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Effect of tree shading on the thermal load of a house in a warm climate zone in Mexico

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ABSTRACT

This paper presents the effect of the shade of a tree on the indoor temperature and thermal loads of a house (*test house)* located in the State of Morelos, Mexico, 18° 50' 43" north latitude and 99° 10' 44" west longitude. Energy Plus was used to simulate different geometries of the shadow of a tree and the simulation results were compared with experimental measurements of the house without air-conditioning, for one warm and one cold week of the year 2011. The results showed that the maximum temperature difference between the measured and simulated temperatures with both geometry models of tree-shading was 1.7°C. When the effect of tree shading is not considered, it was found that there is a maximum temperature increase of 4°C in the warm week compared with the measured results. In the cold week, the temperature increase was 1.3°C compared with the measured results. Simulation results for an air-conditioned tree-shaded test house show that total annual energy consumption for cooling and heating to achieve thermal comfort represents a substantial energy savings of 76.6% when compared with an unshaded house.

Key words: effect of tree shading, thermal loads, energy-efficient house, warm climate.

NOMENCLATURE	
Cp	Specific heat (kJ/kg*K)
l	Thickness (mm)
R	Thermal resistance (K*m^2/W)
U	Thermal transmittance coefficient of(W/m^2*K)
λ	Thermal conductivity (W/m*K)

1. INTRODUCTION

Energy, environment and global climate change are of major concern around the world. Trees can modify both the microclimate around a building and the macroclimate of a region. Tree-shading on buildings can reduce energy consumption of cooling air-conditioning systems or improve the thermal comfort when they are not air-conditioned. Previous research reported on the effect of shade trees on energy use. Those studies fall into two categories (1) large-scale simulation modeling and (2) small-scale controlled experiments or simulation modeling that examined the effect of trees on an individual home (Donovan, 2009). Large-scale refers to the impact of shading trees in an entire community, city or heat islands (Akbari et al., 2001, Donovan et al., 2009, Pandit and Laband, 2010). Small-scale refers to the effects on building or homes Simpson and McPeherson (1996). They evaluated the potential effects of tree shading on residential air conditioning and heating energy use for a range of tree orientations, building insulation levels and climatic zones in California using computer simulation. Their results indicated that trees shading a home´s west exposure produced the largest savings 10-50%. Next largest savings were for southwest and east locations. In the same year, Laverne et al. (1996) examined the energy demand for homes in three areas with different levels of tree shading. Field measurements quantified the density of vegetation that casts shade directly on homes. Aerial photo interpretation was used to evaluate potential wind shielding offered to individual homes by vegetation and adjacent buildings. They suggested that proper placement of trees with regard to seasonal solar gain and wind patterns may yield substantial energy savings. Improper trees placement may yield significant increases in net energy levels for space conditioning. Akbari et al. (1997) quantified the effect of trees shading on the cooling costs of two similar houses in Sacramento, California. Their results showed that the trees reduce energy costs between 26% and 47%. They simulated the effect of the trees on both houses using the DOE-2.1E3 and concluded that the simulation underestimated the energy savings of the trees by as much as twofold. Simpson et al. (1998) and Gomez Muñoz (2010) extended their results to a regional scale. The methodology was suitable for assessment of energy benefits of current or planned urban tree planting programs. They found that large trees can provide 70% of shading of buildings in hot climates. Laband and Sophocleus (2009) conducted a controlled experiment to quantify the impact of tree shading on electricity consumption devoted exclusively to cooling a structure. The building in full sun required 2.6 times more electricity for cooling than the building in full shade. In this trend, Pandit and Laban (2010) developed a statistical model that produces specific estimates of the electricity savings generated by tree shading in a suburban environment. Their estimates reveal that tree shading is generally associated with reduced electricity consumption in the summertime. In summertime, energy savings are maximized by having dense shade. More recently, Hes et al. (2011) presented an approach to treat the shade as a shading coefficient on the wall to address the problems encountered when trying to model trees effectively. They proposed a modeling method to assess the effect of tree shading. All those previous studies documented the impact of tree shading on the cooling demand through theoretical and empirical data. Thus, in the first steps of any project, external tree shading effects need to be accounted for in modeling residential buildings.

