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The effect of solar reflectance, infrared emissivity, and thermal insulation of roofs on the annual thermal load of single-family households in México

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Abstract

In Mexico, as a result of the Mexican climate and predominant construction techniques, a significant part of the heat flow between single-family houses and the environment occurs through the roof. Because of this, reducing the energy expenditure for air conditioning requires a knowledge of the thermal properties of roofs, including the solar reflectance (SR) and infrared emissivity (IE) of the outer surfaces and the thermal conductivity of the bulk material. Here we present the result of TRNSYS simulations of a sample household, where we systematically vary **SR**, **IE**, and thermal insulation of the exposed rooftop. Our results show that the greatest reductions in annual thermal load occur in cities with warmer climate. Thermal insulation itself only becomes important when both of the other properties are inappropriate for the local climate.

Keywords: Cool Roofs, reflective/emissive coverings, TRNSYS, building simulation.

1. Introduction

Mexico has a predominantly warm climate, which creates a high energy demand for cooling residential buildings. Households in Mexico are primarily built with brick or cinder block walls and mostly flat, poured concrete roofs. Due to these two factors, roofs are the construction element that interacts the most with solar radiation and infrared radiation from the atmosphere. Because of this, a large amount of the thermal loads that occur in a representative Mexican househld occur through the roof.

The effect of solar reflectance on household roof surfaces has been a research subject in several countries recently, and the concept of Cool Roofs has been coined to reflect its importance. Cool roofs have high levels of solar reflectance, and present one of the proposed measures for mitigating the probelm of urban heat islands. (Taha, 2008). In warm places, highly reflective roof surface treatments reduce solar heat gains and therefore the cost of air conditioning (Akbari et al., 1999) as well as CO_2 emissions (Akbari et al., 2009). It has been estimated that increasing the solar reflectance of urban roofs can reduce air conditioning loads as much as 50% in some cities of the United States (Taha et al., 1992).

In cities with temperate climate, with seasons requiring both cooling and heating, increasing solar reflectance can reduce the thermal load during the hot season but also increase the load during the cold season (Syneffa et al., 2007). Shi and Zhang (2011) studied the effect on a building’s thermal loads of both long-wavelength emissivity and exterior solar reflectance. They used this simulation to estimate the annual heat load of their reference building given the climatic conditions in 35 cities around the world. In warm climates, increasing solar reflectance and emissivity results in an important annual reduction in heat load. In cold weather, the lowest possible values of solar reflectance and emissivity result in the lowest heating costs. In temperate climate, however, where heating and cooling are both needed at different times of the year, the least expensive combination of solar reflectivity and infrared emissivity was found for values between 0.1 and 0.9.

We studied the effect of roof SR and IE on annual heat loads (cooling + heating), as well as the variation caused by two levels of thermal insulation. We considered a single-family house built with materials and dimensions commonly used in Mexico, simulated using the climate conditions of 20 different cities. The results of this study may be useful to government agencies charged with developing new regulation for energy efficiency in buildings. Also, the manufacturers of paint for roofs and walls can use them to evaluate the potential effect of their products in different geographic zones in Mexico.

2. Methodology

In order to determine the effect of SR and IE on annual heat loads, we developed a numerical simulation program in TRNSYS. We defined a single-family household representative of Mexico, and used climate parameters from 20 representative cities from the four thermal zones defined in Mexican regulations. The definition of the zones is based on the concept of The definition of climatic zones is based on the concept of "Refrigeration Degree-Days", with a reference temperature of 10°C (RDD10), and "Heating Degree-Days", with a reference temperature of 18ºC (HDD18).

Table 1: Criteria for defining thermal zones in Mexico

Thermal Zones	Refrigeration Degree-Day RDD10	Heating Degree-Day HDD18	Type of Region
1	> 5,000		Low elevation, tropical and arid-warm
2	3,500 – 5,000		Sub-tropical and arid-dry
3	< 3,500	< 3,000	Mexican Plateau, semi-arid and temperate
4		> 2,000	Semi-arid and temperate, cold winters

Thermal zones 3 and 4 are subdivided in three categories (A, B, and C), according to their average annual procipitation.

