THERMAL MONITORING, SIMULATION AND EVALUATION OF A LOW-COST HOUSING PROTOTYPE BUILT IN SANTA CATARINA, SOUTHERN BRAZIL

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ABSTRACT

This paper presents results of simulations and measurements concerning the thermal performance evaluation of a single-storied house prototype, built in Canoinhas (26º10'38"S), Santa Catarina, in Southern Brazil. This prototype was developed in order to attend a national program, which was created by the Federal Government in order to subsidize low-cost housing with a maximum subsidy of US$2,500 for the construction of 'do-it-yourself' units. This study was developed in three stages: first, measurements of outdoor and indoor temperatures of the prototype were carried out during the summer (from December 2006 through February 2007); second, thermal simulations were made with IDA- Indoor and Climate Energy (Sweden) using original properties and characteristics of the monitored prototype; and the third stage consisted of thermal simulation with modified parameters (improvements) such as the composition of the wall panels, for three other climatic conditions, i.e. different geographical locations (Curitiba 25º25'40"S, Florianópolis 27º35'S and Porto Alegre 30º 01'59"S), which belong to two different thermal zones in Southern Brazil. As a result, it was possible to evaluate the prototype's thermal performance and choose the best building configuration for each case, for winter and summer conditions.

INTRODUCTION

According to the *Ministério das Cidades* [1], in 2007 the Brazilian housing deficit encompassed 7.223 million units. The greatest part of this deficit is located in urban areas and in the northeastern and southeastern regions of the country. Over 10 million units of the existing low-cost dwellings require basic infra-structure and about 84% of the families earn up to three minimum wages (around US$ 700 monthly).

Since the 1970s, several new buildings systems have been developed as an alternative to the traditional systems and processes in order to supply the Brazilian housing demand. Among these systems there was a number of unsuccessful experiences without any concern about local characteristics such as climate, and local particularities. Consequently the real estate financing system offers credit only for building systems consisted of brick and concrete masonry. Besides that, none of the traditional credit lines for the construction of dwellings contemplate families with a monthly income of up to three minimum wages, which means that 84% of the population are excluded from real estate financing.

In 2006, the southern Brazilian state of Santa Catarina received US$23 millions within the low-cost housing program PSH (*Programa de Subsídio à Habitação de Interesse Social)* for subsidizing low-cost dwellings for families with a monthly income of up to US$420. Although some consider this a "great advance", the program is unable to provide sufficient affordable housing with the minimum requirements of security, habitability and sustainability.

Santa Catarina is the second greatest Brazilian producer of pine forests. In association with the local housing cooperative (*Companhia Habitacional – COHAB*), the state determined the choice of pre-fabricated wood housing units for meeting the demand for low-cost dwellings. Thus, entrepreneurs linked to the Brazilian Association of Mechanically Processed Wood Industry (*Associação Brasileira da Indústria de Madeira Processada Mecanicamente - ABIMCI*) sponsored the construction of an innovative wood housing prototype, which resulted from the present research.

The prototype was developed in order to meet the requirements of the above mentioned low-cost housing program PSH, (under a small budget U$4,500) and was based on well succeeded experiences with the building system wood light frame. This building system consists of small sized reforestation wood elements and double wall panels composed of plywood. The resulting single-storied house is passively conditioned. Built area corresponds to 48.93m². The roof consists of fiber cement tiles and pinewood ceiling. The double walls have a pinewood structure 2''×3''. Internal panels have a wall thickness of 9mm and external (façade) panels of 12mm, which yields a wall thermal transmittance (U-value) of 2.167 $W.m^{-2}.K^{-1}$. Figure 1 shows the prototype's plan. Table 1 presents the thermal properties of the employed building materials.

FIGURE 1 – FLOOR PLAN

TABLE 1 –THERMAL PROPERTIES / BUILDING MATERIALS

METHODOLOGY

The procedure adopted for the thermal performance analysis comprehended the following steps:

- On site measurements of indoor and outdoor temperatures: PT100 thermocouples, attached to a data logger (Lynx MCS 1000) were used to record air temperatures every minute with an hourly sampling period;
- Thermal simulations of the monitored building prototype were carried out with the IDA Indoor Climate and Energy (ICE) thermal simulation software (version 3.0, Build 15) [2], developed by EQUA, Sweden (www.equa.se) for two sets of conditions: 1) different climatic conditions; 2) different external wall compositions.

