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Methodology of Energy Management in Housing and Buildings of Regions with Hot and Dry Climates

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Additional information is available at the end of the chapter

Abstract

In this chapter, power consumption and electrical demand in buildings or housing due to the utilization of HVAC systems are shown to be intimately linked to construction materials. This work proposes a methodology of energy management intended to analyze and evaluate actions aimed at saving and efficient use of electric energy of HVAC systems applied to regions with hot and dry climates. The methodology consists of: (1) characterization of local climatology using the concept of degree-hours (DH). (2) Utilization of a Fourier-type mathematical model to calculate hourly temperature using only daily maximum and minimum temperatures as well as an empirical model to compute energy efficiency (EER) of air-cooled air conditioning units. (3) Thermal simulation applying a software developed by the authors based on ASHRAE's Transfer Functions methodology to calculate hourly cooling loads, the adequate sizing of air conditioning equipment and the rate of heat extraction. (4) System analysis, identification of improvement actions, evaluation of viable alternatives of saving and efficient use of energy. The advantage of this proposal is its flexibility because it can be applied to any climatology and easily adaptable to the conditions of energy usage anywhere in the world.

Keywords: energy management, HVAC systems, degree-hours

1. Introduction

In regions of extreme climates, whether warm, cold or both, the use of HVAC systems is important to maintain comfort and adequate conditions for its occupants. However, the amount of electricity consumed depends on several factors such as the cooled/heated area,

construction materials, climate of the region, fenestration, user's energy management, thermal insulation, lighting or internal heat loads, among the most important ones. However, social-economic and cultural issues also play a significant role [1].

One of the main problems encountered in HVAC systems is oversizing. This leads to an unnecessary increase of electrical demand on the power supply system and its consequent environmental impact [2]. For example, in the northwest region of Mexico which is characterized by a dry hot climate in summer, maximum outdoor temperatures of 45–47°C and even higher are usually encountered in July and August. For these conditions, retailers and HVAC technicians normally size the capacity of air conditioning using a rule of thumb that has been deeply rooted for years: "1 ton capacity for 20 square meters of cooled area." This criterion is generally applied without any valid technical or scientific basis.

This heuristic approach does not take into account if the building is well insulated or if there are elements for energy saving. As a consequence, the air conditioner is generally oversized by a factor which varies from 1.5 to 2. On the other hand, since 1990, in Mexicali, Baja California, Mexico, a city with more than one million inhabitants, the federal government initiated a sponsored program through Comisión Federal de Electricidad (CFE), the state electric power company, intended to support energy saving strategies and specific actions oriented to the residential sector. These actions started by financing insulation of ceilings and the replacement of incandescent lamps with fluorescent ones. Subsequently, in 1997 began the replacement of old low-efficiency air conditioning units with high-efficiency equipment. In this program, the package, split, mini-split and window type units were considered and by 2003 the actions to replace old low-efficiency refrigerators were launched. This program called Program for Integral Systematic Saving [(ASI) by its acronym in Spanish] still continues to operate and has even expanded to other cities with hot climate in the country [3].

Energy efficiency of residential housing and buildings is of concern not only in Mexico but around the world because of its impact on future energy requirements, due to the accelerated growth of our modern cities during the next decades. Thus, several studies oriented to analyze and improve efficiency of this sector using regional passive elements (attics, ventilation, gardening, wall materials, roof ponds, and insulation) or feasible strategies of energy saving have been carried out [4–7].

On the other hand, recent studies are being developed to investigate the utilization of nanoparticles as energy carriers or thermal storage materials for applications in heat transfer systems. The effect of these materials on the effectiveness of heat transfer in heat exchangers of different geometries has been simulated by taking advantage of latent heat of melting-solidification change of phase. The use of nanoparticles added to reflective paints as an additional energy saving option has also been proposed. However, even more research is still needed in this field to consider these materials as a truly effective, technical, safe and economic option [8–12].

Nevertheless, there is still no standardized criterion for the correct sizing of cooling or heating units applicable in Mexico, so oversizing becomes a serious problem for the energy supplier

and makes the user pay unjustifiably for additional and unnecessary capacity. For this reason, the UABC's Institute of Engineering has been working on several projects oriented toward the efficient use and energy saving which at the same time let us obtain a reliable methodology to determine and characterize the energy performance of the residential sector as well as public and private buildings in order to standardize the energy calculation and provide solid technical elements to analyze, implement and evaluate effective actions of saving and efficient use of electric energy.

2. Energy management methodology

2.1. Climatology: degree-days and degree-hours

For understanding the energy behavior of a building or a household, it is imperative to know very well the climate of the region where it is located since its climate determines whether heating, cooling or both are required for any period of the year. This is also essential for calculation of heat gain or heat losses. It does not matter if the building is in the design stage or it has already been built; any energy analysis is intimately related to local climate. As previously mentioned, degree-days have been the main variable used to correlate energy and climate. Before having the advantages provided today by the availability of current online weather databases, the cooling or heating degree-days were computed just considering a simple arithmetic addition or subtraction between the outdoor temperature and an estimated base temperature.

As an example, at any given day, the maximum temperature reached 35°C and the minimum temperature was 22°C, the average temperature is $T_{av} = (35 + 22)/2 = 28.5°C$. The most used base temperature in the USA is 18.3°C (65°F). Since T_{av} is greater than 18.3°C, the degree-days are then (28.5−18.3) = 10.2 cooling degree-days. The same base temperature is also utilized for estimating heating degree-days [13].

