Personal Thermal Comfort Management in existing Office Buildings using Energy-efficient Fans

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***Abstract*—Recent studies have shown that using energy-efficient fans along with air-conditioning system provides a thermally comfortable environment for occupants at a reduced energy consumption in hot and humid climates. In this paper, a wireless sensor and actuator network (WSAN) is used to collect data regarding the usage of personal fans by occupants in an existing air-conditioned office-space room. The data are analyzed to gain insights on the use of personal fans with respect to temperature, time of the day and other factors. The field data are compared with the SET (Standard Effective Temperature) model outlined in the ASHRAE 55-2013 Standards which evaluates the cooling effect of increased air movement. The proposed work suggests guidelines on incorporating occupant preferences in a decentralized framework for better thermal comfort and improved energy savings in existing air-conditioned buildings.**

***Index Terms*—thermal comfort; wireless sensor and actuator networks; air movement; personal control**

I. Introduction

Air-conditioning systems account for more than 50% of the total energy consumption of commercial buildings in hot and humid tropical climate such as Singapore [1]. Recently, researchers have shown that there is a preference for more air movement among the people in hot and humid environments in both naturally-ventilated and air-conditioned buildings [2], [3]. The recommended design set-point in Singapore is between 23°C and 25°C [4]. Zhai et al. [2] report that the occupants in hot and humid climates are comfortable even at 28°C by providing elevated air movement through the use of fans. Moreover, it is well known that setting the thermostat set-point higher in tropical climates can result in significant energy saving [5]. The air-conditioning electricity consumption could reduce by about 3% for an increase of 1°C in the air-conditioned indoor temperature [6]. Enhancing the thermal comfort of occupants through the use of energy-efficient fans enables us to set the air-conditioning temperature set-point higher, resulting in lower energy consumption by the buildings. Although a number of studies have been conducted in climate chambers establishing the effectiveness of fans in providing better comfort and saving energy, implementation in operational buildings has not been advancing at the same pace. In this project, information regarding desktop fan usage among office occupants is obtained by deploying environmental sensors in a multi-occupancy office-space air-conditioned room. The occupants are provided with personally controlled fans integrated with a wireless sensor node and the data regarding the fan speed set by the occupants is collected for different temperature setpoints during the working hours. These data obtained are correlated with the environmental parameters and compared with the ASHRAE Standards 55-2013 SET (Standard Effective Temperature) model. The crucial factors to incorporating occupant preferences in order to enhance the thermal comfort of the occupants and gain energy benefits are discussed.

Section II discusses the recent advancements of utilizing wireless sensor and actuator networks as well as occupant feedback to better incorporate thermal preferences of occupants. In Section III and IV, the experiment setup details and the sensors employed are described. The experimental data analysis are presented in Section V highlighting the variation of the fan usage by the occupants with respect to temperature and time of day. In Section VI, the field data obtained are compared with the comfort zones estimated by ASHRAE 55-2013 Standards SET(Standard Effective Temperature) model. The energy usage consequences and limitations are discussed in Section VII and the paper is concluded in Section VIII.

II. Thermal Comfort in Buildings

Conventionally, the thermal comfort of occupants in built spaces is assessed by the Predicted Mean Vote (PMV) theory by P.O.Fanger [7]. According to this theory, the thermal comfort of the occupants depends on four environmental factors, namely *air temperature, relative humidity, mean radiant temperature, air velocity and two personal factors, namely clothing insulation (clo) and metabolic rate (met)*. If the calculated PMV (Predicted Mean Vote) lies between -0.5 to 0.5, then the thermal environment is considered to be comfortable and satisfactory for more than 80% of the occupants in that space. This PMV model is only applicable to air-conditioned spaces with air speed maintained at less than 0.2 m/s at all times. ASHRAE Standards 55-2013 [8] provides the guideline for assessing thermal comfort for elevated air speed ($>$ 0.2 m/s) by utilizing the SET (Standard Effective Temperature) model to find the adjusted PMV and consequently, comfort zone is said to be achieved when the adjusted PMV lies in the [-0.5,0.5] range. In the application of these thermal comfort models, the focus is on the environmental factors and the personal factors are usually assumed.

