Influence of Global Solar Radiation on Indoor Environment: Experimental Study of Internal Temperature Distribution in Two Test Cells with Different Roof Systems

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Abstract: This work is part of a large experimental study on the distribution of internal temperatures in two similar test cells, but with different systems of coverage. The main goal of this paper is to present results on an experimental field to determine the influence of solar radiation on the internal environmental conditions of different roof systems. Dry bulb temperature and internal surface temperatures were measured in two test cells with different roof systems (green roof and conventional ceramic roof). Their thermal performances were compared on days with differing air mass domain, based on dynamic climatic approach. This research was based on the spatial and temporal approaches of dynamic climatology, from the climatic regime of the city of Itirapina, São Paulo State, analysed as representative episodes. Climatic data were provided by an automatic weather station and verified by satellite imagery, and the internal temperatures of the cells were collected by thermocouples installed on the surfaces of ceilings, floors, walls, and suspended inside the buildings. The results indicate that the solar radiation is mainly responsible for the great variations in temperature and its impact on indoor environments, since there were great differences in temperature inside comparing the two days of the experiment. This refutes the notion that the outside temperature is responsible for daily variations in temperature inside buildings.

Key words: Dynamic climatology, solar radiation, air mass domain, internal temperatures, test cells.

1. Introduction

Architecture has a fundamental role in creating built environments, and the relationship between buildings and their surrounding environment is a determining factor in the architectural design process, following housing standards, determined by the needs of individuals, particularly with respect to human comfort based on the principles of natural conditioning [1]. However, the widespread deployment of building typologies needs to be undertaken with caution. Morillón [2] discussed the need for climatic adaptation of designs rather than imposing an “ideal model” for all buildings in different regions. In this sense, the appreciation of design stage becomes a preponderant

consideration, which will allow the adoption of solutions to an architecture that increasingly integrates technology and environment within a particular environmental, cultural and socioeconomic context [3].

The logical process of modern construction is to work with natural forces not against them, in order to take advantage of their potential to inform the design of buildings more adapted for human comfort [4], also taking into account the climate conditioning factors (topography, geographic location, vegetation cover, etc.), which can influence the orientation of the project, the volumetric design of the building and the selection of construction materials, with the aim of designing a built environment that is most appropriate for its users.

The physical interface between the natural and built environments has been studied by research scholars, who clearly reaffirm the importance of architecture in

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the interaction between these two aspects, with the goal of creating comfortable and functional spaces for users. For Egan [5], thermal comfort is conditioned primarily for activities and the energy dissipated as heat generated by the activities and equipment used within indoor environments, and proposes comfort zones based on criteria of internal temperature and relative humidity. As a tool for analysis of human comfort, the authors use climate maps to determine the volumetric design of the buildings according to the region, and suggest avoiding solar radiation.

In architectural projects, two aspects should be studied and evaluated carefully, according to the region and climatic rhythm of the seasons: the sun and the wind. For colder regions, for example, the project must seek the maximum utilization of solar radiation, as opposed to warmer regions, where it is necessary to minimize direct sunlight exposure, according to the apparent path of the sun. In the latter situation, different cultures have used shading devices to control solar input to the indoor, but its efficiency directly depends on the project of building [6]. Aroztegui [7] previously suggested limiting the consideration of climatic variables during the design phase for defining the minimum requirements for thermal comfort. In another study, the same research study emphasizes the importance of the design phase in decision making related to climate adaptation, in terms of seeking the best thermal performance of the building [8].

There is growing concern about the need to adopt more conscious forms of construction, which seek environmental compliance, improved energy efficiency in buildings, and therefore reduce the use of natural resources, while achieving better economic performance and user satisfaction. In this sense, considering the thermal performance and comfort, aligned to improved energy efficiency within the concept of sustainability, the architectural design must address the following issues during its development: orientation, prevailing winds, the apparent path of the sun and routine activities inside buildings. The

emphasis should also be on geometry and spatial distribution of these spaces, and environmental characteristics around the building, such as vegetation, the presence of water bodies, etc. [3]. In several countries, including Brazil, numerous studies have attempted to generalize recommendations for architectural design, aimed at improving passive thermal conditioning systems [9].

Among the many environmental factors that interact with the built environment, this paper aims to show experimentally that the primary influence on thermal conditions within buildings is solar radiation, since it triggers all the other processes such as heat exchange, change in humidity and air circulation.

