Thermal performance of low-cost single-family one-floor housing typologies in the South of Brazil

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ABSTRACT: The concept of sustainable buildings involves environmental impacts with the energy expended to thermal conditioning, as well as the thermal comfort of occupants. Energy efficiency in buildings and thermal comfort are well-consolidated attributes in developed countries and there are already standards accepted and applied to construction in order to achieve these objectives. In developing countries these requirements are not consolidated especially when it comes to housing for the low-income population, where costs are the main condition. Considering that the building thermal performance for low-income families and their thermal comfort in developing countries is one of the aspects of sustainability that still deserves attention, this paper presents the results of evaluation of thermal comfort and thermal performance of low-cost housing typologies in the South of Brazil. The thermal performance was determined by the calculation of thermal parameters, such as the inner surface condensation, the global flow heats coefficients, and the radiant asymmetry among others. Additionally, the perceived thermal sensation has been carried according to the Predict Mean Vote (PMV). The survey was carried twice a week during a month in summer and winter of 2012. Indoor and outdoor temperatures were measured in order to compare against the occupant's opinion. The results indicate the low building thermal performance. The envelope of the buildings is not compatible with the local climate. The housing with ceramic materials presented the best performance. The criterion for radiant asymmetry is not satisfied for the roofs. This result demonstrates the importance of this element for small houses, but this element has been neglected by designers. Occupants consider the houses uncomfortable for both winter and summer. However, the degree of dissatisfaction was highest for the summer, revealing a higher tolerance to cold. The rooms appointed as the most uncomfortable have unfavourable solar orientation, towards west and south. During the interviews, high (39°C) and low (8°C) indoor air temperatures were registered, revealing the poor conditions of indoor thermal environment.

Keywords: low-income housing; thermal comfort; thermal performance energy; comfort

INTRODUCTION

The concept of sustainable buildings involves environmental impacts with the energy expended to thermal conditioning, as well as the thermal comfort of occupants. Energy efficiency in buildings and thermal comfort are well-consolidated attributes in developed countries and there are already standards accepted and applied to construction in order to achieve these objectives. However, in developing countries these requirements are not consolidated especially when it comes to housing for the low-income people, where costs are the main condition. Several studies have approached thermal performance of low-cost housing. In Mexico, studies were carried in order to determine physical characteristics of low cost housing, occupants' social and physical conditions, as well as energy consumption, indoor environment climate and the occupants' thermal sensation. Air temperature, globe temperature, relative humidity and wind speed were monitored. Surveys recorded the physical characteristics of houses, established the occupants' thermal sensation as well as with measurements. The research pointed passive thermal strategies based on regional needs and economic limitations [1]. In an exploratory study in Mexico, dry bulb temperature and air humidity were measured with the objective of verifying the human adaptation to indoor thermal environment. The environment was low-income housing. Concomitantly a daily survey was applied along two weeks. The study demonstrates that the occupants' habits are important to adapt the house to external condition and, consequently, improve thermal comfort, such as opening and closing windows, wearing appropriate clothes, among others [2]. In a study carried in Chile, South America, focusing on the low income housing, items like thermal comfort, ventilation, internal humidity and thermal bridges were evaluated for a social house prototype by simulations and in situ measurements. The main results were the inadequacy of the house to both winter and summer conditions. Condensation problems during winter occupation, excessive air infiltration and thermal bridges demonstrated that the house envelope was inadequate in the winter. In the summer the lack of ventilated attic and an unfavourable solar orientation promoted the overheating of the house [3]. A study of perceived thermal sensation in self-produced and economic housing demonstrated that people's thermal preferences are in concordance with their socioeconomic and cultural group. Dry bulb temperature, globe temperature, relative humidity and wind humidity were monitored. The Intervals Means of Thermal Sensation Method was the basis to determine the neutral temperature (ISO10551). Preferences, acceptance and tolerance of thermal environment were compared with measurements. The results pointed that self-produced housing is more acceptable than the economic housing with significant differences in perceived thermal sensation, even when the indoor thermal environment conditions are similar [4].

In Brazil, a despite of government housing policy, the insufficient investments on low-cost housing and the urgency in solve the housing deficit contribute to the low housing quality which historically presents problems regarding thermal comfort and energy efficiency. The occupants are the most affected with this practice, since, in order to improve their thermal comfort, they must use artificial conditioning, which is incompatible with their incomes. In a previous study in situ, measurements for typical Brazilian low-cost housing have been taken in order to verify their thermal performance and to propose suitable patterns for them. The results demonstrated the poor thermal performance of house envelope as well as the design, which did not consider elementary guidelines such as solar orientation, natural ventilation and solar radiation protection of windows by the use of shutters [5]. This paper aims to contribute with guidelines for low-income housing with regard to thermal performance and occupants' thermal comfort through de evaluation of five occupied houses in southern Brazil.

