Analysis of thermal behaviour of a low cost, single-family, housing prototype considering specific climatic conditions

Alessandro Morello[1], Giane Grigoletti[2] and Miguel A. Sattler[1]

[1] Núcleo Orientado para a Inovação da Edificação, UFRGS, Porto Alegre, Brazil
[2] Departamento de Arquitetura e Urbanismo, UFSM, Santa Maria, Brazil

ABSTRACT: MORELLO [1] [2] monitored the outdoor and indoor air temperatures of a low cost housing prototype built in Porto Alegre, in the South of Brazil during one year. This prototype has undergone several evaluations since its construction in 1999. A previous paper partially described the results of the monitoring, comparing measured indoor and outdoor air temperatures and annual heating and cooling degree-hours [3]. The aim of this research is to evaluate the thermal behaviour of the prototype considering specific climatic conditions observed during the period of measurements, such as temperature amplitudes greater than 10°C and hot and cold spells, in order to verify the adequacy of thermal parameters of the building envelope chosen at the design phase. Two procedures established by ABNT [4] [5] [6] [7] [8] to evaluate the thermal behaviour were used. Time lag, decrement factor, thermal effusivity and indoor air temperature variation were analysed, considering the comfort zone established by GIVONI [9] and ABNT [7]. In spite of presenting satisfactory thermal transmittance and time lag for Brazilian standards, indoor air temperatures of the prototype exceeded the boundaries of the comfort zone defined by Givoni.

Keywords: thermal behaviour, low cost housing

1. INTRODUCTION

MORELLO [1] [2] monitored the outdoor and indoor air temperature of a low cost single-family housing prototype built in Porto Alegre, in the South of Brazil during 2003 and 2004. The prototype has undergone several previous evaluations since its design in 1999. Some findings were published by the author [3], including bioclimatic charts generated with Analysis Bio software considering the comfort limits for indoor air temperature as defined by GIVONI [9] for winter and summer, and calculations of heating and cooling degree-hours. Outdoor and indoor air temperatures and relative humidity were recorded on an hourly basis for 352 days of measurements. The monitoring of thermal performance of the prototype was carried out using an indoor climate analyser located in the geometric centre of the living room/kitchen, with the sensors positioned at 1.10 meters from the floor. ABNT [6] establishes three procedures to evaluate thermal behaviour of low cost housing. The first procedure is a simplified method based on requirements and criteria that the housing unit must satisfy. The second procedure is based on computational simulations considering the typical design day. The third procedure involves monitoring indoor air temperature over at least three consecutive days using appropriate equipments. This paper intends to present the prototype thermal behaviour considering outdoor air temperature variation characterized by a sequence of consecutive days with temperature amplitudes of greater than 10°C, daily temperature variation being characterized by minimum air temperatures below 18°C and maximum air temperatures above 29°C, as well as hot and cold spells. The method was based on the selection of daily hourly sequences with the characteristics presented, between simultaneous values of outdoor and indoor air temperatures. The analysis was based on two procedures defined by Associação Brasileira de Normas Técnicas (ABNT): simplified method (calculations of the thermal parameters: absortivity, thermal transmittance, heat capacity, time lag, solar factor and window size) and measurement. In addition to the parameters above, decrement factor and thermal effusivity were also calculated. The analysis considered the comfort zone for developing countries established by GIVONI [9] and the criteria established by ABNT [4] [5]. The limits were between 18°C and 29°C, and between 12°C and the maximum daily outdoor temperature, respectively.

2. THERMAL BEHAVIOUR OF PROTOTYPE

2.1 Thermal parameters

Absortivity, thermal transmittance, heat capacity, time lag, solar factor, window size for ventilation, decrement factor and thermal effusivity were calculated according to ABNT [4] [5] [6] [7] [8], GIVONI [10] and YANNAS & MALDONADO apud GOULART [11]. Absortivity determines behaviour with respect to radiant heat exchange. Thermal transmittance determines the rate of heat flow through building components. Heat capacity is obtained by multiplying density, thickness of building components and specific heat and expresses the heat storage capability of a building. Time lag expresses the difference between the maximum outdoor and indoor air temperatures. Solar factor is obtained by multiplying absortivity, thermal transmittance and external resistance (inverse of surface coefficient). Window size determines ventilation conditions inside buildings and is expressed as percentage of floor area. Decrement factor is the ratio between the temperature amplitudes of outdoor and indoor air temperature. Thermal effusivity, the capacity of building components to absorb and release heat, is defined as square root of the product of thermal conductivity, density and specific heat. These parameters are presented on Table 1.

