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Influence of Air Movement on Human Thermal Sensation in a Tropical Humid Climate

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Abstract-In tropical humid climates, air velocity plays an important role in comfort, promoting heat exchanges between users and the environment. The objective of this study is to analyze the influence of air movement on the thermal sensation of occupants of classrooms with mixed-mode ventilation systems in hot humid climate in Brazil during the spring and summer seasons. The environmental variables were recorded according to the criteria required by ISO 7726:98. Simultaneously, questionnaires were applied to obtain the personal variables, later statistically analyzed. Students from five classrooms participated in the field study, totaling 1072 valid votes. During the field study in classrooms, about 70% and 60% (spring and summer, respectively) of the students' thermal sensation responses were within the comfort zone (± 1), according to ISO 7730:05. The association between two ventilation systems can aid in thermal comfort and in the reduction of energy expenditure in regions with high indoor temperatures.

Keywords- *Thermal Sensation, Mixed-Mode Ventilation, Tropical Humid Climate*

I. INTRODUCTION

The human perception of air movement depends on environmental factors, including air velocity, air temperature, mean radiant temperature and relative air humidity, as well as personal factors such as thermal sensation, clothing insulation and level of activity [1]. Over the last few years, several studies have focused the influence of air velocity on thermal sensation and on human comfort [2-6], however most of them have addressed the collection of empirical evidence to support the application of airflows. Air movement can be used to compensate for increased air temperature and to improve the thermal comfort in hot climates [7] because air velocity affects human body heat losses, directly influencing the users´ thermal comfort [8]. In a review article, we have listed the positive and negative aspects of air movement on human comfort, specifying when it is desirable or not [1]. Comfort ratings are required to ensure proper applications of air movement in indoor environments. Several studies have shown that, in hotter climates or environment conditions, occupants accept and even prefer relatively high air velocities to remain thermally neutral [9-14].

In order to thermally assess the indoor environment, the commonly used international standards are ISO 7730: 2005 [15], EN 15251:2007 [16] and ASHRAE 55:2013 [17], which specify accurate physical criteria for the production of thermally acceptable environments, criteria that include temperature, air velocity, and relative humidity. It is necessary to consider the fact that environments are made up of people who interact with them and produce heat. Some studies have observed that modern buildings are more complex than thermal comfort standards can provide [18-20]. Schools are a category of buildings that, with a high level of environmental quality, can considerably improve attention, concentration, learning, hearing and performance of occupants [21]. Experiments in real environments may bring results complementary to those discussed earlier. Thus, the aim of this study was to analyze the influence of air movement on the thermal sensation of classroom occupants with mixed-mode ventilation during the spring and summer seasons in a tropical humid climate in Brazil.

II. METHODOLOGY

The method adopted for this work was based on the analysis of the relationship between air velocity and thermal sensation in classrooms with mixed-mode ventilation systems (natural ventilation and mechanical ventilation). This method is based on environment and subjective data collections, simultaneously provided by the building´s users. In the climatic context of the analyzed city, other studies have been developed over the years, such as those performed in offices [22], open spaces [23] and food courts [24]; none in classrooms though.

A. Study Area

The field experiment was conducted in five classrooms. Measurements were made during the spring (October and November, 2016) and summer (March, 2017) in the city of Campo Grande (20º26'34" S, 54º38'45"W, 592 at 700 m altitude), capital of the state of Mato Grosso do Sul, located in the Midwest region of Brazil. The population of Campo Grande is 863.982 inhabitants [25]. According to the Köppen-Geiger classification, the local climate lies in a transition zone between subtypes sub-tropical humid (Cfa) and (Aw), characterized as a tropical humid climate with a rainy season in the summer and a dry season in the winter (Fig. 1) [26].

