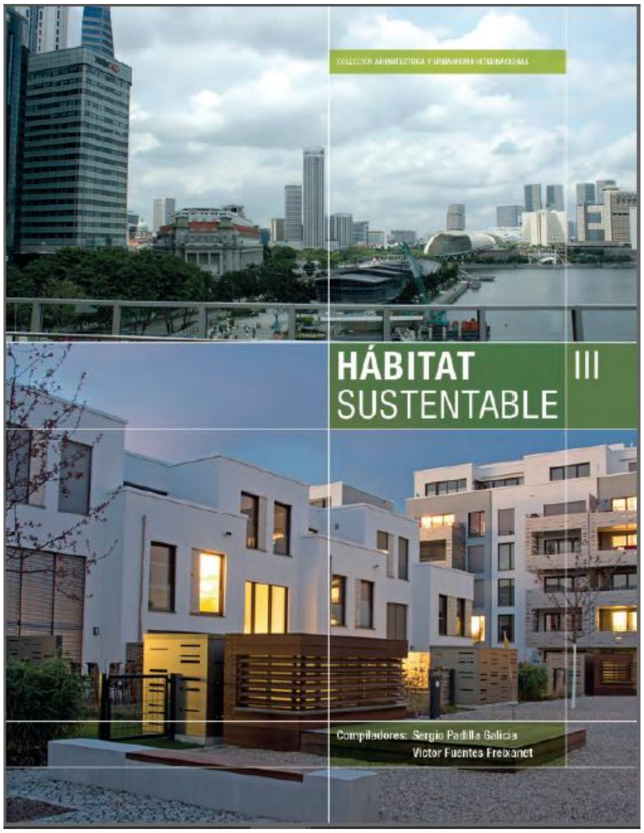


Gómez-Azpeitia, Gabriel (2019).
ORCID: 0000-0001-5316-6483
Gómez-Amador, Adolfo (2019).
ORCID: 0000-0002-1071-0861
Chávez González, Martha Eugenia (2019).
ORCID: 0000-0002-2341-5861
Bojórquez-Morales, Gonzalo (2019).
ORCID: 0000-0001-9303-9278
Romero Moreno, Ramona Alicia (2019.
ORCID: 0000-0002-5853-0229

Affordable Housing for Hot and Sub-Humid Climate in Mexico as Result of a Thermal Comfort Study.
p. 231-245
En:

Hábitat sustentable III / Sergio Padilla Galicia y Víctor Fuentes Freixanet, compiladores. Ciudad de México: Universidad Autónoma Metropolitana, Unidad Azcapotzalco, 2019. (Colección Arquitectura y urbanismo internacional)

Fuente: ISBN 978-607-28-1753-1 (versión electrónica)

Affordable Housing for Hot and Sub-Humid Climate in Mexico as Result of a Thermal Comfort Study

Gabriel Gómez-Azpeitia
Coautores: Adolfo Gómez-Amador
Martha Eugenia Chávez González
Gonzalo Bojórquez-Morales
y Ramona Alicia Romero Moreno

PALABRAS CLAVE:
vivienda de bajo costo, vivienda bioclimática, desempeño térmico; confort térmico adaptativo; centro comunitario

KEYWORDS:
low cost housing, bioclimatic housing, thermal performance, adaptive thermal comfort, community centre

RESUMEN

El artículo presenta un prototipo de vivienda de bajo costo desarrollada con base en estudios de campo llevados a cabo en Colima, México (clima cálido sub-húmedo). Los estudios de campo se dirigieron a un tipo de vivienda promovido por el gobierno mexicano, llamado "vivienda económica". Son viviendas de 45 m^2 construidas con muros de block de cemento y cubiertas con losas de concreto, sin aislamiento térmico. Su diseño atiende a requerimientos de costo, pero carece de criterios sobre eficiencia energética y confort térmico. A partir de los resultados de la investigación, estudiantes asesorados por profesores desarrollaron un proyecto arquitectónico, utilizando estrategias bioclimáticas como dispositivos de sombreado, masa térmica, ventilación natural (ventilación cruzada), ventilación inducida (efecto stack) y ventilación nocturna (intercambio de radiación de onda larga).

ABSTRACT

A prototype of low-cost housing developed on basis of field studies carried out in Colima, Mexico (hot and sub-humid climate) is presented. Field studies were addressed to a type of affordable housing promoted by the Mexican government, called 'vivienda económica'. These 45 m2 housings are constructed of concrete block walls and concrete slabs for roofs, without any kind of thermal insulation. Their design concept only attends cost requirements, but it lacks criteria on energy efficiency and thermal comfort. Consequently, their occupants have adapted to extreme temperatures. Besides the thermal evaluation of pre-existing housing, two field studies were carried out consisted in a poll about the occupants' opinion concerning their houses and a thermal comfort survey according to ISO 10551, within the adaptive model approach. With results of such inquiries, undergraduate students advised by professors developed an architectural project. Main bioclimatic strategies considered were shading devices, thermal mass, natural ventilation (cross ventilation), winds induced ventilation (stack effect) and nocturnal ventilation (long-wave radiation exchange).

Universidad Veracruzana
ggomez@ucol.mx

Introduction

Research project

In 2001, the Mexican government launched the National Affordable Housing Program (*Programa Nacional de Vivienda Económica* PNVE) with the purpose of providing single-family housing for low-income people. Within this frame, the program has promoted the construction of serial houses across the country, whose price should not exceed 116.7 times the official minimum monthly wage, i.e. around USD 13,400[1] The price includes land. While the program has benefited a large number of families, in cities with hot climate the houses' occupants have been problems in terms of thermal comfort and high consumption of energy.

Thus the National Housing Commission (*Comisión Nacional de Vivienda* CONAVI) and the Science and Technology National Council (*Consejo Nacional de Ciencia y Tecnología* CONACYT) were awarded funding to seven public universities in order to develop the research project 'Thermal Comfort and Energy Saving in Affordable Housing of Mexico: regions of hot climate, both dry and humid'.

The studied hot dry cities were Mexicali (32°39'54" N), Hermosillo (29°04'23" N) and La Paz (24°08'05" N); the hot humid were Mérida (20°59'00" N) and Veracruz (19°12'00" N); and the hot and sub-humid were Culiacan (24°49'00" N) and Colima (19°12'50" N).

The research covered two seasons. During the first (August 2005 to October 2007) a diagnosis was led in order to identify operational features of affordable housings in each city, their thermal performance and their energy consumption. Two field studies were conducted too. One of them inquired the occupants' opinion in regard to their houses and the other one surveyed about the thermal perception of the occupants according to the Adaptive Thermal Comfort Model (ATCM) standardized by ISO 10551. As part of the first season, preliminary sketches of bioclimatic houses were developed with the intent to try best alternatives to the local housing markets, in line with each city particular climate and including best spatial conditions and lesser energy consumption possible.