The aim of this paper is to study the effect of a tree shading (large tree) on the indoor temperatures and thermal loads of a house in a warm climate. The Energy Plus program was used to simulate the thermal performance of the house in a non-air-conditioned case and in an air-conditioned case. Interior temperature measurements in each room of the house are shown and compared with the simulated data. The process to simulate the shadow of a tree is described.

2. CASE STUDY

The case study is a two-story house with a total interior area of 80.52 m^2 with a garden area of 48.73 m^2 (see Figure 1 and 2). The test house is located in the center of a housing development and is at a side of a common green area with a swimming pool and a very huge tree 3.5 m far from the Northwest façade of the house. The tree is a perennial tree taller than the house; it is 25 m high, with roughly 35 m shading diameter. The name of the tree is "*ficus microcarpa*". Despite being a very tall tree, its main characteristic is that their foliage grows 1 m of the trunk allowing shading almost from the base of the tree, so the tree shadow covers almost three façades and approximately 70-80% of the roof area is also shaded. The main façade is oriented 60° counterclockwise from north. Behind the house is another house with similar characteristics. On the ground floor are the living room, kitchen, half-bath and storage room. On the first floor there are two bedrooms, two bathrooms and a study.

Figure 1. Site of the monitored house in the housing development.

2.1 Climate Conditions

The test house is located in Morelos State, Mexico, in the municipality of Emiliano Zapata, 18° 50' 43" north latitude and 99° 10' 44" west longitude, at an altitude of 1266 m above sea level. The climate in this region is characterized as warm sub-humid with light rains in summer and annual average temperatures 22.4°C. The minimum temperature recorded in the year of data used in this study is 9.2°C and the maximum is 35.6°C.

Figure 2. Photograph of the test house.

2.2 House Characteristics

Detailed geometrical description of the test house is shown in Figure 3 and Table 1. Figure 3 shows the two-story distribution of the house, named zones M01-M08. Table 1 shows the area, height and volume of each zone in the house. The bedroom (M04) and study (M06) have a 10° tilted roof.

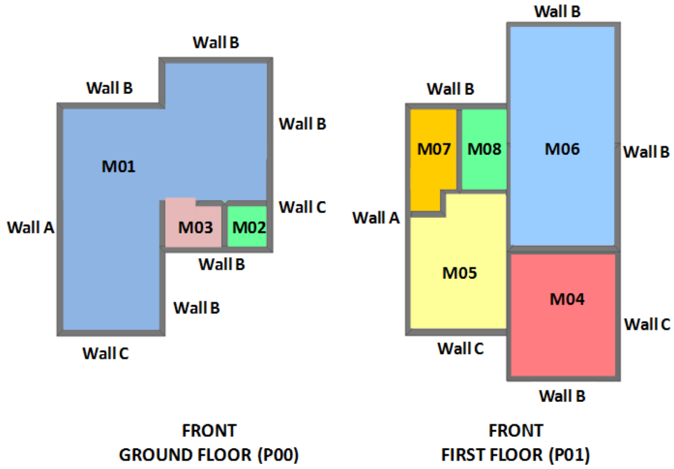


Figure 3. Zone distribution of the house for the ground and first floors.

Table 1. Geometric description of the test house.