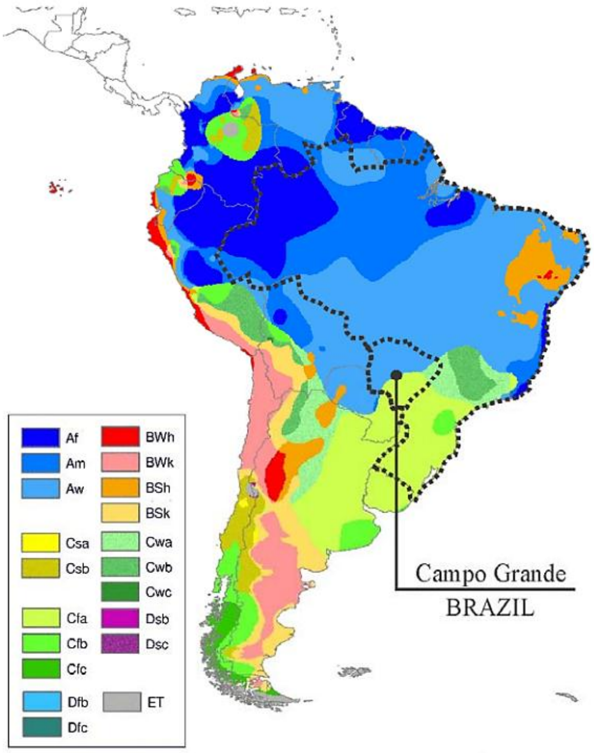

Figure 1. Climatic classification of South America (Brazil highlighted). Adapted from Peel et al. (2007).

During the months the experiment took place, 268 students participated in the survey, which resulted in 1,072 questionnaires. The classrooms analyzed operate with a mixed-mode ventilation system, combining mechanical ventilation (ceiling fans) and natural ventilation. Such rooms offer adaptive opportunities for maintaining indoor temperature, such as window opening and the activation of ceiling fans. During the experiment, students were asked to keep the windows open and the ceiling fans on to check the internal air movement.

B. Measurement rooms and users' profiles

The criteria used to choose the classrooms were the following: (I) windows with easy access and operable by users, open during experiment; (II) rooms with complementary mechanical ventilation provided by ceiling fans; (III) occupants in sedentary activity; (IV) occupants with standard clothing, with only two types of clothing thermal insulation. In the school building, five classrooms that met the criteria were selected.

The activity performed by the students was evaluated as a sedentary school activity, with rates provided by ISO 7730 [15] of 1.2met or 70 W/m². The ISO 7730 standard [15] provides values to calculate the thermal insulation of clothing, and the values found were 0.47 clo and 0.82 clo.

C. Microclimatic Monitoring

In order to understand the thermal environment, it is necessary to monitor the environmental variables collected according to the ISO 7726 criteria [27]. The four environmental variables needed to calculate the thermal indices are: air temperature, mean radiant temperature, air velocity and relative humidity. For the monitoring, a BABUC/A microclimatic station (Fig. 2A) and four Hobo RH/Temp data logger model H08-003-02 (Fig. 2B) were used, both installed at a height of 1.10m during the regular class period. The technical specifications of the equipment used in the data collection and the monitored parameters are shown in Table I.

(a) (b)

Figure 2. Climate monitoring equipment. a) Microclimatic station BABUC/A. b) Data logger sensor Hobo RH/Temp model H08-003-02.

TABLE I. TECHNICAL SPECIFICATIONS OF THE EQUIPMENTS.

Equipment	Specifications			
	Sensors	*Monitored Parameter*	*Precision*	*Measuring Range*
BABUC /A	Globe Thermometer BST 131	Globe Temperature (ºC)	±0.15ºC to ± 0ºC	-10ºC to +100ºC
	Anemometer BSV 101	Air Speed (m/s)	4% > 1m/s	0 to 50m/s
Hobo RH / Temp. Model H08-003-02	Temperature	Air Temperature (ºC)	± 2%	-20ºC to +70ºC
	Relative Humidity	Relative Humidity(%)	± 3%	0% to 95%

The field measurements were performed in the morning for 2 hours per day of collection, and the environmental variables were collected every 5 minutes. In order to characterize the typical use of classrooms, the activities were not interrupted. The BABUC/A microclimatic station was located in the center of the room at a height of 1.10m, which corresponded to the height of the seated students' heads. Two Hobo RH/Temp data logger model H08-003-02 sensors were installed in the classrooms' indoor environment, and two other sensors outdoors, to collect the external environmental variables.

The students remained at their desks during measurements and the equipment was installed as shown in Figs. 3-7.