2.1. Description of the single-family household

The property used as a base case has an area of 48 m² and a volume of 144 m³ (6m x 8m x 3m, Figure 1). It is built from hollow concrete block, with 20% of the north and south walls covered in single-pane glass windows. The roof is a 15cm concrete slab, with plaster finish on the inside and acrylic coating on the outside. The model home is occupied by four people from 3:00 PM to 8:00 AM on weekdays, and all day on weekends. We considered heat gains by the occupants, indoor lighting, and household appliances, as well as an air exchange of 0.5 room volumes per hour and mechanical ventilation of 1.0 1/h.

The materials and thicknesses considered for the roof, walls, and floor, as well as their physical properties, are listed in Table 2.

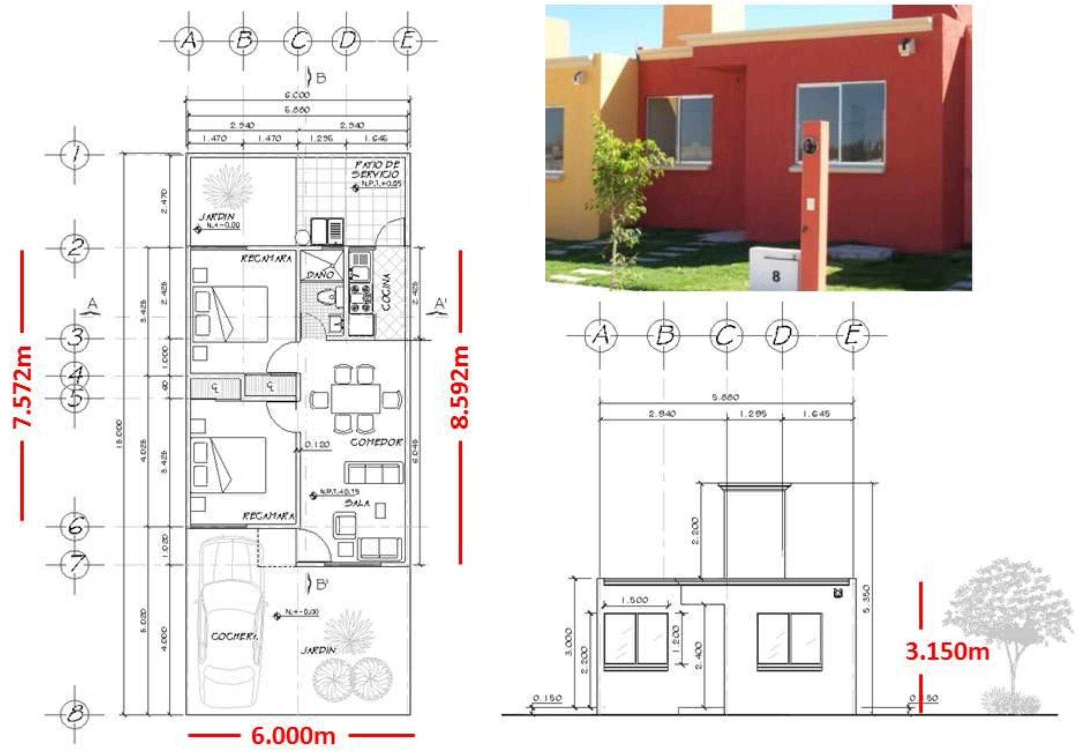

Fig. 1: Case base of single family household, blueprint and front view

Tab. 2: Construction materials and their thermal-physical properties

Building element	**Width (m)**	**Thermal conductivity kJ/h·m·K**	**Specific Heat kJ/kg·K**	**Density kg/m^3**
Roof				
Waterproofing	0.002	0.612	1.47	1290
Thermal isolation	0 - 0.050	0.076	1.54	31
Concrete slab	0.15	6.264	0.9	2300
Plaster	0.02	1.34	0.34	800
Wall				
Mortar	0.025	3.14	0.84	1860
Hollow concrete block	0.15	5.88	0.92	1700
Plaster	0.02	1.34	0.34	800
Floor				
Ceramic tile	0.01	3.769	0.8	2500
Grout	0.01	3.368	0.84	2000
Concrete	0.15	6.264	0.9	2300

2.2. Climate data

Numerical simulation of a building requires climate data representative of its location. These data include ambient temperature, relative humidity, wind speed, and solar radiation, all of them at relatively short time intervals (about 1 hour). We used a climate model built into TRNSYS to generate this information from monthly averages of these three parameters.

We obtained the monthly average temperature, relative humidity, and wind speed for 73 Mexican cities from the National Meteorological System (SMN, 2012), for the years 1981 to 2000. The monthly average solar radiation for this list of cities was obtained from the Solar Radiation Data Service (SoDa, 2013). We selected 20 cities to represent the different thermal zones in Mexico (Table 3).

