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Energy Saving Using Ceiling Fans in Environmental Comfort Systems

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Abstract

Residential and commercial buildings represent a substantial load for electric energy systems. Being the HVAC comfort system of a building an important energy load, its optimization is fundamental for energy-efficient buildings. The literature, supported by theoretical models and simulations, has reported that ceiling fans can save energy when correctly used in HVAC systems. The breeze created by the fan in a room can influence the thermal comfort sensation of the occupants in such way that the air conditioner thermostat can be set some degrees higher in the summer or lower in the winter. This paper aims to present experimental evidences, statistically supported, that the presence of a fan running in a thermally controlled ambient allows to increase the temperature without reducing the thermal satisfaction level of the occupants. The first results have shown that, for an $18m^2$ room, with three occupants, such increase is about three-Celsius degree, saving 0.9 kWh.

Keywords: Ceiling fans, Energy efficiency, Thermal sensation, Thermal comfort.

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1. Introduction

Residential and commercial buildings represent about 30% to 40% of the electricity consumption of the power grids. Heating, Ventilation and Air Conditioning (HVAC) comfort systems account for 39% of the energy consumed in commercial buildings [1-3]. Then, HVAC system optimization plays an important role in energy-efficient buildings design.

The literature has reported the possibility of energy saving when increasing cooling setpoints and decreasing heating setpoints of the HVAC system without a reduction in the occupants' thermal comfort by using individual comfort systems like ceiling and desk fans, foot warmers, heated or cooled seats and workstation surfaces [4-5].

By using parametric simulation study of seven climates and six model types, with empirical corroboration, Hoyt at al. [4] has reported the benefit of widening thermostat heating and cooling setpoints to save energy in a typical medium office building. By increasing the cooling setpoint of 22.2°C to 25°C, 27% of HVAC energy saving was achieved. Reducing the heating setpoint of 21.1°C to 20°C, saves an average of 34% of terminal heating energy.

By using the Predicted Mean Vote model (PMV), Lee et al. [5] has reported that, in the summer, the use of a ceiling fan can allow a increasing of 2.2°C in the setpoint of an HVAC system thermostat without difference in the user comfort. This increase can cut cooling costs from 8% to 16 %.

The human thermal sensation and comfort are subjective concepts, but can be indirectly measured and quantified [1, 6, 7]. It can be said that HVAC systems are not used for heating nor cooling, but for providing the thermal comfort, decreasing the occupants' warm sensation in the summer and cold sensation in the winter. A common interaction with the comfort systems is the choice of the temperature setpoint. The decision to change the temperature setpoint is a reaction of the environment occupant against the thermal discomfort sensation. It is known as the adaptive principle which states that if a change occurs, producing discomfort, people react in ways that tend to restore their comfort. The speed of the air surrounding the occupants' skin is one of the factors that influence the thermal comfort sensation [1, 6, 7], thus, a fan can influence the temperature setpoint value choice and the different setpoint can make a difference in the energy consumption of an HVAC thermal comfort system.

This paper aims to present experimental evidences, statistically supported, that the presence of a fan running in a thermally controlled ambient allows to increase the temperature without reducing the thermal satisfaction level of the occupants. Thus, to evaluate the thermal sensation, experiments have been carried out using volunteers (human in the loop) in a thermally controlled small room.

Once the thermal sensation is a subjective response to be evaluated, another objective of this research was to design an instrument to quantify the volunteer's thermal sensation according to the average room temperature.

2. Materials and Methods

Two experiments were carried out in two days. In both experiments the room temperature was increased from the natural condition, about 23°C to a higher temperature, about 33°C, by means of a 2500W heater. For the second experiment a 60W pedestal fan was added, operating at its maximum speed. The main idea was to compare the hot sensation in both cases.

Three students, two males and one female, occupied the room during the experiments. This room was properly equipped with five temperature sensors, one on each desk and two on different points; humidity, CO_2 concentration and volatile organic compound sensors. This room is shown in Figure 1.

It was developed a measurement instrument to gather the thermal sensation of the people taking part in the experiment. This instrument is a chart containing ten, one for each measurement, linear scales varying from -10 to +10, being -10 the maximum cold sensation and +10 the maximum hot sensation and zero the neutral point of this scale. Figure 2 shows this instrument.