ON SITE MEASUREMENTS

Thermocouples were placed in the geometric center of every room and in the living room also at different heights to account for air temperature stratification, and the data logger was set to record data every minute. The external sensor was installed at a monitoring mast, at a two meters distance to the building and at approximately 2m to the ground (ch#7) properly shielded against direct radiation within a PVC tube covered with an aluminum foil. Temperature monitoring took place from December 6th 2006 through January 20th 2007.

FIGURE 2– MONITORING POINTS

Significant differences were found in temperature readings for each room as a result of the different solar exposures and internal volumes. In order to have one single, representative indoor temperature for the building (later, during simulations indoor temperatures refer to a single zone model), data from all sensors were averaged.

A great daily fluctuation was noticed externally, reaching up to ten degrees centigrade. Indoor air temperature fluctuations were much smaller and night temperatures stabilized around 20ºC.

The bioclimatic analysis of indoor comfort conditions was based on the adaptive comfort method given by ASHRAE [3]. For naturally ventilated buildings, ASHRAE Standard 55 suggests an alternative for the PMV-based method for establishing a comfort zone. Optimum comfort temperature T_{comf} is therefore calculated based on the monthly mean ambient temperature T_{out} [4]:

$$T_{comf} = 0.31*T_{out} + 17.8 \qquad (1)$$

The comfort range for 90% acceptability is 5 K and for 80% acceptability is 7 K. For Canoinhas, summer comfort temperature was 23.6, with a comfort range between 20.1-27.1ºC (for 80% acceptability).

Table 2 presents a summary of the percentages of hours in cold, comfort and hot conditions, indoors and outdoors (for 80% acceptability) for each month, including the corresponding minimum, average and maximum temperatures.

TABLE 2– MONITORING RESULTS - SUMMARY FOR CANOINHAS (for 80% acceptability)

Although the monitoring period consisted of summer months, in December and in January 61.5% and 64.5% of the monitoring hours were in a "cold" condition, i.e. below the lower comfort limit of 20.2 ºC and 20.1 ºC, respectively (for 80% acceptability). The "hot" hours were negligible during the monitoring period, reaching a peak value of only 2% in February. For such outdoor conditions, the prototype showed virtually 100% of the hours in comfort.

SIMULATION RESULTS AND DISCUSSION

The main purpose of performing thermal simulations of the described building was the possibility of testing its behavior under different climatic conditions and also to evaluate the impact of design improvements. Simulations were carried out with the thermal simulation software IDA Indoor Climate and Energy (ICE Version 3.0, Build 15), developed by EQUA, Sweden (www.equa.se). IDA Simulation Environment is a general purpose modeling and simulation tool for modular systems where components are described with equations [5]. IDA Simulation Environment has a solver called IDA Solver, which can solve non-linear algebraic problems without requiring initial guesses from the user. This can be quite a task for a problem with a few thousand unknowns. The application may be used for most building types for calculation of, among others: full zone heat balance; operating temperature at multiple arbitrary occupant locations, directed operating temperature for estimation of asymmetric comfort conditions; comfort indices; daylight level at an arbitrary room location. Modeling and calculation procedures of IDA-ICE are detailed in [6].

A simulation model of the building was created using as inputs its geometry and typology, the thermal properties of its constituent building materials, operation of openings and shutters and occupation patterns for various occupation modes of the apartment. For initial simulations, a climate file was created based on data recorded at the closest meteorological station during the monitoring period and on in situ measurements. When project values were uncertain, minor adjustments were made in order to calibrate the simulation model to measured data.

Comparisons to measured data

The resulting model was found capable of realistically simulating the building's thermal behavior, correlation (R) was 0.94 after adjustments were made. Figure 2 shows the correlation between both data sets and Figure 3 the similarity of temperature curves.

FIGURE 2 – CORRELATION BETWEEN MEASURED AND SIMULATED INDOOR TEMPERATURES

FIGURE 3 – COMPARISON BETWEEN MEASURED AND SIMULATED INDOOR TEMPERATURES

Simulations with other climatic data

After a good agreement was verified between measured and simulated data, climatic data from other cities of Southern Brazil were considered for analysis: Curitiba (25º30'S, 49º20'W, 910m above sea level); Florianópolis (27º30'S, 48º30'W, on the coast: Island of Santa Catarina); and Porto Alegre (30ºS, 51º10'W, at sea level).

