SOME ASPECTS OF THE ENERGY COST LINKED TO THE IAQ. IMPACT OF FREE-COOLING AND HEAT RECOVERY IN OFFICE BUILDINGS.

Topic 3: HVAC Applications in Commercial and Community Buildings

R. Velazquez, S.Alvarez, J.F. Coronel, J. Guerra
Grupo de Termotecnia. Escuela Superior de Ingenieros. Universidad de Sevilla.Avda. Reina Mercedes s/n E-41012, Sevilla (SPAIN)

ABSTRACT

Increasing air exchange rate to improve IAQ may increase energy consumption, but this increase may be compensated for by strategies such as free cooling and heat recovery. The frame of the proposed paper is the examination of the potential at a regional level (the Iberian peninsula) of the different strategies mentioned above in typical office buildings.

Based on a set of reference building morphologies, studies are conducted to evaluate the impact of increasing air ventilation rates for different orientations, quality of the envelope (opaque walls and glazing), operating schedules and indoor set-point temperatures. Then, the impact of the increased air ventilation rates is corrected by introducing the effect of free-cooling, air-to-air heat recovery devices of different types and finally, the combined effect of both energy savings strategies.

The research provides Maps allowing:

1. To identify zones when heating or cooling regimes are dominant, in terms of both, peak load conditions and energy requirements.

2. To compare the expected performance of the two energy saving strategies at a certain locality.

3. To compare the potential benefit of applying a given strategy at different localities.

4. To indicate regions of recommendable application of the strategies and the expected energy savings achievable.

1. INTRODUCTION AND CONTENTS

The energy impact of ventilation must be conceptually examined at two different levels:

- The effect on the building performance of increasing air ventilation rates in order to improve IAQ.

- The potential of reducing the energy impact of increasing air exchanges by means of free-cooling and air to air heat recovery systems.

Free-cooling, sometimes called ventilation cooling, is particularly suited to large office buildings where high heat loads are developed through lighting, computing and other electrical sources. Thus, the building often requires cooling while the outdoor temperatures are lower that indoors. Ventilation rates for cooling will normally be well in excess of that needed to meet the basic fresh air requirements of occupants.

Ventilation heat recovery is the process by which thermal energy is recovered from exhaust air for re-use within the building.

The studies have been conducted based on a set of scenarios representative of the scope of the project. Consequently, the conclusions achieved are only applicable within the range defined by the scenarios.

The scenarios include locations, building morphologies, building operational and constructive characteristics and efficiency of the heat recovery systems.

A first level of **specific information** is provided for a specific building in two locations, Madrid (Spain) and Porto (Portugal). A second level of **generalised information** is provided in a set of maps of the Iberian peninsula (Spain and Portugal). This second step is aimed to know to what extent the conclusions obtained in the first level are applicable to other buildings or locations.

All the information was obtained via hourly based computer simulation, for which it was necessary:

- The generation of the climatic data (Test Meteorological Years) for 35 different locations covering the different climates of the Iberian peninsula.

- A detailed building energy analysis tool (PASSPORT PLUS Software) to obtain the thermal load hour by hour,

- The development of specific routines to characterise the performance of the free-cooling, heat recovery and conventional cooling coil components.

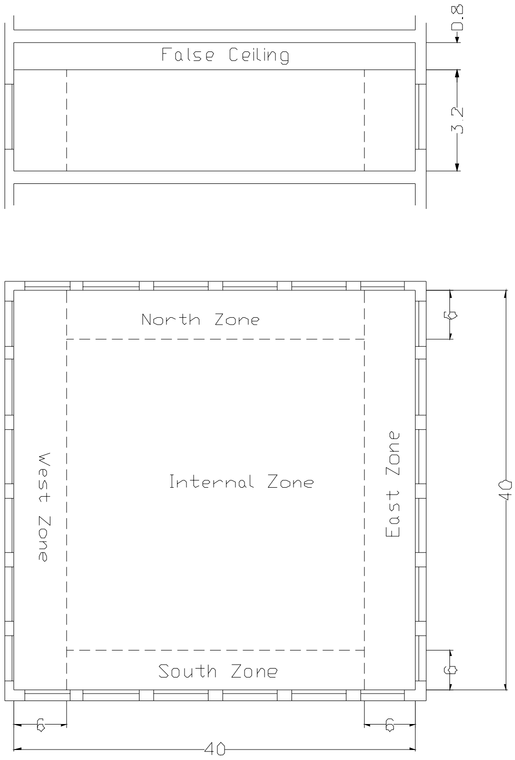
- The development of postprocessors to perform the massive simulations and analyse the results in an automatic way.

- To compile easily available climatic data (monthly mean values) of 40 additional sites of the Iberian peninsula to completely cover the geographic region which would be represented in the maps.

- To develop physical and geographical interpolation procedures to build up the maps.

PASSPORT PLUS has been taken as the basic tool used inside this project for the detailed thermal building performance. Passport Plus is a dynamic simulation software to calculate the thermal behaviour of multi-zones and multi-element buildings. This software package has been developed in the frame of the European research project (PASCOOL) EC-JOU-0013-CT92 of the XII General Directorate of the European Union. This software is totally compatible with the simulation of cooling and heating systems, and has been well tested against results from other programs and experimental values. Its internal structure makes this program very appropriated for the development and incorporation of pre-processors and post-processor software specific for every different application.

2. REFERENCE CASE



A representative office building has been selected. The building has square shape with 1600 m² (40 x 40 m) of floor area in each floor. It will be divided in 6 different zones: south, east, north, west, internal zone and false ceiling (see figure 1). The external zones (south, east, north and west) have an average depth of 6 m; the rest of the usable floor is internal zone. The false ceiling will be simulated as a free floating zone, so that, all the energy results hereinafter will be refereed only to the first five zones.

