Improving thermal comfort conditions in K-12 educational buildings in hot and humid climate: a case study in Cucuta, Colombia

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Abstract. The school buildings in Colombia are built based on geographical locations and regional construction systems. However, external weather conditions and building design can have a significant impact on the thermal comfort of students, which affects the academic performance and productivity. This paper investigates the thermal comfort performance for an educational building in a hot and humid city in Cucuta, Colombia, built under national guidelines. This school is a concrete structure without mechanical cooling. However, field observation discovered that 82% of the time students experienced thermal discomfort. To investigate causes and provide mitigation strategies, a whole building energy simulation is conducted. Design Builder is used to evaluate the indoor thermal conditions compared to outdoor data collected. ASHRAE 55 adaptative model is used for the evaluation. It is found that 79% of the time the thermal conditions are outside the acceptable range during the year. The effect of mitigation measures i.e., occupancy, roof insulation, and natural ventilation rates are investigated through simulations. It is found that occupancy and natural ventilation rate have a significant impact on the indoor temperature and relative humidity, and thus the thermal comfort. Passive design strategies are proposed in optimizing the school building design to meet ASHARE-55 requirements.

1. Introduction

Improving the thermal condition in educational buildings has a significant impact on academic performance regarding attention, concentration, and learning. Recent studies identify the relation between the occupants' performance and thermal comfort, considering that lack of comfort causes "environmental stress"[1]. Furthermore, a favorable learning environment correlates significantly with student participation, and teacher support. The case study building in this paper is located in Cucuta, Colombia, a northeastern city with an annual average of 34°C, 72% relative humidity, and predominant wind direction from the north and southeast [2]. The building has reinforced concrete structure without insulation layer and vertical louvers and light shelves as external shading elements, built under national guidelines focusing on structural calculations but lacks environmental analysis requirements.

Based on the selected building, this research intends to improve the thermal comfort in the classrooms by identifying parameters that cause variation in thermal conditions and implementing a design based on passive strategies without using active ventilation systems by following the ASHRAE standard 55-2010.
Buildings characteristics

Figure 1 shows images of the school selected for the study; the building was measured in a site visit and confirmed through architectural plans. The educational complex has forty classrooms located in 4 two-story buildings, bridges and stairs skewers the building connecting all floors. Each volume is structured by a linear corridor connected with the classrooms. In terms of materiality, the buildings have a concrete heavyweight structure with high thermal mass, and a light sloping roof in plastic tiles and metal structure, without additional ceiling or thermal insulation. The façade counts with sequential openings and vertical louvers in concrete connecting the classrooms with the exterior and a series of discontinuous concrete walls in the corridor defining an outdoor playground area.

Figure 1. Architectural design of the school building.  
Figure 2 Design Builder Model.

The building was measured on a site visit and confirmed through architectural plans, an as-built representation was created in the BIM software Autodesk Revit. The relevant floor plans and building sections could then be exported and used to draw an accurate representation of the buildings' geometry in the energy simulation software Design Builder, the resulting model is shown in Fig. 2. Material properties, occupancy profiles, lighting and electronic equipment specifications were inputted to the model based on a building survey. The building contains 4 blocks with 6 zones including classrooms, stairs and halls.

2. Methodology

The climatic conditions data were obtained through three sources: The Institute of Environmental Studies of Colombia, the local airport, and the climatic design information provided by ASHRAE Handbook Fundamentals. It is worth mentioning that the weather database contains data for the year 2018. In addition, qualitative and quantitative information has been collected through on-site visit; thus, it is possible to compare the simulation results when the outdoor conditions were similar to those acquired by measurements.

Environmental and indoor conditions measured the thermal conditions in the classrooms. The thermal comfort was assessed following ASHRAE Standard 55-2010 [3], defining the study as class III. The indoor measurements were taken at the height of 0.6 m above the floor, representing the average height of the occupant in the seated position. The indoor air temperature (Ta), relative humidity (RH) was measured using the EXTECH 42280 thermometer datalogger.

In addition, a subjective survey with an asynchronous questionnaire to validate the occupant's thermal comfort perspective, the questionnaire addressed the relationship between comfort sensation and thermal preference. The questionnaire is composed of four sections. The first section considers the demographic information; the second section includes thermal sensation preferences; the third and fourth had daylight comfort and air movement questions. The thermal sensation was evaluated with a 5-point scale ending with the choices "cold" and "hot," "slightly cool" and "slightly warmer," and a 5-
point scale for satisfaction. The survey was conducted when participants had been seated for at least 30 min. Scale and verbal anchors translated to Spanish.