However, there are other criteria for calculating degree-days as indicated by Bromley [14] who takes into account not only a variable base temperature but also the duration of the temperature above or below such reference temperature. This information can be obtained online when a weather station in the city or location of interest is available, but what happens if information is not reliable or does not exist at all? In such a case, data from the nearest station or from a region with a similar climate would be useful. Once the degree-day values are obtained for a particular location, then they could be correlated seeking for some relationship between, for example, power consumption or demand to establish patterns of energy behavior in buildings or even to estimate the impact of global warming on the climatology of a particular location [15–17].

In developed countries, a large amount of climatological information is available; however, in nondeveloped countries such as Mexico or in Latin America, there is a lack of data for many locations excepting maybe for the most important cities. Therefore, we have been working on collecting and processing information provided by the National Meteorological Service of 40

Mexican cities with a population of at least 100,000 inhabitants. Instead of working with the degree-day approach, hourly averages were obtained and analyzed on this basis. These are called degree-hours (DH). DH take into account not only the degrees of the outdoor temperature above or below the reference temperature but also the duration of these variations over a day. This procedure can be done for every single day of the year. In **Figure 1**, the concept of degree-hours is shown graphically. This figure also shows the mathematical definition once a function for hourly outdoor temperature is provided.

Two temperatures were set as baselines for summer and winter: 29.5°C (85°F) for cooling DH and 15.5°C (60°F) for heating DH. These values were selected based upon the weather conditions of the northwest of Mexico where the most severe climate in the country is said to be, especially in summertime. As an example, the maximum recorded temperature in Mexicali occurred on July 28, 1995—51.8°C (124°F). In addition, the inhabitants of this region have developed a special acclimatization for these severe conditions not existing in other cities with less aggressive climates. These conditions lead us to consider that the comfort zone is slightly different for the population living in our region from that commonly reported by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [18].

As an example of the application of the DH in the climatological analysis, the results for two cities of northwestern Mexico, Mexicali and Hermosillo, during the summer season are shown in **Figure 2**. Mexicali, the capital of Baja California, is located just on the border with the State of California, USA, while Hermosillo, the capital of Sonora, is 700 km apart to the south. The average monthly temperature in July and August for both locations is very similar, 33°C and 32.2°C, respectively. Statistically there is no difference between them. For each day of a given
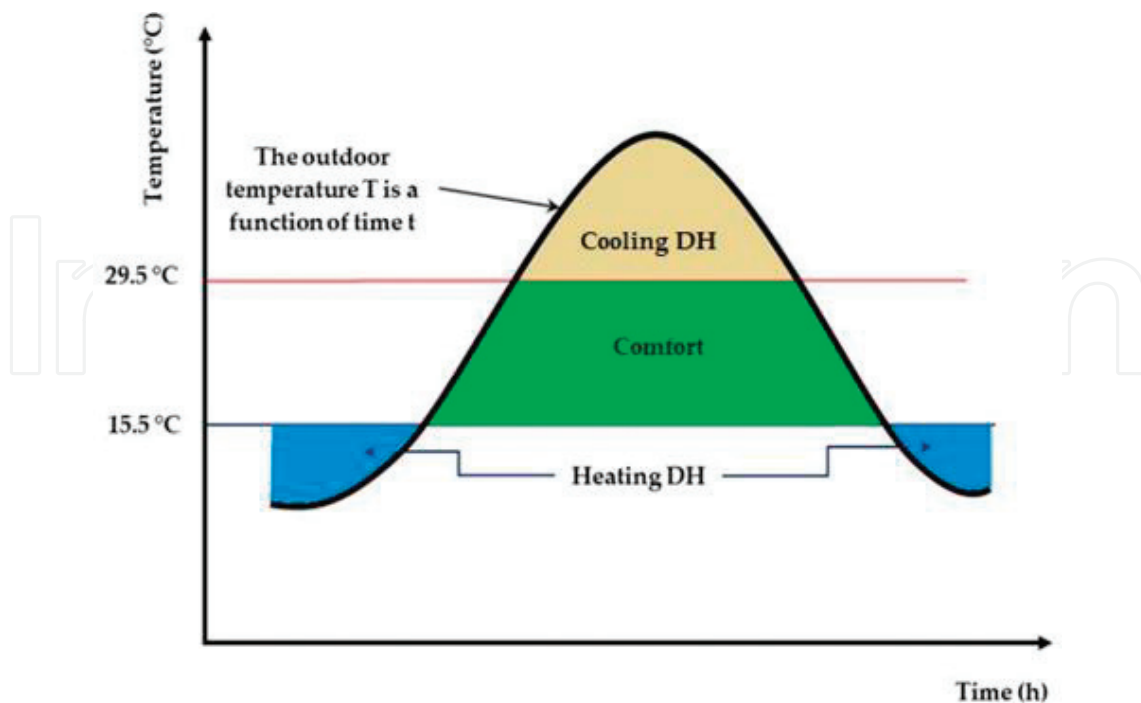

Figure 1. Degree-hours definition.

month, the daily average temperature is calculated as $T_{daily} = (T_{max} + T_{min})/2$ and the monthly average temperature is obtained by averaging the corresponding daily average temperatures. On the other hand, the electricity tariffs in Mexico are based on the average monthly summer temperature. However, even if the monthly average temperature of two or more places is quite similar, this does not mean that the degree-hours are to be the same too. This can be clearly observed in **Figure 2** where the totalized degree-hours during summertime of these two Mexican cities located at the Northwest of the country are compared. The period analyzed was from May to October, and the data were recorded from 1993 to 2001. The statistical difference between DH for both locations is 15%. Thus, as indicated by several authors, the difference, (in percentage) of DH should be similar to the difference (in percentage) of the consumed power by two buildings with the same characteristics situated one in each city, when their energy consumption is compared to each other. In fact, a recent work performed by a graduate student at the Institute of Engineering analyzed the energy consumption of a sample of just over one hundred homes of residential users in these two cities. For the results to be valid, the factors that could introduce variability such as cooled area, constructive system, orientation, occupancy, fenestration or air conditioners efficiency were carefully revised and controlled when analyzed statistically. The results effectively point out that Mexicali users spent, on average, 15% more energy in the summer than Hermosillo's [19]. This figure confirms that electricity consumption and DH are proportional.