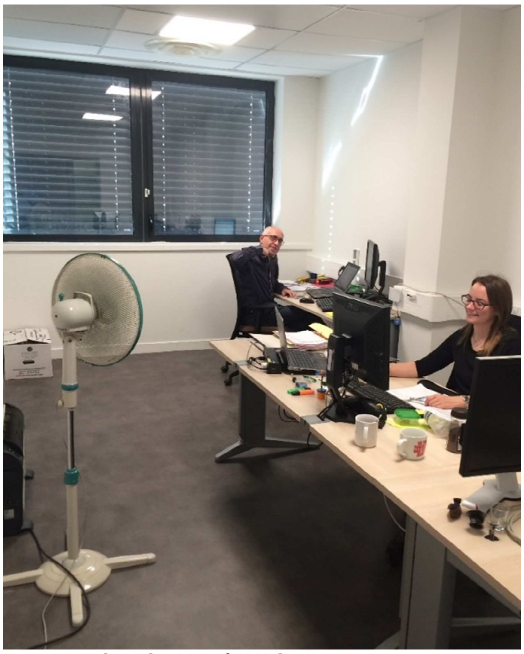

Fig. 1 - Room of 6m x 3m where the experiments have been performed.

2.1. Experiment Flow

At the beginning of each experiment, the students were asked to put a mark on the first scale of the chart, according to their thermal sensation. If they are feeling hot, they should put a mark above zero, if they are feeling comfortable, they should mark on zero, otherwise they should mark below zero, according to the intensity of their sensation. They were asked to do the same for each degree of temperature increase until the end of the experiment.

At the end of the experiment all instruments were collected and the information stored in a matrix to perform an analysis of variance (ANOVA) to determine whether there are differences among the thermal sensation means.

Once the ANOVA showed that temperature does affect the thermal sensation, as expected, it was performed the Tukey’s test to identify the differences between the means, and at which temperatures they occurred.

The experiment flow chart is shown in Figure 3.