During second season (November 2009 to January 2013), the results of the first season were applied on the complete architectural projects and the construction of five Bioclimatic Prototypes of Affordable Housing (BPAH) in the cities of Mexicali, Hermosillo, La Paz, Mérida and Colima. To achieve this, diverse collaboration agreements were signed with government agencies (as local housing authorities), private companies (as those dedicated to housing market and real state), gremial associations (as those of housing promoters) and/or suppliers of construction products. Each city lead negotiations were different according to local situation.

CONAVI and CONACYT granted the main support for BPAHS' construction and additional budget was

Figure 1. Bioclimatic prototype of affordable housing for the city of Colima (BPAH-COL). Left: Upper View (Project). Right: Exterior View.

1. According exchange rate of 19.0792 Mexican pesos per USD (Bank of Mexico, November 04, 2016).

achieved thanks to different local entities that were signed collaboration agreements. Once BPAHs were built, a climate parameter monitoring, both indoor and outdoor, was performed.

This paper addresses only the PNVE diagnosis, field studies, architectural project, construction, monitoring and current use of the BPAH built in the hot and sub-humid city of Colima (BPAH-COL) (Figure 1).

Research site

Colima is a small city in conurbation of two municipalities (Colima and Villa de Alvarez) with approximately 250,000 population. It is placed close to the west coast of Mexico (19° N, 104° W, 500 MAMSL). Its climate is hot and sub-humid with a rainy season of five months. Maximum temperatures exceed 30°C all the year while mean temperatures always are around 25°C. In turn, there are two different conditions regarding relative humidity. April and May are the lesser humid months (between 30 and 75 %), in contrast, during the rainy season the relative humidity can swing between 50 and 100 % (Figure 2). In summary, four climate seasons can be identified: hot and dry season, April and May; warm and sub-humid season, June to October; temperate season, December to February; and transitional season corresponding to the months of March and November.

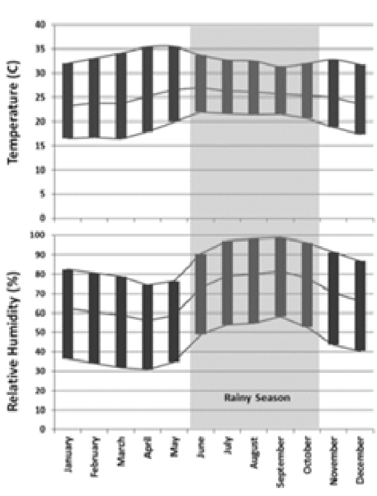


Figure 2. Climate in Colima (SMN, 1950-2010).

Material and methods

First season

In order to accomplish the targets involved for the first research season, several tools, material and methods were applied.

Regards to the diagnosis of affordable housings program, a search in municipal archives were made to find licensed urbanizations as PNVE founds beneficiaries. Once found, tours through urban districts were performed by professors and students. Each tour were identified affordable housing units built, recording its features by means of architectural and photographic surveys, in which spatial schemes and used construction materials were including. With the collected information a mapping of all the affordable housing units was done.

From plans, specifications and photographs of the different found housing models was selected the most representative, regarding to both quantity of units on the city and spatial and constructive solutions. A virtual version of such housing model was elaborated to submit it to thermal and energy simulation by TRNSYS (r) version 16 (TRNSYS, 2005) and Meteonorm (r) version 5.0 (Remund, *et al.*, 2004).

Two separate surveys were applied to representative samples of affordable housing occupants. The first

Table 1. Scale of judgments.

Vote	Sensation scale ANSI/ASHRAE (2004)
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

survey aimed to register subjective assessment about their houses, considering general subjects but especially their environmental and thermal performance. The second survey was a thermal sensation field study which objective was to determine neutral temperatures and thermal comfort ranges according to the Adaptive Thermal Comfort Model (ATCM). For this field study, methods and criteria from ISO 10551 and ANSI/ASHRAE 55 standards were applied. The method for ATCM demands the simultaneous registering of subjective Thermal Sensation Judgments (TSi) emitted by surveyed; As well as Dry Bulb Temperature (DBTin), Relative Humidity (RH), Black Globe Temperature (BGT) and Air Speed (AS) data by mean of measuring equipment complying ISO 7726 standard.

Alternatives of subjective thermal sensation judgments were limited to a symmetrical 7-degree two-pole scale (+3 to -3), as proposed by ANSI/ASHRAE 55 (Table 1).

From results of the thermal sensation field study, seasonal comfort ranges were established as guidelines for projecting an innovative BPAH. Neutral Temperatures (NT) and Comfort Ranges (CR) were estimated by means of regression of subjective Thermal Sensation Judgments (TSi) over Operative Temperatures (OT). In addition to simple linear regression procedure, two alternative procedures were used for data analysis: the Griffiths method (Griffiths, 1990) and that called "Mean Thermal Sensation by Intervals" MTSI (Gomez-Azpeitia, *et al.*, 2007).

Finally, a Bioclimatic Prototype of Affordable Housing for the city of Colima (BPAH-COL) was projected according to local features both climate and socio economics. To achieve this target, a competition among undergraduate students in architecture was hold. Contestants should consider recommendations from results of the research first season, as well as accomplish the obligatory PNVE's budget (up to USD 17,000); therefore, the total area could not exceed 45 m^2.

Competition requirements were use available local materials and implement simple bioclimatic strategies in order not to increase the budget committed. Moreover, houses should work most time in natural running mode, accepting occasionally use of fans but no air conditioning. In addition, projects should consider successive construction stages in order to ease a proper expansion during post-occupancy phase. The winning students' team, advised by University of Colima researchers, developed the definitive project.

Second season

The BPAH-COL was built during the first 2011 semester and once completed, a climate parameters monitoring began. A weather station was placed over the roof and several HOBO data loggers were placed inside. Indoor was recorded: dry bulb temperature (DBTin), black globe temperature (BGT) and relative humidity (RH). Outside was recorded solar radiation (RAD) and dry bulb temperature (DBTout). Data was logged every hour. Again, all the sensors complied with ISO 7726 requirements.

Two monitoring stages were performed: the first one spanned from October to December 2011, and the second from February to April 2012.

Results and Discussion

Evaluation of the PNVE in Colima

Twelve urbanizations with some type of financial support from the PNVE were identified in municipal archives and in field tours. A total of 3,885 affordable housing units were located inside these urbanizations. Area of plots swings between 80 to 140 m2 and up to a third of them measures 100 m2 or least. Nine housing models were found, whose area swings between 23 and 60 m2. Almost 70% of them have only one bedroom and the rest has two.