This paper aims to highlight the importance of basic knowledge of the interactions between environment and buildings, which will mark design a project more appropriate to local climate.

The results of this work are complementary part of the study about distribution of internal temperatures in two test cells, already published by Seixas and Vecchia [10].

2. Methodology

This article has an investigative nature, since it conducts thermal analyses of the performance of two test cells with distinct roof systems on days representing two differing heating scenarios: a heat situation, and a cooler day representing domain of polar Atlantic mass. Data were collected for internal air temperature or DBT (dry bulb temperature) and IST (internal surface temperature) of the ceiling, walls and floor of the experimental cells. This research was based on the concepts of dynamic climatology, defining the typical day for experimental analysis of the results. For dynamic climatology, the succession of types of weather is a result of the air masses movement, specifically the polar masses, which allows the identification of the weather according to their origin, trajectory and dynamic properties. The air masses concept is not definite, because the atmosphere is not

divided clearly. However, researchers adopt the didactic representation of an air mass as a unitary portion of air, which remained stationary on a location and for a period, and acquired unique thermodynamic properties of temperature, humidity and atmospheric pressure [11].

The temperature data were collected using thermocouples installed at predetermined locations in two similar test cells, one with a green roof and the other with a conventional ceramic roof system. Data for the main climatic variables during the two typical experimental days were collected by an automatic weather station at the Center of Science Engineering Applied to the Environment, School of Engineering of São Carlos, University of São Paulo.

2.1 Localization and Characterization of the Test Cells and Automatic Station

The study was conducted at the experimental plot of the climatological station, on the banks of the Lobo Dam, at Itirapina (this city belongs to São Carlos region), São Paulo State, Brazil (22°01'22"~22°10'13" S, 43°57'38"~47°53'57" W) at an altitude of 733 m.

The test cells are constructions of ceramic bricks of dimensions 10 cm × 20 cm × 5 cm and concrete floor slab comprising approximately 5 cm of reinforced concrete, and the construction of the cells differs only in the roof system. They are planned to ensure equivalence to a real situation for data acquisition, and are located on an experimental plot so that they have the same incidence of solar radiation without shadowing one another. The internal dimensions are 2.0 m × 2.5 m, with a default door of 2.1 m × 0.6 m facade facing east and a window of 1.0 m × 0.70 m with northward orientation. The doors and windows are constructed of wood (Fig. 1).

In terms of the roof design, the test cell with a conventional ceramic roof has a slope of approximately 26%, supported by a wooden structure above a horizontal concrete slab, with ceiling height 2.40 m (Fig. 1b). There is an attic between tiles and the slab

with permanent ventilation. The cell with green roof comprises a concrete slab, with a slope of 23% and a 40 cm ledge to contain the substrate and grass, giving a maximum ceiling height of 2.86 m and minimum 2.54 m (Fig. 1a). The green roof is composed of grass, a substrate with topsoil, a blanket drain and a waterproofing layer. This set should be placed on a slab. Although this type of roof construction is simple, the drainage and sealing must be selected and installed with rigorous attention to quality. The green roof was designed to weigh the same as a conventional roof system with wooden frame and ceramic tiles [12]. The slab was sealed with polyurethane resin derived from castor oil (*Ricinus communis*). The use of this resin waterproofing has great relevance because it is biodegradable and non-toxic. Furthermore, it derives from a renewable resource, thereby contributing to sustainable construction [13]. A lightweight and flexible geocomposite drain (MacDrain 2L) is used for drainage of the substrate (partnership with Maccaferri do Brasil Ltda). The core is formed by a three-dimensional blanket composed by filaments of polypropylene, thickness 10~18 mm, and geotextile filters on both sides, non-woven polyester base. For the green roof drainage, two tubes of 3 inches (7.62 cm) PVC (polyvinyl chloride) were placed on the lower ledge, near its ends. The green roof is covered with batatais grass (*Paspalum notatum*), as it is resistant to the action of sunlight and trampling.

2.2 Description of Thermocouples and Automatic Station

The IST and DBT values from test cell were collected

Fig. 1 (a) Green roof test cell; (b) ceramic roof test cell.

through thermocouples type T copper-constantan (alloy of copper and nickel), 2×24 AWG (American wire gauge). The measurements at intervals of 30 min was recorded and stored by a CR10X datalogger. The sampling interval ensured a sufficient data series for the microclimatic-scale analyses conducted in this study.