The averaged monthly DH for a period of 9 years (1993–2001) for the same two cities are shown in **Figure 3**. As it is seen, there are appreciable variations between one region and another. Mexicali's DH are greater for the period of May to September except in June where both cities behave in a very similar way. October is still a summer month in Hermosillo but not in Mexicali. Otherwise, for the nonsummer months, Mexicali's DH have large negative values while Hermosillo's DH are practically zero. This indicates that Mexicali is significantly colder than the capital of Sonora, an example of an extreme climate. Nevertheless, it should be noted
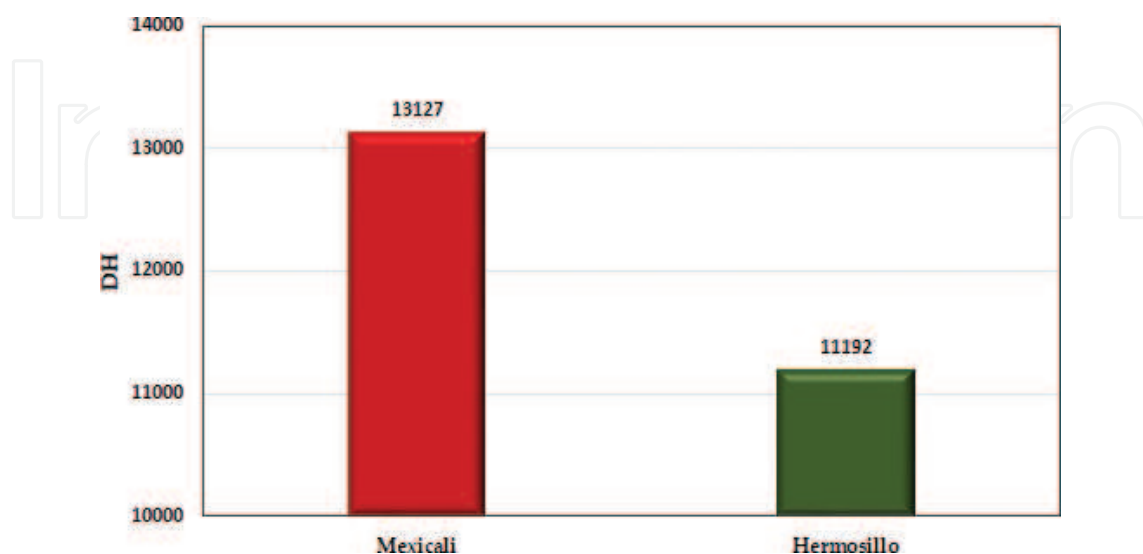

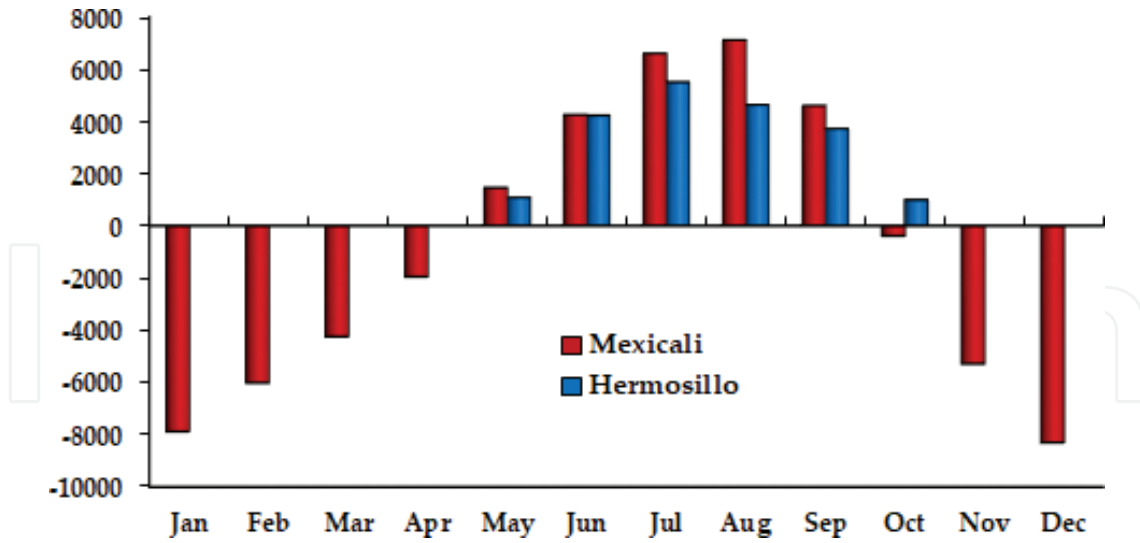**Figure 2.** Average summertime cooling degree-hours for two Mexican cities with similar climate.