Tab. 3: Representative cities in the thermal zones.

Zone 1	Zone 2	Zone 3A	Zone 3 (B and C)	Zone 4
Acapulco	Cuernavaca	México city	S. L. Potosí (3B)	Toluca (4A)
Campeche	Guadalajara	Morelia	Chihuahua (3B)	Tlaxcala (4A)
Culiacán	Hermosillo	Puebla	Saltillo (3B)	Pachuca (4B)
Veracruz	Monterrey	Querétaro	Orizaba (3C)	Zacatecas (4C)

2.3. TRNSYS simulation to determine thermal loads

TRNSYS calculates thermal loads through an energy balance that affects the air temperature inside the building:

$$q_{BAL} = q_{DQAIRdt} + q_{HEAT} - q_{COOL} + q_{INF} + q_{VENT} + q_{TRANS} + q_{GINT} + q_{WGAIN} + q_{SOL} + q_{SOLAIR} \qquad (eq.\ 1)$$

Where q_{BAL} is the energy balance for a zone and should be always close to 0; $q_{DQAIRdt}$ is the change of internal energy of the zone (calculated using the combined capacitances of the building and the air within it); q_{INF} and q_{VENT} are the gains by infiltration and ventilation, respectively; q_{TRANS} is transmission into the surface from an inner surface node; q_{GINT} is internal gains by convection and radiation; q_{WGAIN} represents gains by convection and radiation through walls, roof and floor; q_{HEAT} and q_{COOL}, finally, are the power of ideal heating and cooling. The energy units used by TRNSYS are kJ/h.

The thermal interaction between the external surface of a roof and the environment includes overlapping amounts of convection, solar radiation, and infrared radiation. The resulting net heat, once added to the exterior surface of the roof, flows through the roof by conduction and will also depend on the amount of convection and radiation occurring between the roof's inner surface and the inside of the building.

The influence of **SR** and **IE** on the calculation of thermal loads is established in the following heat flux balance for a node on the exterior roof surface.

$$q_{rad,sol} + q_{rad,IR} + q_{conv,ext} - q_{cond,ext} = 0 \qquad (eq.\ 2)$$

In equation [1], the heat flux $q_{rad,sol}$ corresponds to the solar irradiation gained by the external surface, and will depend on the **SR** of the exposed roof. Meanwhile, $q_{rad,IR}$ corresponds to the loss of heat by infrared radiation to the atmosphere and depends on both the **IE** and the temperature of the external roof surface. $q_{conv,ext}$ is the convective heat flux that occurs between the external roof surface and the atmospheric air. $q_{cond,ext}$ is the conductive heat flux at the node; it is a function of the temperature gradient between the exterior and interior roof surfaces, as well as the thermal conductivity, specific heat, density, and thickness of the roof materials. Therefore, this conductive heat flux has a direct relationship to q_{WGAIN} in eq. 1.

Our TRNSYS simulation calculated the amount of energy that had to be removed (cooling load) or added (heating load) in order to keep the air inside the building within the comfortable range of temperatures between 20°C and 25°C. Our simulation calculates the instant thermal load, including heating and cooling loads, with a time interval of one hour. We determined the **annual load** by integrating the instant thermal load over the whole year. The annual load is an amount of energy (in kWh) and is directly related to the cost of heating and air conditioning.

We performed multiple simulations with different values of SR and IE ranging from 0.1 to 0.9, with increments of 0.1. In addition to the base case, we also considered two levels of thermal insulation: 25 and 50mm of polyurethane foam. These simulations were carried out for each of our 20 cities. Given the great number of simulations needed for this analysis, we wrote a script in C++ to automate the calculations.

3. Results

3.1. Annual cooling and heating loads

The effect of SR and IE on heating and cooling loads is well defined. We present our results in Figure 2, with sample data for the city of Acapulco for cooling and Toluca for heating. The lowest possible cooling load requires the highest values of SR and IE, as the former dictates the heat to be gained from radiation and the latter determines the heat to be lost. Reducing heating loads requires the opposite combination. We also frequently observed that an effect of IE on the thermal load is reduced at high values of SR.