METHOD

Five single-family one-floor low-cost housing typologies with different solar orientations located in Santa Maria, southern Brazil, were selected and evaluated in respect of thermal performance and occupants' thermal comfort. The evaluation of the thermal performance was based in requirements and criteria obtained from the appliance of thermal parameters which consider the building performance in a global basis, that is to say the global heat flow coefficients, the radiant asymmetry, ventilated attic, superficial condensation, thermal inertia and natural ventilation. The parameters were calculated according to the procedures described below. The criteria are also presented and are in concordance with a method previously proposed [6]. Occupants' perceived thermal sensation was estimated by the level of satisfaction according to Predicted Mean Vote (PMV) proposed by Fanger and standardized by the International Organization for Standardization (ISO7730) [7] and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [8].

Climate, indoor, comfort conditions

Outdoor and indoor air temperatures, relative humidity and global solar radiation were assumed equals to Porto Alegre [9], whose longitude to the studied city and WMO Climatological Normals are similar to Santa Maria, since there are not local systematized climate data. The climate parameters, indoor conditions, and comfort conditions are presented on Table 1. The outdoor air temperatures for summer are considered equal to sol-air temperatures [9]. The comfort zone adopted is according to Givoni's Bioclimatic Chart for developing countries [10]. For cold conditions the design-day of 10% is assumed [11].

Table 1: Climate and indoor conditions

Winter
Outdoor air temperature for simulations 7,5°C
Typical amplitude outdoor air temperatures 10K
Air relative humidity 95,0%
Indoor air temperature for simulations 18,0°C
Summer
Maximum outdoor air temp. for simulations 33,5°C
Minimum outdoor air temp. for simulations 23,0°C
Air relative humidity 72,0%
Indoor air temperature for simulations 29,0°C

Thermal resistance, thermal transmittance, time-lag

Thermal resistance R_t, transmittance U, time-lag φ, necessary values for calculations, were defined according to Brazilian standards [12].

Temperature amplitude decrement

Temperature amplitude decrement is calculated according to [13] $\mu = e^{-0,1309 \times R_t \times \sqrt{B1+B2}}$, where R_t is the thermal resistance of element (wall, fenestration, roof) and B1 and B2 are defined by [12].

Coefficient of volumetric heat loss and load

Coefficient of volumetric heat loss is computed according to $GV_{loss} = \frac{Q_T}{V(t_e - t_i)}$ [13], where V is the volume of the indoor space, t_e and t_i are outdoor and indoor temperatures respectively. The volumetric coefficient of heat loss can be broken down into different contributions of heat loss: air flow through the building and heat loss through the walls and the windows (air infiltration). The volumetric coefficient of heat gain GV_{gain} is given by the same formula, but Q_T is considered the maximum heat flow corresponding to maximum $_{Tsol\text{-}air}$ for every external surfaces of building. These coefficients must be lower than 4.0 for GV_{loss} and 18.0 for GV_{gain} [6].

Condensation on inner surfaces

The analysis of condensation on inner surfaces is based on the heat flow under steady state across walls and roof at night in the winter. The internal surface temperatures are analysed when indoor air temperature, minimum outdoor air temperature and air relative humidity are respectively 18°C, 7,5°C and 95% [9].

Radiant temperature asymmetry

The radiant temperature asymmetry is the difference between the plane radiant temperatures of the opposite sides of a small plane element. This parameter is important in comfort conditions. The plane radiant temperature is given by $T_{rp} = \sum_i t_{si} \times f_i$, where T_{rp} is the plane radiant temperature, T_{si} are the inner surface temperatures and f_i are the angle factors according to [14]. For winter conditions, the analysis has to consider the rooms with the smallest internal surfaces temperatures or with large surfaces of windows, mainly windows without opaque elements. For summer conditions, the analysis has to consider rooms with western, northern and southwestern walls because these receive a higher level of radiation in the summer. In addition, horizontal surfaces (roofs) must be analysed. The values of 9°C (roof) and 14°C (walls) are adopted for maximum radiant temperature asymmetry (corresponding to 20% people expressing discomfort).

Besides parameters presented above, coefficients that consider the priority solar orientation of roof (>0.5), ventilated attic only in the summer and windows with northern orientation in order to provide solar heating in the winter are also evaluated.

Occupants' perceived thermal sensation

The survey was carried during the summer (January, February in the afternoon) and the winter (July in the morning) in 2012. While questionnaires were applied, indoor and outdoor air temperatures were measured to compare against the opinion of the housing occupants. The sample size for survey consisted in 5% of total houses, that conserves its original features, that is nine houses distributed on five typologies.