Figure 3. Average monthly DH for two Mexican cities (1993–2001). T_{ref} = 29.5°C (summer), 15.5°C (winter).

that carrying out this type of analysis requires having reliable climatological information. On this depends greatly the success of our work.

2.2. Outdoor temperature model

In order to facilitate the calculation of either DH analysis or thermal simulation of a building the authors developed a simple Fourier-type model for estimating hourly outdoor temperature from data recorded by meteorological stations. When working with climate data for the first time, there is a huge amount of information to process and organize and it is a common practice to work with extensive databases. The aim of using a mathematical model is to reduce the complexity of calculation when performing thermal simulation in buildings. This led us to simplify the energy analysis and assessment of a particular system. Besides, the use of a model let us working with only a few set of correlation coefficients instead of an enormous quantity of data, thus releasing disk and memory space. When analyzing the outdoor temperature of a particular region, no significant changes have been observed in its seasonal patterns along a period of several years. This means that the monthly average temperature remains almost the same year after year over a period of time and the natural variation encountered from a year to another is compensated when more years are taken into account. Although this premise is valid for monthly temperature, Mexicali's DH have increased consistently since 2007 [20].

Since the outdoor temperature is given on an hourly arrangement, the model was intended to be on the same basis. So, the model for estimating the hourly temperature is stated as

$$\Theta(t) = \langle \mu \rangle + A \cos \left(\frac{2\pi t}{24} \right) + B \sin \left(\frac{2\pi t}{24} \right) \tag{1}$$

where $\Theta(t)$ represents the dimensionless hourly outdoor temperature for a particular day defined in Eq. (2), T_{max} and T_{min} are the recorded maximum and minimum temperature and $T(t)$ the calculated value of temperature for time t.

$$\Theta(t) = \frac{T_{max} - T(t)}{T_{max} - T_{min}} \tag{2}$$

$\langle \mu \rangle$, A and B are the mean value and the two coefficients of correlation given by:

$$\langle \mu \rangle = \frac{1}{24} \sum_{t=1}^{24} \mu(t) \tag{3}$$

$$\mu(t) = \frac{1}{N} \sum_{n=1}^{N} \Theta_n(t), n = 1, 2, \ldots Ndays \tag{4}$$

$$A = \frac{2}{24} \sum_{t=1}^{24} [\mu(t) - \langle \mu \rangle] \cos\left(\frac{2\pi t}{24}\right) \tag{5}$$

$$B = \frac{2}{24} \sum_{t=1}^{24} [\mu(t) - \langle \mu \rangle] \sin\left(\frac{2\pi t}{24}\right) \tag{6}$$

The model was tested using hourly data for various locations in Mexico and Cuba as well as for different years. The statistical deviation from experimental and calculated values did not exceed 5%. For purposes of thermal analysis calculation and buildings simulation, this figure is more than acceptable. Furthermore, the model was integrated as a linked module into the simulator which was developed by the authors to compute the hourly outdoor temperature for a selected location provided the maximum and minimum temperature of any given day. On the other hand, the simulator is based on the ASHRAE's Transfer Function method [21] which, instead of using a large climate database, it used the Fourier model which was incorporated to generating daily hourly temperatures by using only T_{max} and T_{min}. The main reason for doing this is that for certain locations only maximum and minimum temperatures are recorded or available. In **Figure 4**, the experimental and the calculated values using Eq. (1) are shown for the day August 21.
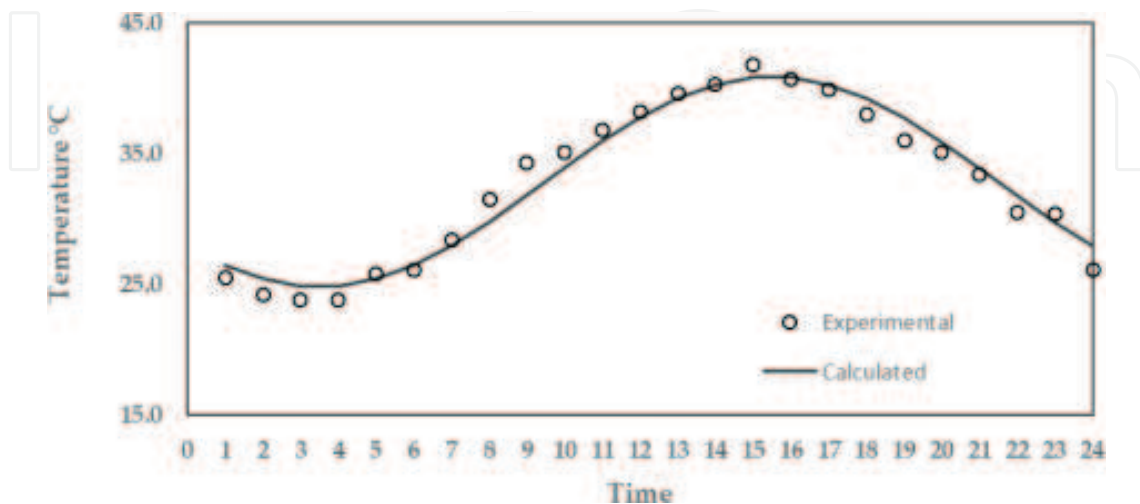

Figure 4. Outdoor temperature using the Fourier-type model. Mexicali, August 21.