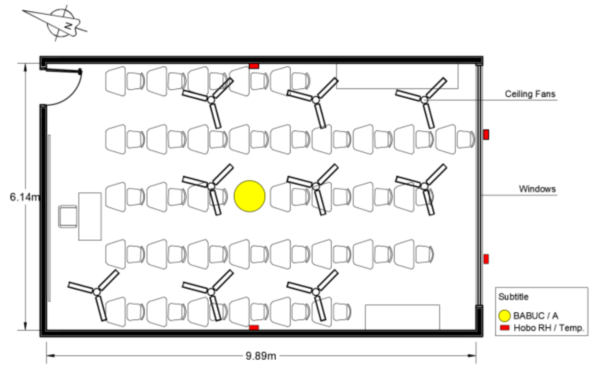

Figure 3. Classroom A

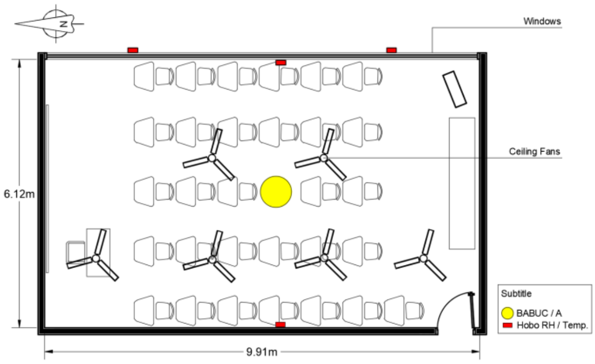

Figure 4. Classroom B

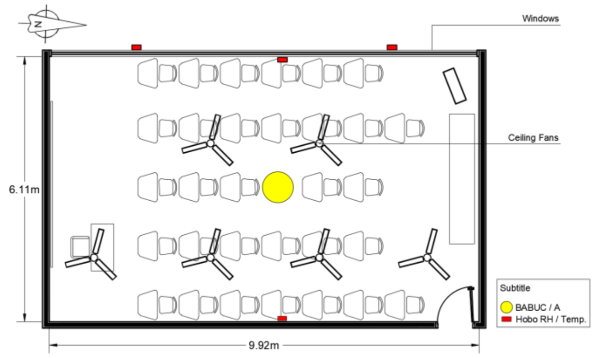

Figure 5. Classroom C

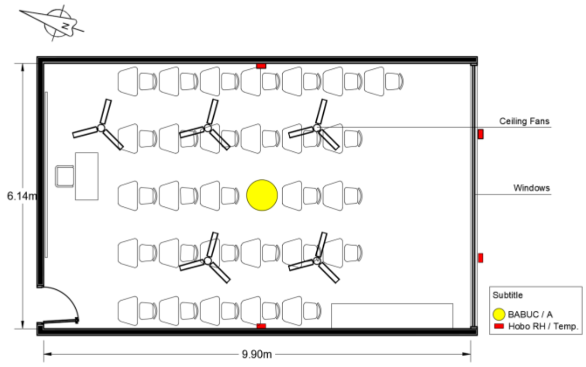

Figure 6. Classroom D

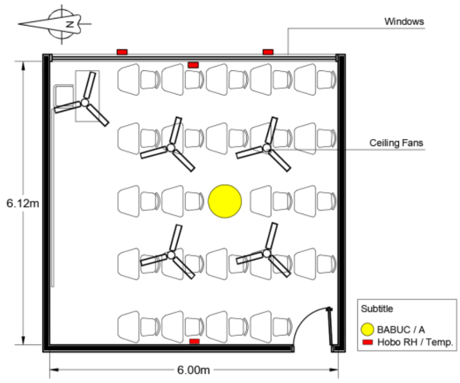

Figure 7. Classroom E

D. Questionnaire of subjective research

The main objective of the questionnaire was to analyze the thermal comfort and the thermal sensation of the occupants. In a complementary way, the questionnaire also included questions related to thermal state, thermal preference and air velocity. The questionnaire was organized in four parts:

- Environmental data, such as collection period, date and type of ventilation system;
- Anthropometric data, such as the students’ age, weight, height and clothing;
- Subjective evaluation of thermal sensation;
- Subjective questions about thermal state, thermal preference and air velocity.