Respects to spatial schemes in floor plan, the nine identified models are very similar to each other. Its design concept only seems to meet requirements of costs but seems to forget minimal criteria of energy efficiency and thermal comfort.

Most frequent model was that called R1A (Figure 3), which incidence reached 58.3%. R1A is composed

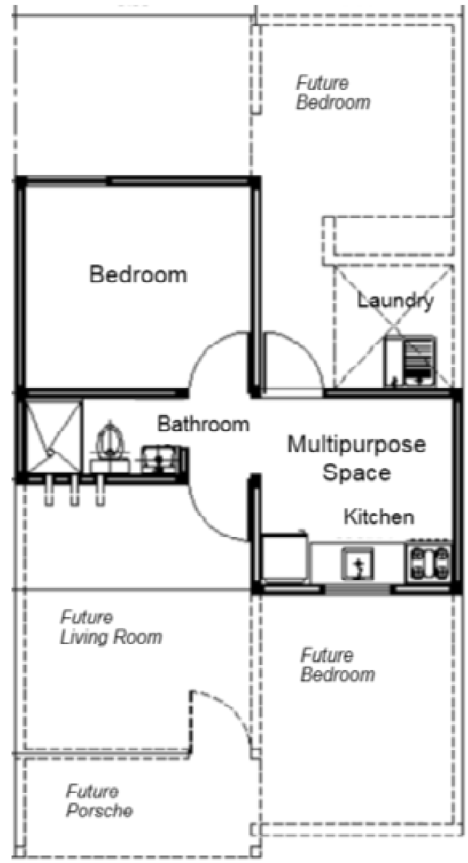


Figure 3. R1A model of affordable housing was the most built in Colima up to 2006. Floor Plan.

by one bedroom, one multipurpose space that includes a minimal kitchen, and one bathroom. The roofed area is 23.8 m2 and usually is insert in 80 m2 plots. Its design contemplates possibility of future expansions, such as a living room, a porch and up to a couple of additional bedrooms, but on a single floor exclusively. Therefore, whenever the occupants would decide to expand their homes, open spaces inside plot would be reduced dramatically.

Once all the affordable housing units were identified and located, a random sample of 351 units was selected to apply the first considered poll in the research project, tending to integrate a diagnosis about the PNVE.

As for the number of people per housing, almost half of surveyed units had three or four occupants, but in 28% there was five occupants or more, which is worrying.

Regarding to construction materials, most used were solid concrete block for walls (62.5%) and concrete slabs for roofs (98%). Practically all the visited houses lack of thermal insulation, on both roof and walls. Most of external walls (70%) are light colors.

Most of surveyed (46.3%) qualified their affordable housing as better than their former house, instead 19% considered affordable housing is too small, and 8% said it is worst. Despite negative judgments 91% of surveyed contemplates to keep living in affordable housing. Rooms most poorly assessed due to their small size were the kitchen (70%) and the bedroom (62%). Indeed, 62% of surveyed has modified their homes, one fourth of them to expand. Also 62% expressed intent to make changes in the future, regardless of whether they had already done so or not.

As to environmental performance, natural ventilation and daylighting were the best. More than 80% of surveyed so considered. Conversely worst performances were about thermal and acoustic subjects, according to said by more than 70% of respondents. Despite that natural ventilation turned out well assessed, bad thermal conditions demand people use fans for improving air movement. 71% of cases correspond to pedestal fans, mostly within bedrooms (46%). Ceiling fans are only used in 4% of houses, always in the living room.

In the case of warm seasons (both dry and subhumid), 64% of respondents rated their homes as uncomfortable. The one considered worse place was the bedroom (51%) and the best one was the living room (within the multipurpose space) (30%). For the temperate season, this opinion shifts. The 67% of surveyed considered their homes comfortable, the bedroom was the best-evaluated place (50%) and the multipurpose space (especially the kitchen) was the worst (44%).

Thermal performance and thermal comfort

Because a thermal evaluation of affordable housing was an essential input to identify aspects to be improved in a bioclimatic prototype to propose, this evaluation was approached by two different means. On the one hand, a thermal simulation of the most used housing model; and on the other hand, a field study of thermal comfort according to the ATCM.

Simulation process considered two scenarios:

a) The building works in free running mode. Natural ventilation is the only cooling strategy. Ventilation is calculated considering 10 air changes per hour. This scenario sought to determine occupants' probable thermal sensation through Predicted Mean Vote (PMV) according to ISO 7730 (2005).

Table 2. Scale of subjective judgments for PMV determination.

Vote	Sensation scale (ISO 7730:2005)
< -3	Too cold
-3 to -2	Cold
-2 to -1	Slightly cool
-1 to -0.5	Comfortably cool
-0.5 to 0.5	Comfort
0.5 to 1	Comfortably warm
1 to 2	Slightly warm
2 to 3	Hot
3 >	Too hot

b) The building works by active cooling systems, regularly air conditioning. This second scenario sought to estimate the energy demand that air conditioning would imply.

In both scenarios, building features were identical.

In the frame of the first scenario, simulation predicts a moderate building thermal performance. Mean maximum temperatures indoors (DBTin) were above 28°C during warm seasons, highest in May (30.5°C). These temperatures were the lowest among the seven studied cities. Nevertheless, calculated PMV by simulation resulted truly high. Table 2 shows the symmetrical 9-degree two-pole scale (+3 to -3) used to determine the subjective judgments in regard to the PMV (ISO 7730:2005).

Probable thermal sensation of occupants is uncomfortable most of time according to simulated PMV. Table 3 shows the results from simulation for 24 hours per day of every month. According to this, mornings would be the only comfortable time throughout the year (from 3:00 to 12:00; PMV = 1 to -1); rest of time, people should feel uncomfortable. Worst conditions occur during evening period (16:00 to 22:00) of April to July when PMV exceeds 2 (hot thermal sensation). In fact, mean PMV exceeds one (slightly warm sensation) for nine months (March to November). Conversely, people should feel 'comfortably cool' (PMV < 0) a little before noon (from 8:00 to 11:00) during three first months of the year. First simulation scenario's conclusion is most of time should prevail bad thermal conditions within affordable housing in Colima.

As to the second scenario, a 25°C set-point was considered for air conditioning operation. This temperature is a little lesser than the neutral temperature suggested by ANSI/ASHRAE 55: 2010 (25.5°C considering mean DBTout = 25.7°C). From selected set-point it was determined a monthly energy demand of 175.8 w/m2 (600 BTU/h per m^2). Because the roofed surface of affordable housing covers approximately 24 m^2, required capacity of air conditioning equipment was set at 1.2 refrigeration tons (14,400 BTU/h, i.e. 4,219 W). Simulation indicates that air conditioning's use increases 70% the energy consumption and consequently the corresponding monthly payment, regarding to energy consumption and monthly payment of a free running building. In this regard, Colima case suffered the greatest impact, despite of it did not present the worst conditions with respect to the seven studied cities, according to the thermal simulation results.