In the four facade the percentage of glazed area is 60 % and 40% the opaque one. The exterior walls, glazing, floors and ceilings are typical constructive element for these kind of buildings, with a medium level of constructive quality.

Figure 1: Scheme of one floor of the building

- Walls: Double brick (12 cm), insulation layer (5 cm), single brick (7 cm) (U = 0.57 W/m²K)
- Glazing: Double glazing 6-6-6 mm, Global solar Transmitance = 0.66 (U = 3.4 W/m² K)
- Window Frames: Aluminum, low airtightness
- Roof: Concrete (3 cm), air layer and extruded polystyrene (3 cm), ceramic space between girders. (U = 0.61 W/m² K)

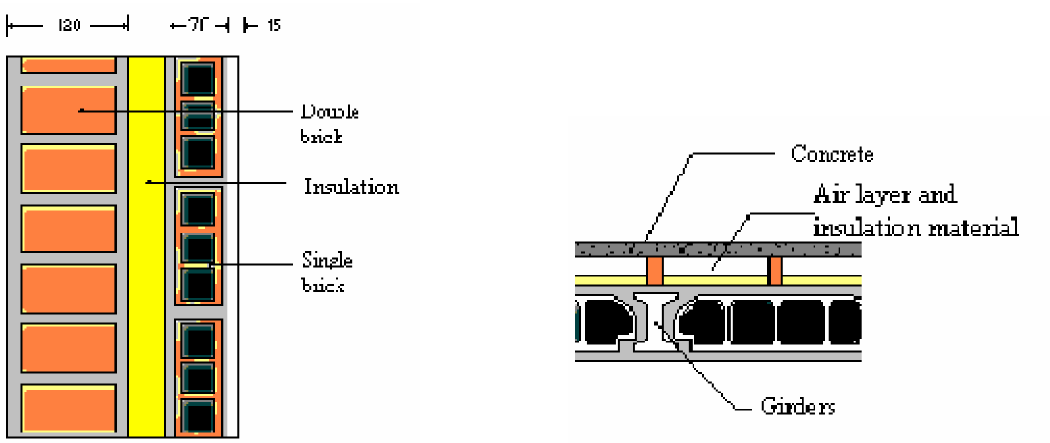
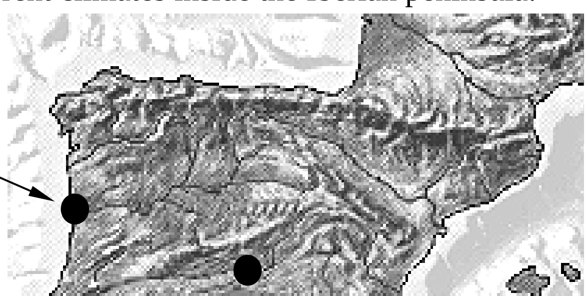


Figure 2: Scheme of wall and the roof

This building will be studied in two different climates inside the Iberian peninsula:

- Porto (Portugal)



Latitude: 41° 08’ N
Longitude: 08° 36’ W
Altitude: 10 m

- Madrid (Spain)
  Latitude: 40° 27’ N
  Longitude: 06° 06’ W
  Altitude: 650 m

Figure 3: Madrid and Porto geographical location.

The sensible internal gains have been considered to be 30 W/m^2 (lights, occupation and equipment), constant during all the working hours. The working or occupation period is 9-14 and 16-19 hours. The infiltration rate out of the occupation period will be considered as 0.5 air changes per hour (ach) (2560 m^3/h). The occupation density during the working period is about: 1 occupant / 10 m^2.

The size of the air conditioning equipment and the total supply air flow used by the air distribution system have been calculated using the cooling peak load of each zone. It has been assumed that the five different zones have five different air treatment units and its distribution system. The cooling peak load is for all the cases higher than the heating peak load. So, for every different zone and every different ventilation level, there will be a different cooling peak load and consequently a different system size.

3. BUILDING ENERGY PERFORMANCE

3.1. Building energy performance - Reference case

The energy requirement calculations has been performed using 26.5 °C as set point for cooling and 20 °C for heating. The equipment operates during the working period every day, being the building under free floating evolution the rest of the time. The reference ventilation rate has been fixed 1 ach (1420 L/s) during the working period (for this building, 1 ach is equivalent to 8.9 liters of air per second and occupant). The supply air flow has been sized using the peak cooling load of the building (without the ventilation load). Consequently, the supply air flow depends on the zone and the climate. The following table shows the energy requirements and the peak loads zone by zone and for all the building.

Location	Zone	Sensible cooling requirem. (kW·h/m²)	Total[1] cooling requirem. (kW·h/m²)	Heating requirem. (kW·h/m²)	Sensible cooling peak (W/m²)	Heating peak (W/m²)
Madrid	South	117.4	122.3	6.4	116.2	72.2
	East	117.1	122.8	10.8	162.0	79.9
	North	72.3	76.7	12.3	97.2	72.3
	West	116.1	121.5	12.8	152.5	79.9
	Intern.	53.4	57.0	3.5	59.2	38.8
	Building	**81.1**	**85.5**	**7.2**	**98.6**	**58.2**
Porto	South	115.3	130.7	2.1	106.4	55.0
	East	109.0	125.8	3.6	136.9	64.6
	North	64.7	78.9	3.6	88.9	61.0
	West	107.9	125.8	4.2	148.9	66.2
	Intern.	49.5	61.9	0.8	56.9	28.7
	Building	**75.7**	**90.1**	**2.1**	**91.3**	**45.9**

[1]Total: (Sensible + Latent)

Table 1:Energy requirements and load peaks for the building placed in Madrid and Porto.

It can be observed in the previous table and in the figure 4 that the cooling requirements are much more important than heating for all the zones, both in Madrid and Porto (remember that ventilation reference level is 1 ach). The latent cooling requirement (Total - Sensible) is much more important for Porto than for Madrid (Porto has a higher level of outdoor humidity).