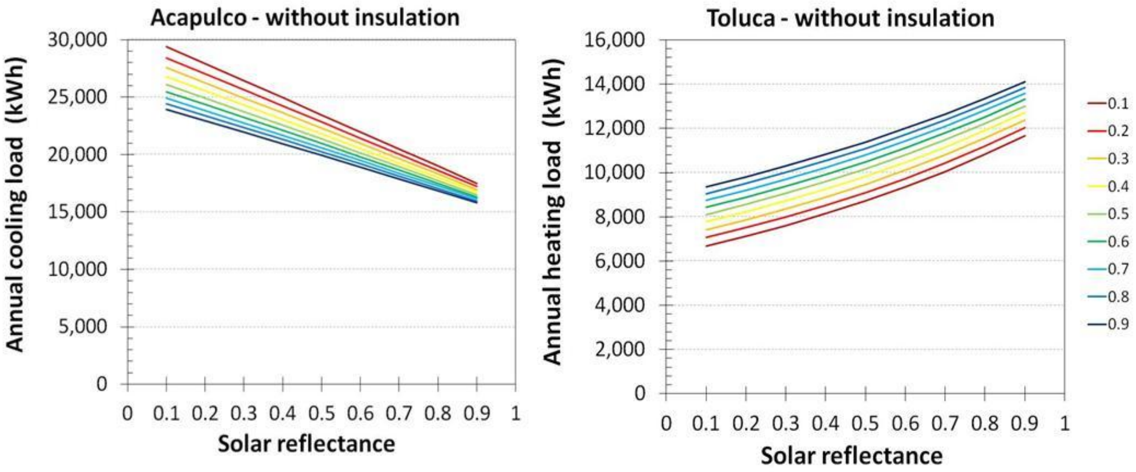

Fig. 2: Annual heating and cooling loads as a function of SR and IE

In this type of building, where the surface area of the roof is relatively high for the total volume of the building, the optical properties of the outer roof surface have an important effect on the thermal load of the building. For the case of Acapulco, the thermal cooling load can be reduced from 29,399 kWh in the worst case (SR=0.1 and IE=0.1) to 15,828 kWh in the optimal case (SR=0.9 and IE=0.9), a reduction of 46.2%. In the case of Toluca, the heating load can be reduced by 52.6%, from 14,110 kWh to 6,689 kWh.

The maximum and minimum values of annual cooling and heating loads for all the other cities are presented in Figure 3. Note how the largest changes in cooling loads occur in Zones 1 and 2, which also normally have the highest absolute cooling loads.

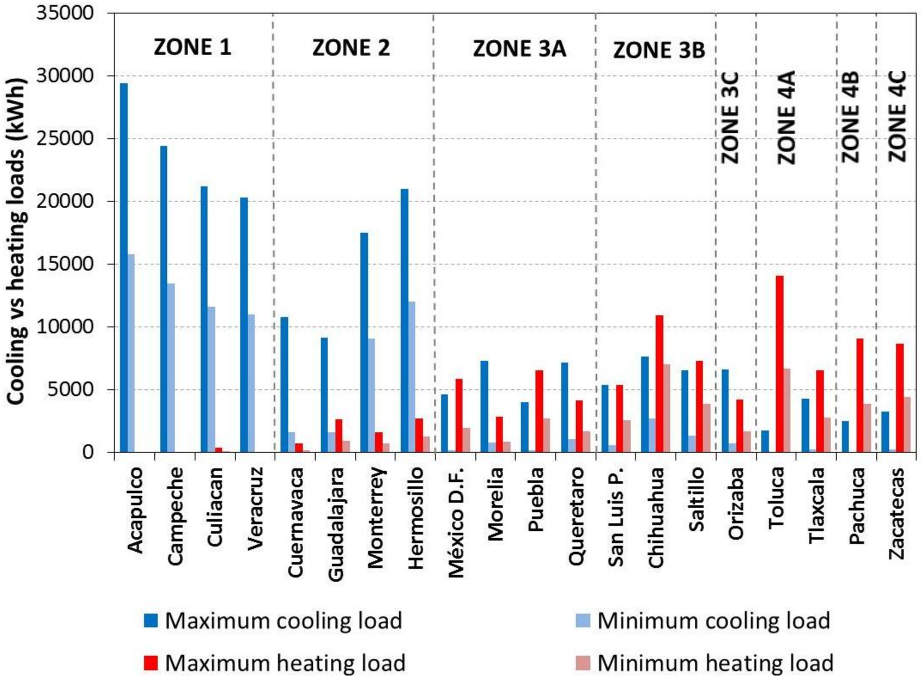

Fig. 3: Maximum (SR=0.1 and IE=0.1) and minimum (SR=0.9 and IE=0.9) values of the cooling and heating loads, by city and thermal zone.

