THERMAL COMFORT ANALYSIS OF A NATURALLY VENTILATED BUILDING

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ABSTRACT

The main objective of this paper is to analyse the thermal comfort of users of a naturally ventilated building, located in the city of Florianópolis, Brazil. The analysis was performed by using the EnergyPlus computer programme. Different window areas, with automated and manual control of windows were simulated in order to improve the natural ventilation efficiency. The assessment of thermal comfort of users for the actual building and for the models simulated was performed by using the method proposed by Givoni and the method indicated in ASHRAE Standard 55. It was observed that the automated control of windows is the best alternative to improve thermal comfort.

INTRODUCTION

The natural ventilation is an important strategy to improve thermal comfort in buildings that are located in hot and humid climates. The air velocity at certain limits can provide the sensation of cooling by decreasing the rate of evaporation from the skin surface. Also, natural ventilation may improve the indoor air conditions.

Gratia et al. (2004), based on a study for office buildings, stated that natural ventilation may be sufficient to guarantee the thermal comfort of users, although some strategies to decrease internal heat gains may be necessary.

Raja et al. (2001) showed that infiltration and natural ventilation can be used to improve thermal comfort in some buildings, but their efficiency depends on the climate conditions. They also state that manual opening control is an alternative to reach internal comfort temperatures in the building.

Natural ventilation has been used in buildings as a main strategy to reduce the internal heat gains and also the energy consumption related to air conditioning systems. ECG19 (1993) stated that the final energy cost of a naturally ventilated building is 40% less than a conditioned building. During summer conditions, buildings become a heat source. Therefore, using natural ventilation to dissipate the internal heat gains and reduce energy consumption is an efficient strategy (Woods et al., 2009).

Manioglu and Yilmaz (2006) showed that the building envelope is the most important parameter in the passive architecture as it affects the indoor temperatures. Thus, analyses of thermal comfort in buildings should consider both building envelope and natural ventilation.

Liping and Hien (2007) analysed natural ventilation in buildings located in Singapore, where the climate is considered as hot and humid. Research on natural ventilation strategies has proven that full-day ventilation can improve the thermal comfort in hot-humid climates. The authors investigated four strategies of ventilation and different materials in the building envelope, by using the programme TAS (Thermal Analysis Software).

The ventilation strategies were nighttime-only ventilation, daytime-only ventilation, full-day ventilation and no ventilation. The authors concluded that a window-to-wall ratio of 24% was the ideal to achieve the best thermal comfort conditions in buildings. Horizontal shading devices were recommended for all façades in order to improve thermal comfort.

As seen, building simulation programmes allow for many benefits such as the possibility of performing thermal and energy performance analysis for different alternatives (Mendes et al., 2005).

Consequently, the main objective of this study is to analyse the thermal comfort of users of a naturally ventilated building located in Florianópolis, southern Brazil.

METHOD

First, the building was simulated in EnergyPlus as a base case. Then, different models were simulated to improve the efficiency of natural ventilation. Different window-to-wall ratios and control of windows opening, such as automated and manual, were simulated. In order to assess the thermal comfort in all models, air temperature and relative humidity obtained from the simulations were analysed by using two methods: Givoni (1992) and ASHRAE Standard 55 (2004).

Both Givoni and ASHRAE methods were applied to evaluate the thermal comfort conditions in the building. Based on that, it will be possible to assess the differences between them. Also, the results will

demonstrate which method is more restrictive and accurate for the building analysed.

Case study

The building is three storeys high with a total floor plan area of 2904 m^2. Each floor has eight classrooms, a corridor and two halls.

The building main façade is South oriented (Figure 1). Figure 2 shows the floor plan. The building surroundings are mainly composed of a car park and a small vegetation area.
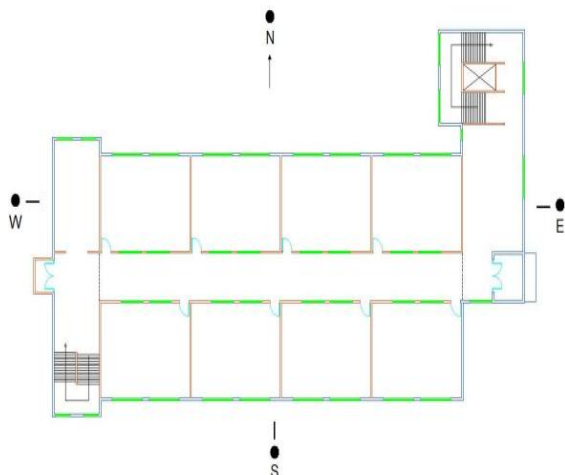

Figure 1 Main façade of the building

Figure 2 Floor plan of the building

The North and South façades contain 6.40 m x 1.25 m windows. Each window has horizontal shadings as shown in Figure 3.