Table 1: Thermal parameters calculated for the prototype and values established by ABNT (2004, 2005).

Thermal parameters	Unit	Wall parameters	Roof parameters
ABNT (2005b)			
Thermal transmittance*	$\frac{W}{m^2 \, ^\circ C}$	3.12 ≤ 3.60	2.13 ≤ 2.00 1.14 ≤ 2.00
Solar factor*	-	7.6 ≤ 4.0	6.8 ≤ 6.5 3.7 ≤ 6.5
Time lag	h	3.0 ≤ 4.3	1.0 ≤ 3.3 1.7 ≤ 3.3
Window size**	%	25 > 15	-
ABNT (2004b, 2004c)			
Thermal transmittance	$\frac{W}{m^2 \, ^\circ C}$	3.12 ≤ 2.50	2.13 ≤ 2.30 1.14 ≤ 2.30
Absortivity	-	> 0.6	without criterion
Heat capacity	$\frac{kJ}{m^2 \, ^\circ C}$	197 ≥ 130	without criterion
Window size**	%	25 > 8	-
Decrement factor *, ***	-	0.74	0.91 0.87
Indoor effusivity ***	$\frac{W \times s^{\frac{1}{2}}}{m^2 \, ^\circ C}$	1.055 (calculated for the living room/kitchen)	

* the first and second value for the roof corresponds to winter and summer conditions respectively
** the area of openings include the door area
*** there are no criteria established by ABNT

On table 1, the third column presents the values calculated for the prototype (first value) and criteria established by ABNT (second value).

Among the parameters presented on table 1, the prototype did not satisfy the ABNT criteria of roof thermal transmittance, subject to winter conditions, and the wall and roof solar factor, subject to winter conditions [5]. The prototype also did not satisfy the ABNT criterion of wall thermal transmittance [7]. The minimum area of openings for natural ventilation was calculated considering the front and back door area. If the front and back door area were not considered, the prototype would not satisfy the ABNT criterion of window size [7] [5]. The opening system must allow for night ventilation without compromising the privacy and security of building occupants. In this case, the door area could not be considered and openings must have shutters or another system that would allow for night ventilation. If the door area was not considered, the percentage of window size would be reduced by 4%.

2.2 Monitoring of the indoor air temperature

2.2.1 Thermal amplitudes higher than 10°C

According to AROZTEGUI & BRIZOLARA [12], daily temperature amplitudes equal to or higher than 10°C justify the use of thermal inertia to reduce heat flow and indoor air temperature amplitudes. Porto Alegre frequently presents daily temperature amplitudes with these characteristics, according to SATTLER [13], AROZTEGUI & BRIZOLARA [12] and MORELLO [1].

Figures 1, 2 and 3 present sequences of consecutive days that presented daily temperature amplitudes higher than 10°C, for both winter and summer conditions. The sequences correspond to intervals from May 26th to May 31st (figure 1), July 28th to August 02nd (figure 2) and January 03rd to January 08th (figure 3). The difference between the highest outdoor and indoor air temperatures was less than the difference between the lowest outdoor and indoor air temperatures for the three sequences presented. That is, the decrement factor is greater for the maximum temperatures than for the minimum. The variation of the indoor air temperatures is nearly constant for winter conditions. The indoor air temperature remained above 12°C for the six days (figures 1 and 2). A mean difference of 6°C to 7°C was verified between the daily lowest outdoor air temperatures and the lowest indoor air temperatures, with a maximum difference of 10°C. However, considering the lowest limit of the comfort zone defined by GIVONI (1992), minimum indoor air temperatures remained below 18°C almost every day for two sequences representing winter conditions, principally for the sequence in figure 1.

Maximum indoor air temperatures remained above the highest limit of the comfort zone defined by GIVONI [9], equal to 29°C, for at least three consecutive days (see figure 3). However the indoor air temperature did not exceed the highest value of outdoor air temperature, criterion established by ABNT [6].