3.2. Annual thermal load

In general, we see three patterns in the effect that SR and IE have on thermal loads.

1. *High energy requirement for cooling (high SR and IE)*

The first kind of pattern is represented by locations with high cooling requirements, with low or null heating requirements. In these cases, the annual thermal load behaves like the cooling load. Acapulco, for example, has an annual heating load of zero. In Culiacán, similarly, the annual heating load is 375 kWh, merely 3% of the minimum cooling load (11,608 kWh). The cities in Zones 1 and 2 show this pattern, where the recommendation is to have high values of SR and IE (Fig. 4).

In all cases we observe that the effect of IE decreases at high values of SR. For the case of Guadalajara, the effect of IE on the annual load is practically zero when SR equals 0.9.

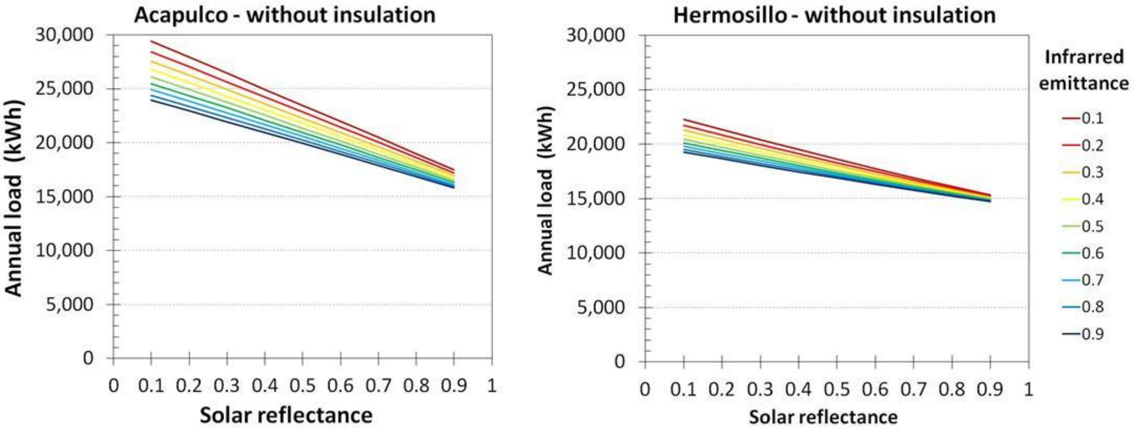

Fig. 4: Annual thermal load of cities with a high cooling requirement, Zones 1 and 2.

2. *High heating energy requirements (low SR and IE).*

The second pattern includes the opposite case, cities with high heating and low cooling energy requirements. Of the 20 cities we selected only Toluca (Zone 4) presents this behavior, which is heavily influenced by the thermal heating load.

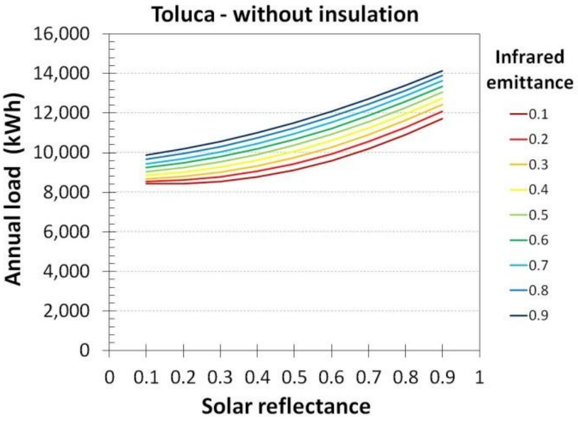

Fig. 5: Annual thermal load for the city of Toluca; high heating requirement

3. *Heating and cooling needs of similar magnitude*

With the exception of Toluca, all the cities in Zones 4 and 3 present similar heating and cooling loads. Therefore, their optimal values of SR and IE are different from the extreme values previously shown (Figures 4 and 5).