Site		Description	Area (m^2)	Height (m)	Volume (m^3)
Floor	Zone				
P00	M01	Living–Diningroom–Kitchen	27.40	2.62	71.79
P00	M02	Storage room	1.38	1.7	2.35
P01	M03	Half-bath	2.37	2.62	6.22
P01	M04	Bedroom	10.04	2.62	26.30
P01	M05	Main bedroom	9.92	3.21	31.84
P01	M06	Study	17.66	3.21	56.69
P01	M07	Bathroom 1	3.61	2.62	9.46
P01	M08	Bathroom 2	3.24	2.62	8.49

Table 2 shows the component materials of the envelope of the house and their thermophysical properties as referenced in the Energy Plus libraries. The envelope colors are light yellow (paint) and brown-gray (adobe-concrete natural color). The front façade has three windows and the back façade five windows; all windows have aluminum frames and 3 mm clear glass. The front façade has two doors; the main door is made of wood and the storage-room door is made of steel. The back façade has two doors of glass with aluminum frames. The technical description (material and geometrical specifications) of the façade openings are shown in Table 3.

Table 2. Building materials

Part	Material Name	*l* [mm]	*Cp* [J/kg*K]	λ [W/m*K]	*ρ* [kg/m^3]
Ground floor	Tile	8	840	1.30	2300
	Mortar	4	1000	0.50	1300
	Concrete	100	1000	0.97	2117
Floor-first Floor	Tile	8	840	1.30	2300
	Mortar	4	1000	0.50	1300
	Concrete	100	1000	0.97	2117
	Plaster rendering	2	1000	1.00	2000
Wall A	adocreto	150	900	0.87	1857
Wall B	Plaster rendering	2	1000	1.00	2000
	adocreto	150	900	0.87	1857
	Plaster rendering	2	1000	1.00	2000
Wall C	adocreto	150	900	0.87	1857
	Plaster rendering	2	1000	1.00	2000
Sloping roof	Plaster Board	13	840	0.16	900
	Air space	23	1008	0.03	1.23
	Concrete	100	1000	0.97	2117
	Air space	50	1008	0.03	1.23
	Tile	10	1000	0.06	380
Flat roof	Plaster Board	13	840	0.16	900
	Air space	23	1008	0.03	1.23
	Concrete	100	1000	0.97	2117

Table 3. Technical description of façade openings.

Façade	Zone	Description	Material	Area (m^2)	U (W/m^2*K)
Front	M01	Main door	Wood	1.68	2.041
	M01	Window 1	Glass	1.97	5.83
	M03	Window 2	Glass	0.33	5.83
	M04	Window 3	Glass	1.96	5.83
	M05	Terracedoor	Glass	3.62	5.83
Back	M01	Back door	Glass	4.4	5.83
	M01	Back door	Glass	4.4	5.83
	M01	Window 4	Glass	1.21	5.83
	M06	Window 5	Glass	2.16	5.83
	M07	Window 6	Glass	0.33	5.83
	M08	Window 7	Glass	0.33	5.83

3. METHODOLOGY

Figure 4 presents the methodology followed for the thermal simulation and its comparison with the measured data. The location, climate conditions, properties of materials and building characteristics were input. For the Energy Plus simulation, two cases were considered, a house with tree shading and a house without tree shading. For the case of a house with tree shading, two geometry models of tree shading were considered, a tree as flat cover and a tree with foliage.

The indoor temperatures of the house obtained from the simulations of a non-air conditioned test house, for the two geometry models of tree shading and without shading, were compared with measured temperatures. Then, simulations for an air-conditioned test house were performed. The thermal loads were calculated using the tree as flat cover and house without tree shading.