Each classroom has a 1.00 m x 2.10 m door, and above each door there is a 4.80 m x 0.50 m window.

The window-to-wall ratio (WWR) for both North and South façades is 24.8%. Window area and ventilation area are slightly different, but they were considered the same in the simulations. Single clear glass 2.5 mm thick is used in all windows.

The doors are made of wood, 30 mm thick. The shadings are fixed and made of concrete, with a dimension of 50 cm.

Figure 3 Horizontal shadings

The thermal properties of all building components were obtained from the Brazilian standard NBR-15220 (ABNT, 2005). Table 1 shows the materials and thicknesses of walls, roof and floor.

The building is occupied from 8:00 to 22:30, during weekdays. The classrooms are occupied in the morning (8:00-12:00); in the afternoon (14:00-18:00) and at night (19:00-22:30). During the intervals just ¼ of the lighting system is used.

Table 1 Materials and thicknesses of walls, roof and floor

COMPONENT	MATERIALS
Internal walls	- mortar (2.5 cm) - brick with eight circular holes (10 cm) - mortar (2.5 cm)
External walls	- mortar (2.5 cm) - double bricks with six circular holes (15 cm) - mortar (2.5 cm)
Roof	- mortar (2.0 cm) - thermal insulation (23.0 cm) - concrete slab (5.0 cm) - mortar (2.0 cm)
Floor	- mortar (2.0 cm) - thermal insulation (23.0 cm) - concrete slab (5.0 cm) - mortar (2.0 cm) - ceramic floor (1.0 cm)

As the colour of the façades is light, the solar absorptance was taken as 0.4.

Since the study was carried out in an educational building, it was considered a total of 30 students and one lecturer in each classroom. The value adopted for the heat dissipated by students and teacher was 60 Watts and 70 Watts, respectively.

The lighting power density in the classrooms is 15.6 W/m², considering lamps of 32 Watts and ballasts of 7 Watts. In the corridors and halls, the lighting power density is 3.0 W/m².

There is no air conditioning system in the building.

The Models

The building is located in Florianópolis, capital of Santa Catarina. Figure 4 shows the location of the city of Florianópolis in the state of Santa Catarina.

Figure 4 Location of the city of Florianópolis

As for the climate data, the TRY (Test Reference Year) of Florianópolis was used (Goulart, 1998). Based on this climate data, the average temperature in summer and winter period is 24°C and 17°C, respectively. The average relative humidity during the year is 82.7% as shown in Figure 5.
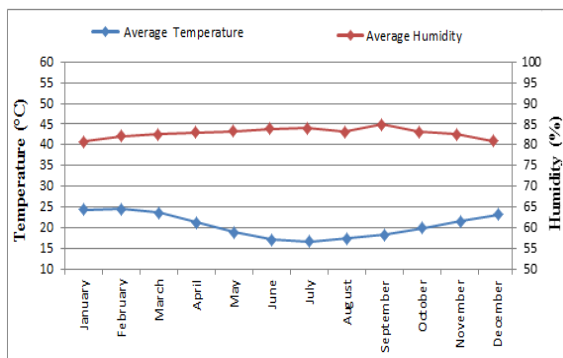

Figure 5 Relative humidity and average temperature in one year Average temperature and humidity for the climate data of Florianópolis.

The city of Florianópolis is at an altitude of 7.0 m above sea level, and its latitude (−27.67°) and longitude (−48.55°). The climate, the average temperature is lowest in July (16.6°) and highest average in February (24.5°). The average humidity does not vary much throughout the year being the lowest in January (80.6%) and highest in September (84.9%). The average wind speed in the city is 3.0 m/s.