The discussion of the results obtained from the questionnaires was based on the seventh scale of thermal sensations of ISO 7730 [15], comprising values between -3 (cold) and +3 (hot). The question related to the air movement acceptability focused on the students' feelings about air velocity, with values ranging along -2 (very low), -1 (low), 0 (neutral), +1 (high) and +2 (very high) (see Table II).

TABLE II. AIR MOVEMENT ACCEPTABILITY SCALE.

Unacceptable	Acceptable			Unacceptable
-2	-1	0	1	2
Because too low air velocity	But too low air velocity	Enough air velocity	But too high air velocity	Because too high air velocity

The students began to answer the questionnaire half an hour after being seated at their desks to avoid any influence from their previous activities. Each student answered the questionnaire four times during the same experiment.

E. *Data Analysis*

The results were statistically treated using the analysis of variance (ANOVA) and hypothesis t test (Student t-test) with significance level $p < 0.05$. The database was organized in electronic spreadsheets and the results were correlated with each other to yield the analyses.

III. RESULTS AND DISCUSSION

The age of the students ranged from 10 to 17 years and the weight from 27 to 92 kg. The sample of respondents reflected a balance of genders. Table III summarizes the details of the students´ profiles for each station analyzed. The average value found for the thermal insulation of clothing was 0.48 clo.

TABLE III. OCCUPANTS' PROFILE PER SEASON.

Sample data		Season	
		Spring	Summer
Gender	Female	248 (48.1%)	276 (49.6%)
	Male	268 (51.9%)	280 (50.4%)
Age (year)	Minimum Average Maximum Standard deviation	10 13.26 17 1.68	10 12.89 17 1.75
Height (m)	Minimum Average Maximum Standard deviation	1.37 1.60 1.84 0.10	1.30 1.58 1.82 0.09
Weigth (kg)	Minimum Average Maximum Standard deviation	27 51.98 90 11.62	27 51.37 92 12.15
Thermal insulation of clothing (clo)	Minimum Average Maximum Standard deviation	0.47 0.48 0.82 0.06	0.47 0.48 0.82 0.07

Table IV shows the indoor climate variables observed during the experiments. The minimum air temperatures found were 26.9ºC (spring) and 27.9ºC (summer), and the maximum was 30.9ºC during the summer. The indoor air velocity varied from 0.04 to 0.65 m/s during the spring and from 0.02 to 0.95 m/s during the summer; and the mean air velocity found was 0.28 m/s and 0.30 m/s in the spring and in the summer, respectively.

TABLE IV. ENVIRONMENTAL VARIABLES PER SEASON.

Collected data		Season	
		Spring	Summer
Air temperature (ºC)	Minimum Average Maximum Standard deviation	26.9 29.3 30.3 1.00	27.9 28.9 30.9 0.85
Mean radiant temperature (ºC)	Minimum Average Maximum Standard deviation	29.3 30.7 32.0 0.81	27.7 29.7 33.5 1.14
Air velocity (m/s)	Minimum Average Maximum Standard deviation	0.04 0.28 0.65 0.16	0.02 0.30 0.95 0.22
Relative humidity (%)	Minimum Average Maximum Standard deviation	46.1 54.1 59.5 4.25	59.2 69.2 81.7 6.29

The percentage of students who indicated "neutral" thermal sensations represented 29.5% in the spring season and 32.6% in the summer (Fig. 8). The percentage of participants who reported being "slightly cool" or " slightly warm" was over 40% during the survey conducted in the spring and 33.9% in the summer. Less than 25% reported, in both seasons, that they were "cool" or "warm." The highest percentage of respondents who rated their thermal sensation as "hot" occurred in the summer season: 14%. The students who thermally accepted the classroom environment indicated thermal sensations that varied from -1 to +1, totaling 71.1% in the spring and 66.4% in the summer. These results did not reach the goal of 90% thermal acceptance, considered the ideal by the thermal comfort norm [17].

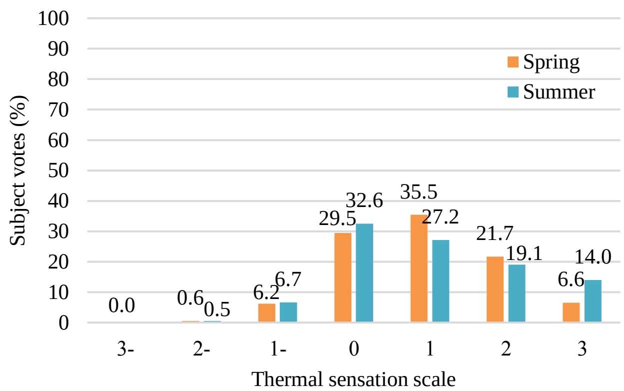

Figure 8. Users' thermal sensation scale.