Curitiba has a high elevation, which is responsible for the coldest winter of all Brazilian capitals. The climate is humid subtropical and according to Koeppen's classification the climate type is *Cfb*. Great daily and seasonal fluctuations of the air temperature characterize Curitiba's climate.

Florianópolis is located on the Island of Santa Catarina. The climate is humid mesothermic without a dry season (*Cfb*, according to Koeppen) and is characterized by a high humidity, hot summers and mild winters.

Porto Alegre has a temperate subtropical climate, with hot summers and cold and rainy winters (for Brazilian standards). According to Koeppen's classification the climate type is *Cfa*.

For each location, the corresponding test reference year (TRY) was used (from the database available at www.labeee.ufsc.br). Simulations were performed for winter and summer months. In order to account for heat gains due to occupation and operation of equipments, apart from thermo physical characteristics of the envelope, thermal loads were included in the simulation model, according to a pre-defined schedule.

Thermal performance evaluation

Results were obtained in terms of indoor temperature variations for the months with the highest and lowest outdoor average temperature for Curitiba, Florianópolis and Porto Alegre. Such months, based on TRY data, were slightly different for the three locations: for Curitiba, the months of February (hottest) and July (coldest) were elected, and for the other two cities, January and June, respectively.

It was verified that the building system has a satisfactory thermal performance with regard to the low temperatures in winter for all three localities. Thus, in winter indoor temperatures are usually above outdoors. In summer, when daily maxima can be substantially high and well above upper comfort limits (according to the adaptive comfort method), indoor temperatures can get slightly higher than outside. Such rise in the indoor temperature patterns in summer is due to several factors such as: direct solar gains through the openings (considered unshaded for the simulations), insufficient ventilation rates, thermal loads through the envelope among other factors.

Comfort analysis

Comfort temperatures were calculated for both months considered for analysis, for the three locations, according to the adaptive comfort method by ASHRAE [7]. Corresponding comfort ranges were obtained for 80% and 90% acceptability.

Three conditions were taken into account for the simulations: a) "prototype", i.e. original configuration (roofing system comprising of fiber cement tiles and pinewood ceiling, double walls with a pinewood structure 2''×3'', internal panels with wall thickness of 9mm and façade panels with 12mm, which yields a U-value of 2.167 $W.m^{-2}.K^{-1}$); b) "prototype 1", i.e. internal panels with a pinewood structure 2''×4'', wall thickness of 12mm and façade panels with 15mm, yielding a U-value of 1.813 $W.m^{-2}.K^{-1}$; c) "prototype 2", i.e. with thermal insulated panels (rock wool 7.5cm thick) between internal and external panels (9mm e 12mm thick, respectively), yielding a U-value of 0.494 $W.m^{-2}.K^{-1}$.

Simulations were carried out for summer conditions with all windows open during the day (from 7:30am to

9pm) and for winter conditions only partly opened and from 2pm to 4pm. With regard to outdoor temperatures in the three locations, it could be verified that in the coldest month Porto Alegre presents the highest percentage of hours of cold, followed by Curitiba and Florianópolis. However, Curitiba has the most extreme minimum temperature in this period. In summer, Porto Alegre shows the highest maximum temperature of all three locations and the highest percentage of hours of heat.

TABLE 3– SUMMARY – SUMMER AND WINTER

In the comfort analysis the original prototype shows in general a good performance under hot conditions. Only for Florianópolis the modifications in the original scheme lead to improvements in the comfort levels in summer. For cold conditions, the introduction of insulation is quite important, as the plywood building system has a low thermal mass.

In general the addition in the original project of an insulating layer between wall panels may contribute to raise indoor temperatures in winter and comfort levels, but can also cause thermal discomfort due to heat.

Heating and cooling degree-hours

The degree-hours procedure is a simplified, practical method for determining cumulative temperatures over the course of a season. Originally designed to evaluate energy demand and consumption, degree-hours are based on how far the average temperature departs from a pre-defined comfort level (Tb or base temperature).

In summer, Tb was assumed to be the upper limit of the comfort range according to the adaptive comfort method and in winter, the lowest limit was considered, for 80% acceptability.

The sum of heating and cooling degree-hours was obtained for Curitiba, Florianópolis and Porto Alegre, for the three configurations aforementioned (“prototype”, “prototype 1” and “prototype 2”). Table 4 summarizes results of heating and cooling degree-hours.