The first step was to determine the thermal zones of the building. Each floor was divided into 11 thermal zones, representing 8 classrooms, 1 corridor and 2 halls. The final model is composed of 33 thermal zones. The classrooms measure 9.5 m x 7.3 m x 3.5 m. Figure 6 shows the thermal zones division, which are the same for each floor.
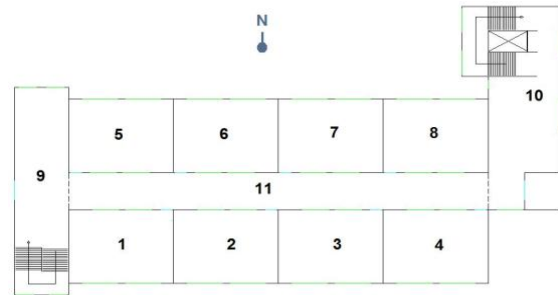

Figure 6 Thermal zones

The thermal properties of all components were considered in all simulations.

The building is occupied only over the weekdays. During weekends all the lightings are off. Figure 7 shows the schedule of occupation of classrooms. Occupation of 100% at 9:00, for example, indicates that there is occupation from 8:00 to 9:00.
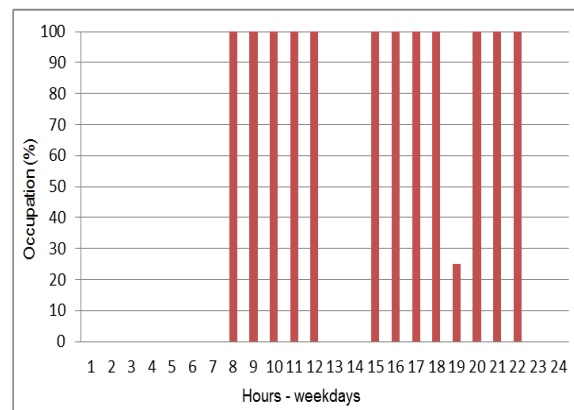
Figure 7 Schedule of occupation of classrooms

The final 3D model can be seen in Figure 8. The surroundings were not considered in the simulations.
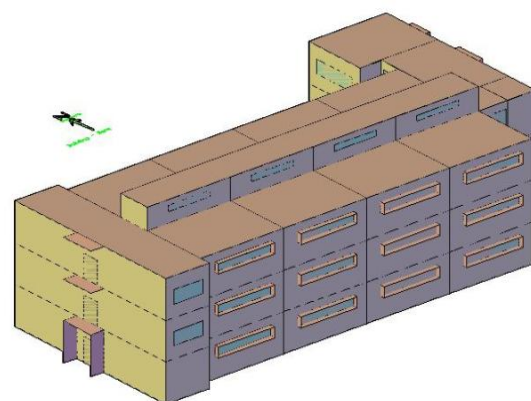

Figure 8 South view of the model

Natural Ventilation

The natural ventilation was modelled by using the Airflow Network. The Cp (pressure coefficient) was calculated by the EnergyPlus programme.

The windows were considered with opening factor of 0 (closed) and 1 (open). The air mass flow coefficient

and exponent when the windows were opened were 0.0001 and 0.66, respectively (Liddament, 1986).

The first analysis was based on the base case using the real WWR of 24.8%. In the first step, it was considered that just the external windows were opened during the occupied period (08:00 – 22:30).

In the second step, it was considered that the internal windows (above the classrooms doors) were also opened allowing for cross ventilation.

Moreover, three different values of WWR were analysed, i.e., 8%, 20% and 30%. For these cases two scenarios were simulated, i.e., internal window closed and internal window open.

This study also considers the influence of two different control types for window opening: manual and automated. The manual control opens the windows when there are occupants in the zones and closes when the occupants leave.

The automated window control will open the windows when there are occupants in the zones and the internal temperature is higher than external temperature.

For the base case and Model 1 to 4 it was considered that the external windows were always open during the occupied period as it reflects the real behaviour of the building.

The different alternatives to evaluate the thermal comfort of users are listed in Table 2.

The doors are considered closed in all simulations to represent the real user's behaviour. The size of internal windows is kept as in the actual building.