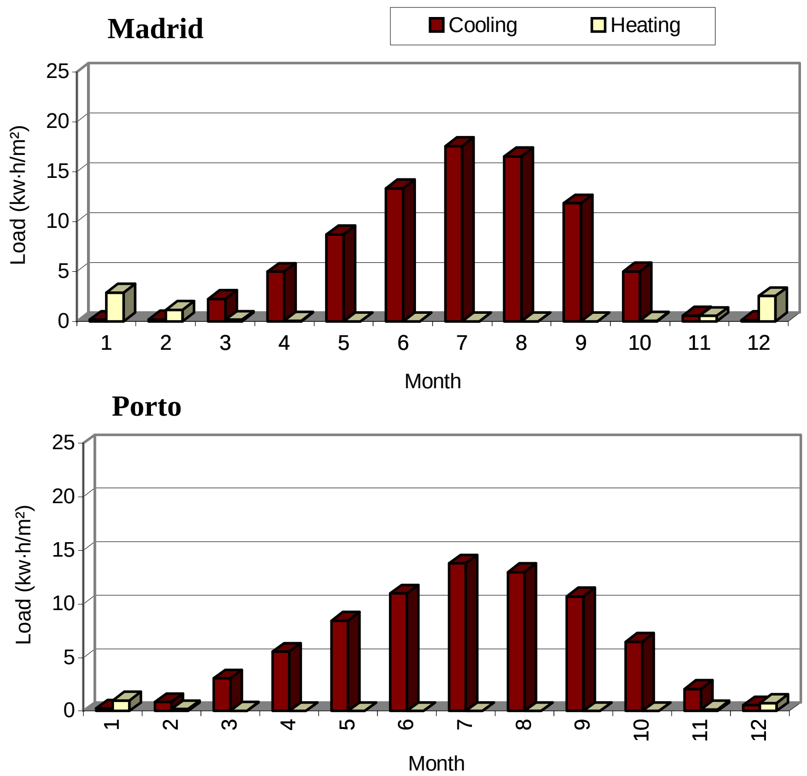


Figure 4: Monthly energy requirements (heating and cooling) for Madrid and Porto

Figure 4 shows the monthly building energy requirements (cooling and heating) for the whole building placed in Madrid and in Porto.

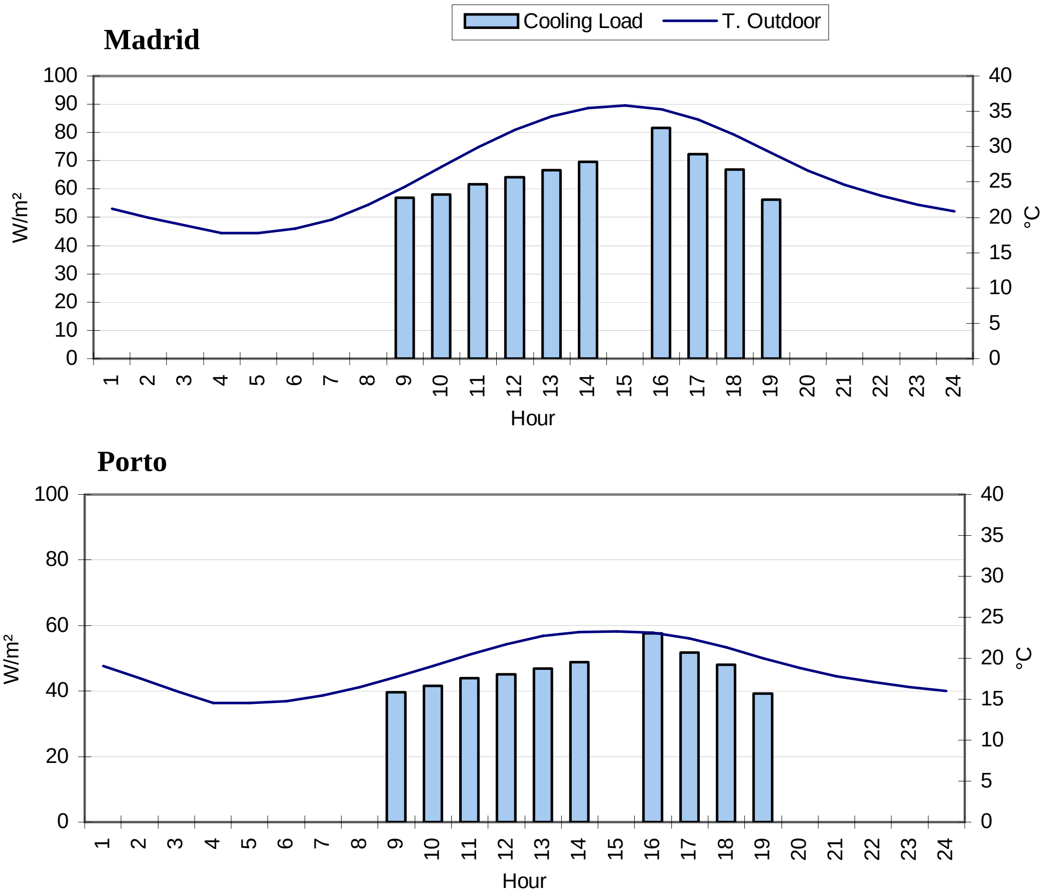


Figure 5: Hourly cooling load and outdoor dry bulb temperature for a typical summer day in Madrid and Porto

Figure 5 shows the hourly evolution for a typical summer day, 15th of July (this day is not mandatory the cooling peak day). Together with the cooling load hourly evolution, we have graph the exterior ambient dry bulb temperature.