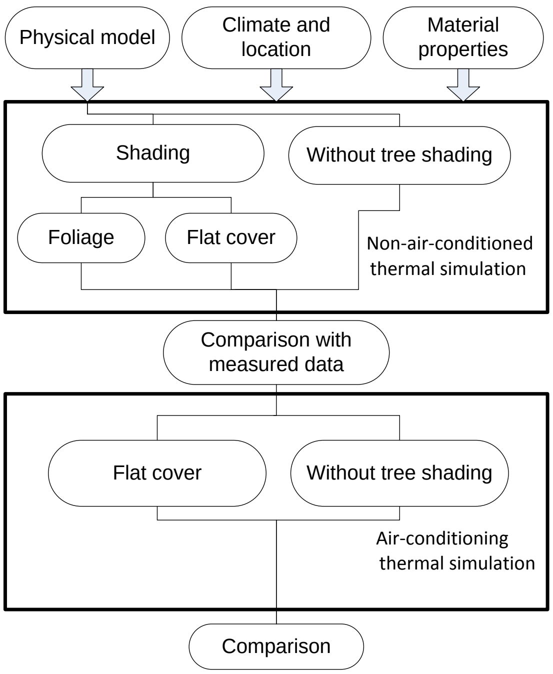
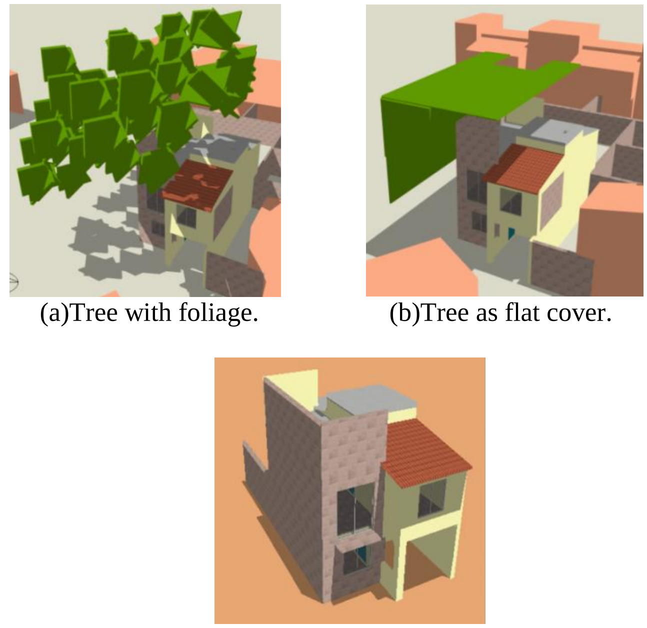


Figure 4. Methodology of the simulation study.

4. SIMULATION OF THE HOUSE WITH TREE-SHADING

The test house geometric characteristics were input into the Design Builder software, which is an interface to Energy Plus, which allows drawing the geometry and envelope features. Adjacent houses were simulated to include the effect of their shading on the house. Also, the tree shading on the side of the house was included for the simulation. Due to the complex geometry of the tree, it was necessary to test several geometries to simulate the effect of the shading on the house. Figures 5a and 5b present two of the shading geometries considered: tree with foliage and tree simulated like a cover.

The geometry of a tree with foliage (Figure 5a) was represented with sets of two prismatic planes intersecting each other at a right angle; the arrangement of the prismatic planes was repeated until the shape of the tree was reproduced. The simulated tree as a flat cover (Figure 5b) was represented with three flat planes that were perpendicular to each other and projected a shadow, like the area of the house shaded by the tree. Finally, the house without any shading (Figure 5c) was considered, in order to quantify and compare the indoor temperatures and the thermal loads of the house with shading and without shading.



(a)Tree with foliage. (b)Tree as flat cover.

(c)House without tree shading

Figure 5. Test house with shading and without shading.

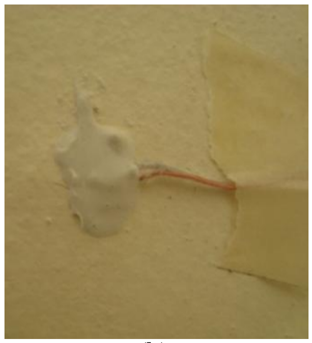
4.1 Thermal Simulations

The Design Builder and Energy Plus programs were used to simulate the cases shown in Figures 5a, 5b and 5c. The dry bulb temperature, relative humidity, global solar radiation, wind direction and wind velocity were collected from an automatic meteorological station every 10 minutes. Then, the climate conditions, location, properties of materials, and building characteristics were input into the Energy Plus program. We want to point out that the thermal properties for the house materials used in the analysis change very little with the temperature, thus they can be used both for shading and no shading simulations. The tree shading reduces the incident solar radiation on the house envelope, but it does not change thermal properties of the envelope. The average monthly floor temperature measured on-site (Neymark et al. 2008) and infiltration of 0.5 air changes per hour were input (Sherman, 2003, ASHRAE, 2004). As the house was uninhabited internal gains and ventilation were not considered.