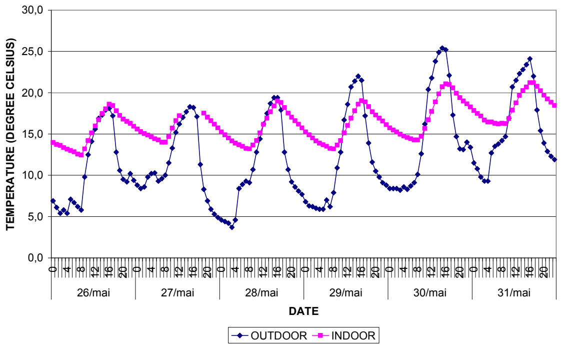

Figure 1: Outdoor and indoor temperature between May 26th and May 31st, 2004.

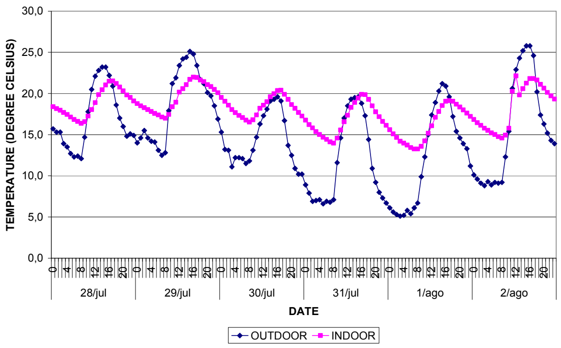

Figure 2: Outdoor and indoor temperature between July 28th and August 02nd, 2004.

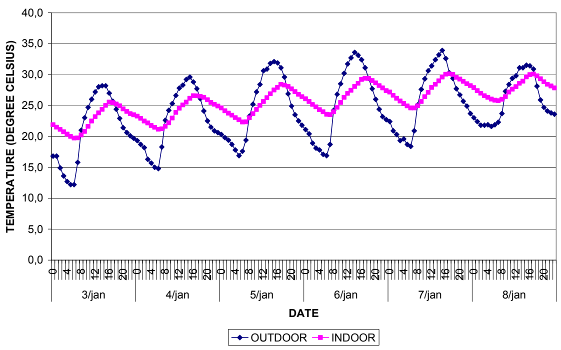

Figure 3: Outdoor and indoor temperature between January 03rd and January 08th, 2004.

2.2.2 Daily variations between values below 18°C and values above 29°C.

The sequences were selected because they presented summer (temperature above 29°C) and winter (temperature below 18°C) conditions according to GIVONI [9] on the same day. The sequences correspond to intervals represented by figure 4 (September 02nd to September 07th) and figure 5 (October 14th and October 19th).

Figure 4 illustrates a situation where three days presented such characteristics: September. 05th, 06th and 07th. The highest outdoor air temperature increased for six consecutive days. The highest indoor air temperature remained close to highest outdoor air temperature during the first three days of sequence. Although outdoor air temperature exceeded 34°C, the indoor air temperature did not reach 29°C (the highest limit of comfort zone defined by Givoni). However minimum indoor air temperatures recorded were below 18°C, except on September 07th.

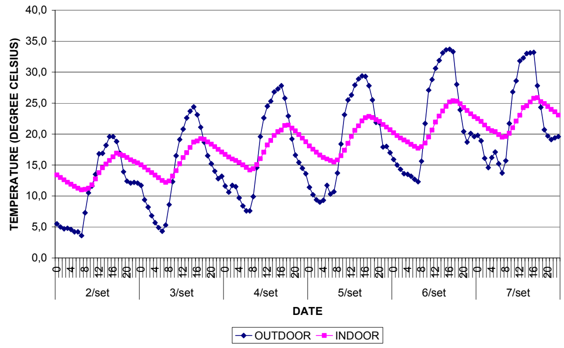

Figure 4: Outdoor and indoor temperature between September 02nd and September 07th, 2004.

A similar situation was verified for the sequence in figure 5, where two days presented the same characteristics: October 17th and 18th. The highest outdoor air temperature increased for five consecutive days. The indoor air temperature initially remained close to the maximum outdoor air temperatures recorded. From the sixth day on (October 17th), the difference between the highest indoor air temperature and the highest outdoor air temperature increased. Despite outdoor air temperature reaching 34°C (October 18th), indoor air temperature did not exceed 29°C. Minimum indoor air temperatures recorded were above the lowest limit of the comfort zone defined by GIVONI [9] on October 18th and 19th.