It can be noted that there are an interval of time (14 to 16) where the conditioning equipment is switch off and thus the loads are zero. The behavior of the whole building has been calculated adding zone loads. Therefore, the building performance is very closed to the behavior of the internal zone, due to the “weight” of the internal zone with respect to the outer zones.

Building energy performance - Regional Evaluation

Maps showing the regional distribution of peak loads and energy requirements have been included. For the building morphology defined before, these maps represent averages of 6 different combinations of constructive and operational characteristics defined as follows:

Variation	Walls	Windows	Internal Gains (W/m²)
1	Reference wall without insulation	Single	30
2	Reference wall	Double	30
3	Reference wall	Double & Reflecting	30
4	Reference wall without insulation	Single	20
5	Reference wall	Double	20
6	Reference wall	Double & Reflecting	20

These maps are not extrapolation of the evaluation of the reference building, but have been calculated with the same detail in the reference building. The reference wall is the one defined in the figure 2. The maps will always represent averages of the above mentioned buildings combinations.

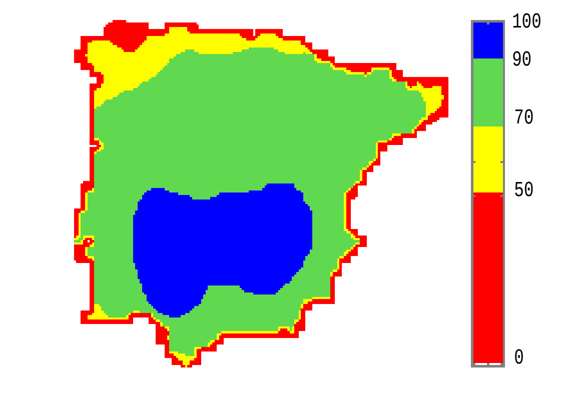
It can be seen that at regional level:

- Peak cooling is always higher than peak heating, although both variables are in the same order of magnitude.

- Cooling requirements are considerable higher than heating requirements, except in a small zone in the northwest of the Iberian peninsula where they are of the same order. Typically, it can be said than cooling requirements are about 5 times bigger than heating requirements. In synthesis, for 1 ach, cooling is dominant.

Next maps show the distribution of the average cooling and heating energy requirements for the office building simulated (all of then with a ventilation rate of 1 ach) within the Iberian Peninsula

Cooling (kW·h/m²) **Heating (kW·h/m²)**



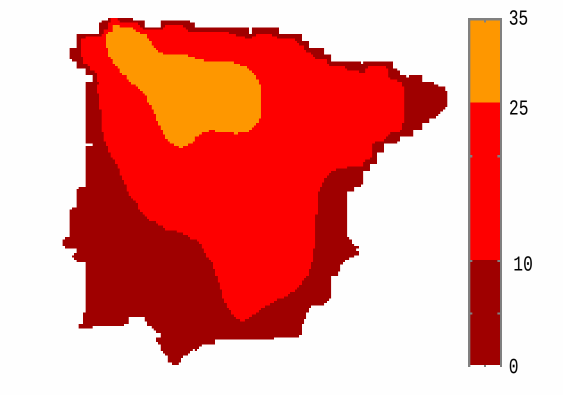


Figure 6:Iberian Peninsula maps of the average energy requirements for cooling and heating.

4. BUILDING ENERGY PERFORMANCE WITH DIFFERENT VENTILATION LEVELS

Equivalencies referred to the building:

ach	1	2	3	4	7.6	8.1
L/(s·occupant)	8.9	17.8	26.7	35.6	67.6	72.0
L/(s m^2)	0.89	1.78	2.67	3.56	6.76	7.20

Figure 7 represents the monthly distribution of the building (the whole building) sensible energy requirements with different ventilation levels for Madrid. It can be seen that the cooling requirement has been concentrated in the summer months cause the ventilation air during winter and intermediate months has became the cooling loads into heating loads.

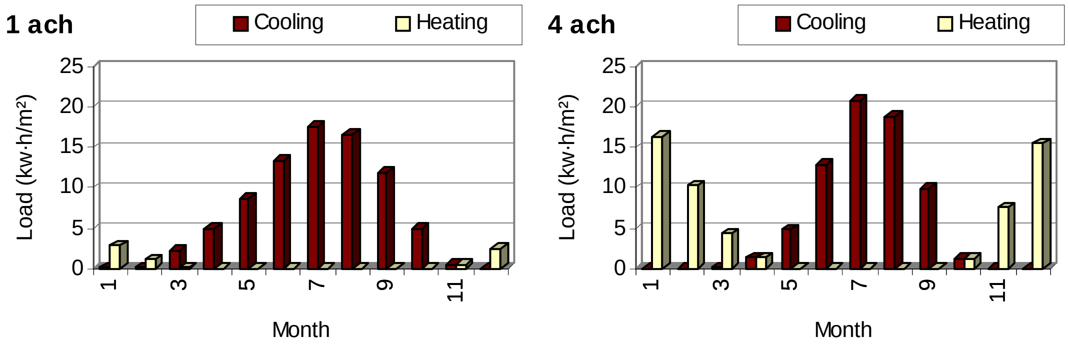


Figure 7: Monthly energy requirements (heating and cooling) for the whole building with different levels of ventilation in Madrid.

When the ventilation levels increase the overall values of energy cooling requirements remain almost unaltered. However the energy heating requirements do increase significantly with the ventilation levels. Next figures show these effect for Madrid and Porto. The difference between total and sensible cooling are not so important for Madrid, but is not negligible for Porto. So the high level of humidity in Porto is a very important factor.