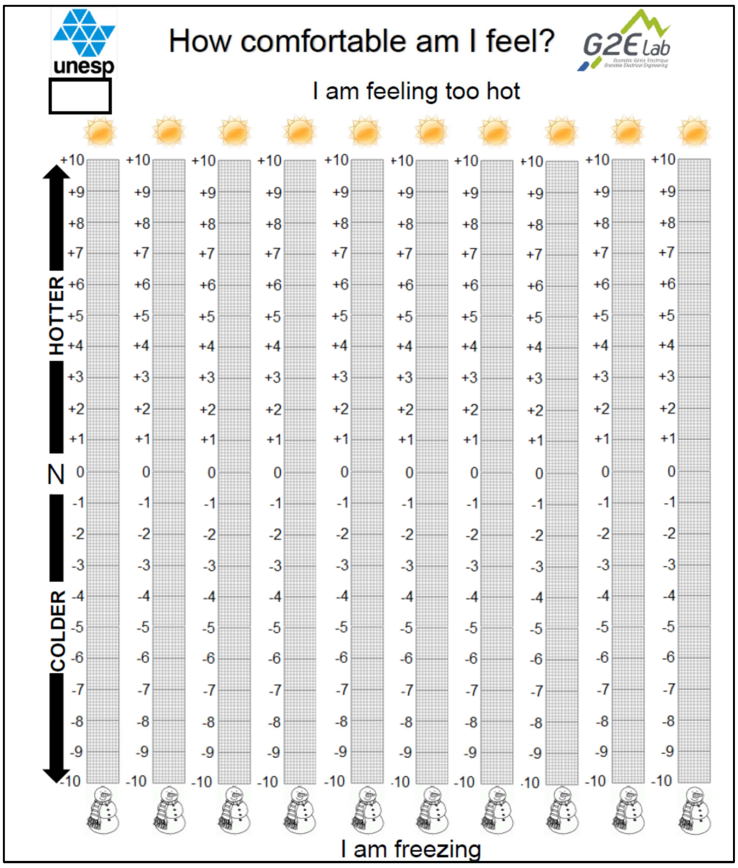

Fig. 2 – Measurement instrument designed to gather people thermal sensation

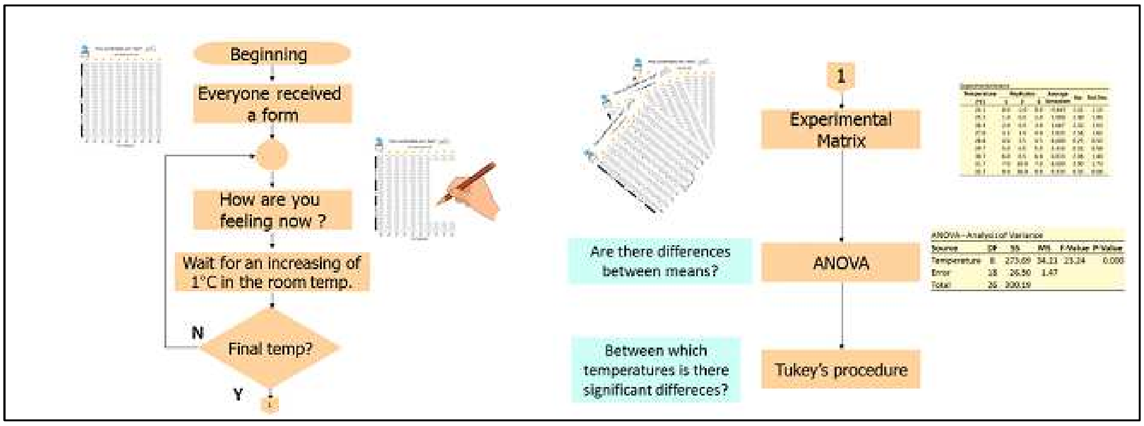

Fig. 3 – Experiment flow chart

3. Results

3.1 Heating the room

In both experiments the room was heated by a 2500W electrical heater. The evolution of room average temperature is shown in Figure 4. During this measurement, the heater average power was 2553W. To increase the temperature of this room in 1°C it took 1424 s.

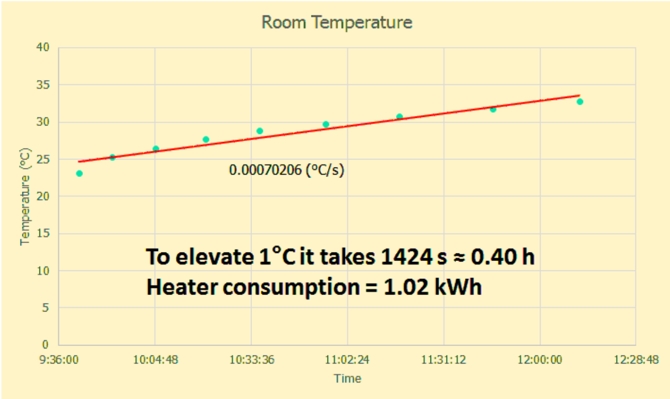

Fig. 4 – Room average temperature during the first experiment

3.2 Results from the first experiment – Fan turned off

The results from the first experiment (Fan off) is shown in Table 1. The three participants' thermal sensation was measured for nine different temperatures.

Table 1 – Participants' thermal sensation for nine different temperatures with the fan turned off

Temperature (°C)	Replicates 1	2	3	Average Sensation	Var	Std Dev
23.1	0.0	-2.0	0.0	-0.667	1.33	1.15
25.2	1.0	0.0	2.0	1.000	1.00	1.00
26.4	2.0	0.0	3.0	1.667	2.33	1.53
27.6	3.5	1.0	4.0	2.833	2.58	1.61
28.8	4.0	3.5	4.5	4.000	0.25	0.50
29.7	5.0	6.0	5.0	5.333	0.33	0.58
30.7	6.0	8.5	6.0	6.833	2.08	1.44
31.7	7.0	10.0	7.0	8.000	3.00	1.73
32.7	9.0	10.0	9.0	9.333	0.33	0.58

From Table 1 can be seen the thermal sensation for the participants for temperature ranging from 23.1°C to 32.7°C, followed by its mean, variance and standard deviation. The dispersion of the measurements is shown in Figure 5.

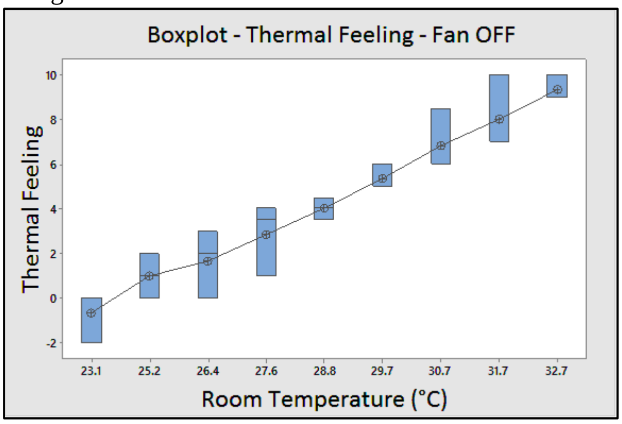

Fig. 5 - Dispersion of participant's thermal sensation

From Figure 5 can be seen that the average thermal sensation increases as the temperature increases. The data from Table 1 was used to perform an analysis of variance (ANOVA) to confirm statistically that there are differences, at least, between two the means. In fact, ANOVA is the statistic used for the following hypotheses test.