TABLE 4– SUMMARY – HEATING AND COOLING DEGREE-HOURS

According to the degree-hour method Curitiba presents the most critical condition in winter and Porto Alegre in summer. However it should be stressed that the three southern locations (subtropical) are mostly characterized by cold and not by heat, which would be the most common condition in Brazil (tropical). Correspondingly, the heating load for Curitiba is the highest for the first prototype configuration, which may be neutralized by adding insulation to the wall panels. Analogously, the highest cooling load is for Porto Alegre and only a slight improvement is noticed between the three different prototype configurations.

Except for Florianópolis, where “prototype 2” will eliminate the need for cooling in summer, in all other situations the cooling load indoors will be higher than outdoors. Thus, it is here confirmed the need of adding insulation to the prototype for Florianópolis. Considering also the advantage of adopting “prototype 2” for the coldest month in Curitiba, this configuration is indicated for both locations.

CONCLUSIONS

Results of thermal monitoring of the wood prototype in Canoinhas, Southern Brazil, which took place in summer, showed that the prototype presented 100% of the time in thermal comfort for 80% acceptability. Simulations of the same prototype showed that, regarding its thermal performance, it could be adequate to other locations in the south of the country, with or without improvements in the original project.

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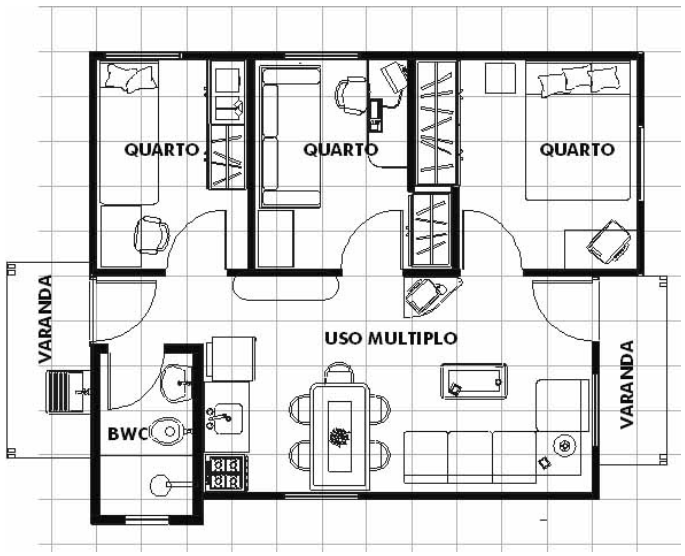

FIGURE 1 – FLOOR PLAN

TABLE 1 –THERMAL PROPERTIES / BUILDING MATERIALS

	Thermal conductivity (W/m.K)	Specific heat J/(kg K)	U-Value $W.m^{-2}.K^{-1}$
Floor (concrete)	0.65	840	3.088
Walls (plywood)	0.15	2300	2.167
Ceiling (wood)	0.15	840	0.15
Roof (fiber cement)	0.65	2300	0.025

TABLE 2 – MONTHLY COMFORT TEMPERATURES FOR CANOINHAS

Month	Tout (ºC)	Tcomf (ºC)	90%		80%	
			Tcomf min (ºC)	Tcomf max (ºC)	Tcomf min (ºC)	Tcomf max (ºC)
Dec. 2006	20.2	23.7	21.2	26.2	20.2	27.2
Jan. 2007	20.0	23.6	21.1	26.1	20.1	27.1
Feb. 2007	19.5	23.5	21.0	26.0	20.0	27.0