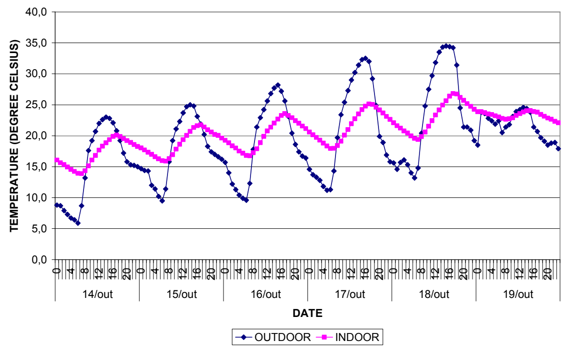

Figure 5: Outdoor and indoor temperature between October 14th and October 19th, 2004.

2.2.3 Hot and cold spells

The sequences represented in figures 6 to 9 were selected because they are representative of building thermal behaviour when it is subject to hot and cold spells, which are common for the climate of Porto Alegre.

Figures 6 and 7 illustrate an increase of between 17°C and 32°C in the highest outdoor air temperature for four days and of between 26°C and 33°C during one day. Temperature amplitudes approximately equal to 20°C and 16°C (figures 6 and 7 respectively) were recorded. Indoor air temperatures remained below the lowest limit of the comfort zone defined by GIVONI [9] almost every day during the sequence illustrated in figure 6. However they remained above 12°C every day except August 18th, when the lowest outdoor air temperature was approximately 2°C. Indoor air temperatures remained close to maximum outdoor air temperatures recorded in the sequence illustrated in figure 7. Both of sequences presented maximum indoor air temperatures exceeding the highest limit of comfort zone defined by Givoni on August 20th and 21st. However they did not exceed the highest outdoor air temperature, the limit established by ABNT [6].

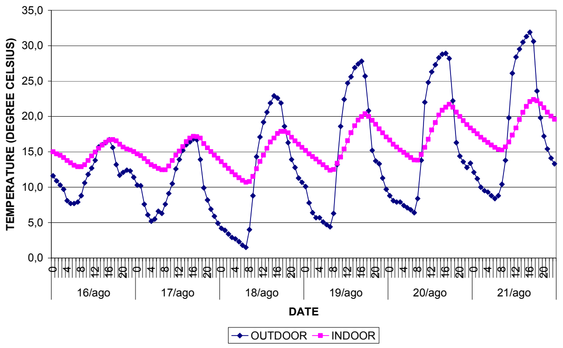

Figure 6: Outdoor and indoor temperature between August 16th and August 21st, 2004.

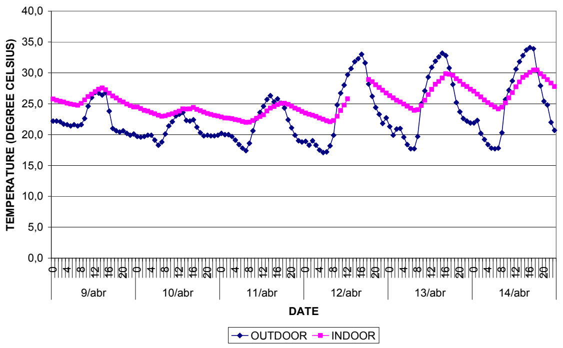

Figure 7: Outdoor and indoor temperature between April 09th and April 14th, 2004.

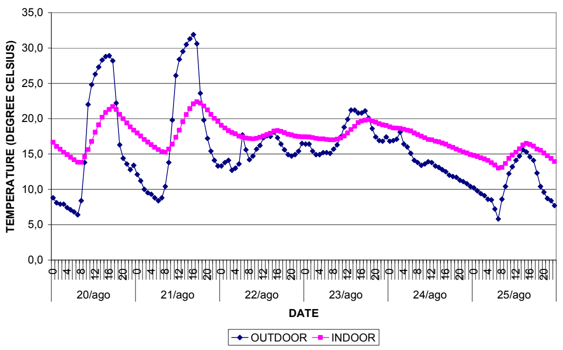

Figure 8: Outdoor and indoor temperature between August 20th and August 25th, 2004.

As figure 8 illustrates, outdoor air temperature fell over one day. Outdoor air temperature reached 32°C on August 21st and 18°C on August 22nd. However temperature amplitudes were reduced by 23°C, to at least 5°C. The highest indoor air temperature exceeded 22°C on August 21st. Minimum indoor air temperatures remained below the lowest limit of the comfort zone defined by GIVONI [9] every day except August 23rd. Indoor air temperatures fell below 12°C on August 24th and 25th, however, they remained above maximum outdoor temperatures.