Table 2 Models to evaluate the thermal comfort of users

BASE CASE	- WWR 24.8% - internal windows closed - manual control
	- WWR 24.8% - internal windows open
MODEL 1	- WWR 8% - internal windows closed - manual control
	- WWR 8% - internal windows open
MODEL 2	- WWR 20% - internal windows closed - manual control
	- WWR 20% - internal windows open
MODEL 3	- WWR 30% - internal windows closed - manual control
	- WWR 30% - internal windows open
MODEL 4	- WWR 24.8% - manual window control
MODEL 5	- WWR 24.8% - automated window control

Thermal Comfort

The thermal comfort assessment was based on the Analysis Bio computer programme (LabEEE, 2011) and ASHRAE Standard 55 (ASHRAE, 2004). Analysis Bio evaluates the percentage of comfort and discomfort hours based on a weather file and parameters established in the bioclimatic chart proposed by Givoni (1992). This chart (Figure 9) presents boundaries of comfort zones, which are based on air temperature and air relative humidity.

The entire comfort zone proposed by Givoni was considered as the boundaries for the evaluation of thermal discomfort hours.
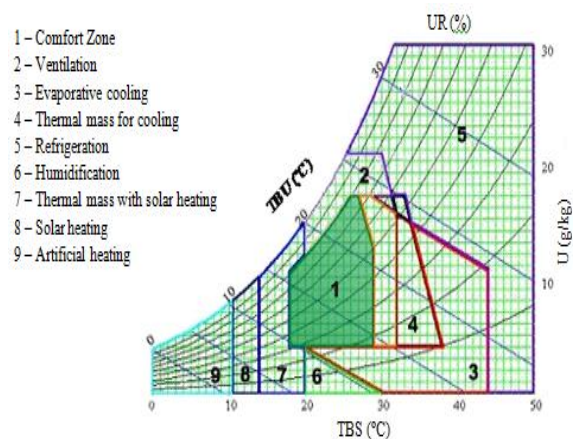

Figure 9 Bioclimatic chart of Givoni

The method presented in ASHRAE 55 was also applied. This figure takes into account the acceptable indoor operative temperature based on the external monthly temperature. Additionally, this method does not consider humidity or air speed limits.

The ASHRAE Standard 55 demonstrates a different method to determine limits of thermal conditions in naturally ventilated buildings (Figure 10). This standard has two acceptability limits (90% and 80%).

For this study, the acceptability limit of 90% was adopted. Hence, the average outdoor air temperature of each month in Florianópolis was calculated. As for the indoor operative temperatures, they were obtained from the simulations.

The results were applied into the Ginovi chart and into Figure 10 for the calculation of discomfort and comfort hours.

For the calculation of hours of discomfort, we used the simulation results by plotting them in the charts of Givoni and ASHRAE Standard 55. The result was the percentage of hours of comfort and thermal discomfort.
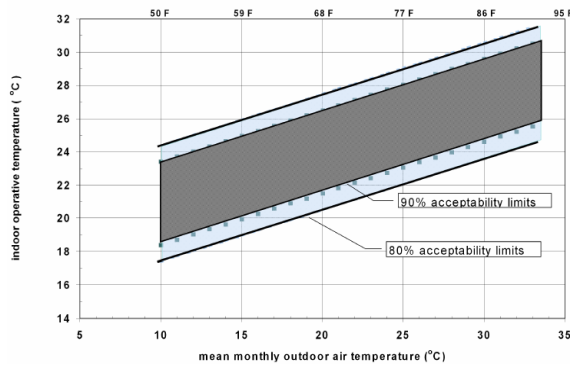
Figure 10 Indoor operative temperature as a function o mean monthly outdoor air temperature as proposed by ASHRAE 55

The average outdoor air temperature for each month in Florianópolis is presented in Table 3. Also, it contains the minimum and maximum indoor operative temperatures for acceptability of 90%, based on ASHRAE 55.

Table 3 Average outdoor air temperature and operative temperature for Florianópolis based on ASHRAE 55

MONTH	AVERAGE OUTDOOR AIR TEMPERATURE (^{O}C)	OPERATIVE TEMPERATURE (^{O}C)	
		MIN	MAX
January	24.79	22.90	27.90
February	24.26	22.70	27.70
March	24.34	22.80	27.80
April	21.50	21.70	26.40
May	18.97	21.00	26.10
June	16.99	20.50	25.10
July	17.50	21.70	25.20
August	17.10	21.60	25.10
September	19.90	21.10	26.20
October	19.69	21.30	26.10
November	21.31	22.00	26.60
December	22.64	22.20	27.10

RESULTS AND DISCUSSION

Based on the bioclimatic chart proposed by Givoni and considering the external temperature data for Florianópolis, it was verified that there is thermal discomfort in 79% of the hours along the year.