Type-T thermocouples are resistant to corrosion in humid environments and are suitable for measurements of air temperature (operating range is between -270 °C and 400 °C, oxidized in certain environments only above 370 °C). This type thermocouple comprises a positive thermoelement (Cu100%) and a negative thermoelement with Cu55%Ni45% (constantan). The resulting emf (electromotive force) ranges between -6.258 mV and 20.872 mV. The accuracy of the thermocouples is significant, i.e., temperature error ranges between ± 0.1 °C and 0.2 °C, since the thermocouples are in perfect condition to use [14]. Despite the experimental measurements have been made with the precision of hundredth unit, we chose to present rounded numbers, according to the “theory of errors” [15], for more realistic representation of the incident inherent in real-world data collection scenarios. The data of climate variables were collected and stored by an automatic weather station of Campbell Scientific Inc. Other equipments used were necessary

to keep the automatic station running, such as a rechargeable 12 V battery, solar panel and a CR10X datalogger, which were exclusive and configured to the needs of the station. The data collection programming for test cells and automatic weather station was taken from Campbell’s PC200W software for subsequent connection with used dataloggers.

The thermocouples were calibrated by placing them in a container with ice to check the temperature before their installation in the test cells, and were monitored periodically via a digital infrared thermometer with laser sight during the period of data collection.

All measurements in the test cells were performed with doors and windows closed in order to eliminate the influence of airflow.

2.3 Installation of Temperature Sensors

To measure DBT, the thermocouples were suspended at the centre of the cells, 1.70 m above the floor. To record the surface temperature of the surrounding, the sensors were placed at the geometric centre of the ceiling and floor plans and the axis of each wall, also 1.70 m above the floor, according to Fig. 2.

In each test cell, six sensors for IST data acquisition were placed in small holes and covered surfaces with thermal grease. A sensor for DBT with a shelter made

Fig. 2 (a) Schematic section for green roof test cell; (b) schematic section for ceramic roof test cell.

of PVC pipe (white colour, length 0.30 m, 4" diameter) was surrounded by a blanket of plastic with metallized surface (foil) for better insulation of the thermocouple.

2.4 Climatic Analysis of the Data Series

According to Monteiro [16], the climate of central São Paulo state is controlled by equatorial and tropical air masses, resulting in two distinct periods: a dry season with warm and dry winter, between April and September; and a rainy season with hot and humid summer, from October to March. In the dry season, the tropical Atlantic air mass and polar Atlantic mass predominated, and this season is characterized by low rainfall, sparse cloud cover, low relative humidity and lower average temperature than the rainy season. The rainy season is dominated by the equatorial continental mass, and has higher average temperatures with abundant precipitation and high relative humidity.

In this work, the climatic regime of Itirapina was analysed as representative episodes, according to Vecchia's [17] adaptation of Monteiro's [18] definition of weather types. This comprises two basic steps: pre-front (the beginning of the process), characterised by foreshadowing and advancement of the polar Atlantic mass; and the post-front (the final step of this process), represented by the domain and transition or tropicalization phases of the polar air mass. From the recognition of climatic events recorded during the study, through analysis of meteorological variables and confirmation via satellite images, two typical experimental days were extracted for evaluating the thermal performance of test cells.

Data were collected from January to April 2013. The climatic episode recorded in March was selected to represent two typical experimental days: one represented heat, i.e., with maximum solar radiation and clear sky without clouds, according to reference values from the Climatological Normals 1960-1991 [19]; the other representing conditions for domain of the polar Atlantic mass, characterised by lower outdoor air temperature and greater cloud cover and relative

humidity. These representative days were compared in order to determine the influence of solar radiation within the built environments.

3. Results and Discussion

March 4 (Julian day 63) was taken as representing the heat situation for analysis of thermal performance between the green roof and the conventional test cell. This state was chosen due to its remarkable warmth, exceeding the 27 °C mean maximum temperature for the San Carlos region [19]. The temperature range for this day was 14 °C (minimum 18 °C, maximum 32 °C). The sky was clear, with global solar radiation reaching 779 W/m² (Fig. 3a). March 19 (Julian day 78) was chosen as the typical experimental day for the polar air mass domain. The temperature range for this day was 5 °C (minimum 15.5 °C, maximum 20.5 °C). It showed lower global solar radiation (256.5 W/m²), increasing relative humidity, extensive cloud cover but no rain (Fig. 3b). The satellite images for Brazilian southeast region were provided by the National Institute for Space Research [20]. A complete analysis for the period of collected data can be found in Ref. [10].