4.2 Measurements

The recorded data included air temperatures and the wall and roof temperatures of the different zones of the house. Air temperatures were monitored with four caliber 30 T-type thermocouples located in zone M01 (living room dining room kitchen), zone M04 (bedroom), zone M05 (main bedroom) and zone M06 (study hall). Thermocouples measuring the air temperature were placed 2.1 m from the floor and 0.2 m from the walls (Figure 6a). In the bedroom (M04), the interior and exterior surface temperatures of the roof and façade wall were measured. Thermocouples were attached to the surfaces with high conductivity cement (Figure 6b). All thermocouples were connected to an acquisition system.

(a)



(b)

Figure 6. a) Thermocouple to measure air temperature. b) Thermocouple tip to measure the wall surface.

5. RESULTS

5.1 Measurement and Simulation

The measured and simulated temperatures are presented for two weeks of the year 2011, a warm week (April 2-8) and a cold week (December 1-7). Temperatures of the rooms, ambient temperature and zone-simulated temperatures for the warm week are presented in Figures 7-10. It is shown that the simulation results from the tree with foliage and from the tree as a flat cover were in close agreement with the measured data for all zones (zones M01, M04, M05 and M06). The greatest difference between the geometry of tree with foliage and the measured temperature was 0.6°C, the same value was obtained for the tree flat-cover geometry (zone M06). Additionally, it was numerically demonstrated that in the house without shading, the maximum indoor air temperatures in the upper floor zones were higher than the maximum outdoor ambient temperatures. The maximum difference between the simulated and the measured temperatures was 4.0°C, in zone M05. This indicates that without the shading the direct solar gains through the envelope are significant. The maxima of the indoor air temperature of the space on the ground floor (M01) of the unshaded house were also higher than those of the shaded-house, but were slightly lower than the outdoor maximum ambient temperatures.

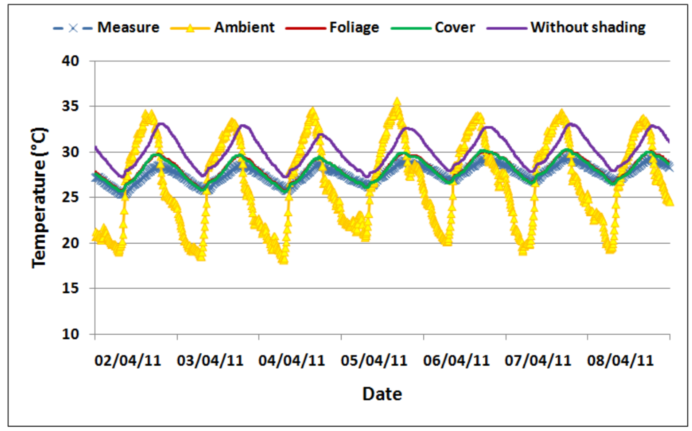


Figure 7. Measured, ambient and computed temperatures in Living–Dining room–Kitchen (zone M01) - warm week.