Thus, buildings located in Florianópolis should make extensive use of some strategies to increase the number of comfort hours per year.

The base case results when the internal windows were closed, using the Analysis Bio programme, are presented in Table 4.

It can be observed that Zone 29 has 69% of discomfort hours. This zone is located on the top floor and is North oriented. The zone that has the maximum numbers of comfort hours is Zone 02, representing a total of 41.5% of comfort hours during the year. The base case achieved an average of 37.2% of comfort hours against 62.8% of discomfort hours. These results represent the actual building. The average of comfort hours increased only 1.9% (average comfort hours of 39.1%) when considering the internal windows open to allow for cross ventilation.

Table 4 Base case results for classrooms – Givoni

ZONES	COMFORT HOURS (%)	DISCOMFORT HOURS (%)		
		WARM	COLD	TOTAL
Zone 01	41.1	35.3	23.6	58.9
Zone 02	41.5	35.7	22.8	58.5
Zone 03	41.3	35.2	23.5	58.7
Zone 04	40.5	35.7	23.8	59.5
Zone 05	36.6	38.0	25.4	63.4
Zone 06	36.9	37.9	25.2	63.1
Zone 07	37.0	37.8	25.2	63.0
Zone 08	36.6	38.1	25.3	63.4
Zone 12	41.0	35.4	23.6	59.0
Zone 13	41.3	35.2	23.5	58.7
Zone 14	41.0	35.4	23.6	59.0
Zone 15	40.0	36.1	23.9	60.0
Zone 16	35.8	38.5	25.7	64.2
Zone 17	35.9	38.3	25.8	64.1
Zone 18	36.7	37.9	25.4	63.3
Zone 19	36.1	38.3	25.6	63.9
Zone 23	37.3	37.5	25.2	62.7
Zone 24	37.1	37.7	25.2	62.9
Zone 25	37.0	37.8	25.2	63.0
Zone 26	36.9	37.9	25.2	63.1
Zone 27	31.7	41.8	26.5	68.3
Zone 28	31.5	41.1	27.4	68.5
Zone 29	31.0	41.4	27.6	69.0
Zone 30	31.2	41.5	27.3	68.8
Average	**37.2**	-	-	**62.8**

By using the method proposed by ASHRAE 55 for the same base case, the comfort hours for Zone 29 and Zone 02 increased to 49.3% and 59.7%, respectively (Table 5). And the average comfort hours increased to 55.8%.

Table 5 Summary of results for the base case

METHOD	COMFORT HOURS (%)		DISCOMFORT HOURS (%)
Givoni	Zone 29	31.0	69.0
	Zone 02	41.5	58.5
	Average	**37.2**	**62.8**
ASHRAE 55	Zone 29	49.3	50.7
	Zone 02	59.7	40.3
	Average	**55.8**	**44.2**

The building code of Florianópolis indicates that the minimum windows are to be used is 8%. Thus, considering this minimum value of 8% it was observed (Table 6) that the average of comfort hours decreased in comparison to the base case results for Givoni and ASHRAE 55. The values presented in

Table 5 to Table 9 represent the zones with the minimum and maximum comfort and discomfort hours, and the average based on comfort and discomfort hours for all zones.

Considering the internal windows open, the average of comfort hours increased only 1.7%, as observed in the previous case.

Table 6 Summary of results for model 1 – WWR 8%

METHOD		COMFORT HOURS (%)	DISCOMFORT HOURS (%)
Givoni	Min	31.0	69.0
	Max	41.5	58.5
	Average	**33.9**	**66.1**
ASHRAE 55	Min	48.9	51.1
	Max	59.2	40.8
	Average	**54.4**	**45.6**

Table 7 shows the results for WWR of 20%. Comparing such results to the base case results it can be noticed a small increase in the average comfort hours for both methods: Givoni and ASHRAE 55. As for the simulation with the internal windows opened, the comfort hours increased 2.4%.

