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Comparative economic assessment of the energy performance of air-conditioning within the Mexican residential sector

Ivan Oropeza-Perez

Department of Architecture, Universidad de las Américas Puebla, Ex Hacienda Sta. Catarina Mártir 72810, San Andrés Cholula, Puebla, Mexico

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ABSTRACT

This work shows a sensitivity analysis of the economic impact of different energy performances of air-conditioning within the Mexican housing sector. For this purpose, a cooling-load calculator program in function of the indoor temperature is developed. The program also calculates the electricity consumption along with the expenditure with the different residential rates of the Mexican Federal Commission of Electricity (CFE, initials in Spanish) set according to the season of the year and zone of the country. After the results onto the national-scale scenario are validated with the literature, a sensitivity analysis is carried out by changing three parameters that are considered as influential on the consumption and which can be considered as energy saving strategies. With these strategies, it is found that the indoor temperature decrease due to the use of a passive cooling system is the most important characteristic to take into account followed by the coefficient of performance (COP) of the air-conditioning and the increase of the comfort temperature set-point, respectively. Thereby, an economic analysis is carried out, finding an annual saving up to 770 USD within a single air-conditioned dwelling having a payback period of 3 years for using a combination of passive cooling techniques and increasing the comfort temperature set-point; or a 2 years payback period if the air-conditioning is changed by a high-efficient equipment.

1. Introduction

The use of air-conditioning (AC) to achieve indoor thermal comfort is a common practice in countries which are mainly under warm conditions (Shin and SL, 2016; Rana et al., 2015). Several reasons drive to the use of this type of active cooling method: its reliability, its control and its efficiency to reach thermal comfort under extreme conditions are amongst of them (Zhou et al., 2015). Nevertheless, the utilization of this cooling technique increases the electricity demand of the building (International Energy Agency, 2013).

Because of a great extent of the most consuming countries of AC have a mostly fossil-fuel-based electricity generation (International Energy Agency, 2013), the extensive use of AC increases the climate change effect (International Energy Agency, 2013). Mexico is amongst these countries, having an electricity demand for AC within the residential sector calculated at 8.9 TWh in 2011 (3% of the total national demand) (Oropeza-Perez and Østergaard, 2014).

Thereby, different cooling passive strategies have been developed in Mexico and other countries in order to have thermal comfort by not using energy and thus to meet the international agreements that consider the decrease of greenhouse gases emissions such as Kyoto and Paris (Bastide et al., 2006; Cancino-Solórzano et al., 2010; Lokey, 2009; Huacuz, 2005; Assimakopoulos et al., 2002; Oropeza-Perez and Morillon-Galvez, 2011; Haase and Amato, 2009; Yik and Lun, 2010; Cardinale et al., 2003; Laverge et al., 2011; Florides et al., 2002; Garde et al., 1999; Tablada et al., 2009). This passive cooling strategies are often, however, not affordable enough for all building' users, especially regarding the initial investment (Yik and Lun, 2010; Cardinale et al., 2003; Laverge et al., 2011; Florides et al., 2002; Garde et al., 1999; Tablada et al., 2009).

Nonetheless, different methods along with the passive cooling techniques can be used in order to achieve indoor thermal comfort and still saving energy and money. Moreover, different low-carbon scenarios have been analyzed in order to find their feasibility of implementation (Kwon and Østergaard, 2012; Østergaard, 2009, 2010; Østergaard and Lund, 2011). The purpose of this document is to show the economic feasibility of using techniques of energy saving and to achieve a payback period taking case studies within the Mexican residential sector as examples.

E-mail address: ivan.oropeza@udlap.mx.

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Nomenclature

ρ	Density of the indoor air $\left(kg/m^3\right)$
COP	Coefficient of performance of the air-conditioning [dimensionless]
C_p	Specific heat of the indoor air (kJ/kg K)
D_{AC}	Electricity rate of the air-conditioning (W)
E_{Conv}	Convective heat transfer rate from the surfaces (J/s)
E_{Vent}	Heat transfer rate due to natural ventilation, controlled and not controlled (J/s)
E_{AC}	Cooling rate due to air conditioning/heating (J/s)
E_{Int}	Internal heat loads, including direct solar gains (J/s)
ED_{AC}	Annual electricity demand of the air-conditioning (Wh)
$Q_{gained/lost}$	Heat rate gained or lost without considering mechanical systems (J/s)
T	Indoor temperature (C)
T_1	Indoor temperature at 0 s (C)
T_2	Indoor temperature at 3600 s (C)
T_{indoor}	Indoor temperature calculated by EnergyPlus (C)
$T_{set\text{-}point}$	Comfort indoor temperature set-point (C)
t	Time (s)
V	Volume of the thermal zone $\left(m^3\right)$

2. Cooling load calculator

2.1. Climatic regions in Mexico

In the country four main climatic regions are defined as shown in Fig. 1 (Vidal-Zepeda, 2005; Sevicio Meteorológico Nacional, 2015). These regions are described by their mean monthly temperatures as shown in Fig. 2 (Vidal-Zepeda, 2005; Sevicio Meteorológico Nacional, 2015). It is noticed that for the temperate region there are only two months with temperatures somewhat higher than 30 °C, whereas for the dry tropic and hot humid regions all the months have the highest temperature above 31 °C. The arid region presents five months below 30 °C.