Tables 1 and 2 and Fig. 4 show the results for the test cell with green roof.

To help visualise the data presented in Tables 1 and 2, a perspective diagram was prepared from the volumetric data of the cell with green roof, considering only the interior in order to facilitate understanding of the image, with the sensors and their respective maximum and minimum temperatures for both experimental days (Figs. 5a and 5b).

For March 4, 2013, the north and west walls showed the highest maximum temperatures (30.5 °C), followed by the east wall and the dry bulb sensor DBT 04 (30 °C). The lowest wall temperature was recorded by the sensor installed on the south surface (29.5 °C) due to the apparent path of the sun. The lowest maximum temperature was recorded by the ceiling sensor (IST 14). At approximately 28.5 °C, this was 1.5 °C cooler than the value recorded by the DBT 04. This finding

Fig. 3 (a) March 4, 2013: maximum value registered for solar radiation, the sky was clear and no precipitation (São Paulo State inside the red circle); (b) March 19, 2013: polar air mass domain: Increased relative humidity and cloudiness, but no precipitation, and decrease of external air temperature (São Paulo State inside the red circle).

Table 1 Values for external air temperature, DBT, and IST (at their time) (°C), March 4, 2013.

Local (indicators)	Outside (external air)	Green roof (inside)						
		IST 32 (floor)	DBT 04 (1.70 m)	IST 24 (south)	IST 26 (west)	IST 28 (north)	IST 30 (east)	IST 14 (ceiling)
Temperature	Max. (°C) (time)	32 (4 p.m.)	26 (6:30 p.m.)	30 (5:30 p.m.)	29.5 (5:30 p.m.)	30.5 (5:30 p.m.)	30.5 (5:30 p.m.)	30 (5 p.m.)
	Min. (°C) (time)	18 (6:30 a.m.)	21.5 (7 a.m.)	21 (7 a.m.)	20.5 (7 a.m.)	20.5 (7:30 a.m.)	20.5 (7:30 a.m.)	20.5 (7:30 a.m.)
Temperature range (°C)		14	4.5	9	9	10	10	9.5

Table 2 Values for external air temperature, DBT, and IST (at their time) (°C), March 19th, 2013.

Local (indicators)	Outside (external air)	Green roof (inside)						
		IST 32 (floor)	DBT 04 (1.70 m)	IST 24 (south)	IST 26 (west)	IST 28 (north)	IST 30 (east)	IST 14 (ceiling)
Max. (°C)	20.5	20	20	20	20	20.5	20	20
(time)	(3:30 p.m.)	(8 p.m.)	(5 p.m.)	(5:30 p.m.)	(5:30 p.m.)	(5:30 p.m.)	(6 p.m.)	(6 p.m.)
Min. (°C)	15.5	18	17	17	17	17	17	18
(time)	(3:30 a.m.)	(8 a.m.)	(7 a.m.)	(7 a.m.)	(7 a.m.)	(7:30 a.m.)	(7 a.m.)	(7 a.m.)
Temperature range (°C)	5	2	3	3	3	3.5	3	2

Fig. 4 Temperatures charts for green roof, March 4, 2013 and March 19, 2013.

Fig. 5 (a) Perspective diagram for March 4, 2013; (b) perspective diagram for March 19, 2013 (units in m).

shows that internal temperature is mainly influenced by the surfaces that transmit more heat, which raises doubts about the applicability of the calculation of mean radiant temperature, since the value obtained has no physical meaning.

In the case of minimum temperatures, all walls recorded equal values (20.5 °C), and the highest minimum temperature was recorded by the ceiling sensor (IST 14), which demonstrates the best performance of the green roof in relation to night-time heat loss. The heat exchange process is slowed by the action of the green roof insulation, due to its thermal physics constitution, the mass and thermal resistance, shading action caused by the grass, among other beneficial thermal effects characteristic of this type of roof system.

On March 19, 2013, all sensors showed similar maximum and minimum temperatures, as illustrated in Fig. 5b. This was attributed to the predominance of the main meteorological conditions imposed by the polar Atlantic mass, i.e., low incidence of solar radiation due to increased cloud cover, falling external air temperature, and increased relative humidity.