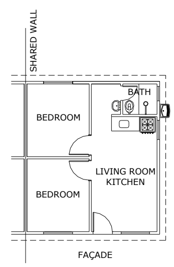
The occupant who stayed at home all day was chosen to respond to the questionnaire and express their momentary sensation with the thermal environment according to seven-point scale (hot, warm, slightly warm, neutral, slightly cool, cool, cold) [7].

During the application of questionnaire the interviewee was sitting in a stool in the middle of the living room. At the same time, indoor and outdoor air temperatures were measured with a digital thermo hygrometer. For winter conditions, the relative humidity was also measured (data of relative humidity for summer conditions have been discharged due to problems of instrument calibration).

Table 2 illustrates the floor plan and the characteristics of the five houses evaluated according the thermal parameters and the number of interviewees for each housing typology.

The questionnaire consisted of questions about the impressions of the thermal behaviour and thermal satisfaction with the house during winter and summer and during the time of the interview. The questions were about whether the interviewee considered the house hot or cold for summer and winter, if he used artificial heating and cooling and what kind of system was used, which rooms are more uncomfortable in summer and winter, if he opened the windows during the summer, how many people lived in the house, among others.

Table 2: Floor plan and characteristics of houses evaluated.

house/number interviewees/ façade orient.	Floor plan	Characteristics
H1/1/NE		Detached house Area 41m^2 (7,5m×5,5m) External walls in concrete panels 10cm thickness, yellow colour Roof in asbestos tiles 6mm thickness with internal layer in concrete of 5cm of thickness Attic without ventilation
H2/2/N H3/2/S H4/2/W H5/2/E		Semi-detached house Area 35m^2 (6,5m×5,4m) External walls in ceramic blocks 11cm thickness, green colour Roof in ceramic tiles without internal layer Attic permanently ventilated

FINDINGS

Thermal parameters

The calculated thermal parameters for the five houses are presented on Table 3.

Table 3: Calculated parameters for the five houses.

Par.	H1/ SE	H2 / N	H3 / S	H4 / W	H5 /E
A	4.7295	3.6752			
B	except on shutters and ceiling	except on shutters and walls			
C	roofs do not satisfy the criterion				
D	19.6159	21.0537	18.8804	20.6498	21.4465
E	0.50	0.25	0.75	0.00	0.00
F	yes	no	yes	no	no

A: GV_{loss}, W/(m³.K)
B: condensation on internal surfaces
C: radiant temp. assimetry ΔT_{rp}
D: GV_{gain}, W/(m³.K)
E: southern or southeastern roof / total roof area $coef_{roof}$
F: northern orientation windows

The houses with ceramic blocks and brick tiles presented GV_{loss} lower than the house with concrete panels. Despite of the roof without an internal layer, since these houses have a shared wall, they are less exposed to the winds and heat losses at night. In hot conditions, their performance was inferior, except for the house with southern orientation to whose the shared wall is west, which receives high solar radiation during the summer. Only houses H2 to H5 satisfied the criterion GV_{loss}<4.0W/(m³.K). For GV_{gain} (<18.0W/(m³.K)), the houses did not satisfy the criterion. Condensation on inner surfaces is present in all houses, although the H1 house does not present condensation on the ceiling due to higher thermal resistance. The excessive radiant asymmetry for roof is present in all houses. This result indicates that the roof is a weak component for one-floor housing, so deserves attention in design. In relation to solar orientation of roof, the H1 house is the only one that satisfied the criterion. The northern orientation criterion is only satisfied by H1 and H3 houses.

The analysis of different contributions for GV_{loss} demonstrated that the walls are the weakest element of envelope for H1 house (53% on total losses). The roof is responsible for 45% of gains in summer conditions. For houses H2 to H5, the roof is responsible for 50% of losses (in the winter), whereas, in the summer, the roof is also the principal contributor (63% to 72%) followed by the western wall (17% to 22%) except for H3 house whose western wall is the shared wall. In this case, the eastern wall is the second greater contributor (13%), although the roof is the greatest contributor (72%).

Additionally, the natural ventilation was also analysed for summer conditions and the windows do not provide sufficient ventilation mainly at night, when shutters must be closed for security (effective area for ventilation less than 20% of window dimensions).

Occupants' perceived thermal sensation

Table 4 presents the results obtained from the interview application and the PMV model in the summer. The data were organized according to temperature intervals. Each occupant was questioned during eight days and the results were considered according to the expressed vote with the most frequency. The measurement period was characterized by high temperature amplitudes, minimum temperature equals to 14°C, maximum temperature equals to 36°C; the registered relative humidity was between 40% and 85% (meteorological data).

Table 3: Calculated parameters for the five houses in the summer.