Field study

As outcome of the thermal comfort field study, 608 surveys were collected. After two consistence tests 8 surveys were discarded because of there were air conditioning working at the moment of survey or because recorded data of GBT were unreliable (±10K in regard to DBTin). So, 600 reliable surveys were considered for its analysis: 81 corresponding to the warm and humid season (September and October 2006); 120 relating to the transitional season (November 2006); 200 concerning to the temperate season (January and February 2007); and 199 relating to the hot and dry season (April and May 2007).

Air Temperatures recorded indoors exceed the results of simulation. Mean temperature corresponding to the complete field study was 28.6°C (S.D. = 2.1), but during the warm seasons almost reaches 30°C. As to maximum temperatures, these exceed 30°C in all seasons (Table 4).

These thermal conditions give rise to interesting responses from surveyed, as shown in Table 5. Mean thermal sensation (TSi) corresponding to the complete field study was 0.7 (S.D. = 1.1), which is within the comfort range (TSi = +1 to -1), although closer to the upper limit. In the warm seasons, in change, mean TSi overcomes such limit, especially the warm and humid season. During such season no one manifested cold

Table 3. Occupants' probable thermal sensation (PMV).

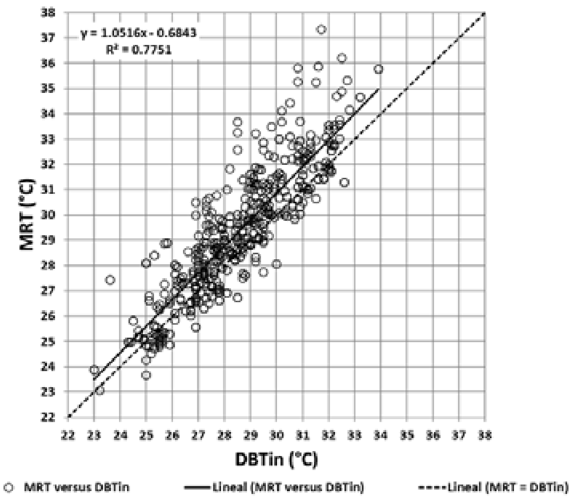
	Months											
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.01	0.96	1.13	1.28	1.76	1.47	1.5	1.18	1.04	1.10	1.12	1.03
2	1.01	0.96	1.13	1.28	1.76	1.47	1.5	1.18	1.04	1.10	1.12	1.03
3	0.56	0.66	0.77	0.91	1.2	1.09	1.15	0.97	0.85	0.86	0.82	0.78
4	0.44	0.52	0.61	0.73	0.96	0.91	1.00	0.86	0.73	0.74	0.7	0.67
5	0.15	0.39	0.45	0.59	0.74	0.75	0.86	0.75	0.62	0.62	0.55	0.58
6	0.06	0.12	0.32	0.48	0.53	0.64	0.73	0.64	0.56	0.51	0.43	0.49
7	0.00	0.07	0.09	0.39	0.19	0.52	0.62	0.54	0.49	0.45	0.38	0.20
8	-0.14	-0.07	-0.04	0.09	0.1	0.45	0.57	0.46	0.17	0.13	0.29	0.08
9	-0.26	-0.16	-0.1	0.07	0.1	0.46	0.29	0.47	0.15	0.12	0.13	0.01
10	-0.25	-0.14	-0.05	0.15	0.22	0.52	0.63	0.56	0.20	0.20	0.34	0.04
11	-0.12	-0.04	0.11	0.55	0.69	0.66	0.77	0.70	0.49	0.59	0.53	0.18
12	0.15	0.19	0.63	0.83	0.96	0.89	1.00	0.92	0.67	0.83	0.81	0.68
13	0.72	0.70	0.96	1.16	1.23	1.23	1.25	1.16	0.97	1.08	1.11	0.96
14	1.08	1.05	1.30	1.48	1.5	1.59	1.56	1.39	1.3	1.31	1.40	1.24
15	1.36	1.32	1.56	1.73	1.73	1.89	1.81	1.56	1.57	1.56	1.67	1.44
16	1.55	1.52	1.77	1.89	1.87	2.11	2.02	1.69	1.71	1.75	1.85	1.60
17	1.69	1.66	1.93	2.02	2.07	2.3	2.21	1.84	1.79	1.9	1.95	1.70
18	1.72	1.76	1.96	2.23	2.18	2.37	2.35	1.95	1.85	1.9	1.92	1.76
19	1.67	1.8	1.94	2.12	2.21	2.38	2.38	1.96	1.82	1.85	1.86	1.74
20	1.58	(1.76	1.88	2.07	2.18	2.32	2.35	1.91	1.73	1.77	1.82	1.68
21	1.46	1.60	1.79	1.93	2.04	2.2	2.21	1.75	1.58	1.66	1.69	1.55
22	1.32	1.43	1.66	1.77	1.88	2.04	2.05	1.58	1.42	1.53	1.57	1.40
23	1.15	1.27	1.48	1.6	1.69	1.84	1.87	1.43	1.27	1.38	1.43	1.27
24	1.01	1.12	1.32	1.42	1.51	1.65	1.69	1.30	1.22	1.24	1.28	1.15
Mean	0.79	0.85	1.03	1.20	1.30	1.41	1.43	1.20	1.05	1.09	1.12	0.97
S.D.	0.69	0.68	0.72	0.70	0.72	0.70	0.66	0.51	0.56	0.58	0.60	0.59

S.D. = Standard deviation.

Table 4. Air Temperature data recorded during field study (DBTin).

Season	Number of data	Mean (± S.E.)	S.D.	Max	Min
Total	600	28.6 (±0.2)	2.095	33.9	23.0
Warm and Humid (Sep-Oct)	81	29.5 (±0.3)	1.042	32.8	25.7
Transitional (Nov)	120	27.8 (±0.3)	0.845	32.5	23.2
Temperate (Jan-Feb)	200	27.3 (±0.2)	0.761	30.3	24.3
Hot and Dry (Apr-May)	199	29.9 (±0.2)	1.178	33.9	23.0

S.D. = Standard deviation.
S.E. = Standard error.