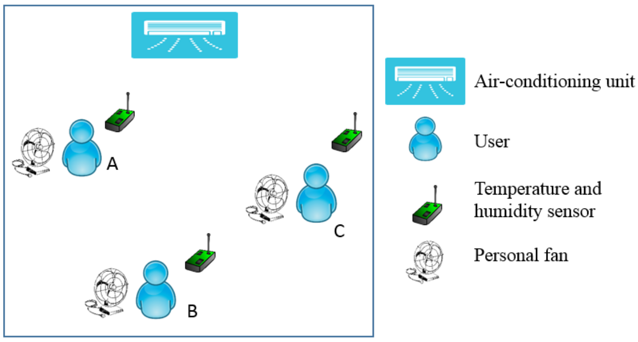

Fig. 1: Schematic of the WSN for personalised thermal comfort

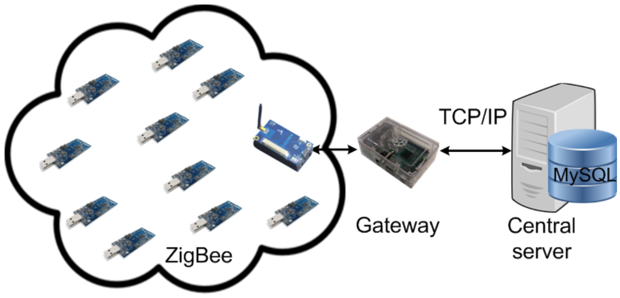

Fig. 2: WSAN architecture including wireless nodes, gateway and a central server

With the advancement in mobile computing and wireless sensor networks, it is now feasible to collect information about the local micro thermal environments inside the buildings and comfort feedback from the occupants even in operational buildings. Considering the fact that both new and existing buildings are increasingly becoming sensor-rich, many recent works have focused on developing a human-centric or occupant-driven thermal comfort strategies that also aim at reducing energy consumption of the air-conditioning systems. Most of these research works involve obtaining occupant feedback on thermal comfort through mobile or desktop devices, forming personalized comfort profiles and set-point scheduling by minimizing the discomfort or maximizing the comfort felt by the occupants [9]–[12]. Additionally, the papers also report reduction in the energy consumption of the air-conditioning systems as a result of implementing the occupant-driven set-point optimization strategies. The drawback of this approach is that these frameworks cannot be readily applied to existing buildings where the setpoint control through BMS (building management system) facility does not exist. In this paper, a decentralized approach is followed whereby the air-conditioning set-point can only be fixed at certain set-points and local cooling is employed to satisfy the occupant's thermal comfort. Some of the benefits of this approach as compared to the centralized approach are : (a) convenience of deployment in existing buildings (b) better incorporation of personal preferences as occupants have direct control to some extent over their local micro-environment and providing the occupants with control is known to have a positive effect on their satisfaction [13]. The schematic of this approach is shown in Figure 1.

III. Monitoring and Control System Description

In order to conduct the experiments, a wireless sensor and actuator network has been developed. The WSAN has the features of monitoring the ambient environment as well as enables the occupants to control their personal fans and then collects this user preferred set point input. The WSAN consists of multiple sensor and actuator nodes communicating with each other via ZigBee protocol [14]. Wireless communication facilitates easy deployment of the sensor and actuator nodes in the environment. Each node is equipped with a microcontroller board, a ZigBee module, sensing module, a driver board for controlling fan and power supply unit.

The sensor and actuator node transfers the acquired information to a base station, which is a single board computer and act as a gateway. This gateway is connected to a local area network that forwards the data to a central server. The server in turn can also send requests or control commands to the sensor and actuator nodes via the gateway. The system architecture of the WSAN is illustrated as in Figure 2.

A TCP client is executed at the gateway to communicate with the TCP Server application at the central server and exchange data. A MySQL database is setup at the server side to store the data for subsequent analysis.