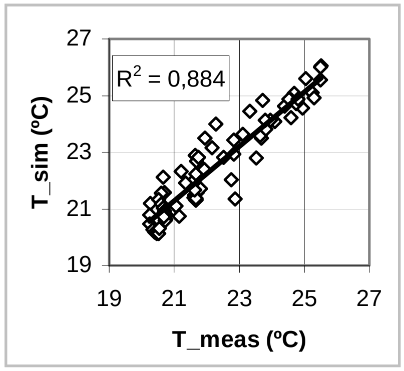

FIGURE 2 – CORRELATION BETWEEN MEASURED AND SIMULATED INDOOR TEMPERATURES

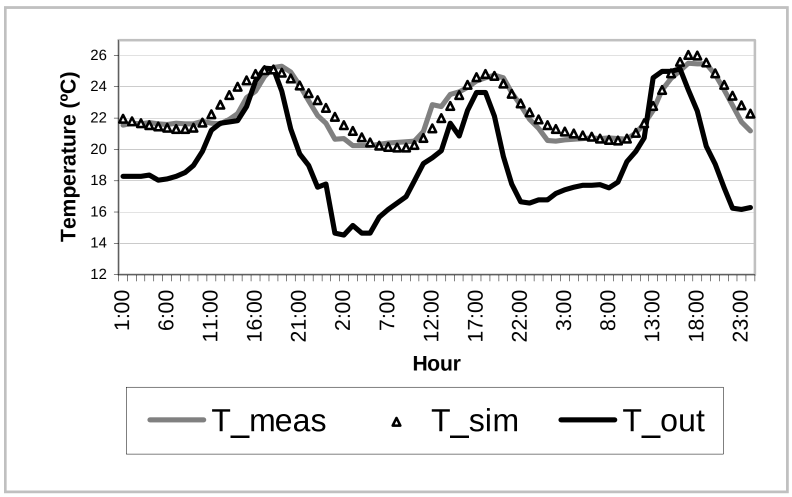

FIGURE 3 – COMPARISON BETWEEN MEASURED AND SIMULATED INDOOR TEMPERATURES

TABLE 3 – SUMMARY – SUMMER AND WINTER

LOCATION	Configuration	Cold %	Comfort %	Heat %	Tmin (ºC)	Tavg (ºC)	Tmax (ºC)
CURITIBA – Summer (February)	*Prototype*	21	71	8	14.7	23.2	31.5
	Prototype 1	21	70	8	14.6	23.1	31.6
	Prototype 2	25	68	7	14.9	23.4	31.2
	Outdoors	**56**	**38**	**6**	**13.0**	**20.7**	**31.0**
CURITIBA – Winter (July)	*Prototype*	40	55	6	8.4	18.8	28.4
	Prototype 1	34	60	6	9.3	19.1	27.8
	Prototype 2	0	69	31	15.2	23.0	29.5
	Outdoors	**85**	**15**	**1**	**-2.0**	**12.0**	**26.0**
FLORIANÓPOLIS – Summer (January)	*Prototype*	3	81	16	20.1	26.6	37.1
	Prototype 1	7	80	13	19.9	25.7	35.1
	Prototype 2	5	95	0	20.8	25.0	36.0
	Outdoors	**18**	**70**	**12**	**18.5**	**24.8**	**36.0**
FLORIANÓPOLIS – Winter (June)	*Prototype*	19	78	3	15.0	21.9	28.0
	Prototype 1	9	82	9	15.6	22.3	28.0
	Prototype 2	0	80	20	20.8	25.0	28.3
	Outdoors	**75**	**25**	**1**	**4.0**	**17**	**29.5**
PORTO ALEGRE – Summer (January)	*Prototype*	8	64	28	16.8	27.1	37.0
	Prototype 1	8	64	28	16.8	27.1	36.9
	Prototype 2	7	65	28	17.1	27.2	36.6
	Outdoors	**1**	**27**	**72**	**12.5**	**24.6**	**36.5**
PORTO ALEGRE – Winter (June)	*Prototype*	10	85	5	12.8	20.1	27.8
	Prototype 1	7	80	13	13.8	20.7	27.9
	Prototype 2	0	54	46	20.4	24.8	29.4
	Outdoors	**88**	**10**	**0**	**2.5**	**14.9**	**26**

TABLE 4 – SUMMARY – HEATING AND COOLING DEGREE-HOURS

LOCATION	Configuration	Heating/Cooling Degree-Hours
CURITIBA – Summer (February)	*Prototype*	78
	Prototype 1	82
	Prototype 2	62
	Outdoors	**51**
CURITIBA – Winter (July)	*Prototype*	979
	Prototype 1	816
	Prototype 2	0
	Outdoors	**4581**
FLORIANÓPOLIS – Summer (January)	*Prototype*	215
	Prototype 1	190
	Prototype 2	0
	Outdoors	**206**
FLORIANÓPOLIS – Winter (June)	*Prototype*	215
	Prototype 1	149
	Prototype 2	0
	Outdoors	**2300**
PORTO ALEGRE – Summer (January)	*Prototype*	593
	Prototype 1	595
	Prototype 2	534
	Outdoors	**422**
PORTO ALEGRE – Winter (June)	*Prototype*	127
	Prototype 1	77
	Prototype 2	0
	Outdoors	**78**