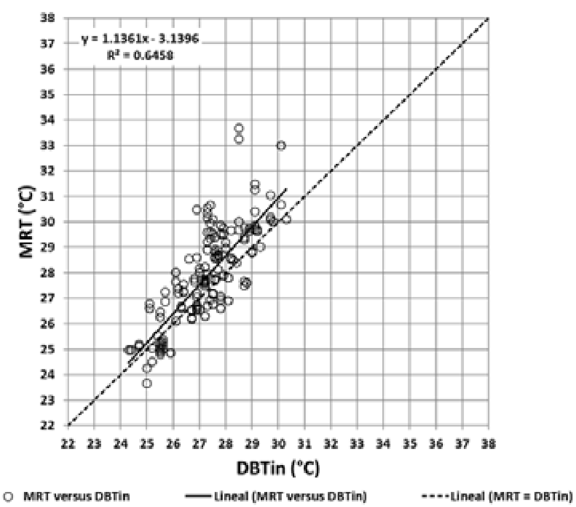


Figure 4. Mean Radiant Temperature (MRT) versus Air Temperature indoor (DBTin). Up: data from complete field study. Down: data from temperate season.

sensation ever, so the judgments range (TSi = 0 to +3) is clearly asymmetrical. For its part, temperate and transitional seasons record better conditions as indicates the mean TSi which is close to neutral sensation (TSi = 0 and S.D. lesser than 1.0), particularly the temperate season which furthermore presents an almost symmetrical swing (TSi = +3 to -2).

It is interesting too, to contrast these results with the probable thermal sensation calculated by simulation in terms of PMV. Table 6 shows the relevant issues of such comparison. The PMV previsions for the temperate and transitional seasons are clearly overestimated regarding to the real TSi of respondents. For such seasons, mean PMV from simulation is around the judgment +1, being that the actual mean TSi is around neutral sensation. Opposite, during the warm and humid season, the actual mean TSi overcomes the calculated PMV. Likewise, maximum TSi recorded in field study for each season is superior to all simulated PMV.

A good indicator of how buildings envelope works in the process of heat exchange among indoors and outdoors is the comparison between Air Temperature and Mean Radiant Temperature MRT (Nicol & McCartney, 2001). MRT is an indicator calculated from recorded data of DBTin, BGT and AS. Therefore, a comparison between DBTin and MRT corresponding to the field study can help to understand the thermal performance of affordable housings. Figure 4 shows two scatter plots where both parameters are correlated. In the plot corresponding to the complete field study (left) it can be seen that mostly MRT data is upper of Air Temperature (DBTin), i.e. built elements are emitting long wave radiation to inside, which increases more the high Air Temperatures ($r2 = 0.77$, $n = 600$, $Pr < 0.05$). This occurs even at the temperate season, the least warm period of the year ($r2 = 0.64$, $n = 200$, $Pr > 0.05$) as the plot on the right shows. This is an evident outcome of lack of thermal insulation on housing envelope.

Table 5. Thermal Sensation Judgments recorded during field study (TSi).

Season	Number of data	Mean (±S.E.)	S.D.	Max	Min
Total	600	0.7 (±0.1)	1.102	3.0	-2.0
Warm and Humid (Sep-Oct)	81	1.4 (±0.2)	1.042	3.0	0.0
Transitional (Nov)	120	0.2 (±0.2)	0.845	3.0	-1.0
Temperate (Jan-Feb)	200	0.1 (±0.1)	0.761	3.0	-2.0
Hot and Dry (Apr-May)	199	1.1 (±0.2)	1.178	3.0	-2.0

S.D. = Standard deviation
S.E. = Standard error

Table 6. Comparison between TSi (from the field study) and PMV (from simulation).

Season	TSi Mean	PMV	TSi Maximum	PMV
Total	0.7	1.12	3.0	2.38
Warm and Humid (Sep-Oct)	1.4	1.07	3.0	1.90
Transitional (Nov)	0.2	1.12	3.0	1.95
Temperate (Jan-Feb)	0.1	0.82	3.0	1.8
Hot and Dry (Apr-May)	1.1	1.25	3.0	2.23

Table 7. Acceptance of the thermal environment of housing (percentage of responses).

	Usually acceptable	
Season	Yes	No
Total	76.0%	24.0%
Warm and Humid (Sep-Oct)	66.7%	33.3%
Transitional (Nov)	78.3%	21.7%
Temperate (Jan-Feb)	93.0%	7.0%
Hot and Dry (Apr-May)	61.3%	38.7%

Regarding to answers about acceptance of the thermal environment, it was found that occupants express a high acceptance of their homes, particularly in the temperate season in which the judgment 'Usually acceptable' achieves 93% of responses. In turn, the hot seasons got the highest quota of disapproval, in which more than one of each three occupants qualified the thermal environment of their homes as 'Usually unacceptable'. Anyway, all the time a favorable acceptance prevails in the occupants' judgments (Table 7).

This opinion is confirmed with responses about how much is tolerable (or not) the thermal environment of their homes. During the hot seasons most of respondents consider it was 'slightly tolerable', and during the less warm seasons most opined that it was 'tolerable'. Very few (less than 10%) considered 'intolerable' their homes. No one qualified as 'extremely intolerable' (Table 8).

In order to estimate the neutral temperature (NT) for each season, it was calculated operative temperatures (OT), an indicator of the actual feeling of people, which in turn comes from Air Temperature (DBTin) and Mean Radiant Temperature (MRT). Besides, OT is widely used in international standards as ASHRAE 55: 2010 and EN 15251: 2007. As can be seen in table 10, OT always achieves relatively high values. During the lesser warm seasons mean OT is around 25°C, but in hot seasons overcomes 30°C. Alike, maximum OT is always upper to 30°C (Table 9).

The main objective of the field study was to find what thermal conditions were qualified by respondents as suitable, in order to use them as set-point for the thermal performance of new affordable housing designs. Results of Neutral Temperatures (NT) calculation by a simple linear regression are shown in Table 10. There can be seen that most of values are above 26ºC except those of the Warm and Humid season, which surprisingly is lesser which turns unreliable the result. Moreover, the regression coefficients (RC) of less warm seasons are too low, and therefore the resulting NT could be unreliable too.

Table 8. Tolerance of the thermal environment of housing (percentage of responses).

Season	Really Tolerable	Tolerable	Slightly Tolerable	Intolerable	Extremely Intolerable
Total	18.0%	39.3%	39.3%	3.3%	0.0%
Warm and Humid (Sep-Oct)	16.0%	19.8%	54.3%	9.9%	0.0%
Transitional (Nov)	27.5%	56.7%	14.2%	1.7%	0.0%
Temperate (Jan-Feb)	25.5%	57.5%	16.5%	0.5%	0.0%
Hot and Dry (Apr-May)	5.5%	18.6%	71.4%	4.5%	0.0%

Table 9. Operative Temperature during field study (OT).