Another advantage of using the Fourier-type model is that DH calculation becomes quite simple, so it is not necessary to integrate numerically a large quantity of data every time it is needed, but only performing the integration once by using the model already obtained and substituting the appropriate values of $\langle\mu\rangle$, A and B for the location of interest. In this manner, the cooling DH are defined as

$$DH_{cooling} = \int_{T_0}^{T} \int_{0}^{24} T(t)dtdT \qquad (7)$$

After substitution of Eq. (1) and Eq. (2) onto Eq. (7) and integrating, we obtain

$$DH_{cooling} = 24\big[(T_{max} - T_0) - \langle\mu\rangle(T_{max} - T_{min})\big] \qquad (8)$$

where T_0 is the reference temperature. The same procedure applies for heating DH.

2.3. Thermal simulation

The computational program has been one of the most useful tools for energy analysis. The software is built in modular form, and each module performs a specific type of calculation; moreover, because of its versatility, it is programmed on Excel spreadsheets. The general structure of the program is shown in **Figure 5**. In the module of data entry, all the required information about location, building dimensions, orientation, materials, occupancy, fenestration, internal loads, lighting, actual or estimated HVAC efficiency, and so on, is entered. The module is linked to an internal database where other information such as latitude, longitude, maximum and minimum temperatures, solar parameters, ASHRAE coefficients and thermal resistances is stored.

The next stage is calculating the hourly outdoor temperature, the sol-air temperature and the amount of direct and diffuse radiation over the surfaces of the building. The ASHRAE Transfer Function method is then used for estimating hourly heat gains, cooling load and heat extraction rate. As mentioned earlier, instead of using a large climatological database for each location, the program was configured to work with only a representative sample of data. We have observed that correlation between degree-hours (DH) and the rate of heat gain, cooling load and heat extraction is excellent for regions of dry, hot climates. It is common to encounter a correlation coefficient over 97% with these three factors. However, the DH correlate very well not only with cooling load or heat gain but also with monthly electricity consumption or demand as well as with air conditioning consumption.

2.3.1. ASHRAE transfer functions method

The simulator used in this work is based on the Transfer Functions method (TFM), as reported by the ASHRAE [22]. The authors developed an earlier version of the simulator in 1996 adapting this methodology from the version published in 1992. However, the program has been updated and improved constantly ever since. TFM consists basically in providing a model to consider the dynamic response of a building to heat transfer. As it is known, heat is introduced into a space by mean of three basic mechanisms, namely, radiation, convection and
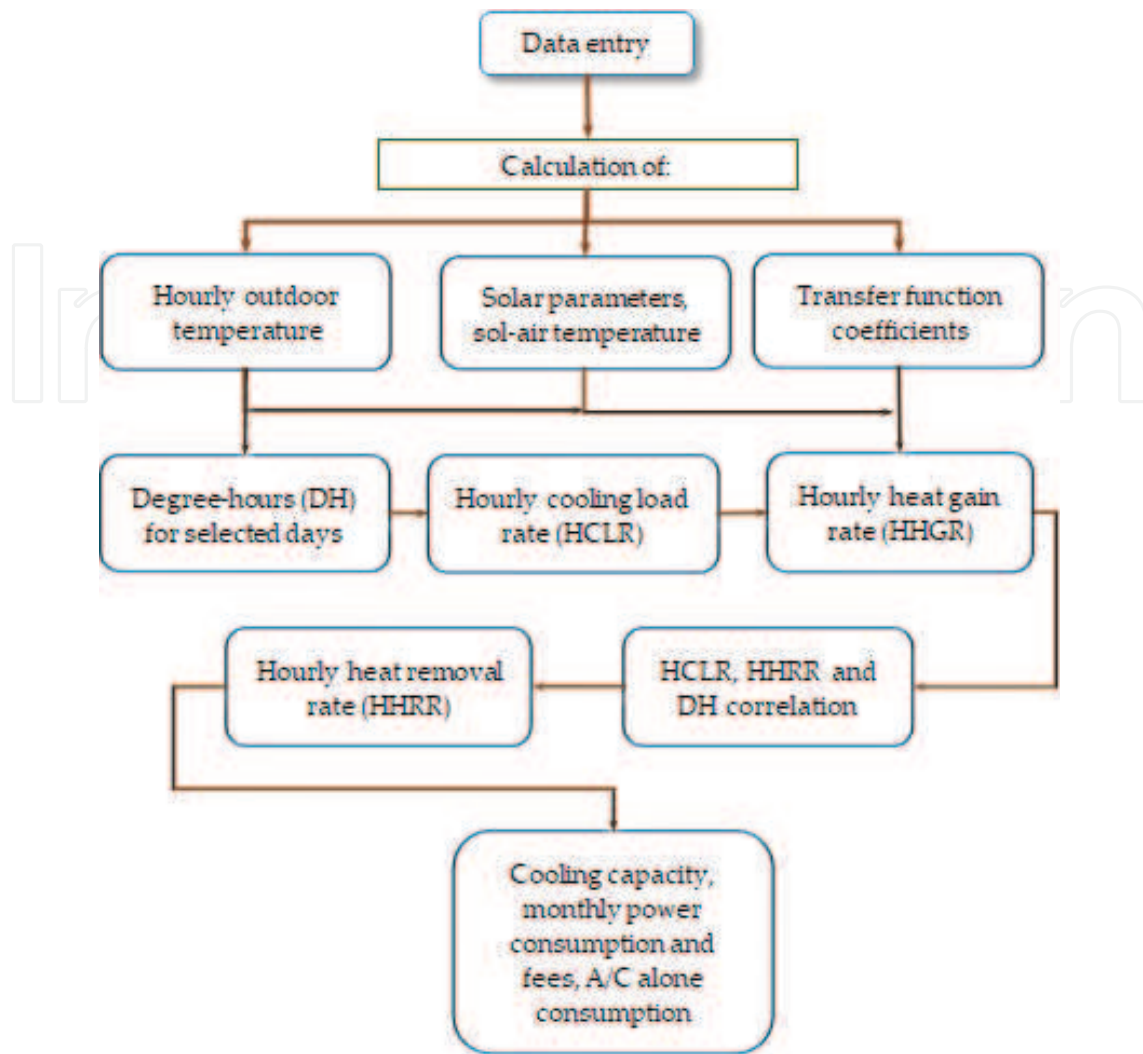
Figure 5. General structure of the thermal simulator.