**Table 01.** Summary of students sample.

|       | Age  | Weight (Kg) | Height (m)  | Metabolic rate (met) | Clothing Insulation |
|-------|------|-------------|-------------|----------------------|---------------------|
| Min   | 6-7  | 19.6-22     | 1.12-1.18   | 1.4                  | 0.71                |
| Max   | 11-12| 37.4-39.3   | 1.24-1.50   | 1.4                  | 0.71                |
| Median| 8-10 | 28.2-27.4   | 1.28-1.33   | 1.4                  | 0.71                |
| Total |      |             |             |                      | 180                 |

*Notes: Metabolic rate of 1.4 met refers to seated with light activity and clothing insulation in 0.71 clo to medium-length skirt blouse and shoes according to ASHRAE 55-2010*

**Table 02.** Thermal environment questionnaire section.

| Question                                      | Answers         | Scale |
|-----------------------------------------------|-----------------|-------|
| Thermal Sensation                             | Cold            | -3    |
| What is your current thermal sensation?       | Cool            | -2    |
|                                               | Slightly cool   | -1    |
|                                               | Neutral         | 0     |
|                                               | Slightly warm   | +1    |
|                                               | Warm            | +2    |
|                                               | Hot             | +3    |
| At this moment you consider this environment:| Comfortable     | 0     |
|                                               | Uncomfortable   | +1    |
| How do you want to modify the room temperature? | Higher temperature | -1    |
|                                               | No change       | 0     |
|                                               | Lower           | +1    |

*Notes: Questionnaire was developed according to ASHRAE 55-2010*

The surveys identified that about four-fifths (82%) of students have a perception of thermal discomfort inside the classrooms, about two-thirds (65%) noticed an acceptable air quality, and just over three-quarters (78%) requested a decrease of indoor temperature. Visual discomfort, including dark areas in the classrooms, was the most recurrent complaint among students. The survey showed that children between 7 and 12 years old are much more sensitive to high temperatures than adults besides expressing their perception with clear concepts about their thermal environment.

The simulation was performed with the use of the Design-Builder software [4]. Once the thermal comfort results are obtained, comparative studies were developed between the operative temperature, humidity ratio, relative humidity, wind speed, dry bulb temperature, and dew point temperature parameters to evaluate the performance of different configurations. In addition, four variables are evaluated: occupancy levels, natural ventilation rate, roof insulation thickness, and shading design.

The results presented design trends, and a time series analysis improved the reading results. Variations were analyzed in monthly and daily periods. The parameters were selected in the range accepted by ASHRAE 55-2010, allowing variations within the comfort zone due to physical, environmental, and cultural adjustments. Finally, the building's passive strategies are established, focusing on a north classroom as a standard type.
3. Results

3.1. Building Conditions

These simulation results are used to identify the thermal condition in the building configuration. Dry bulb temperature identified the discomfort and heat stress periods, the dew point temperature analysis established the condensation periods, while the humidity ratio parameters described the moisture content. In addition, wind speed and wind orientation were collected to identify impact patterns of evaporation on surfaces and how the moisture is transported from the outdoor to the indoor.

Figure 3 shows that at most 21.2% of the time over the one-year period, the indoor thermal condition for the classroom standard type complies with the ASHRAE 55-2017 thermal comfort ranges criteria (80% acceptability limits). The monthly analysis shows that November is the period with the highest number of overheating hours. 11.2% of the time, the indoor operative temperature is above 34.2°C, under a half of the time (49.5%), operative temperatures are over 28°C which is the threshold used to identify a discomfort period, and 8.5% of the time the temperature is over 36°C which establishes a thermal stress period.

Figure 3. Correlation between indoor temperature and outdoor temperature in 2018.

Notes: the ASHRAE threshold line is located in 28°C for thermal discomfort and 36 °C for heat stress.

A time-series analysis defined that November 13th is the day with the highest number of overheating hours as shown in the Figure 4, 98% of the time the classroom is in thermal discomfort. The dry bulb temperature is 27.2°C at 7:00 and 42.5°C at 17:00 hours, defining the thermal discomfort and thermal stress hours are between 14:00 and 22:00 hours.