Season	Number of data	Mean (± S.E.)	S.D.	Max	Min
Total	600	29.0 (±0.2)	2.229	34.8	23.1
Warm and Humid (Sep-Oct)	81	30.1 (±0.4)	1.744	33.7	27.2
Transitional (Nov)	120	28.1 (±0.4)	1.996	34.5	23.1
Temperate (Jan-Feb)	200	27.6 (±0.2)	1.505	31.5	24.3
Hot and Dry (Apr-May)	199	30.4 (±0.3)	2.059	34.8	23.4

S.D. = Standard deviation.
S.E. = Standard error.

Table 10. Neutral Temperatures (NT) according to Simple Linear Regression

Season	RC	r2	NT
Total	0.274	0.309	26.6
Warm and Humid (Sep-Oct)	0.222	0.139	24.0
Transitional (Nov)	0.120	0.081	26.2
Temperate (Jan-Feb)	0.107	0.045	26.4
Hot and Dry (Apr-May)	0.316	0.307	26.8

RC = Regression Coefficient.

These are typical bias that simple linear regression procedure returns when certain conditions of the sample are present. One of them is when few data sets are available. That may be the case: no season collected more than 200 data sets. In order to avoid such bias two alternatives procedures were applied too.

Griffiths' method calculates the NT from the mean TSi and the mean OT, assigning a regression coefficient drawn from laboratory studies. NT of the European standard EN 15251: 2007 were calculated with a regression coefficient of 0.5, which seems to be the value than better expresses the feel variability of people throughout the day, inside free running buildings (Humphreys, at al 2016).

On the other hand, the MTSI method determines separately the mean OT from each one of the seven points of the comfort scale (-3 to +3) with the purpose of submitting them to a linear regression. Therefore, the fundamental difference with the simple linear regression method is that instead obtaining the regression line from the complete data sets, the line comes from only the mean OT of each comfort scale's point. Line's intersection with ordinate zero (scale's point corresponding to neutral votes) defines the NT's value (Gomez-Azpeitia, e*t al.*, 2014).

The NT values obtained by such methods are shown in Table 11. Those come from Griffiths are higher than the simple linear regression ones and those come from MTSI are higher yet. It is obvious that these values are more adjusted to the reality.

In the case of the MTSI method, the outcomes are very close to the mean OT of the group of respondents who manifested neutral sensation, so more that 'comfort temperatures', these values rather should be considered as "conformity temperatures". This suggests until where individuals are capable to adapt, even at so high temperatures like these, or yet higher, how it occurs in the other cities studied on the research project (Gomez-Azpeitia, *et. al.*, 2009; Gomez-Azpeitia, *et al.*, 2014).

Table 11. Neutral Temperatures (NT) according to alternative procedures.

Season	Griffiths' Method	MTSI Method
Total	27.7	28.4
Warm and Humid (Sep-Oct)	27.4	29.2
Transitional (Nov)	27.6	27.9
Temperate (Jan-Feb)	27.4	27.3
Hot and Dry (Apr-May)	28.1	28.6

Figure 5: Left: Aerial view of *Fraccionamiento Buenavista*. BPAH-COL is within white ring. Source: Google Earth. Right: Site Plan.

Hence, values from the Griffiths method were those to use as set point in the new affordable housing design. The corresponding comfort range was established in the same terms of the ANSI/ASHRAE 55: 2010 standard, this is ±2.5 K.

Design, construction and monitoring of the BPAH-COL

The Institute of Land, Urban Planning and Housing of the State of Colima (*Instituto de Suelo, Urbanización y Vivienda del Estado de Colima,* INSUVI) donated the land to build the BPAH-COL. It is located in *Fraccionamiento Buenavista*, a consolidated suburb at the city western limit, just on the municipality of Villa de Alvarez. The suburb extends on 22 hectares where around 1020 inhabitants reside in 255 single-family housings. Most of inhabitants correspond to low-income population (Figure 5).

As commented above, the preliminary project of the BPAH-COL was selected from a competition among undergraduate students in architecture. Sixteen teams of three students each, submitted their proposals timely. The winner project (Figure 6) was corrected and adapted with advice of professors within the research team.

Because of size limitations mentioned above, BPAH had to be resolved in few spaces: bedroom, bathroom, living room, kitchen and a small dining room. Thinking on expansion needs, the dining area was arranged in such way as a staircase could replace it in future. Outside at the patio, there is a laundry space and a gray water treatment system (Figure 7).

According to design guidelines previously developed, based on two references, one national (Dirección General de Normas e Insumos de Vivienda, 1988) and other local (Gómez Azpeitia, 1990), the bioclimatic strategies considered were: shading devices, thermal mass, natural ventilation (cross ventilation), wind induced ventilation (stack effect) and nocturnal ventilation (long-wave radiation exchange).

In this regard, one difficulty was how to achieve cross ventilation, despite the architectural solution

Table 12. Average data recorded during October-December 2011.

Parameter	Max	Min	Mean
Air Temperature Indoors DBTin (°C)	28.2	22.0	24.8
Black Globe Temperature BGT (°C)	27.4	21.3	24.0
Relative Humidity RH (%)	92.2	50.5	75.9
Air Temperature Outdoors DBTout (°C)	29.9	19.7	24.1
Solar Radiation Rad (w/m2)	825.5	0.6	221.8

Figure 6: BPAH-COL winner project.

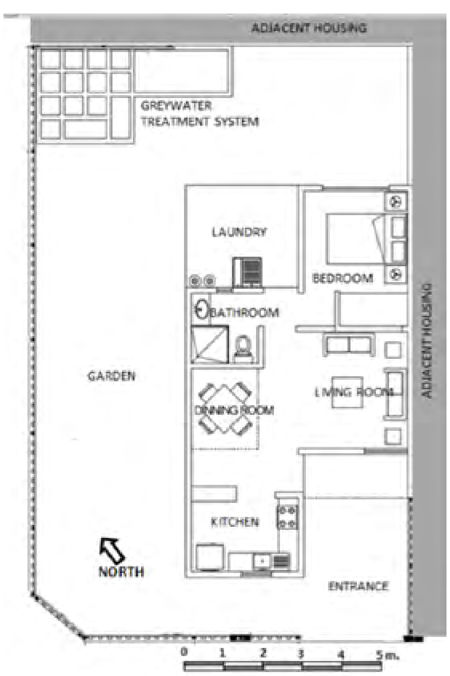


Figure 7: BPAH-COL Floor Plan.

extremely compact that demanded the budget. This objective was achieved by means of practicing openings (upper and below) on the divider wall between the bedroom and the living room, at the center of the house. This allows maintaining a constant airflow between windows of both rooms without obstacles and simultaneously guarding privacy (Figures 8 and 9).