In the 11 cities that show this pattern, the optimal IE values were all 0.1. SR values varied between 0.4 (Pachuca) and 0.9 (Morelia, Querétaro, San Luis Potosí, Chihuahua, Saltillo and Orizaba). The optimal value of SR depends on the given value of IE. In Mexico City, for example, an arbitrary IE value of 0.1 leads to an optimal SR value of 0.7; nevertheless, an arbitrary IE of 0.9 has an optimal SR of about 0.3 (Figure 6).

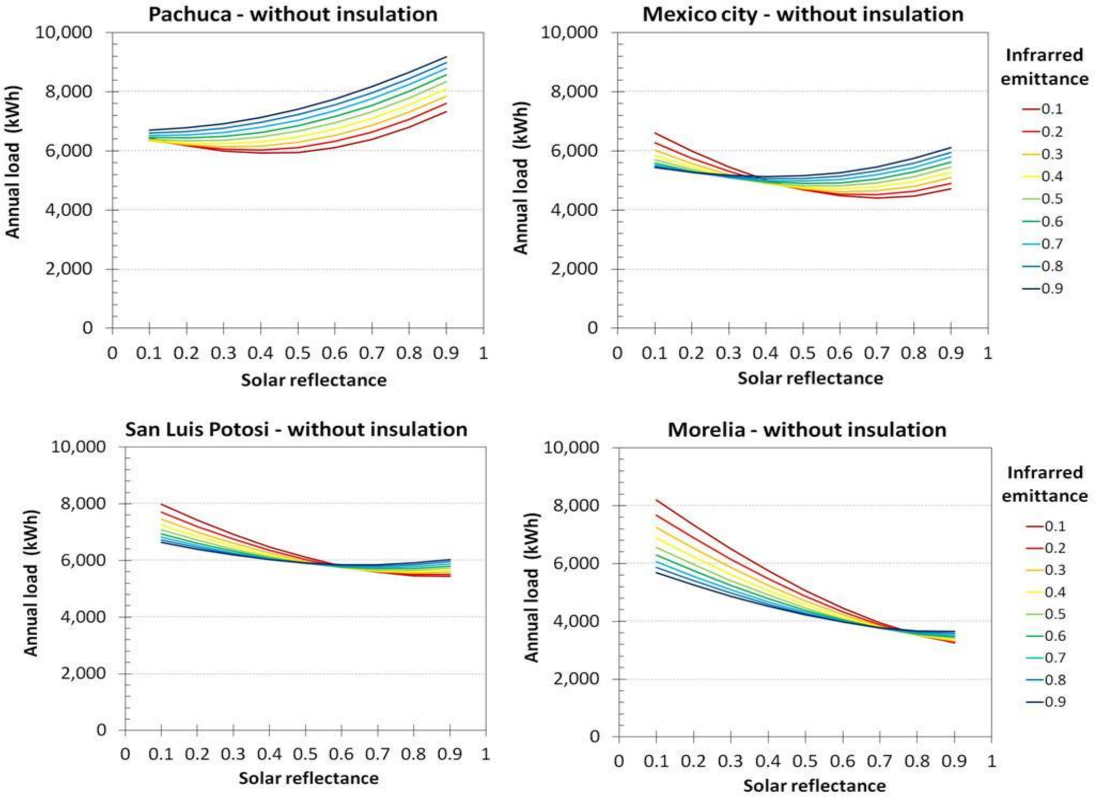

Fig. 6: Annual thermal load for cities located in Zones 3 and 4.

Figure 7 presents the maximum and minimum values of annual thermal loads. The difference between maximum and minimum values is caused by varying IE and SR of external roof surfaces. This graph shows that the greatest annual load corresponds to cities in Zones 1 and 2, which have high cooling loads, and also that these cities show the greatest difference between maximum and minimum annual load values for a roof without thermal insulation.