With Figs. 1 and 2 one can claim that Mexico is mostly under warm conditions therefore the use of AC is mainly necessary.

2.2. Air-conditioning consumption in the Mexican housing sector

According to a prior study, in 2011 in Mexico there were 5.2 million air-conditioned dwellings, being 26.7 million the total Mexican households (Oropeza-Perez and Østergaard, 2014). Therefore, conditioned dwellings accounted for 19.5% of the total residential stock. If the annual growing rate was estimated at 7.5% (Rosas-Flores et al., 2011), the number of household with AC by 2015 is calculated at 6.9 million.

Furthermore, the electricity demand of AC is estimated at 11.8 TWh for 2015. This is considering that in 2011 the consumption was determined at 8.9 TWh (Oropeza-Perez and Østergaard, 2014) and that the AC devices have the same energy performance than 2011, i.e. same COP and same daily period of use. This figure has the same order of magnitude than the calculated by Rosas-Flores et al. (2011) and the CFE (Comisión Federal de Electricidad, 2015; Comisión Nacional para el Uso Eficiente de Energía, 2007; Secretaría de Energía, 2015) considering the annual growing rate calculated by the same authors, i.e. 7.5% (Rosas-Flores et al., 2011).

The distribution of the air-conditioned dwellings by climatic region is shown in Table 1. Notice that by 2015 there are 30.2 million dwellings, i.e. an annual growing rate of 3.1%. This is less than the half of the growing rate of conditioned dwellings. This is explained by the fact that Mexican people has reached a higher

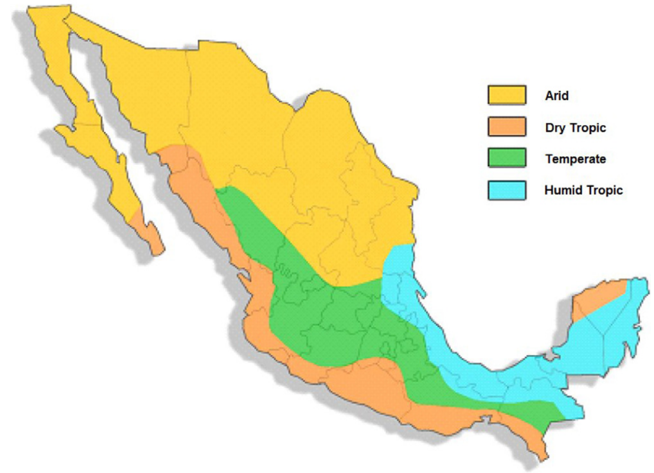

Fig. 1. Main climatic regions in Mexico (Vidal-Zepeda, 2005; Sevicio Meteorológico Nacional, 2015).

purchase power in the last years combined by the depletion of the AC prices (Lezama, 2014). There is even the fact that for some sector of the Mexican society, having an AC means achieving a higher social status (Lezama, 2014).

2.3. Air-conditioning demand calculation

To carry out the economic analysis of the AC consumption, a cooling-load calculator program is developed. The program starts with the heat balance of the thermal zone, considering that a single dwelling is the thermal zone and that the indoor air temperature is well-mixed (Etheridge, 2012):

$$\rho \cdot c_p \cdot V \cdot \frac{dT_{cond}}{dt} = \{E_{Int} + E_{Conv} + E_{Vent} + E_{AC}\} \approx \rho \cdot c_p \cdot V \cdot \frac{dT_{free}}{dt} = \{E_{Int} + E_{Conv} + E_{Vent}\}. \quad (1)$$

If it is considered that the zone is on a free-running building (not using AC), the sum of the different heat rate of gains/losses can be simplified as a general heat rate of gain/loss and be equaled to the heat rate by using AC/heating, i.e. the heat transfer by using AC/heating:

$$Q_{gained/lost\_free} \approx Q_{gained/lost\_cond} \approx -E_{AC}. \quad (2)$$

This is valid if $[E_{int} + E_{conv} + E_{vent}]_{free} \approx [E_{int} + E_{conv} + E_{vent}]_{cond}$ and assuming that internal heat loads are dominating the heat transfer. Therefore, if the total of gain/loss by E_{int}, E_{vent} and E_{conv} is removed/added by AC/heating, the general heat rate of gain/loss can be shown as follows:

$$\rho \cdot c_p \cdot V \cdot \frac{dT_{free}}{dt} = -E_{AC}. \quad (3)$$

The differential equation is rearranged as:

$$\frac{dT_{free}}{dt} = -\frac{E_{AC}}{\rho \cdot c_p \cdot V}. \quad (4)$$

The differential of temperature of the thermal zone shown in Eq. (4) can be determined within an hour (3600 s) if the equation is solved by integrating the differentials, setting an interval from 0 to 3600 for dt and an interval of $T_2 - T_1$ for dT, and considering that the term $E_{AC}/\rho \cdot c_p \cdot V$ has a constant value during the period of one hour (Blanchard et al., 1998):

$$\int_{T_1}^{T_2} dT_{free} = -\frac{E_{AC}}{\rho \cdot c_p \cdot V} \int_0^{3600} dt. \quad (5)$$