As shown in Fig. 9, a higher frequency was observed in the votes considered as "neutral"; 37.4% in the spring and 42.3% in the summer. Over 40% of students voted that the air movement sensation was "too low" and "low" in both seasons. It is possible to identify that the majority of samples are concentrated in the three categories considered acceptable (-1, 0 and 1).

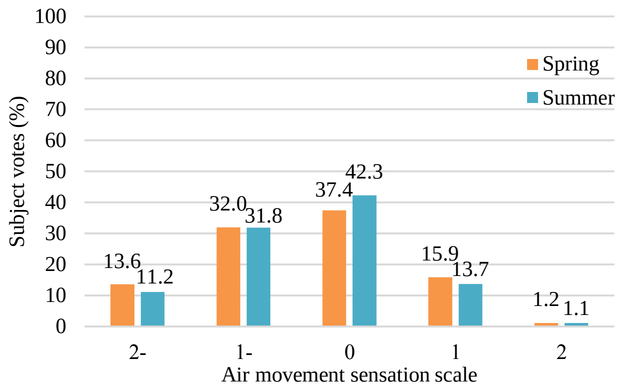

Figure 9. Users' air movement sensation scale.

When the users' votes were correlated with the air movement (Fig. 10), more than 80% of the students evaluated it as acceptable in the analyzed seasons. Less than 15% assessed it as unacceptable, due to the fact that air velocity is very low or very high, both in the spring and summer season.

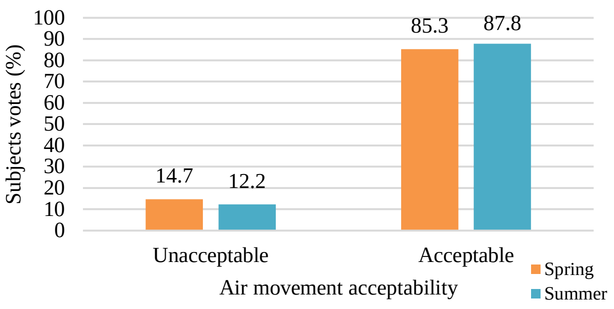

Figure 10. Users' air movement acceptability.

Figs. 11 and 12 gather the values of the students' votes that indicated whether air movement was acceptable or unacceptable combined with air velocity collected at the time of questionnaire responses. In both seasons, the air movement acceptability was equal to or higher than 80% for all velocities collected in the field. In the summer season, the votes related to the acceptability of air movement were found to increase as air velocity raised simultaneously. Similar results were observed in a study conducted in classrooms in hot and humid climates [28].

In the end, linear regressions were performed between the thermal sensation votes and the air movement sensation votes to estimate the neutrality condition of the votes of thermal sensation, carried out also between the votes of thermal sensation and air velocity. In Fig. 13 it is observed that as the air movement sensation votes approximate the classification of "high" or "very high" (1 and 2), the thermal sensation votes approach the "neutral" (0), in both seasons. These results are consistent with previous research, in which the use of air velocity allows for the thermal comfort in environments located in hot weather [7].

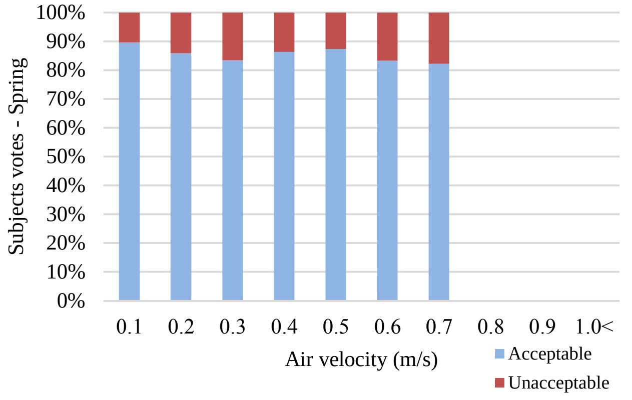

Figure 11. Air movement acceptable correlated with air velocity - Spring.