Figure 9 illustrates indoor air temperature behaviour when the highest outdoor air temperature fell by 11° (September 7th and 8th), from 33°C to 22°C (September 8th) and when it fell 19° from 33°C to 14°C (September 9th). The lowest outdoor air temperature also changed from 13°C to 8°C in three days. Indoor air temperatures remained close to maximum outdoor air temperatures. The lowest indoor air temperature recorded was 11°C (September 10th). Indoor air temperatures remained below 18°C, the lowest limit of comfort zone defined by GIVONI [9] for almost two consecutive days. The lowest indoor air temperature recorded was 13°C, above the lowest limit established by ABNT [6].

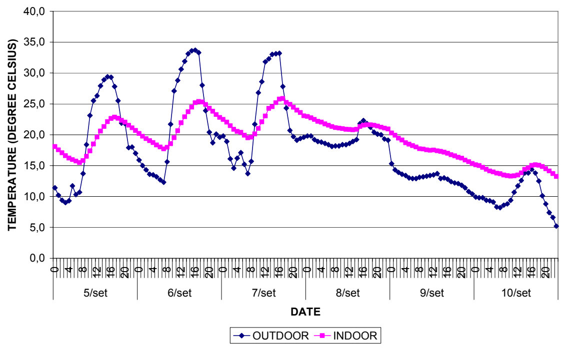

Figure 9: Outdoor and indoor temperature between September 05th and September 10th, 2004.

3. DISCUSSION OF FINDINGS

Considering parameters calculated according to procedures from ABNT [4] [5] [6] [7] [8], the prototype satisfies the criteria established. However, considering the prototype behaviour illustrated by measurements, other parameters can be considered and added to parameters established by ABNT [4] [5] [6] [7] [8].

Despite indoor air temperatures were below the lowest limit of the comfort zone defined by GIVONI [9], they remained above 12°C for almost all of the time, satisfying the criterion established by ABNT [6]. During the period of measurements, the relative humidity was within the comfort zone by Givoni for 67% of the time [1].

The prototype responded to sudden drops of outdoor air temperature by rapidly decreasing in indoor air temperature. Although the prototype was monitored with no occupancy, which would increase the indoor heat gains, the openings were maintained closed during the entire measurement period, what avoid losses from natural ventilation, leaving only losses from infiltration.

The prototype demonstrated a slow response to the increase in outdoor air temperature. Increases is characterized by large outdoor air temperature amplitude (mean temperature remains practically constant), which can cause this behaviour. Indoor air temperatures remained below maximum outdoor air temperatures for the entire period representative of summer conditions, satisfying the criteria established by ABNT [6]. However it exceeded 29°C for eighteen days of the sequences presented (total of fifty four days).

MORELLO [1] analysed seven consecutive days with the lowest daily minimum average temperature for winter conditions and the highest daily maximum average temperatures for summer conditions. Indoor air temperatures remained below 12°C during approximately 50% of hours, and always below 18°C. Indoor air temperatures remained always below the highest outdoor air temperature for summer conditions. The highest outdoor air temperature recorded was 30°C. However the indoor air temperature exceeded 29°C during approximately 30% of hours.

A rapid response to sudden decreases in the outdoor air temperature of the prototype may be associated to a small thermal inertia of the building. Thermal inertia is expressed by the time lag and heat capacity parameters according to ABNT [4] [5] [6] [7] [8]. Despite satisfying criteria established by ABNT, the prototype response expressed by measurements indicates that thermal inertia is not sufficient. Other parameters could be considered and added to the parameters established by ABNT, such as the decrement factor and indoor effusivity.

Occupancy of the building was not considered. Heat gains associated to occupancy would give an indoor air temperature increase, but, for summer conditions, these increases could result in indoor air temperatures exceeding 29°C more often. The openings were kept closed during the entire measurement period, which contributed to a reduction of heat losses.

4. CONCLUSION

The highest limit of indoor air temperature established by ABNT (equal to the highest outdoor air temperature) for summer conditions in the Porto Alegre area should be revised, considering its climate that frequently presents yearly temperatures above 30°C.

Regarding building thermal inertia, other parameters could be considered in the thermal evaluation, such as the decrement factor and indoor effusivity. The time lag criteria and heat capacity criteria established by ABNT could be revised to consider regional specific climatic conditions.

Regarding procedure three established by ABNT (monitoring of indoor air temperature at least over three consecutive days), a longer sequence of consecutive days could be considered and, depending on the region being analysed, special climatic conditions, such as temperature amplitudes greater than 10°C, and hot and cold spells could be considered as well.

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