Stack effect was achieved by two openings in line with prevailing winds over the dinner area. This allows exit the hot air through there. Because of the openings lack of glass, this arrangement works too for long-wave radiation exchange during nights (Figures 10 and 11). When a staircase occupies the dinner area space, occupants shall execute the same arrangement higher yet. So, stack effect will be more efficient and long-wave radiation exchange will keep working through the staircase volume.

Shading devices were calculated in order to avoid most of solar radiation all the year and thermal mass was resolved by solid clay brick walls (0.15 m thickness). All surfaces (both roof and walls; inside and outside) are white.

Monitoring

First stage (October to December 2011)

Average collected data is shown in Table 12. It is clear that indoor temperatures, both DBTin and BGT, have a shorter swing than DBTout (approximately 60% lower). However mean temperatures corresponding to the three parameters are very similar.

In addition, it is clear that BGT is the lowest temperature recorded. BGT can be considered a good approximation of the

Figure 8: Cross Ventilation. Interior view. Openings in divider wall.

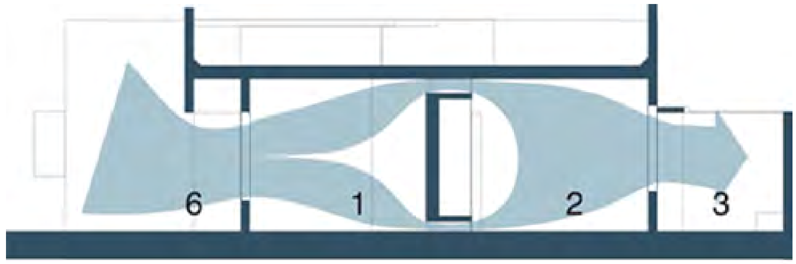


Figure 9: Cross Ventilation. Section: 1. Living room; 2. Bedroom; 3. Backyard; 6. Entrance.

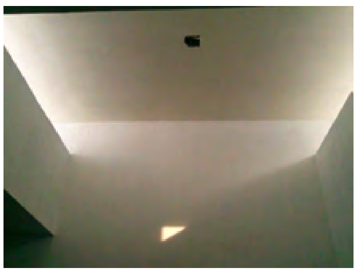


Figure 10. Stack effect and long-wave radiation exchange. Interior view. Upper openings for hot air exit.

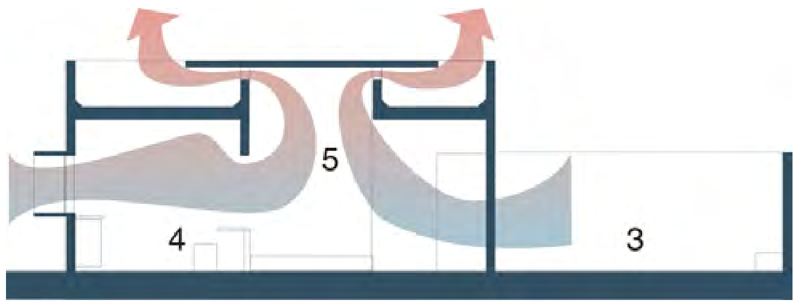


Figure 11. Stack effect and long-wave radiation exchange. Section: 4. Kitchen; 5. Upper openings for hot air exit (over dining room); 3. Backyard.

thermal radiation status inside the building, hence it can be construed that housing envelope is performing in fact a cooling effect. This is very favorable for hot climates even in the fresher season of year, like this is the case.

Second stage (February to April 2012)

Figure 12 shows only April data because of April is the hottest month of the year. There Air Temperature (DBTin) is always highest than MRT (r2 = 0.99, n = 617, $p < 0.05$). This time MRT = BGT because it is about an unoccupied house with closed windows and therefore no Air Speed (AS) considered. Contrary to conventional affordable housings measured during the field study, building elements are discarding long wave radiation toward outdoors performing a cooling effect, even in overheated periods.

Figure 13 shows paths of hourly DBTout (dotted line) and OT (continuous line) within BPAH-COL during a standard April day, averaged from monitoring data.

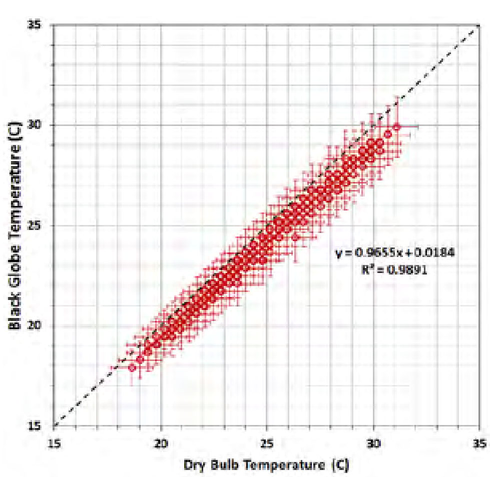


Figure 12. Correlation among Mean Radiant Temperature (MRT) and Air Temperature (DBTin) inside BPAH-COL; April 2012.

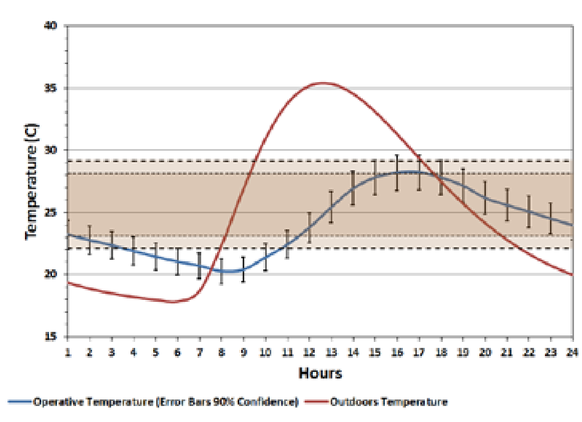


Figure 13. Thermal performance of the BPAH-COL during April 2012, comparing Hourly Operative Temperatures (OT) of Month Standard Day and Month Hottest Day (April 18) among Hourly Outdoors Temperatures (DBTout) of Month Standard Day.

Figure 14. Educational activities for neighbours. Engineering students train neighbours in the living room, on safety and maintenance of home electrical installations (left). Children perform recreational activities in the dining room (right), while homemakers attend a Dressmaking Workshop in the living room (bottom).

Likewise, path of hourly OT recorded during April 18, the month's hottest day (dashed line), is shown too. There it can be seen that DBTout use to be above 35°C at noon, but the OT's paths, both those of the standard day and of April 18, never exceeds the upper comfort limit according to the results from the thermal comfort field study (gray field and dashed lines). The time in which OT elapses below the lower comfort limit don't pose any problem; because of it is not about too low temperatures (they are never below 20ºC). Furthermore, this occurs at night and people could resolve the possible cold feeling by means of additional clothing or slight blankets.