In addition to outdoor temperature, indoor conditions are also influenced by relative humidity, solar radiation, wind speed and direction. Analysis of these climatic parameters are carried out. On November 13th, the range of outdoor wind speed is between 0 and 3.7 m/s with a north and southeast direction with the maximum value at 15:00 and the minimum from 21:00 to midnight. The max solar radiation is 0.84 kWh/m2 at 13:00, the daily average outdoor humidity ratio is 20.14 g/kg while indoor 18.52 g/kg, revealing a 9 g/kg difference which means that natural ventilation will bring in moisture from outdoor to indoor.
3.2. Occupancy Configuration

The effect of occupancy on indoor thermal conditions and thermal comfort is carried out. According to current regulations, four levels of occupancy: 1.35 m²/person according to the national standard NTC 4595[7], 2.85 m²/person based in ASHRAE, 1.65 m²/person, identified in the building performance, and an empty classroom were selected. Comparing the current two regulations, ASHRAE proposes 1.5 m² more per person than the national regulations, resulting in the reduction of 1.49 g / kg of humidity ratio and only 0.06 °C of temperature operating and decreasing by 36% the level of occupancy per classroom.

In addition, the level of activities, metabolic rate, and level of clothing isolation were assumed, influencing heat perception among students. In this paper, we have not considered day by day occupancy prediction and simply assume the same occupancy schedule for each school day as educational building occupancy patterns are fairly consistent throughout the week. The classroom zones have been assumed occupied in 95% from 08:00 until 15:00. During 20% of the day, sportive activities are performed outside the classroom; Therefore, short periods of adaptation to internal climatic conditions are considered periods of thermal discomfort.

Figure 5. Effects of occupancy on the hourly indoor operative temperature in November.

Notes: Temperature in grades Celsius (°C), 2.85 m²/person defined by ASHRAE and 1.35 m²/person defined by Colombian national standard NTC 4595.
Figure 6 shows that with the increase of occupancy, the operative temperature increases; For example, on November 13th the indoor operative temperature at noon is 38.06°C for a 100% occupancy, 36.22°C for current conditions, and 35.86°C for an empty classroom, showing a 2.2°C difference. The increase of occupancy also increases indoor humidity ratio, on November 14th, the value decreases from 22.09 g/kg for full room, 21.61 g/kg for current conditions, and 13.04 g/kg for an empty classroom, revealing a 9.05 g/kg difference.

**Figure 6.** Effect of occupancy on hourly indoor operative temperature on November 13th.

3.3. Natural Ventilation configuration

This school building relies on natural ventilation without a mechanical system for cooling. The natural infiltration and ventilation model in Design Builder was set with a programmed maximum air change rate (ACH); The effect of natural ventilation on the indoor thermal conditions is studied by varying the rate from 1-6 ACH. As shown in Figure 7, with the increase of natural ventilation rate the indoor operative temperature decreases.

For example, in November, for 1 ACH, the operating temperature is 34.0°C on average, while 31.6°C and 31.3°C for 5 ACH and 6 ACH on average respectively. Thus, it shows that the 5 ACH to 6 ACH ranges established by ASHRAE 55-2010 for school buildings can reduce the operating temperature by 2.6 °C and achieve the accepted comfort temperature range for hot and humid areas of 90%, at 28.96 °C and 26.48 °C for 80% acceptability for a period of one year.

**Figure 7.** Effect of natural ventilation on the hourly indoor operative temperature November.
The operative temperature decreases significantly concerning the airflow for November 13th, decreasing from 37.0°C for 1 ACH to 34.4°C and 34.0°C for 5 ACH and 6 ACH, which shows that natural ventilation has a significant impact on indoor thermal conditions and is the most effective passive strategy to reduce overheating in free-running buildings without mechanical cooling.

**Figure 8.** Effect of natural ventilation on the hourly indoor operative temperature on November 13th.

![Figure 8](image)

**Notes:** ACH air changes per hour and temperature in grades Celsius (°C).

### 3.4. Roof Configuration

The building has a sloping roof in tiles and a metal frame. The galvanized steel tile with zinc coating and fluoropolymer paint is the most common roof material used in the region. Each sheet has ridges reinforced, and fixing screws with a thickness of 0.45 mm and a width of 1070 mm without an insulation material layer contributes to overheating the upper floor. Therefore, five roof configurations with different insulation materials were selected to study their ability to improve thermal conditions: Open cell spray foam, fiberglass, polystyrene, and EPS Foam, with the roof configuration remained, and adding an eteboard in the inner layer. The metal frame and thermal bridges were not added in the construction layer data.