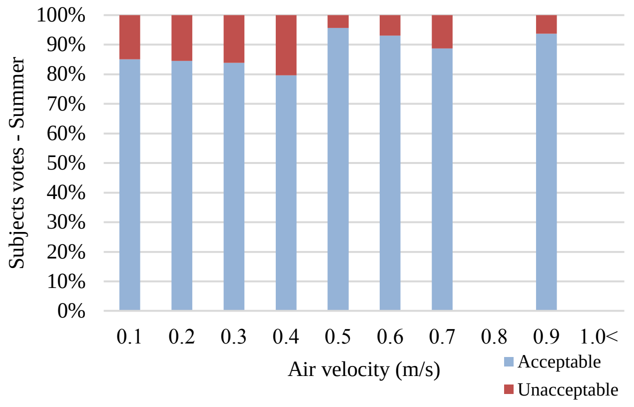

Figure 12. Air movement acceptable correlated with air velocity – Summer

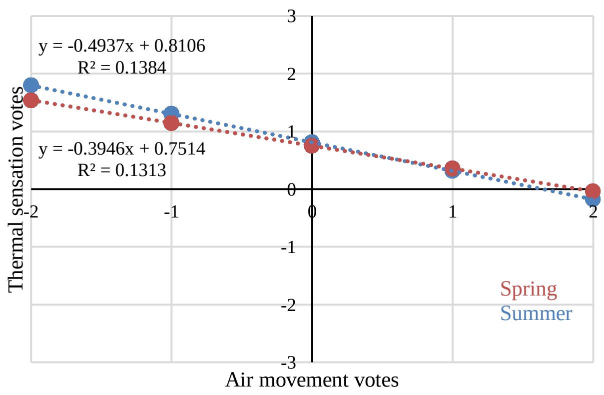

Figure 13. Linear regression between the votes of thermal sensation and air movement

The variation of the thermal sensation votes was analyzed in comparison with the air velocity collected in the field studies, and it was observed that the thermal sensation ratings are directly proportional to the air velocity (Fig. 14), proving that the indoor air velocity directly influences the users´ thermal comfort sensation.

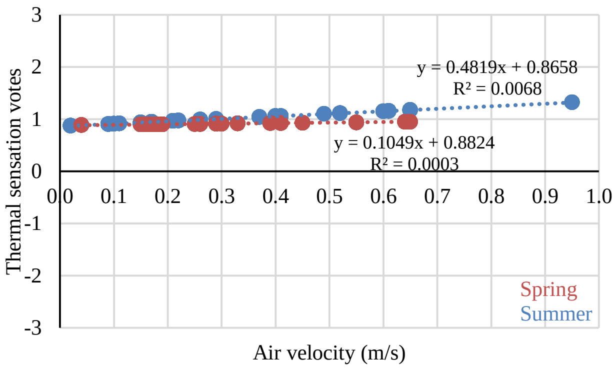

Figure 14. Linear regression between the votes of thermal sensation and air velocity

IV. CONCLUSIONS

This article investigated the influence of air movement on the students´ response of thermal sensation when seated in a classroom with a mixed-mode ventilation system. It is important for occupants to be able to control the indoor airflow according to their personal preference, as this factor helps achieve thermal comfort.

Despite the high temperatures found in classrooms, the research results showed that air movement was considered acceptable by more than 80% of students. Although air velocity found in the collections are close to or above 0.80 m/s, considered the maximum acceptable by the norm [17], it is noticed that, with the increase of indoor air velocity, there is a rise in the votes of acceptability, especially in the summer season that presented the highest indoor temperatures. Based on the results of data collection in classrooms located in a tropical humid climate, it is concluded that:

- The association between two ventilation systems, such as natural and mechanical (ceiling fans), can aid in thermal comfort and in the reduction of energy expenditure in regions with high indoor temperatures;
- The acceptability of air movement was equal to or higher than 80% for all velocities collected; the users may accept and even prefer air velocity higher than that determined by the norm;
- The air movement exerts influence on the thermal sensation responses; it has been observed that the thermal sensation votes are directly proportional to the air velocity.

V. ACKNOWLEDGMENT

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