This means a real improvement over the conventional prototypes of affordable housing built throughout the city, where most of whose occupants manifested uncomfortable judgments in regard to overheating of their homes during night time in both hot seasons (55% in the Hot and Dry season: 65% in the Warm and Humid season). Contrary, less than 5% of responses shown unconformity because of cold, in these same hot seasons.

Current use

Since 2014, BPAH-COL hosts a Community Center operated by the University of Colima, where various Faculties participate in multidisciplinary mode according to neighborhood needs. The Center activities base on a diagnosis prepared and updated by social work students each semester. The diagnosis and its updating is fed by interviews, sensory journeys, cartographic analysis and direct observation. As a result of this, diverse problems have been found regarding to public health, social life and education, so as lack of recreational places. Once the main issues are detected in each semiannual diagnosis, social work students prepare community development activities that include educational workshops, attention of individual or familiar conflicts, and management support of collective initiatives. Thus, teachers and students of architecture, graphic design, engineering, medicine, psychology, nursery, pedagogy, physical education, nutrition, and engineering have developed work programs within the Community Centre (Figure 14).

As part of this, postgraduate students in architecture elaborated an Urban Improvement Program. They also addressed a community development workshop where several neighbors joined in exercises of participatory planning and participatory design. In turn, undergraduate students, also in architecture, prepared conditioning proposals for several neglected places within the suburb. With these proposals, neighbors and students have refurbished sport fields, home gardens and playgrounds, published a neighbor's bulletin, and designed signage for suburb open spaces. Graphic design students supported these initiatives by means of the Community Centre graphical image and posters design about neighbors' activities and festivals.

Conclusions

The research objectives were successfully achieved. BPAH-COL is a physical demonstration of it is possible to offer affordable housings with good thermal performance but without increasing cost. Only it is necessary to take suitable scientist knowledge and an innovative attitude for refining design processes. Nowadays BPAH-COL works as a support community centre open to all kind of visitors, and it serves as didactic tool about how to get a better habitat.

Acknowledgments

The CONAVI-CONACYT Found, CONAFOVI-2004-01-20, supported this research. Besides, authors manifest their acknowledgment to participant students, especially Blanca M. Chavez, Christian Carrillo and Gabriel Gomez-Alvarez who elaborated the BPAH-COL architectural project; and Jose Maria Espinoza who was in charge of BPAH-COL construction and climate monitoring.

References

ANSI/ASHRAE:55 (2010), *Standard 55-04 Thermal Environmental Conditions for Human Occupancy,* Atlanta GA: American Society of Heating Refrigeration and Air-Conditioning Engineers.

Dirección General de Normas e Insumos de Vivienda (1988), *Clasificación de la Vivienda de Interés Social en Clima Cálido Húmedo*, México, DF., SEDUE.

EN 15251 (2007), *Indoor environment input parameters for design and assesmen of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* Comité Européen de Normalization, Brussels.

Gómez-Azpeitia, G. (1990), *Recomendaciones bicolimáticas para la arquitectura en la ciudad de Colima*, Colima, Col., Author´s edition.

—————, Ruíz, P., Bojórquez-Morales, G., and Romero, R.A. (2007), *Producto 3. Monitoreo de condiciones de confort térmico*, Reporte Técnico CONAFOVI. 2004-01-20, Colima, Mexico.

—————, Bojórquez-Morales, G., Ruíz, P., Marincic, I., González, E., & Tejeda, A. (2014), "Extreme Adaptation to Extreme Environments in Hot Dry, Hot Sub-humid and Hot Humid Climates in Mexico", In *JCIA Journal of Civil Engineering and Architecture, 8*(8 (81)), 929-942.

—————, Bojórquez-Morales, G., Ruíz, P., Romero, R., Ochoa, J., Perez, M., & *et al*. (2009), "Comfort temperatures inside low cost housing. Case: Six warm climate cities in Mexico", *Architecture and Energy and the Occupant's Perspective. Proceedings of 26th Conference on Passive and Low Energy Arqchitecture,* Quebec City, Les Presses de l'Université Laval.

Griffiths, I. (1990), Thermal Comfort Studies in Buildings with Passive Solar.

Features, Field Studies, Rep. Commission of the European Community, ENS35

090 UK.

Humphreys, M., Nicol, F., and Roaf, S. (2016,) *Adaptive Thermal Comfort: Foundations and Analysis*, Routledge, London and New York.

International Organization for Standardization (1995), *ISO 10551 Ergonomics of the Thermal Environment: Assesment of the Influence of the Thermal Environment Using Subjective Judgement Scales,* Switzerland.

ISO 10551 (1995), *Ergonomics of the Thermal Environment: Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales*. ISO (International Organization for Standardization), Switzerland.

ISO 7726 (1998), *Ergonomics of the Thermal Environment: Instruments of Measuring Physical Quantities.* ISO (International Organization for Standardization), Switzerland.

Remund, J., & Kunz, S. (2004). *Meteonorm (Version 5.107)*: Meteotest.

ISO 7730 (2005), *Ergonomics of thermal environment-analytical determination and interpretation of thermal confort using calculation of the PMV and PPD indices and local thermal comfort criteria*. ISO (International Organization for Standardization). Switzerland.

Nicol, F. and McCartney, K., (2001), *Final Report (Public) Smart Controls and Thermal Comfort (SCATs)*, Oxford, UK, Oxford Brookes University.

SMN (1950-2010) *Normales Climatológicas.* Retrieved 2015, from Servicio Meteorológico Nacional http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=42&Itemid=75

TRNSYS (2005), *Simulation Studio (Version 16)*, USA, Solar Energy Laboratory, University of Wisconsin-Madison.

Abbreviations

ATCM: Adaptive Thermal Comfort Model
AS: Air Speed
BGT: Black Globe Temperature
BPAH; Bioclimatic Prototype of Affordable Housing
BPAH-COL; Bioclimatic Prototype of Affordable Housing for the city of Colima
BTU: British Thermal Unit
CONACYT: Science and Technology National Council
CONAVI: National Housing Commission
INSUVI: Institute of Land, Urban Planning and Housing of the State of Colima
DBTin: Dry Bulb Temperature Indoors
DBTout: Dry Bulb Temperature Outdoors
K: Kelvin degrees
MRT: Mean Radiant Temperature
NT: Neutral Temperature
OT: Operative Temperature
MTSI: Mean Thermal Sensation by Intervals Method
PMV: Predicted Mean Vote
PNVE: National Affordable Housing Program
RH: Relative Humidity
RAD: Solar Radiation
SMN: National Meteorological Service
TSi: Thermal Sensation Judgment
W: Watt