IV. WSAN Deployment

The map of the office-space room where the experiment is conducted is shown in Figure 3 indicating the occupant and sensor/actuator nodes locations. The occupants are provided with a personal fan setup that consists of a commercially available DC fan integrated with a wireless sensor and actuator node that can log the interactions of the occupant with the fan. Whenever the occupant changes the speed of the fan, this information is sent to the server along with the time at which the speed was changed. The temperature and relative humidity near the operating area of the occupant are measured by the wireless sensor nodes. In addition to these parameters, outdoor temperature and CO_2 (carbon dioxide) concentration in the room are also monitored for the entire experiment period. The mean radiant temperature inside the room is monitored at two representative locations - one near the window and one far from the window as shown in the Figure 3. The environmental parameters are monitored every 2 minutes. The specific environmental sensors used and their measurement accuracy are given in Table I. Prior to the start of the experiment, the occupants are informed to set the fan speed according to their preference so that they feel thermally comfortable. The thermostat set-point of the air-conditioner is varied between 25, 26 and 27°C to create different thermal conditions. The temperature set-point 24°C and 28°C was found to be uncomfortably cold and hot respectively for certain occupants and hence are avoided in order not to

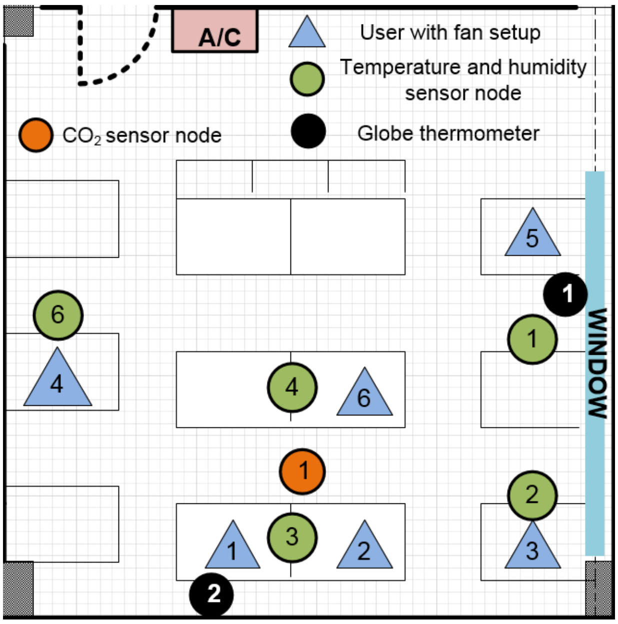

Fig. 3: Sensor deployment in the office-space room

Measured parameter	Sensor used	Accuracy
Temperature (°C)	Sensirion SHT11	±0.4°C
Relative humidity (%)	Sensirion SHT11	±3 %
Mean radiant temperature (°C)	PCE Heat Index WBGT Meter	±0.6°C
Air speed (m/s)	PCE Hot Wire Anemometer	±(5% + 1d) reading
CO_2 (ppm)	K30	± 30 ppm ± 3 % of measured value
Power (W)	Plugwise	1%±0.2W