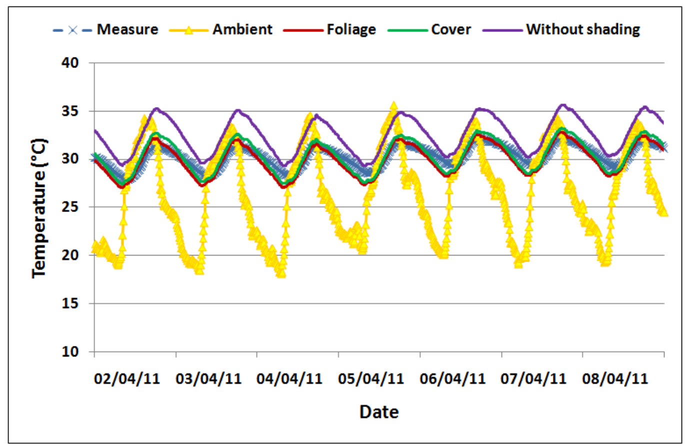


Figure 8. Measured, ambient and computed temperatures in Bedroom (zone M04) - warm week.

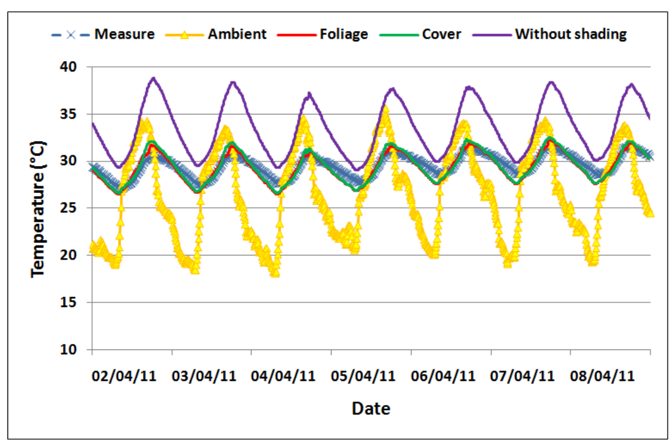


Figure 9. Measured, ambient and computed temperatures in Main bedroom (zone M05) - warm week.

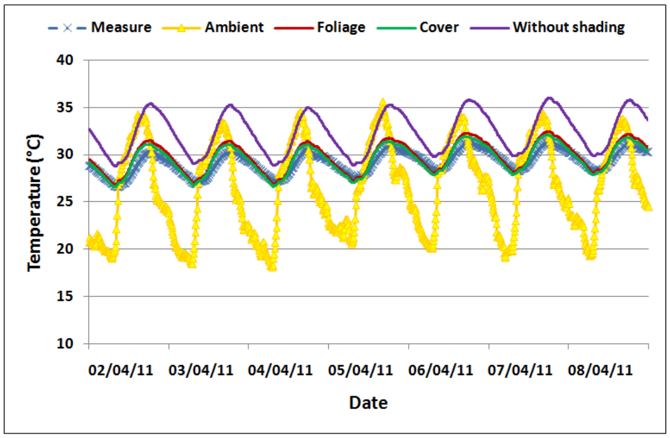


Figure 10. Measured, ambient and computed temperatures in Study (zone M06) - warm week.

The interior measured and simulated air temperatures of zones M01, M04, M05 and M06, as well as the ambient temperature, for the cold week, are presented in Figures 11-14. Similar to the warm week case, the house with the tree with foliage and the house with tree as flat cover were close to the measured data.

The house with the tree with foliage presented the highest difference of 1.7°C between the measured and simulated indoor air temperatures for zone M05. The maximum indoor air temperatures were lower than the maximum outdoor air temperatures. The geometry model of tree as a flat cover showed a higher mean difference between the measured and simulated indoor air temperature of 0.6°C in zone M04. In the house without shading (Figure 14), the highest difference between the measured and simulated mean air temperature was 1.3°C in zone M05.

The amplitude of the indoor air temperature of all the zones, for the two weeks, is smaller than that of the ambient temperature, indicating that the thermal properties of the house envelope are adequate.

The results obtained for the two weeks showed that the two tree-shading geometries are good approaches to simulate in Energy Plus the shading on the house produced by the tree. However, the tree as a flat cover showed differences less than 1°C for all zones in the two weeks of measurements.