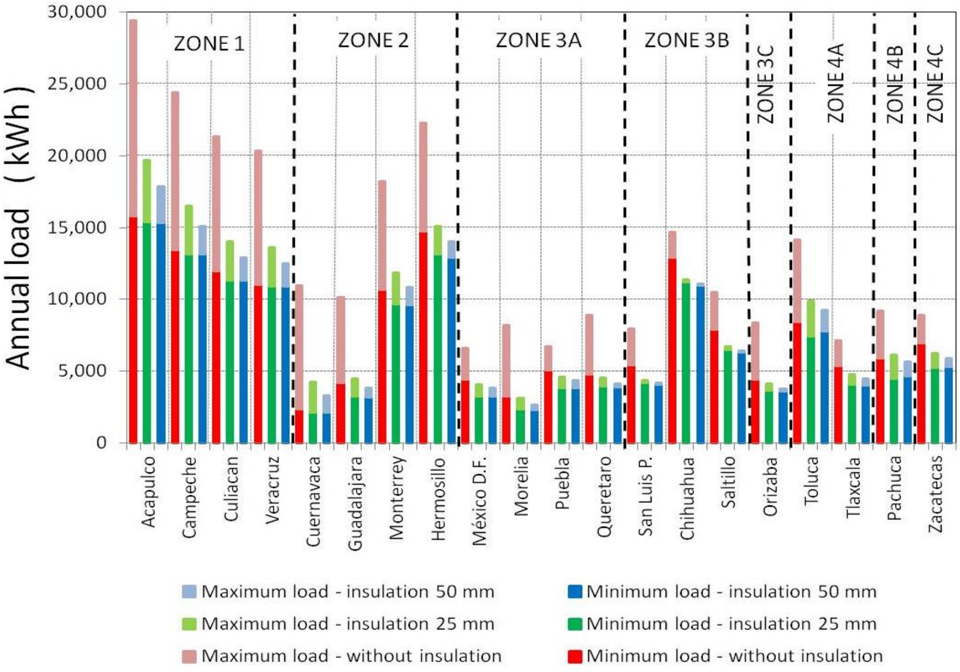

Fig. 7: Maximum and minimum annual load, by city

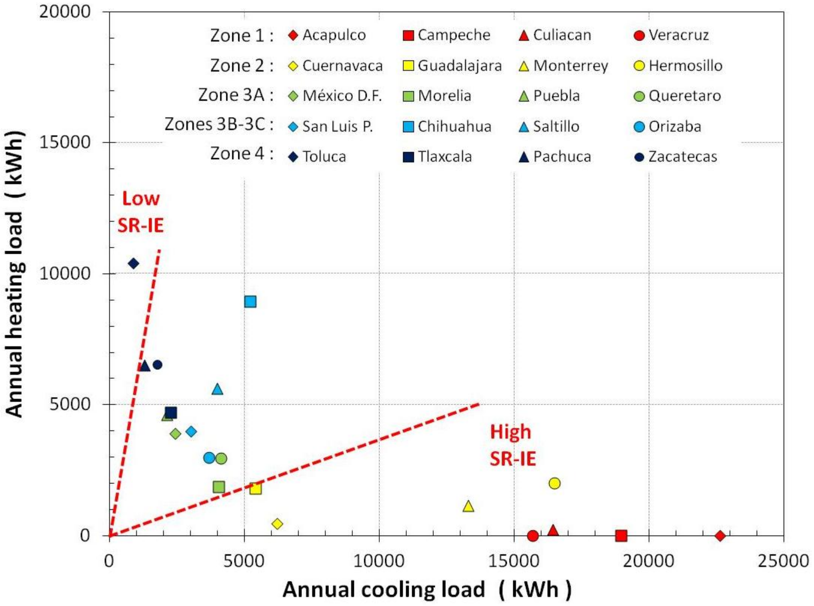

Fig. 8: Comparison of mean values of annual heating and cooling loads

3.3 The effect of insulation on annual thermal loads

Adding thermal insulation to the external surface of the roofs significantly reduced thermal loads when the SR and IE values were inadequate. This effect is particularly important for cities in Zone 1. We consider Acapulco and Toluca as representative examples.

Figure 9 shows a comparison of annual thermal loads with different levels of thermal insulation for Acapulco. Insulation has an important effect only when SR and IE have very low values. For example, under the worst possible conditions (SR=0.1 and IE=0.1), thermal insulation decreases the heat load by 32.9% or 39.1% (for 25mm or 50mm of polyurethane foam). In the same location but with the best possible surface properties, this reduction amounts only to 2.8% and 3.1%, respectively. Figure 9 also shows that the effect of SR and IE is reduced by proper insulation.