TABLE I: Sensor type and measurement accuracy

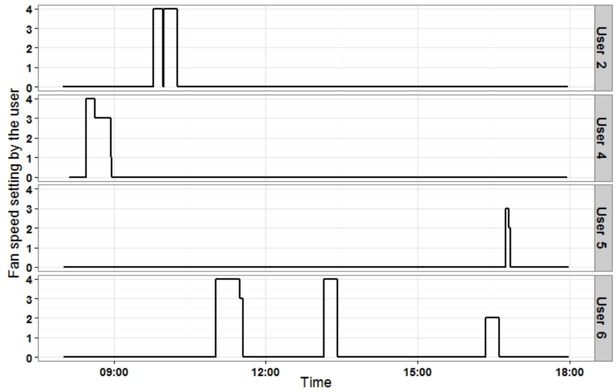

Fig. 4: Fan speed settings by the occupants on a typical working day

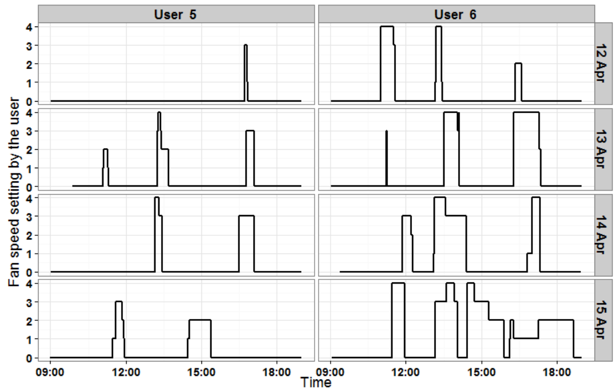

Fig. 5: Fan speed settings by the users 5 and 6 on different days

disturb the routine activities of the occupants. A total of six occupants were provided with a fan setup each including one experimenter. The air speed provided and the energy consumed by each of the fans for the different knob settings are measured beforehand. The average air speed and power consumption can be seen in the Table II.

V. Data Analysis

Figure 4 shows the fan speed settings by the occupants on a typical working day with set-point at 25°C. This figure shows the variation between the personal preferences of the occupants. The common factor between the occupants is that they use the fan only for a short period of time, presumably after a low-activity break where they move around the office (to get coffee, printing etc) or a high-activity break (such as going outdoors for lunch).

Fan speed setting	Air speed (m/s)	Power Consumption (W)
0	0	1.3
1	0.36	3.6
2	0.66	5.1
3	0.94	6.7
4	1.26	7.5

TABLE II: Air speed and power consumption of the fan setup for different knob settings

Figure 5 shows the fan speed settings for two occupants over different days. The set-point on days 12 and 13 was fixed at 25°C and the set-point on days 14 and 15 April was fixed at 26°C. The difference in the time of usage of the fan among the same user can be attributed to the fact that the experiments are conducted in the office-space room of a laboratory environment and occupants have a flexible work schedule.

Figure 6 shows the fan usage on the working days for variation in air temperature around the user. The fan speed settings are divided into 3 levels for easy visualization: OFF indicates fan is off, LOW indicates a fan speed setting of 1 or 2 and HIGH indicates a fan speed setting of 3 or 4. It is to be noted the temperature around certain occupants can be different from other occupants at the same time. Table III shows the observed air temperature values for different set-points around the users as measured by the closest temperature sensor node. The occupants seated near the window experience slightly higher temperature than the occupants in other areas

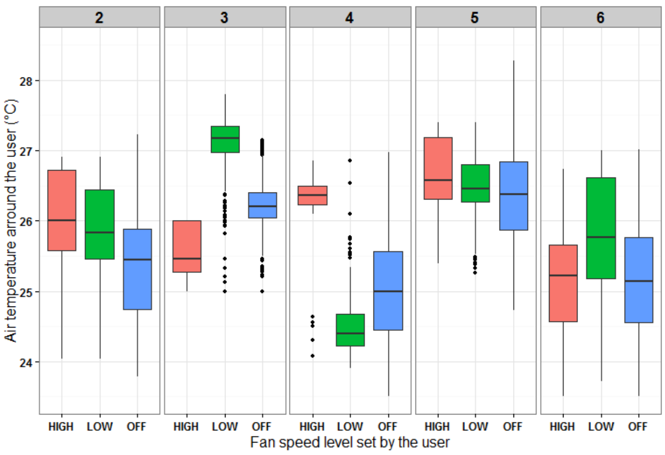

Fig. 6: Variation of fan speed settings with respect to temperature for two different occupants

Setpoint	25	26	27
User 1	24.6 ± 0.3	25.6 ± 0.3	26.7 ± 0.3
User 2	24.6 ± 0.3	25.6 ± 0.3	26.7 ± 0.3
User 3	25.1 ± 0.1	26.2 ± 0.2	27.1 ± 0.3
User 4	24.3 ± 0.3	25.1 ± 0.4	26.3 ± 0.3
User 5	25.7 ± 0.3	26.4 ± 0.2	27.3 ± 0.4
User 6	24.4 ± 0.3	25.3 ± 0.4	26.6 ± 0.3