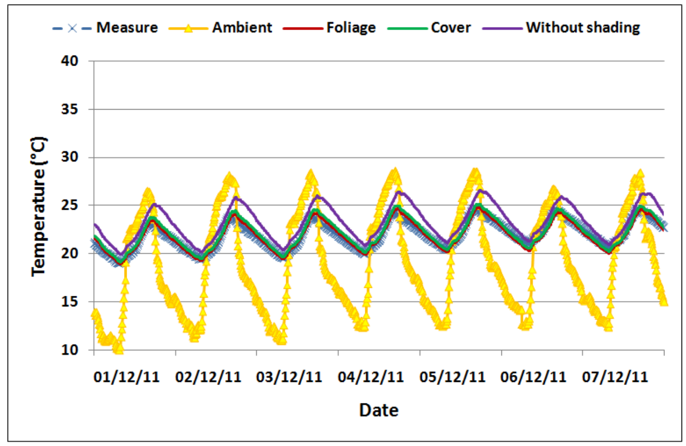


Figure 11. Measured, ambient and computed temperatures in Living–Dining room–Kitchen (zone M01) - cold week.

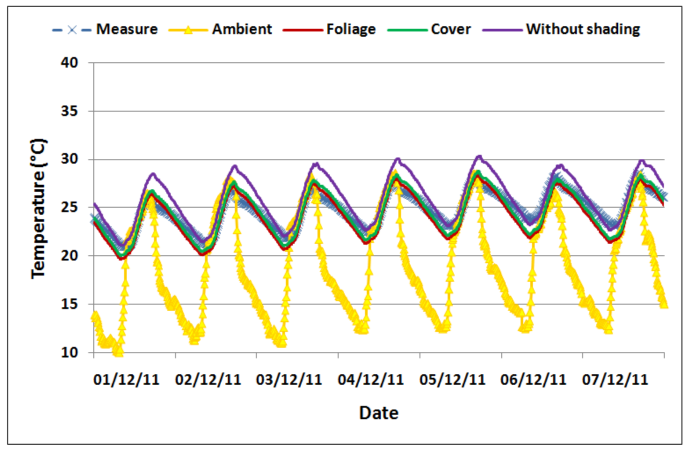


Figure 12. Measured, ambient and computed temperatures in Bedroom (zone M04) - cold week.

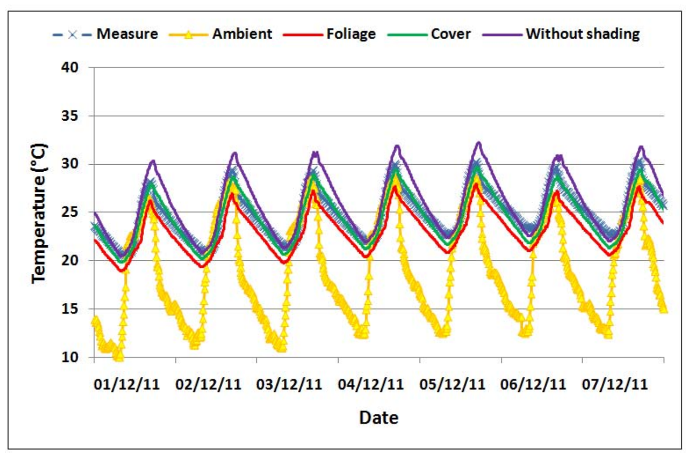


Figure 13. Measured, ambient and computed temperatures in Main Bedroom (zone M05) - cold week.