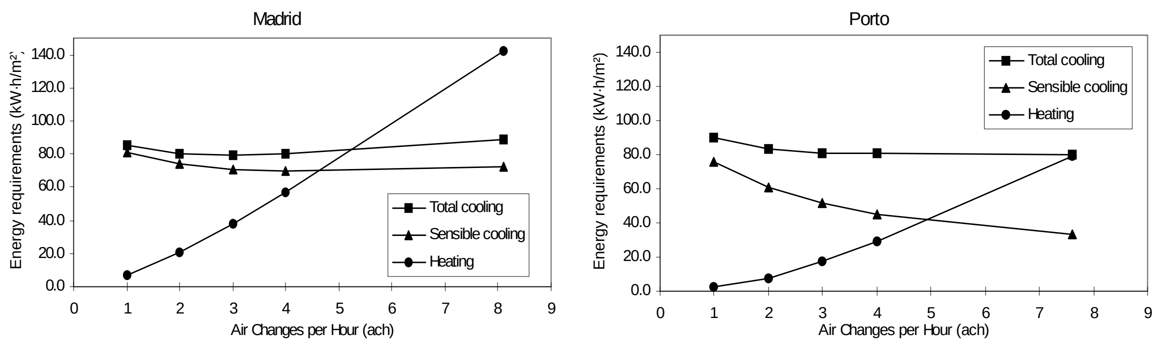


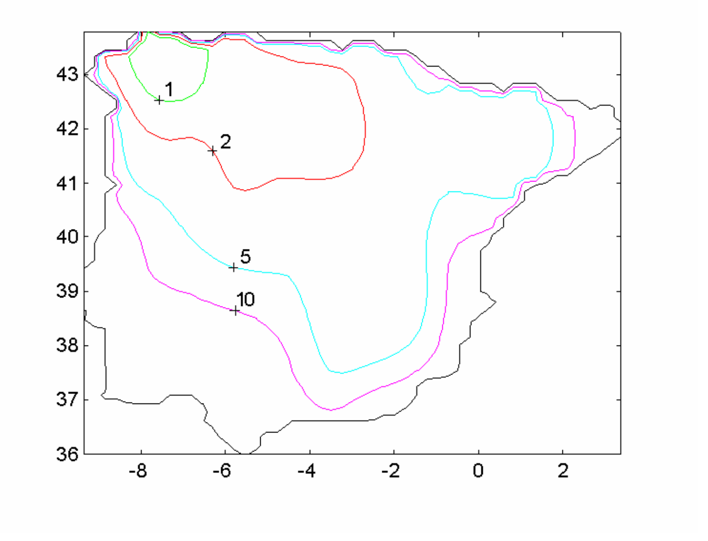
Figure 8: Energy requirements (cooling and heating) evolution with the ventilation level for Madrid and Porto

The peak cooling and heating load increase linearly with the ventilation level, but heating peak load grows more than cooling one.

When the ventilation rate increases, cooling requirement increases or decreases depending on the locations, but they do not change in a significant way in all the Iberian Peninsula. The comparison with the reference case show deviations of within ± 20% in all cases. This variation, positive or negative, is due to the presence of two combined contradictory effects: the cooling months decrease but the cooling requirements associated to each month increase. Heating requirements grows significantly when the ventilation rate increases. This is due to the increase in the number of heating months.

Comparison between cooling and heating requirements show that the zones with dominance of the cooling decrease in such a way that for 4 ach the heating and cooling dominance is split about 50%, as can be observed in the maps of the following figure

Ventilation: 1 ach



Ventilation: 4 ach

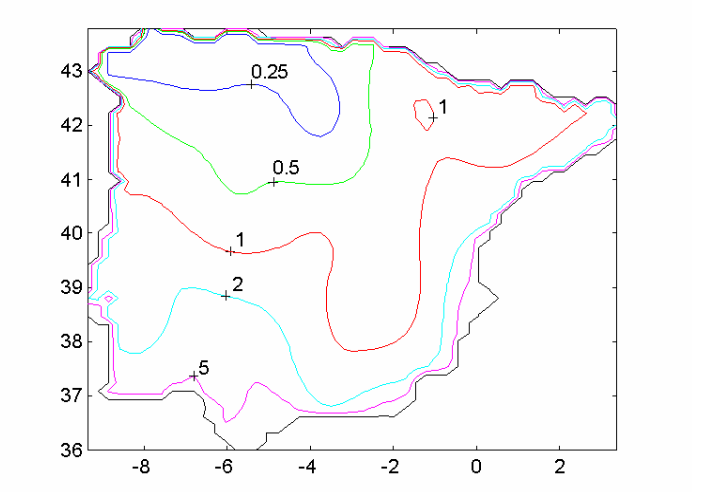


Figure 9: Ratio cooling to heating energy requirements for two levels of ventilation (1 ach & 4 ach)

6. EFFECT OF ENERGY SAVING STRATEGIES ON BUILDING ENERGY PERFORMANCE

6.1 Free-Cooling

The free cooling strategy reduces or neutralizes the cooling energy demands of the conditioned zone using outdoor air. Figure 10 shows the scheme of the air circuit used for the free cooling strategy simulation.