conduction. TFM converts radiation heat gains on walls as a function of the named sol-air temperature defined as

$$t_e = t_0 + \frac{\alpha I_t}{h_0} - \varepsilon \delta R \tag{9}$$

The heat flow can be calculated from a heat balance as

$$\frac{q}{A} = \alpha I_t + h_0(t_0 - t_s) - \varepsilon \delta R \tag{10}$$

where

t_e = Sol-air temperature

t_0 = Outdoor temperature

t_s = External surface temperature

$\frac{q}{A}$ = Heat flow per unit area

α = Surface absorptivity

I_t = Total solar incident radiation on the surface

h_0 = Convection heat transfer on the external surface

δR = Difference between long-wave radiation from surroundings and the radiation emitted by a black body at the same temperature as outdoor temperature

ε = Surface emittance

Also, TFM requires generating a series of Transfer Function coefficients which are used to estimate U-values for each wall or roof into the equation of energy balance. The first step is calculating hourly heat gains by means of the equation

$$q_{e,\theta} = A \left[\sum_{n=0} b_n (t_{e,\theta-n\delta}) - \sum_{n=1} d_n \left\{ \frac{\left(q_{e,\theta-n\delta} \right)}{A} \right\} - t_{rc} \sum_{n=0} c_n \right] \tag{11}$$

where

$q_{e,\theta}$ = Wall or roof heat gain for time θ

$q_{e,\theta-n\delta}$ = Wall or roof heat gain for the time $\theta - n\delta$

A = Surface area

θ = time

δ = Time interval

$t_{e,\theta-n\delta}$ = Sol-air temperature at time $\theta - n\delta$

t_{rc} = Constant interior temperature

b_n, c_n, d_n = Conduction transfer coefficients

Once hourly heat gains have been computed, they can be transformed into hourly cooling loads with the expression

$$Q_\theta = v_0 q_\theta + v_1 q_{\theta-\delta} + v_2 q_{\theta-2\delta} - w_1 Q_{\theta-\delta} - w_2 Q_{\theta-2\delta} \tag{12}$$

where

Q_θ = Cooling load for time θ

q_θ = Conduction heat gain for time θ

v_0, v_1, v_2, w_1, w_2 = Space weight coefficients

Eq. (12) takes into account the dynamic response of the building from a semi-steady state approach once the other variables such as fenestration, occupancy or lighting coefficients are

provided. ASHRAE publications enlist a large amount of data for materials mostly used in nonresidential and residential buildings. Nevertheless, some materials and construction designs commonly encountered in Latin America do not match as the ones reported by ASHRAE exactly. Therefore, for these cases, the corresponding data and coefficients had to be estimated and incorporated to the simulator. For a more detailed discussion of TFM, see [18, 23–25].

2.3.2. Simulation improvement by using DH correlations

When performing a thermal simulation of a building using the Transfer Functions method, calculated heat gains, cooling loads and heat extraction rates are delivered by the program on an hourly basis for a given day. This characteristic allows sizing the capacity of HVAC system and determines when the highest peak demand will occur or what the most important elements responsible for gaining/releasing heat or consuming/demanding power are. Then the results are totalized for that particular day. This procedure must be repeated every single day over a year or for a certain period of time as needed.

In order to improve the calculation performance of the simulator without decreasing accuracy and reliability of the results, the authors decided to carry out a simpler procedure by correlating the degree-hours with daily heat gain, cooling load and heat extraction rates for a few representative days of a year. The reason for doing this is the hypothesis that if the degree-hours are a realistic way of correlating the climate, then they would be capable of explaining or, at least, correlating the energy behavior of a building with reasonable feasibility. According to this premise, the DH for several arrangements were tested and finally it was concluded that 20 summer days are quite enough to reach the same quality and accuracy of results than if a 365-day calculation was made.