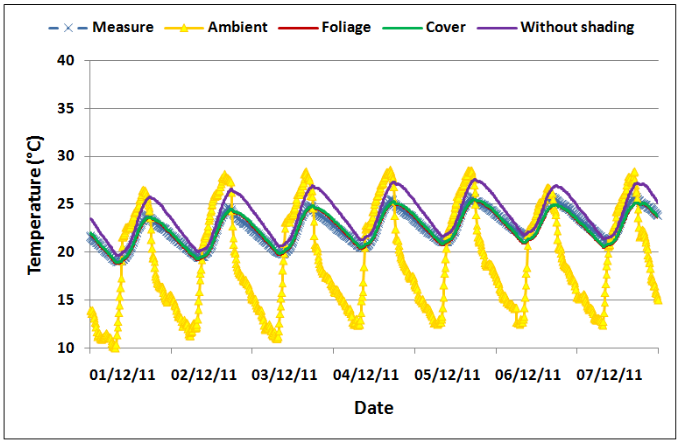


Figure 14. Measured, ambient and computed temperatures in Study (zone M06) - cold week.

5.2. Thermal Loads

The Energy Plus simulations of the unshaded house and the shaded house with the tree as flat cover were considered for air-conditioning thermal load calculations case. The set point indoor temperatures were in the range of 22.5°C-28.5°C, based on the neutral temperature (De Dear, 1998). The solar radiation transmittance through the tree as a flat cover for the annual simulation was not changed, assuming that the tree has the same foliage throughout the year. Average monthly heating and cooling thermal loads for the shaded and unshaded house are presented in Figure 15. The maximum cooling load for the unshaded house was approximately 700 kWh in May, whereas this value for the shaded house was 150 kWh in April. The maximum heating loads for both cases were 50 kWh in December. The annual cooling loads for the unshaded house was 3,160 kWh and for the shaded house was 438 kWh, representing the 14% of the former. The annual heating load for the unshaded house was 135 kWh and for the shaded house was 332 kWh.

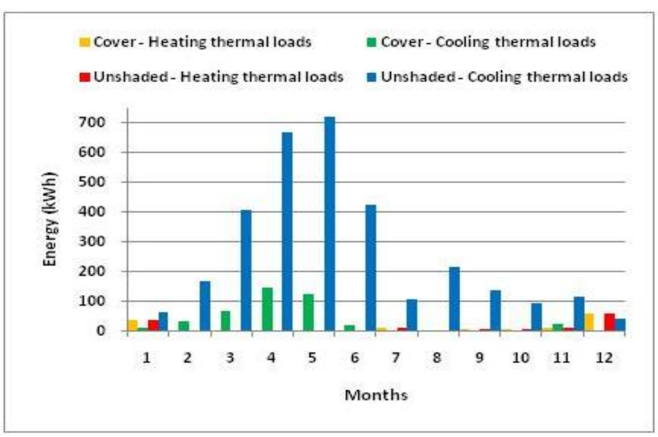


Figure 15. Monthly heating and cooling loads for the tree shaded and unshaded house.

The total annual thermal load (cooling and heating) for the unshaded house was 3,295 kWh and for the shaded house was 770 kWh. This represents a substantial energy savings of the tree-shaded house of 76.6%, with respect to the unshaded one.

7. CONCLUSIONS

The effect of tree-shading on indoor air temperatures for non-air-conditioning and on thermal loads for air-conditioning, was studied through measurements and Energy Plus simulations of a house in a warm climate zone in Mexico. Two geometry models to simulate the tree-shading were analyzed, the tree with foliage and the tree as a flat cover. For non-air-conditioning, simulated indoor air temperatures of both geometries for the tree-shaded house were consistent with the measured data; the maximum difference for both geometries was 0.6°C.

The simulated temperatures for the unshaded house were up to 4°C, upper than the measured ones in the test house with tree-shading. The energy savings on the annual air-conditioning thermal loads by the effect of the tree-shading was of 76.6%.

Based on the present results, tree-shading in warm climates can decrease the indoor air temperature, achieving thermal comfort or getting closer to it, in non-air-conditioned houses. In air-conditioned houses, tree-shading can save a great amount of cooling energy. In Mexico, trees are relatively cheap; it is therefore important to continue studying the effects of tree shading on the thermal behavior on different climates and conditions. Therefore, we suggested including strategies to allow varying the foliage shading around the year to improve Energy Plus simulations of shading trees on houses.

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