TABLE III: Temperature measurements by the sensor closest to the occupant (all values in °C)

of the room. From Figure 6, it can be inferred that temperature alone cannot be the indicator of total fan usage as occupants run the fans at higher speeds even at lower temperature. Figure 7 shows the fan speed set by the users for two setpoints 26°C and 27°C. It can be seen that the occupants use the fans for a prolonged time when they experience higher temperature. This figure also highlights the varied preferences of high and low air speeds among the occupants. During the experiment period, the observed indoor relative humidity was $59 \pm 3.8\%$ and the indoor CO_2 concentration was 1360 ± 264 ppm. The average outdoor temperature for the experiment period was 33.6 ± 2.1°C. The difference between the black globe temperature and the air temperature as measured by the globe thermometers was ± 0.13°C for the sensor near the window (sensor 1) and was ± 0.12°C for the sensor far from the window (sensor 2).

VI. Comparison with ASHRAE 55-2013 SET model

The data obtained are compared with the comfort zones estimated by the SET (standard effective temperature) model described in ASHRAE 55-2013 standards. The SET model requires six inputs namely air temperature, relative humidity, air speed, mean radiant temperature, metabolic rate and clothing insulation rate. The air temperature values are taken from the measurements of the sensor node closest to the occupant. The black globe temperature measured at representative locations is close to the air temperature and hence it is reasonable to assume mean radiant temperature at all locations to be

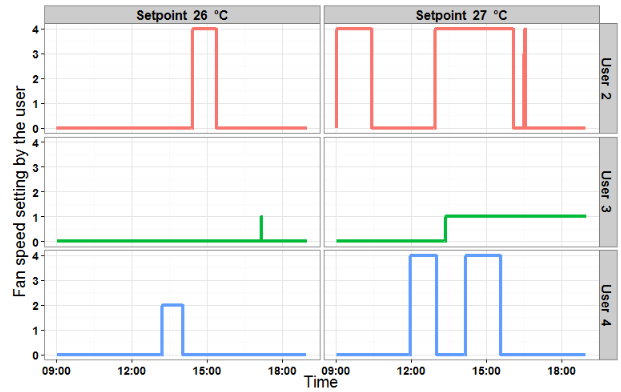

Fig. 7: Fan speed settings by the 3 users (2,3 and 4) for two different setpoints (26°C and 27°C)

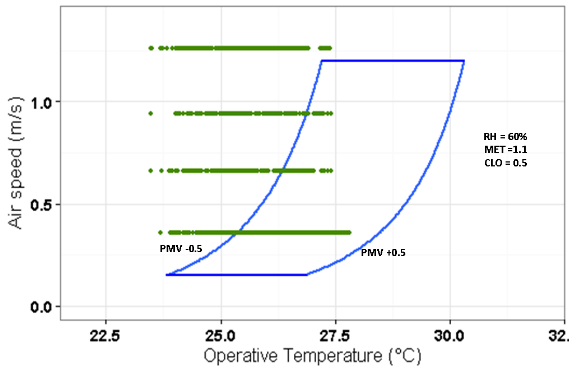

Fig. 8: Comparison with ASHRAE 55-2013 SET model comfort zones

the same as air temperature. The air speed for different fan settings are taken from the Table II. The SET based comfort zone is plotted as the blue contour lines in Figure 8 for relative humidity value of 60%, metabolic rate is assumed to be 1.1 met (typing) and clothing insulation is assumed to be 0.5 clo (summer indoor). The adjusted PMV values are calculated for each data point and if this adjusted PMV lies between -0.5 and 0.5, it is considered to be comfortable for the occupant according to the SET model i.e the interior of the blue contour lines is the comfort zone. Since the occupants were informed beforehand to set the fan speed for comfortable environment, any field data point (represented by the green dots) is considered to be comfortable for the occupant as per occupant preference. It is to be noted that the data points for the fan speed setting of 0 or when the fan is off are not included in this comparison. As seen in Figure 8, the field data points that lie outside the comfort zone predicted by the SET model are in the area of lower temperature and higher air speed. This is evident from the earlier observation that the occupants use fans at lower temperature to restore comfort after breaks and this is not reflected in the SET model.