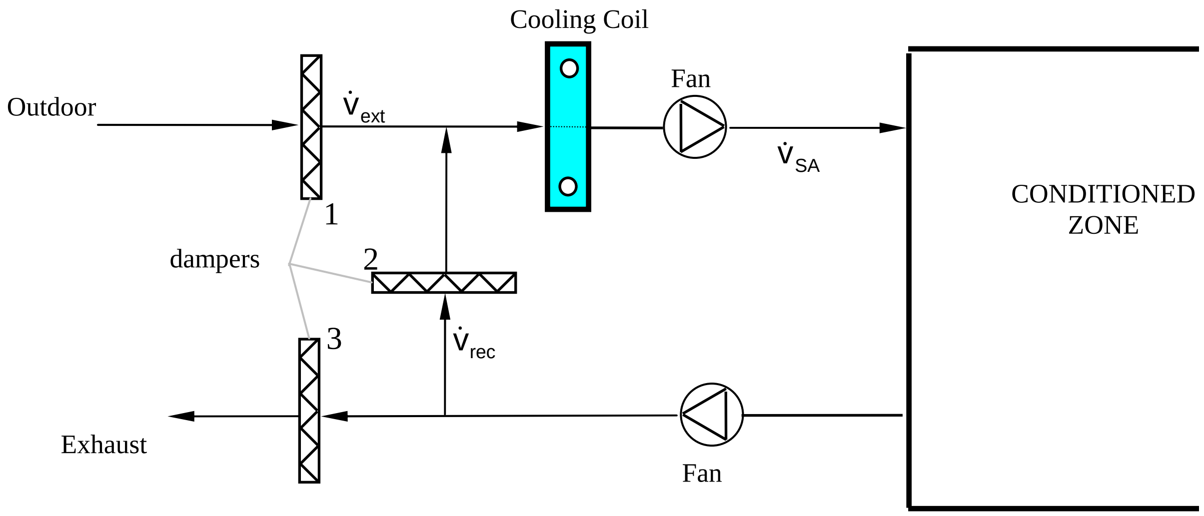


Figure 10: Scheme of the air circuit for free cooling

It is obvious that free cooling strategy only reduces the cooling requirements. Cooling peak has exactly the same value that the one described in the previous section, because in the moment in which the cooling peak occurs the exterior conditions don't allow the use of the free cooling strategy.

Two control schemes will be used for free cooling: temperature control (T) and enthalpy control (H). Table below shows the total and sensible cooling requirements without free cooling (without FC), with free cooling using temperature control (FC control T) and with free cooling using enthalpy control (FC control H) for the whole building, for the different ventilation levels.

The Energy saving has been defined as the percentage of reduction in the cooling energy requirements of the building using free-cooling compared with a reference situation with the same ventilation level but without free-cooling strategy. So, the energy savings depend on the ventilation level of the air conditioning system implemented in the building. When the supply air is all outdoor air (7.6 ach for Porto and 8.1 ach for Madrid), there is no possibility of performing free-cooling. Thus, the relative saving for these cases is zero.

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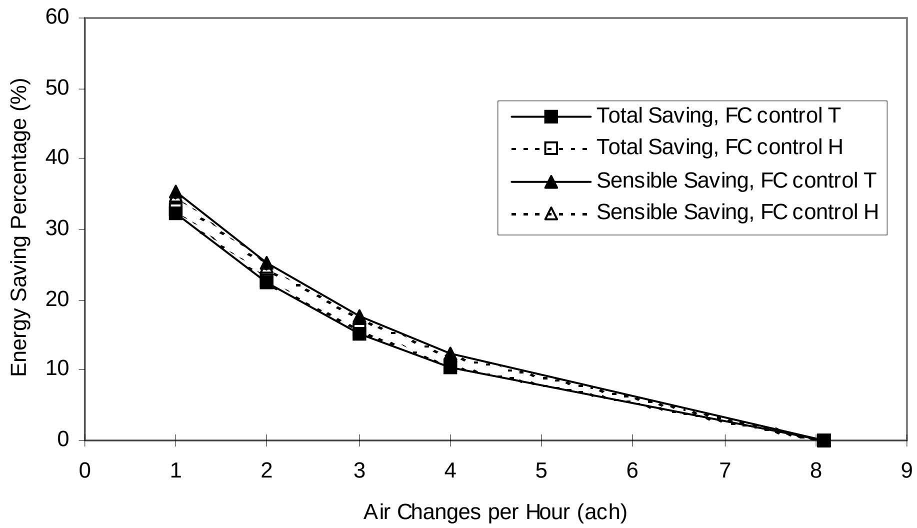

PORTO

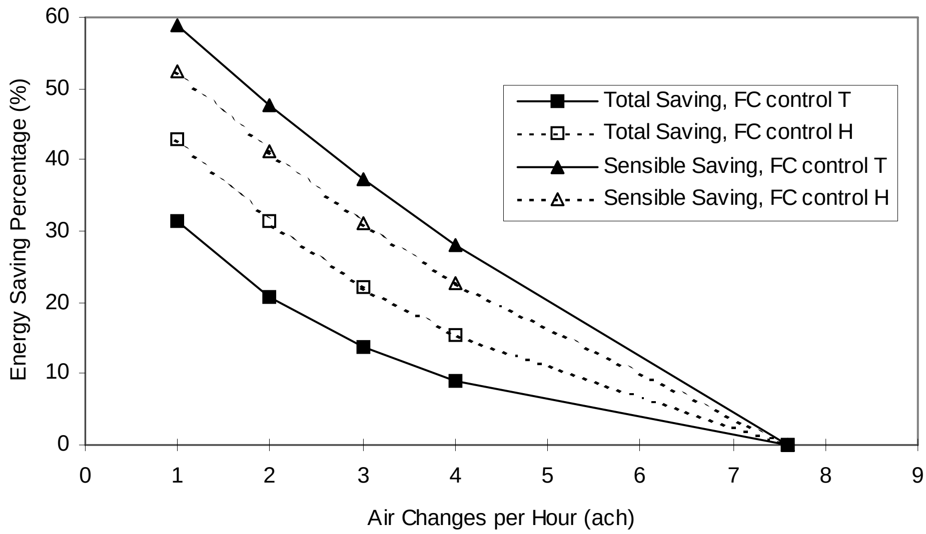

Figure 11: Total and sensible building cooling saving evolution with the ventilation level for different free cooling strategies in Madrid and Porto.

From the previous figure it can be concluded that:

- For Madrid there is basically no difference between temperature and enthalpy controls, but for Porto important differences can be found out.