To examine the findings for the test cell with conventional ceramic roof, Tables 3 and 4 and Fig. 6 show comparisons between typical experimental days.

These data are also presented in Figs. 7a and 7b, which provide better visualization of the data.

In the analysis for March 4, 2013, the maximum temperatures recorded by the walls, floor and dry bulb followed the same pattern identified in the green roof cell, except for the ceiling. In the conventional cell, the IST 14 sensor showed maximum temperature of 30.5 °C, which is approximately 2 °C higher than the ceiling sensor of the cell with green roof (28.5 °C). This temperature differential was limited by the design of the conventional cell, which has an attic with permanent ventilation. This helps to reduce the internal surface temperature of the ceiling in the conventional cell. The minimum temperatures were approximately equal (between 20 °C and 21 °C), except the ground sensor, which showed a minimum of 22 °C.

For March 19, 2013, the conventional cell recorded similar maximum and minimum temperatures for all sensors, similar to the results obtained for the test cell with green roof.

Comparing the two test cells for the typical heat situation, the maximum and minimum temperatures were nearly equal for all sensors, except the ceiling sensors (IST 14), which recorded a lower maximum temperature in the cell with green roof. However, on

Table 3 Values for external air temperature, DBT, and IST (at their time) (°C), March 4, 2013.

Local (indicators)	Outside (external air)	Conventional ceramic roof (inside)						
		IST 32 (floor)	DBT 04 (1.70 m)	IST 24 (south)	IST 26 (west)	IST 28 (north)	IST 30 (east)	IST 14 (ceiling)
Temperature Max. (°C) (time)	32 (4 p.m.)	26 (6 p.m.)	30 (5:30 p.m.)	29.5 (5:30 p.m.)	30.5 (5:30 p.m.)	31 (5:30 p.m.)	30 (5:30 p.m.)	30.5 (5:30 p.m.)
Temperature Min. (°C) (time)	18 (6:30 a.m.)	22 (8 a.m.)	21 (7:30 a.m.)	20 (8 a.m.)	20 (8 a.m.)	20 (7:30 a.m.)	20.5 (7:30 a.m.)	21 (7:30 a.m.)
Temperature range (°C)	14	4	9	9.5	10.5	11	9.5	9.5

Table 4 Values for external air temperature, DBT, and IST (at their time) (°C), March 19, 2013.

Local (indicators)	Outside (external air)	Conventional ceramic roof (inside)						
		IST 32 (floor)	DBT 04 (1.70 m)	IST 24 (south)	IST 26 (west)	IST 28 (north)	IST 30 (east)	IST 14 (ceiling)
Temperature Max. (°C) (time)	20.5 (3:30 p.m.)	20.5 (7 p.m.)	20 (6 p.m.)	20 (6 p.m.)	20 (6 p.m.)	20 (5:30 p.m.)	20 (6 p.m.)	20 (6:30 p.m.)
Temperature Min. (°C) (time)	15.5 (3:30 a.m.)	19 (7:30 a.m.)	17 (7 a.m.)	16.5 (7 a.m.)	16.5 (7:30 a.m.)	16.5 (7:30 a.m.)	16.5 (7:30 a.m.)	17 (7:30 a.m.)
Temperature range (°C)	5	1.5	3	3.5	3.5	3.5	3.5	3

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Fig. 6 Temperatures charts for conventional ceramic roof, March 4, 2013 and March 19, 2013.

Fig. 7 (a) Perspective diagram for March 4, 2013; (b) perspective diagram for March 19, 2013 (units in m).

the cooler experimental day, both test cells had identical thermal performance. This finding demonstrates the important influence of global solar radiation incidence on the internal environment.

4. Conclusions

From the analyses, it is evident that incident solar radiation on surfaces influences both external air

temperature and interior temperature, since the day representing polar mass domain showed a thermal range closest to that of the internal sensors, except for the floor sensor, which presented the lowest thermal range on both experimental days. Comparing data from two experimental days, it can be concluded that solar radiation is the determining factor of the thermal conditions in any environment. This refutes the notion

that external temperature is responsible for daily temperature fluctuations within buildings. Another important conclusion of these analyses is that the green roof ensured the best performance on both experimental days. Therefore, this work will contribute significantly to future application of dynamic climatology to the built environment. However, it is important to recognize that thermal analysis is only one of the stages involved in adapting a construction project to local conditions.

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