In **Figures 6** and **7**, the plot of DH versus daily heat gain, cooling load and extraction rates is shown for Mexicali, México and Cienfuegos and Cuba, respectively. It can be observed that the
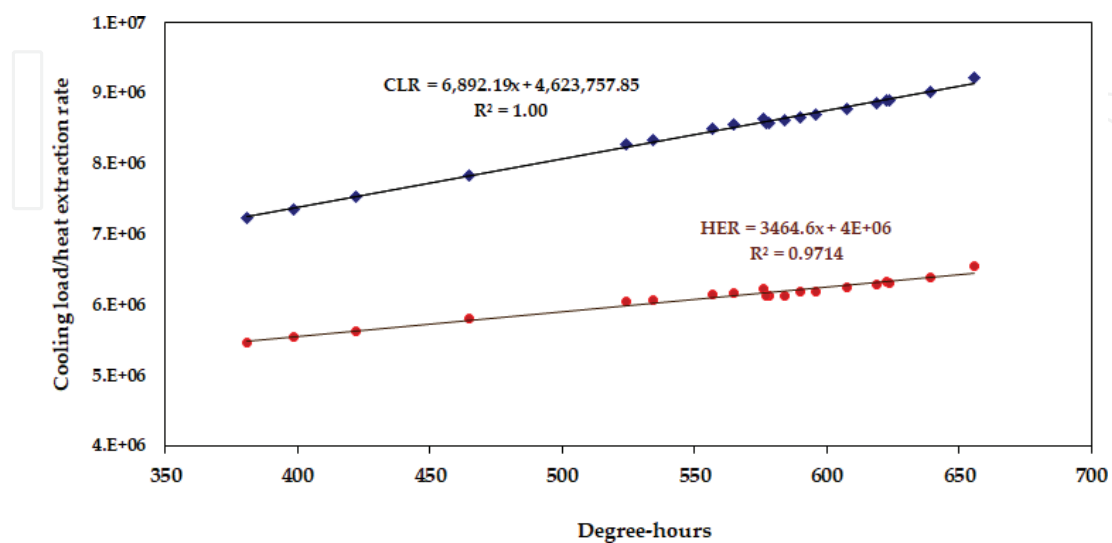

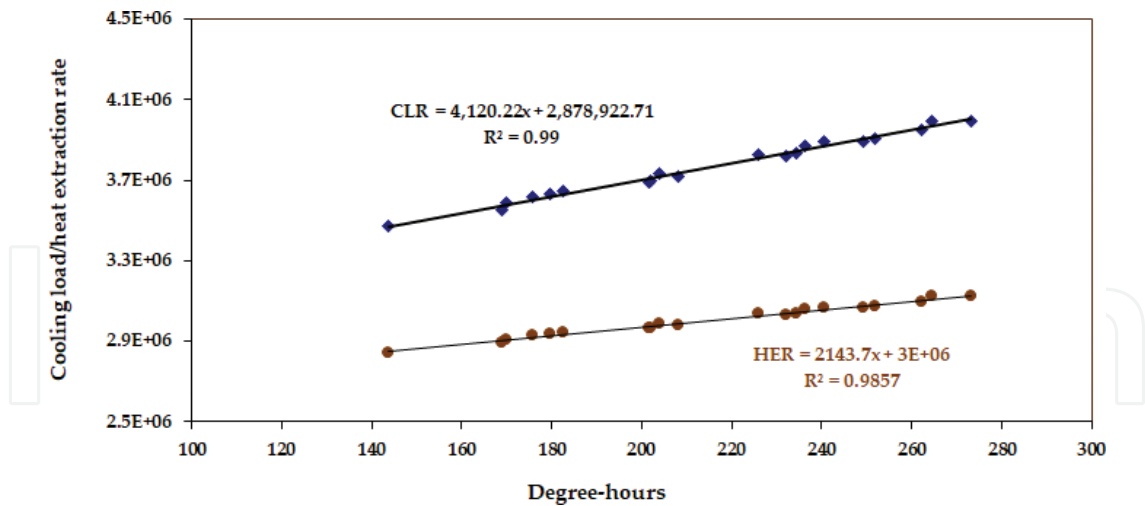**Figure 6.** DH correlation with cooling load and heat extraction rates. Mexicali, México.

Figure 7. DH correlation with cooling load and head extraction rates. Cienfuegos, Cuba.

correlation coefficients R^2 are excellent for both cities. It must be noted that meteorological data for Cienfuegos are available only on a 3-h basis. In spite of this poor quantity of data, the results are still quite satisfactory. Correlation equations are readily obtained from DH and the three variables mentioned earlier, although DH versus cooling load rate (CLR) and DH versus heat extraction rate (HER) are most useful for our purposes.

Thermostat temperature is the reference baseline to calculate DH for the rest of the days of the year. Once the equation is available for CLR, its daily values are generated for the entire year and linked to the next module where daily heat extraction rates are estimated in the same manner as done for cooling load. When the TFM calculation is complete, the results of daily heat extraction rates are then correlated with DH for estimating the power consumption of the building while also including the variation of the air conditioning efficiency. The model that describes how the energy efficiency ratio (EER) varies as the outdoor temperature does is given below. At this stage, the EER values can now be applied together with HER correlation equation for computing the power consumed by HVAC system over the analyzed period of time.

2.3.3. Efficiency of HVAC systems of air-cooled condensing units

It is well known that the energy efficiency of air-conditioning systems varies strongly with the outdoor temperature, and in turn, temperature varies throughout the day. This is especially true for HVAC systems whose condensing units are cooled by outdoor air. Air is not a good conductor of heat and special care must be taken to maintain the proper operating conditions of the equipment. For this reason, a model considering this hourly variation has been incorporated into the simulator for calculating the rate of heat extraction. This allows better accuracy of the results. The model is quite simple and takes the form [26].

$$EER = e^{(a-bT)} \tag{13}$$

where EER is the Energy Efficiency Ratio (W/W, kBtu/kWh), a and b are correlation coefficients depending on the unit model and system (package or split) and T is the outdoor temperature (°F). It should be noted that Eq. (13) fits EER for new units within less than a $\pm 1\%$ difference

between calculated and measured values reported by manufacturers [26]. For older or used equipment, a less than unity correction factor must be used. This factor depends on several issues such as type of unit, age, model or dirt on heat transfer surfaces and should be found experimentally. Of course, such an investigative task is not feasible for most situations. In regions where humidity is small and if the HVAC unit receives appropriate maintenance, the factor value is 1 for all practical purposes. Besides, according to manufacturers, if any significant reduction of EER occurs during the first 5 years of use, it will be attributable to different causes such as refrigerant leakage or major damage to the equipment, among others.