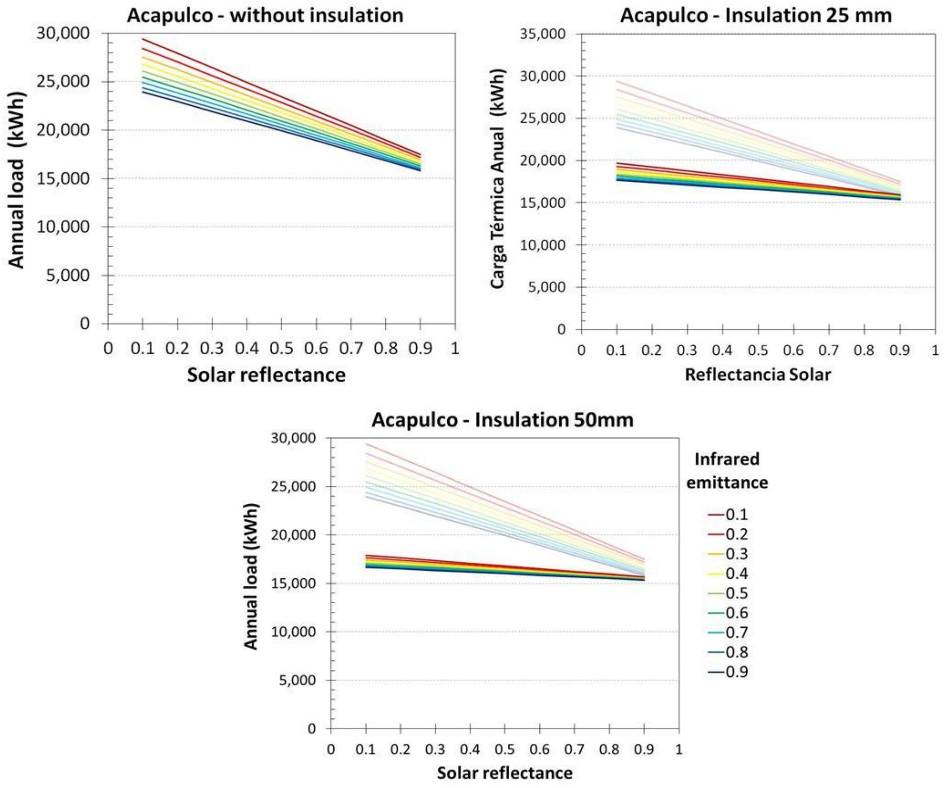

Fig. 9: Annual thermal load with three levels of insulation for the city of Acapulco

In the case of Toluca (Figure 10), 25mm of insulation reduces the annual thermal load even with optimal surface properties (SR=0.1 and IE=0.1), but increasing insulation to 50mm has no effect at all.

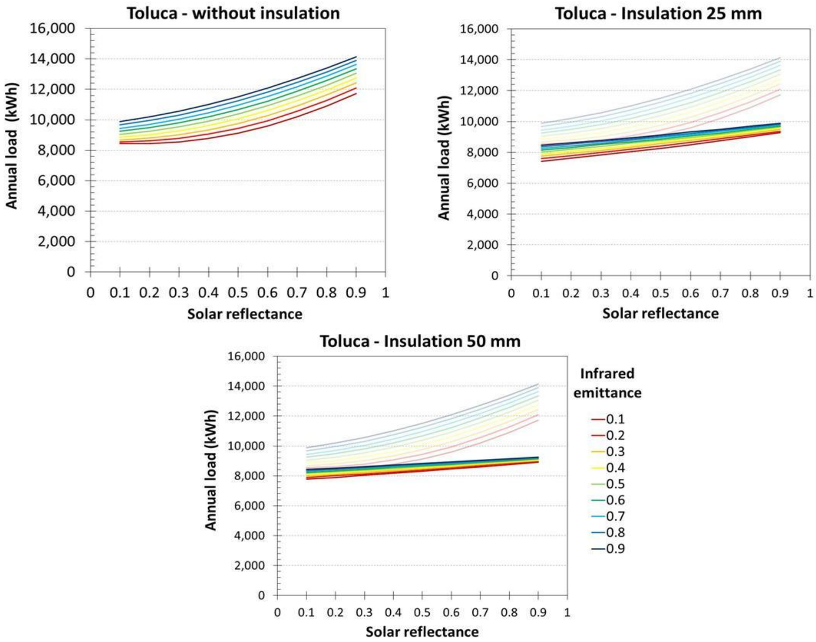

Fig. 10: Annual thermal load with three levels of insulation for the city of Toluca.

Figure 7 shows the maximum and minimum values of annual thermal load in various cities. It is important to note that insulation has a significant effect on the maximum loads (which correspond to bad values of SR and IE), but only in cities such as Chihuahua and Hermosillo does insulation have an important effect when there are adequate values of roof surface properties.

4. Acknowledgments

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