- The cooling saving (total and sensible) without any free cooling strategy decrease with the ventilation level. This effect can be understood if we think that when the ventilation level increases the saving potential of the free cooling decreases, because the maximum air flow that can be used for the free cooling ($\dot{V}_{rec}$, see figure 10) decreases in relation with the ventilation air flow

- The free cooling saving is higher for Porto than for Madrid because Porto has much more hours with exterior free cooling conditions than Madrid.

- As it can be seen in figure 11 for Porto the use of the enthalpy control gives less sensible cooling saving than the use of control temperature. This is due to the fact that the numbers of hours in which the free cooling can be used is for the temperature control. However the total cooling saving are higher for enthalpy control, thus the better control in energy consumption terms is the enthalpy control.

Extrapolating the results to other locations it can noted that the energy savings associated to the use of free cooling are very climatic dependent and also exhibit a strong dependency on the ventilation rates. For instance, for 1 ach, there are zones of hot climate where the energy savings are in the range of 10 to 30%. For mild climate zones, the energy saving of the cooling requirements range between 70 to 90%.

As the ventilation rates increase, the energy savings decrease in such a way that for 4 ach in most of the Iberian peninsula they are below 30%. This is due to the displacement of the cooling requirements to the hotter months.

6.2. Air-to-air heat recovery devices

The purpose of the “energy exhaust air recuperation systems” is to pre-cool the ventilation air during the cooling regime and to preheat it during the heating regime using the exhaust air energy.

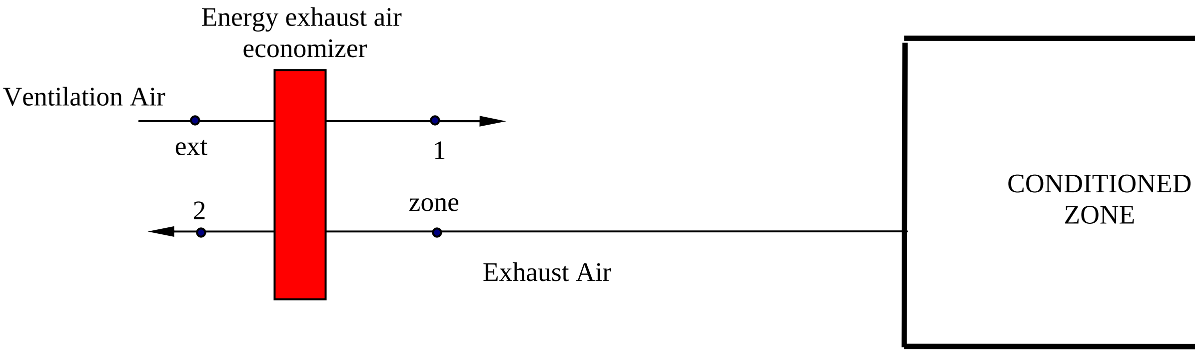

Figure 12: Scheme of the energy exhaust air recuperation

The energy exhaust air recovery (R) has been simulated assuming only sensible energy recovery. Thus, the latent requirements are the same with and without this recovery heat exchanger. It has been considered also a temperature efficiency (η) of the recovery system of about 0.45. (the minimum value prescribed by the Spanish regulations).

The values obtained with an hourly simulation has been plotted in figure 13. Analysis of these figures reveals that:

- The cooling and heating energy saving due to the use of energy exhaust air recovery increases with the ventilation level. The air flow in the recovery heat exchanger is the same that the ventilation air flow, therefore, the size of the recovery system increases with the ventilation level.

- The cooling energy saving is very low (more for Porto than for Madrid). This is logical if we think that free cooling and recovery are two non simultaneous strategies, thus, locations with high free-cooling potential has a low recuperation potential during the cooling season.

- Recovery in heating energy requirements are very important if the ventilation level is high.

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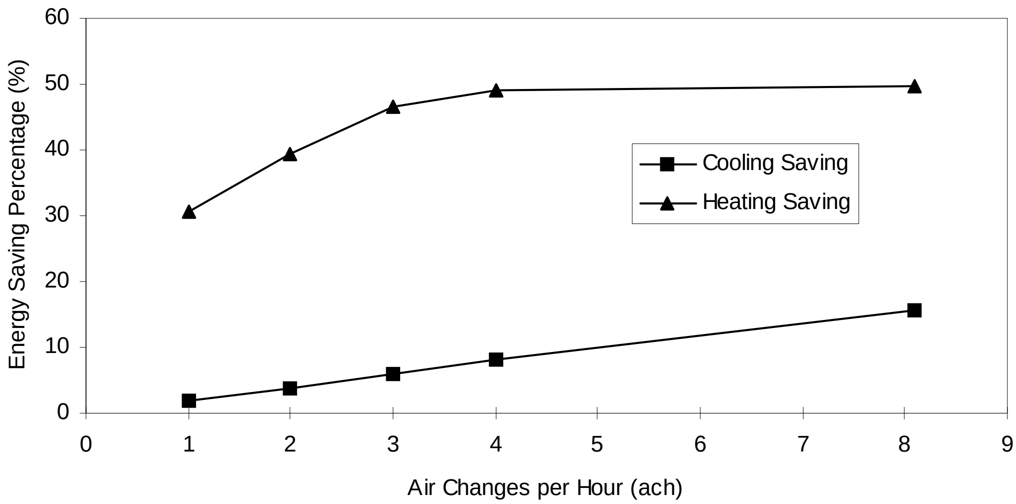