$$\begin{cases} H_0 : \mu_1 = \mu_2 = \cdots = \mu_9 \\ H_1 : \mu_i \neq \mu_j \end{cases}$$

The results from the ANOVA test are presented in Table 2. As the P-value is very small, the null hypothesis of equality among all means has to be rejected at a significance level less than 0.1% [8].

Table 2 – ANOVA results for data in Table 1

Source	DF	SS	MS	F-Value	P-Value
Temperature	8	273.69	34.21	23.24	0.000
Error	18	26.50	1.47		
Total	26	300.19			

Although the rejection of null hypothesis gives the information that there are, at least, two different means, it does not inform which means differ from each other. To answer this question, a multi-comparison procedure must be used. There are several procedures for multi comparison, for this paper the Tukey's procedure was chosen for its popularity and simplicity [9].

The Tukey's procedure consists in testing all pairs of means. It declares two means significantly different if the absolute value between them exceeds the Tukey's statistic. For the purpose of this paper, the interest relies on knowing the first significant difference involving the first mean.

Figure 6 shows the distribution of differences of means according Tukey's procedure for a confidence interval of 90%.

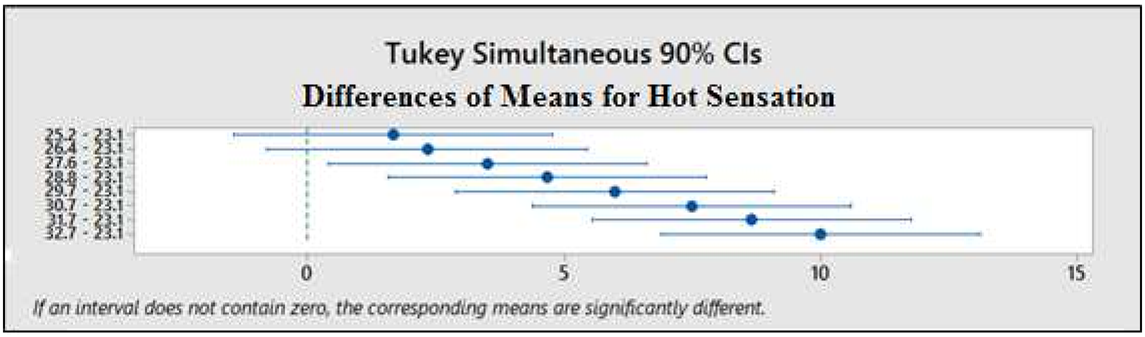

Fig. 6 – Comparison among the thermal sensation means for the first experiment.

From the Figure 6 it can be seen that the first significant increase in thermal sensation occurred when the room temperature reached 27.6 °C.

3.3 Results from the second experiment – Fan turned on

The experimental matrix, ANOVA and dispersion of the means are presented in the Figure 7.

Temperature (°C)	Replicates 1	2	3	Average Sensation	Var	Std Dev
23.4	0.0	2.0	-4.0	-0.667	9.33	3.06
25.4	1.5	4.5	0.0	2.000	5.25	2.29
26.5	1.5	5.9	2.0	3.133	5.80	2.41
27.6	2.5	6.0	1.0	3.167	6.58	2.57
28.6	2.5	6.4	3.0	3.967	4.50	2.12
29.8	3.0	6.5	7.0	5.500	4.75	2.18
30.9	3.5	7.0	10.0	6.833	10.58	3.25
31.8	4.0	8.0	10.0	7.333	9.33	3.06
32.6	4.0	9.2	10.0	7.733	10.61	3.26

ANOVA - Analysis of Variance

Source	DF	SS	MS	F-Value	P-Value
Temperature	8.0	184.7	23.082	3.110	0.022
Error	18.0	133.5	7.417		
Total	26.0	318.2			

