiled from thermal comfort survey

3.2 Overall Comfort

Fan configurations improve air movement by directing airflow towards occupants' bodies. This study observed that occupants' acceptance of air movement increased with these configurations. Fig. 5 demonstrates the impact of personal thermal comfort (PTC) devices, such as desk fans, on occupants' overall comfort.

The study found that occupants' average overall Comfort (OC) ranged from 2.27 to 2.8 across various fan configurations, except for the leg fan. Similarly, Zhou et al. [18] noted that using a personal standing fan about 1.5 meters away maintained occupants' satisfaction with the indoor environment. Comparable results were reported by Tang et al. [21], Yang et al. [22], and Luo et al. [23], who found that PTC fans consistently reduced the perception of heat in indoor environments with temperatures between 29.0 to 32.0 °C.

The leg fan configuration results show that 35% of occupants were dissatisfied with the air movement, as shown in Fig. 4. This suggests a need for more air movement among certain occupants. Additionally, Fig. 9 reveals that 55% of occupants prefer a cooler environment, despite 57% of thermal sensation vote (TSV) responses indicating conditions ranging from slightly cold to cold. Fig. 5 indicates that occupants reported lower comfort levels during the leg fan configuration than others. This may be due to reduced airflow directed towards the upper body during the leg fan setup. Applying these findings to the current study, the dissatisfaction with the leg fan configuration could be due to insufficient air movement around the upper body. This highlights the variability in preferred air direction among occupants, with some preferring airflow towards the upper body. Therefore, these occupants might feel less comfortable and desire more air movement when the airflow is directed only at the legs. As shown in this study, the occupant felt comfortable even in the indoor temperature of 28.6 °C with the presence of additional air movement, ranging from 1.5 to 1.7 m/s. The previous research also found that the air movement above 1 m/s might increase the comfort temperature up to 3 °C [26, 27].

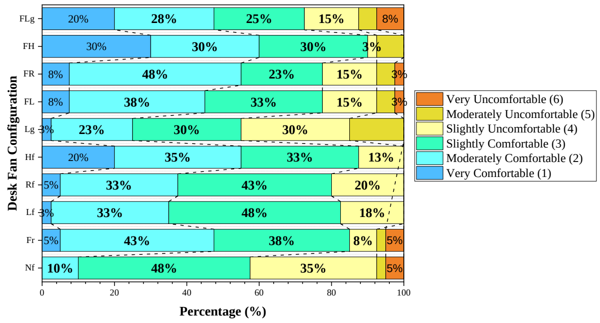


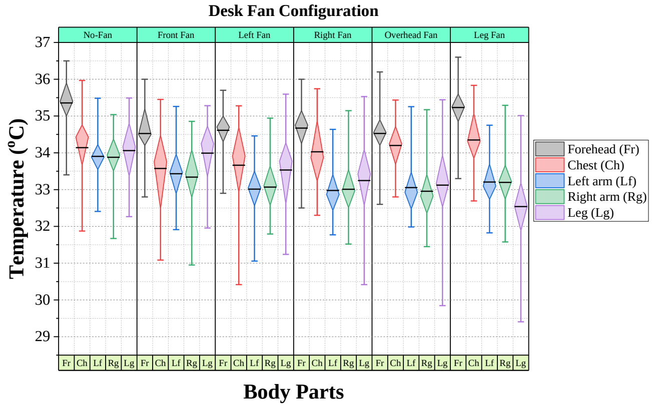
Fig. 5. Result of overall comfort vote (OC) compiled from thermal comfort survey

3.3 Skin Temperature of Occupant

Figure 6 illustrates the variation in skin temperature when there is no air movement and when there is additional air movement from different desk fan setups. The findings indicate that in the absence of a fan, the skin temperatures varied between 33.9 and 35.4 °C, whereas using a fan reduced 0.2 to 2.0 °C. This suggests that air generated by fans could lower the skin's temperature. According to Luo et al. [23], the forehead is consistently the warmest part of the body in all fan settings. This supports their previous discovery that the head area, which includes the forehead, face, and neck, is more responsive to cooling.

The study occupants experienced a greater thermal sensation on their heads compared to other parts of their bodies, particularly at a temperature of 28.0 °C. The prevailing consensus was that the increased air movement enhanced thermal comfort at this temperature. Rissetto et al. [26] discovered a direct relationship between the perception of heat on the head and the preferred airflow direction, with a preference for air blowing towards the head and from the front fan. Luo et al. [23] discovered that desk fans effectively reduce forehead temperatures by 0.3 to 1.5 °C, which is a greater reduction than other body parts. The findings of this study indicate a consistent decrease in forehead temperature ranging from 0.3 to 1.2 °C when using a fan. The occupants generally expressed greater comfort with overhead and front-and-overhead fans. This can be attributed to the improved airflow around the head.

The chest temperature results are consistent with prior studies, indicating a range of 33.2 to 34.8°C when using personal fans. The chest responds more to cold stimuli than hot stimuli, as it cools down when the front fan is activated but not when the side fans are activated. Although the air was perceived to be less intense, occupants reported feeling comfortable with the airflow on their chests, which can be attributed to the cooling effect on their vital organs. The arm temperatures observed ranged from 32.5 to 33.8 °C, aligning with previous studies' findings. Fig. 6 illustrates that leg temperatures declined from 34.1 °C without a fan to 32.0°C when both front and leg fans were utilized. This observation validates the results reported by Luo et al. [29] regarding the lower temperatures of the legs. The occupants experienced a range of comfort levels with leg fans, from slight comfort to slight discomfort. They preferred increased airflow, particularly when both front and leg fans were used together.



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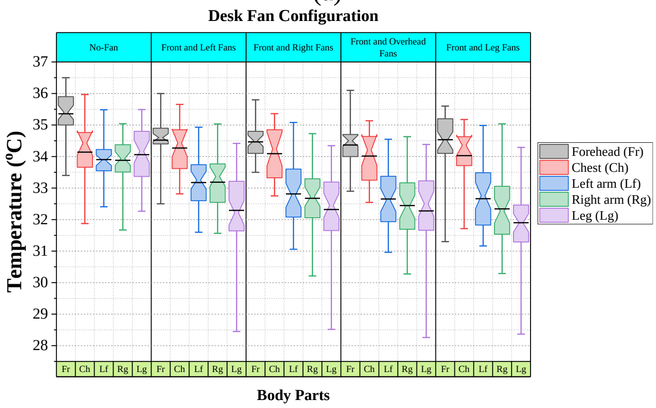

(b)

Fig. 6. Temperature of a body part during (a) No-fan and Single fan, (b) No-fan and Dual fan configurations

4. CONCLUSIONS

The study aimed to analyze the effect of additional air movement generated by desk fan configurations on thermal comfort and skin temperature. The findings indicate that the combination of desk fan usage and AC set point temperature of 29.0 °C, generating additional air movements ranging from 1.5 to 1.7 m/s, successfully reduced the heat sensation perceived by occupants by up to 50%. This combination resulted in overall comfort levels rated as moderately comfortable to slightly comfortable.

Occupants preferred air directions from the front and overhead to maintain thermal comfort. Desk fans effectively lowered skin temperature across various body parts, including the forehead, chest, arms, and legs. Without a fan, the average skin temperature ranged from 33.9 to 35.4 °C. When fan configurations were applied, these temperatures decreased to between 33.2 °C and 34.5 °C. The most significant temperature reduction was observed in the legs, while the chest area experienced the smallest decrease. This demonstrates that fan-generated airflow can significantly enhance thermal comfort by cooling the skin, with different body parts responding variably to the cooling effect.

5. ACKNOWLEDGEMENT

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