An example of the EER variation for a given day is presented in **Figure 8**. For that day, the minimum and maximum temperatures are 43.3 and 27.5°C, respectively. EER is plotted as a function of time and its corresponding value can be read on the left axis while the outdoor temperature is allocated on the right axis. From this graph, it can be seen that as the temperature rises, the efficiency decreases proportionally.

2.3.4. Integrating results

Once the calculations described in previous sections have been completed, the program generates a set of daily and monthly values of DH, cooling load and power consumption. Likewise, the values and percentage of the most important variables contributing to cooling/heating loads are internally stored and displayed for a better understanding. The most important results are presented in a separate spreadsheet where power consumption, maximum peak demand and billing are displayed on a monthly basis. Also, the contribution to cooling load of roof, walls, fenestration, occupancy, lighting, internal loads and infiltration/ventilation is displayed in a graph to show the user in an easy way how the heat loads are distributed all over the building and which of them are the most relevant over the total load.

Finally, beside the monthly consumption table of results, the billing is added. In this manner, not only the energy balance is in sight but also the economic aspects can be visualized at the same time which as a whole allow the user to make better decisions.
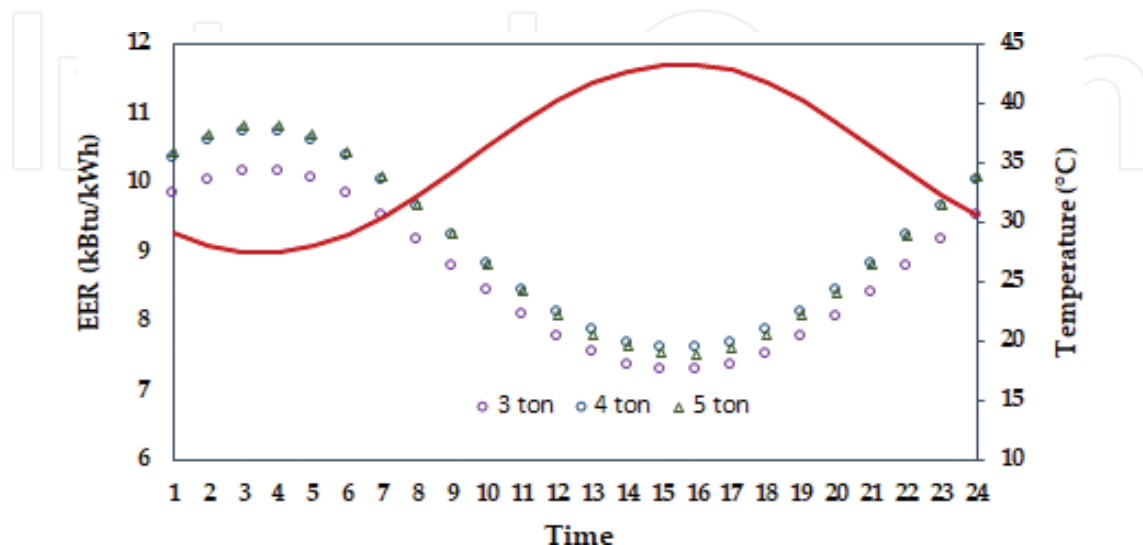

Figure 8. EER variation as a function of outdoor temperature (split units).

2.4. Successful application of the management approach

In 1990, the Mexican federal government started a local program intended to save energy in residential households in the city of Mexicali. The first stage of the program consisted of roof insulation and by 1997, the replacement of old low-efficiency air conditioning systems with new high-efficiency units was initiated. The replacement of refrigerators with more than 10 years of use began in 2003. This program for energy saving is called Program for Integral Systematic Saving ((ASI) by its acronym in Spanish) and remains in progress currently.

The application of the methodology outlined earlier allowed to sustain the energy saving strategies and actions of the ASI program, first in the city of Mexicali then in the rest of the country. Thermal simulation and DH methodology have proven to be a powerful tool for over more than 20 years in which a large number of projects have been developed with the residential, public, governmental and industrial sectors. One of them provided the technical support for the creation of the ASI program. [27]. An evaluation of the impact on consumption habits of inhabitants due to the actions and strategies carried out by the ASI program was made recently [28].

3. Conclusions

The methodology described earlier has proven to be a useful tool for the analysis and evaluation of projects related to saving and efficient use of energy. The use of DH as a primary variable has shown to be an excellent option for the characterization of the climate of a region, especially in hot-dry environments. However, its application is not restricted only to these climates, but it can also be extended to any climate without reducing reliability. Likewise, the utilization of DH greatly simplifies and speeds up the calculation when performing thermal simulation due to its excellent degree of correlation with heat gain, cooling load and heat extraction rates. At the same time, applying the DH criterion also allows to estimate the electrical consumption and demand of HVAC systems in a reliable way. A representative example of the usefulness of this methodology has been its application to the development and assessment of those projects sustaining the energy saving programs of the Mexican federal government, which are currently grouped as the ASI program.

The ASI program started its application as a local energy-saving program in 1990 in the city of Mexicali, with a current population of over 1 million inhabitants, and because of the success and positive impacts achieved in reducing peak demand and energy saving, it has been extended to warm-climate regions all over the country.

Acknowledgements

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