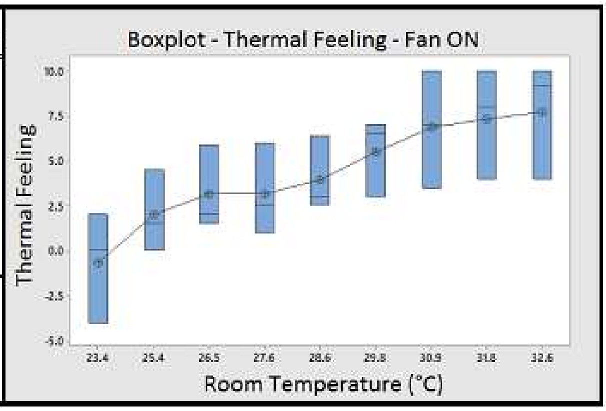

Fig. 7 – Experimental matrix, ANOVA results and dispersion of the means

From the ANOVA, in Figure 7, it can be seen that the null hypothesis of equality of all means can be rejected at a significance level of 2.2 % [1].

According to Tukey's procedure, Figure 8, the first significant increase in thermal sensation occurred when the room temperature reached 30.9°C.

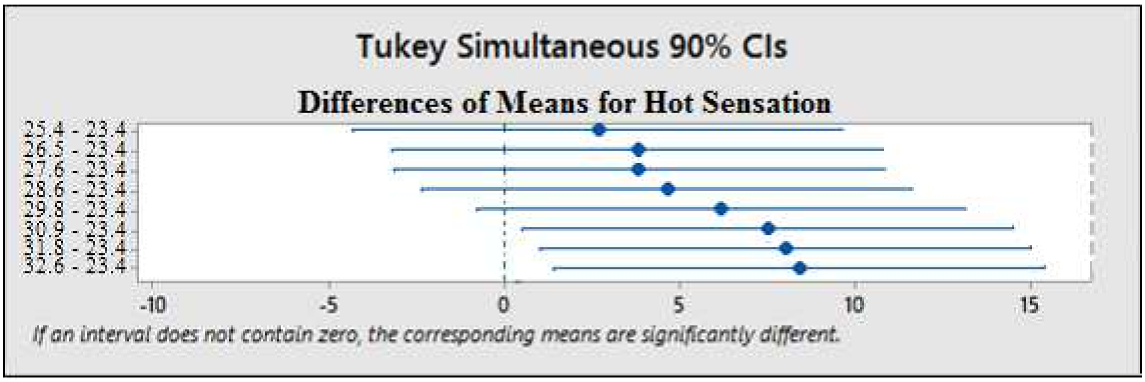

Fig. 8 – Comparison among the hot sensation means for the second experiment.

4. Discussion

In the first experiment, with the fan off, the initial temperature was 23.1°C, the first statistically significant changing in the room occupants thermal sensation occurred at 27.6°C, thus just after the room average temperature had increased 4.5°C, the occupants demonstrated a significant thermal discomfort.

In the second experiment, with the fan on, the initial temperature was 23.4°C, the first statistically significant changing in the room occupants thermal sensation occurred at 30.9°C, thus just after the room average temperature had increased 7.5°C, the occupants demonstrated a significant thermal discomfort.

From the first to the second experiment, there was a gap of 3°C between the temperatures in which a significant thermal sensation was noted. Such gap may be attributed to the breeze created by the fan.

The energy consumption to increase the temperature of the room used in the experiments in 1°C was 1.02kWh, that was completely converted in heat. To decrease the room average temperature of the same 1°C, the HVAC system has to remove the same energy, i.e., 1.02kWh. Considering a typical value of EER (3.30), it will result in a consumption about 0.30kWh.

5. Conclusions

Two experiments was carried out within a thermally controlled environment to evaluate the influence of fans in human thermal sensation.

To conduct these experiments a measurement instrument to gather the thermal sensation from the participants of this research was developed and successfully employed.

In both experiments the temperature inside a small room, with three occupants, has been increased by a heater. It was necessary 1.02 kWh to increase the room temperature in one Celsius degree. In the second experiment a pedestal fan has been running inside the room.

In the experiment with the fan, the occupants' thermal sensation suffered a temperature delay of about three-Celsius degrees. In environments where there is a combined use of fan and HVAC system, this delay allows to increase the setpoint of the thermostat of air conditioner energy without a difference in the user comfort. Considering the gap of three-Celsius degrees this saving can reaches 0.9 kWh.

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