Table 7 Summary of results for model 2 – WWR 20%

METHOD		COMFORT HOURS (%)	DISCOMFORT HOURS (%)
Givoni	Min	32.1	67.9
	Max	42.5	57.5
	Average	**38.2**	**61.8**
ASHRAE 55	Min	50.6	49.4
	Max	62.3	37.7
	Average	**56.2**	**43.8**

The results for model 3 are presented in Table 8. Increasing the WWR to 30% there is a decrease in the average comfort hours of 4.1% when compared to the base case and using the method proposed by Givoni. In this case, the increase in window area provides more efficient ventilation, however, it also allows for a greater heat gain mainly on the north façade.

Table 8 Summary of results for model 3 – WWR 30%

METHOD		COMFORT HOURS (%)	DISCOMFORT HOURS (%)
Givoni	Min	28.3	71.7
	Max	35.8	64.2
	Average	**33.1**	**66.9**
ASHRAE 55	Min	42.7	53.3
	Max	51.8	47.2
	Average	**48.9**	**51.1**

Considering the internal windows open, the average of comfort hours increased 2.1%. Adopting a manual control to open the windows (Table 9), it can be observed that the average of comfort hours increased

2.6% and 3.6% when compared to the base case, for Givoni and ASHRAE 55 results, respectively.

Based on these results it is possible to see that users can influence in the building internal temperature.

Table 9 Summary of results for model 4 – manual window control

METHOD		COMFORT HOURS (%)	DISCOMFORT HOURS (%)
Givoni	Min	33.6	66.4
	Max	44.5	55.5
	Average	**39.8**	**60.2**
ASHRAE 55	Min	51.6	48.4
	Max	59.2	40.8
	Average	**57.4**	**42.6**

The results for an automated windows control system can be seen in Table 10. Comparing these results with the base case results it is possible to observe that the thermal comfort average increases 10.6% using Givoni and 12.3% using ASHRAE 55.

Table 10 Summary of results for model 5 – automated window control

METHOD		COMFORT HOURS (%)	DISCOMFORT HOURS (%)
Givoni	Min	41.9	58.1
	Max	52.9	47.1
	Average	**47.8**	**52.2**
ASHRAE 55	Min	62.3	37.7
	Max	70.8	29.2
	Average	**68.1**	**31.9**

Additionally, it can be observed that increasing the window-to-wall ratio provides a great influence of the air flow inside the building. It reflects in the improvement of the number of comfort hours for both methods applied. This fact shall happen as the air flow helps to increase the sensation of cooling for those buildings located at hot and humid climate as mention before.

The results also show cold discomfort hours as the analysis is for a complete year. In addition, the windows were considered always open (Model 1 to 4) during the occupation period (8h00 – 22h30) to represent the reality of its patterns of use. However, it is possible to observe that the cold discomfort hours decreased by taking into account the use of automated windows (Model 5).

CONCLUSIONS

This study analysed the thermal comfort of users of a naturally ventilated building, located in the city of Florianópolis, southern Brazil. The assessment was based on simulations using EnergyPlus 5.0 and also on the methods proposed by Givoni (1992) and ASHRAE (2004).

Such results demonstrate that it is necessary to find a high-quality ventilation area for each building.

Increasing the WWR may improve the ventilation and the number of comfort hours in the building, but it may also increase solar heat gains.

The only alternative that significantly increased the number of hours of thermal comfort inside the building was the use of automated control of windows opening. In such alternative, the windows are opened only when the outdoor air temperature is lower than the indoor air temperature.

The WWR variation showed insignificant contribution of natural ventilation to increase thermal comfort. Such an insignificant variation occurred even in cases with manual control and cross ventilation. The low influence of cross ventilation is due to the fact that the internal windows are facing an indoor corridor, which actually undermines that strategy.

By comparing the number of comfort hours obtained from Givoni with those obtained from ASHRAE 55, it is possible to observe that the method proposed by ASHRAE is less restrictive. This is due to the fact that it considers only air temperature, while the method proposed by Givoni also considers the air relative humidity. Thus, the method proposed by Givoni is more suitable for Florianópolis, where the average relative humidity is usually higher than 80%.

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