VII. Discussion

The data analysis helps to gain insights regarding the usage of personal fans by occupants in a typical multi-occupancy air-conditioned office-space room. The following observations can be made from this study.

1) The occupants use the fans to restore comfort after low-activity and high-activity breaks and there are individual differences on the pattern of usage. This follows the results in [2] where the authors report that the thermal comfort could be restored immediately after turning on the fans for low-activity breaks and within 5 minutes for high-activity breaks. The duration during which the fans are ON increases as the temperature increases. To track the usage of fans more effectively, a presence detection mechanism needs to be in place which can detect not only the presence of the occupants but also the time of arrival, low activity and high activity breaks. There is extensive research conducted in the occupancy detection and tracking in buildings [15]. The presence detection mechanism can be utilized in conjunction with the environmental sensing to obtain more comprehensive information about the use of personal fans.
2) The highest mean temperature set during the experiment is 27°C. Some occupants expressed dissatisfaction over the environment for this temperature indicating eye dryness and stuffiness, hence it was not feasible to check for higher temperature set-points. The fan used is small desktop fan that could cause local discomfort for prolonged use. A better design for the fan or personal ventilation devices can help alleviate the local discomfort issues. In addition, the humidity and CO_2 observed during the experiment are relatively high for the indoor environment levels. These factors could also have contributed to the discomfort at higher temperature even with the personally controlled air movement.
3) The occupants have varied preferences of using the fans and the fan speed settings for the same environmental conditions. Providing a uniform environment will not improve the thermal comfort of the occupants. In the case of multi-occupancy smart indoor environments, a decentralized approach that learns the occupants preferences and directly controls the local cooling device near the occupant is more appropriate than a centralized approach which aggregates the individual preferences and then sets an optimal environment for all occupants. In addition, as mentioned earlier, providing the occupants with control is known to improve satisfaction levels.
4) The use of fans in conjunction with the air-conditioning systems not only serves to improve occupant comfort but also opens up the opportunity for energy savings in existing buildings. The air-conditioning systems can be operated at an elevated temperature to save energy while the personally controlled fans provide preference-based comfort to the occupants. In general, the energy consumption of the air-conditioning system decreases as the indoor temperature is closer to the outdoor temperature. However, for higher indoor temperature setpoint, the fans needs to be operated at a higher speed or for a longer time and there will be an increase in the energy consumption of the fans. Hence, to maximize the energy benefits obtained from using air-conditioning and fans in co-ordination without affecting the comfort of the occupants, optimal conditions of both air-conditioning setpoint and fan speed settings needs to be calculated. In addition, several other factors like relative humidity, air quality and local discomfort needs to be considered for the well-being of the occupants.
5) Most of the thermal comfort models including the ASHRAE Standards PMV and SET models are steady state models that estimate the thermal comfort of the occupants in steady state thermal environment. In the office building scenario, it is necessary to consider the times when the occupants have elevated metabolic levels after the breaks. In [11], the authors train the time taken by a person to recover from active to sedentary state by using the occupant feedback on thermal sensation. Such models could be integrated into the existing steady state models to account for the thermal comfort of the occupants for the whole working day.

VIII. Conclusion

This paper implements a WSAN to collect data regarding the personal fan usage of the occupants in an air-conditioned office-space room. The data collected are analysed to investigate the effects of the environmental parameters on the usage of the fans. Initial results reveal that detecting the low-activity and high-activity breaks is crucial to understand the occupant preferences for the whole working day. The important factors that need to be taken into account for the use of personal fans in air-conditioned buildings and the energy consequences are discussed. The future work will be focused on learning of occupant preferences and optimal control of the individual fans while considering total energy consumption. The developed WSAN enables both manual control by the occupants as well as the automated control by the central server. Hence, the response of the occupants to smart indoor environments can also be assessed in the same framework.

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