Internal temperature (°C)	Expressed thermal sensation
28.0-29.9	Slightly warm
30.0-30.9	Warm
31.0-39.0	Hot

The occupants were wearing summer clothes (slippers, shorts, and t-shirt). The results indicate that the occupants' level of satisfaction is approximately according to the comfort zone proposed by [10], that is, the hot sensation appears from 30°C. In relation to the questionnaire, the occupants pointed the rooms with windows turn to west as the hottest, they use fans at night (when they have them) and for H2 to H5 houses they pointed the weakness of the roof as a problem. This result corroborates the importance of the roof and the conscious of occupants in relation the poor thermal quality of their houses.

The comparative analysis between indoor and outdoor air temperatures revealed the poor conditions of the analysed houses. When the day was characterized by amplitudes higher than 15°C, the indoor air temperatures momently measured remained below the outdoor air temperatures, however above 29°C, comfort zone maximum level [10]. When the temperature amplitudes were about 10°C or less, the indoor air temperatures were higher than the outdoor ones. This behaviour was verified for the five houses, but the H5 house presented this behaviour for seven days. This house presented eastern façade and a window faced to west, southern façade with a shared wall and received high solar radiation during the summer. This behaviour was verified also for the H4 house, but for three days. The H1 and H2 houses had the best behaviour in relation to comparative analysis of internal and external temperatures according to more adequate solar orientation. The occupants considered their houses hot in the summer (100%).

Table 5 presents the results obtained for winter conditions. The data were also organized according to temperature intervals and each occupant was questioned during eight days. Unfortunately, the occupant of H1 house gave up asking because of their ill-health. The winter period was characterized by minimum temperatures below 4°C (0°C for two days) and maximum temperatures not above 20°C (except 21st and 22nd July when maximum temperatures rose 24°C). The relative humidity was about 40% at nights and about 95% during the afternoons according to meteorological data.

Table 4: Calculated parameters for the five houses in the winter.

Internal temperature (°C)	Expressed thermal sensation
8.0-10.9	Cold
11.0-13.9	Slightly cool
14.0-15.9	Neutral

In this case, the occupants were wearing winter clothing (sweater, coat, pants, and shoes). The results demonstrate that the occupants have more tolerance for winter than summer conditions if considering the limit comfort zone (18.0°C) and in concordance with Brazilian standards that recommend 12.0°C as the minimum indoor air temperatures for low income housing. This result can be connected to the characteristics of winters in southern Brazil where hot spells (a fast increase in temperature that can reach 30°C) are frequent. This alternation promotes the house heating and consequently improves the comfort conditions during short time periods in the winter and could affect the occupants' thermal sensation. Furthermore, the occupants' clothes had high thermal resistance and were typical outdoor clothing.

Considering the indoor and outdoor measured air temperatures during the application of the questionnaires (eight days), all houses presented indoor air temperatures below outdoor temperatures in at least one day, but H4 house presented this behaviour for four days. H4 house does not have a northern façade, therefore it does not receive significant solar radiation in the winter.

With respect to temperatures registered during the application of the questionnaire, the occupants' habit to leave the doors open to ventilate the house may have contributed to the low values verified. This habit can be associated with the tiny area of the houses, so occupants open the doors to feel a greater and more airy internal environment. The occupants also remained on outside when it is sunny to warm up since they do not have heating systems or to avoid them due to economic factors. This habit demonstrates how cold the houses are in the winter and the importance of passive solar heating for low income housing.

The occupants consider their houses uncomfortable in the winter (100%) and pointed the roof as the weakest element of envelope. The windows and doors are also mentioned as weak elements. The infiltration through openings is a recurrent problem in low cost housing.

The results found through the thermal parameters and the occupants' opinions are in concordance. The five houses presented a low thermal performance.

CONCLUSION

This study demonstrated the importance of some guidelines for low-cost housing. The northern orientation of the windows for living rooms and bedrooms is important for solar heating. The shading of western walls reduces heat gains in the summer. The best performance of brick blocks and tiles face to cement elements. The adequate thermal resistance of roofs with internal layers is important in order to increase their thermal resistance (reducing heat gains and losses) and to reduce air infiltration. Shared walls must be to west or east, never to north. Shutters are important in order to allow night ventilation, but they must have a minimum permeability (50% is suggested). For climate conditions of southern Brazil and occupants' socioeconomic profile and their habits towards the analysed housing, summer conditions are more unfavourable than winter conditions. The level of 12°C as minimum seems be acceptable for this population. Complementary studies must be carried in order to define guidelines for more sustainable housing around different geographic regions considering the thermal comfort and thermal performance of low-cost housing according to the specific characteristics of population as well as local economic, technologic and cultural aspects.

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