**Table 03.** Thermal environment questionnaire section.

| Roof Configuration              | Thickness (Inches) | R Value (M2K/W) | U Value (W/M2K) |
|--------------------------------|--------------------|-----------------|-----------------|
| Type 01 R-22 Open cell spray foam | 4.625              | 67.80           | 0.007           |
| Type 02 R-12 Batt Insulation fiberglass | 3.675              | 55.80           | 0.018           |
| Type 03 R-11 Polystyrene | 2.755              | 37.23           | 0.027           |
| Type 04 R-10 XPS-30 Extrude Polystyrene | 2.175              | 33.80           | 0.030           |
| Type 05 Concrete 11 13/16" + EPS Foamboard 4" | 16.43              | 25.20           | 0.040           |

The specific analysis for November shows that the temperature range is lower than in the current conditions; the thermal gain period is more extended by adding a layer of thermal insulation. While in the current conditions, the minimum temperature is at 25.7°C and the maximum is 44 °C, in the five roof configurations, the temperature range is between 29.2 °C and 40.5 °C. Furthermore, the insulation layer with a thickness of 25 cm R-22 open cell spray foam and R-12 batt insulation fiberglass configurations show 1°C lower operative temperature during 8:00 to 16:00, a crucial period in school activities.
On November 13th, the indoor operative temperature shows a range between 35.6 °C and 40.5 °C or the five types of roof configuration compared to the steel tile with metal frame, where the range is between 33.0 °C and 42.2 °C. A decline gradually is identified from midnight to 8:00, reaching a minimum of 35.7 °C and rising at 17:00 to a maximum value of 40.5 °C. This is due to the hours of direct solar radiation exposure and internal gains for occupants' activities.

In this case, the insulation material in the roof improves the thermal comfort for classrooms located on the second floor of the building, reducing the indoor temperature by 3.5 °C and controlling the indoor operative temperature, but also delaying the occurrence of discomfort temperatures.

4. Conclusion

The study presented in this paper focused on improving the thermal comfort in an educational building with natural ventilation located in the northeastern area of Colombia. On the one hand, high levels of temperature and relative humidity while on the other hand, high levels in occupancy and construction systems without insulation layer were among the elements that characterized the building as a case study. A survey collected the thermal comfort votes, thermal perception, thermal preference, and comfort votes were analyzed and identified the students preferred slightly cooler temperatures.
Besides, a building energy simulation evaluated the indoor thermal conditions and compared to data collected on outdoor climatic conditions showing 21.2% of the time over the one-year period, the standard type classroom complied with the ASHRAE 55-2017 thermal comfort ranges.

The occupancy results showed the national standard NTC and ASHRAE with two different occupancy levels and a difference of 0.06°C in the indoor temperature. The standards reduced to 2.5°C the indoor conditions but also decreased 36% the number of students per the classrooms. The natural ventilation results achieved that a renewal rate of 5 ACH maintained the operating temperature lower. As a result, a decrease of 2.6°C was obtained. Mine while, the roof configuration results showed a reduction of up to 3.5°C in the indoor operating temperature, adding an insulating layer in the classrooms on the second floor. Concluding, overheating is the primary concern for a hot semi-humid climate where natural ventilation and adding an insulation layer in the roof configuration significantly influence the thermal conditions.

Therefore, passive design strategies are essential to optimize building design and meet ASHARE-55 requirements. Three strategies were proposed as the most effective: Improving air renewal by cross-ventilation through openings to the north and southeast and manually operable windows to ensure dehumidification, maintaining the occupancy percentage following current regulations, and including insulation layer in the roof configuration.

Further research and validation are needed to evaluate the proposed passive strategies' impacts, besides validating the current elements identified in the building as shading elements, arrangement of external native vegetation, or ventilated double-leaf construction with reflective surfaces. Additionally, more research in a thermal comfort classification according to age and a "clothes adjustment zone" is suggested.

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