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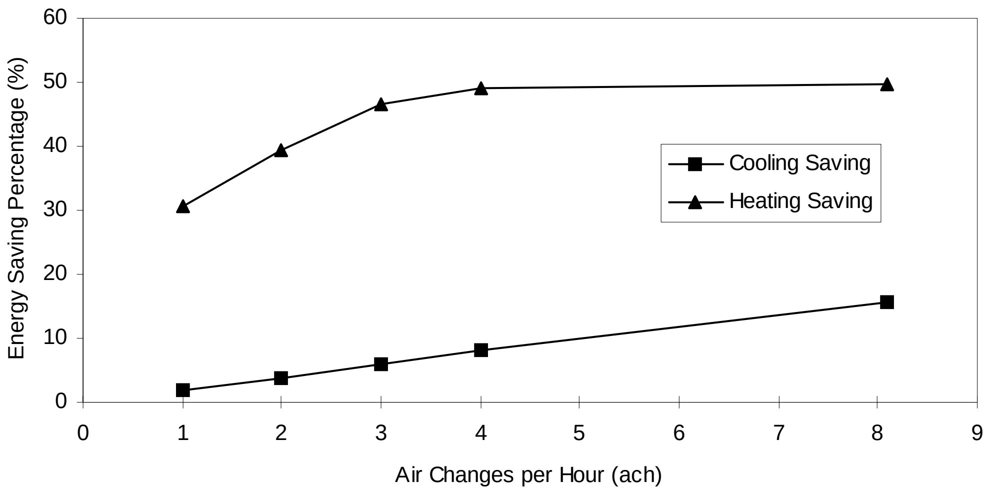

Figure 13: Energy (cooling and heating) building saving evolution with the ventilation level, for the energy exhaust air recuperation in Madrid and Porto.

The geographical extrapolation of the results reveals that:

- The energy savings linked to the use of heat recovery systems are very poor for the cooling regime in all cases.

- For the heating regime the energy savings in relative terms are always significant but, obviously, this technique will have a maximum interest (under a cost / benefit point of view) only in temperate or cold zones and specially in cases of high ventilation rates where the energy savings are, in a considerable region of the Iberian peninsula, higher than 30%.

Note: It has to be mentioned that the efficiency of the heat recovery device was 45%. For a different efficiency, the energy savings are proportional. For instance, if the efficiency were 70%, the energy savings would move from 30% to .7/.45 x 30% = 46.6%

6.3. Free-cooling plus air-to-air heat recovery

This section deals with the heating and cooling (total) energy requirements reduction when free cooling (temperature control has been selected for this section) and air-to-air heat recovery are applied alone or combined.

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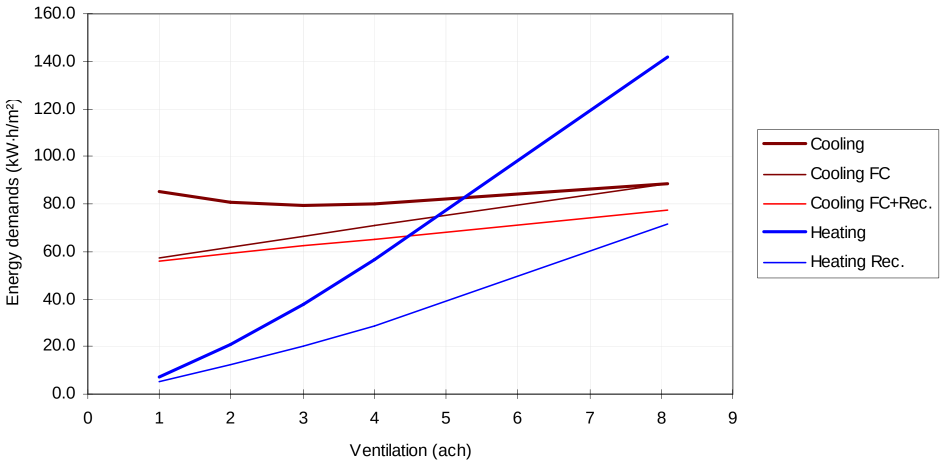

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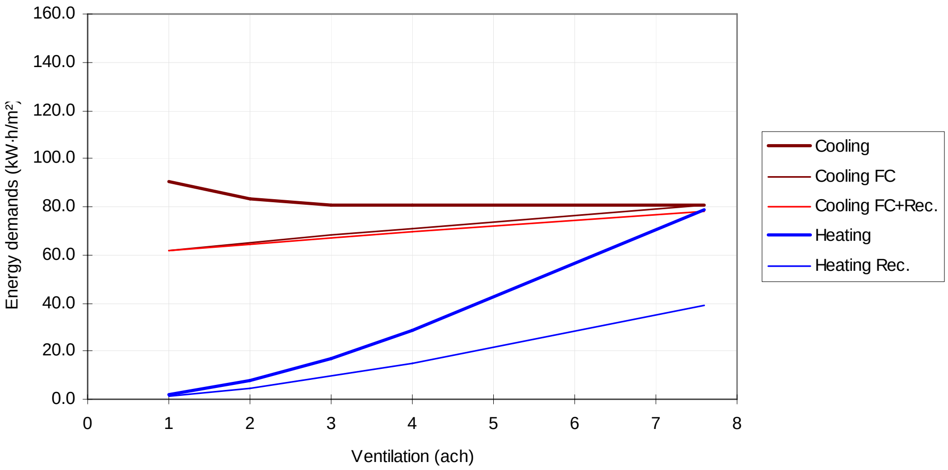

Figure 14: Annual energy (cooling and heating) building demands evolution with the ventilation level, with and without free-cooling (control T) and energy exhaust air recovery in Madrid and Porto.

The values obtained with the simulation has been graphed in the figure 14.It can be seen that:

- The cooling requirements have a light dependence with the ventilation rate. The cooling savings due to the free-cooling decreases with the ventilation rate and the cooling savings due to the heat recovery increases with the ventilation rate.

- The heating requirements have a strong dependence with the ventilation rate (more for Madrid than for Porto). The heating savings due to the heat recovery increases with the ventilation rate.

Following maps show the energy saving that may be defined as the overall energy requirements (cooling + heating) using free-cooling and air-to-air heat recovery divided by the overall energy requirements without free-cooling neither heat recovery

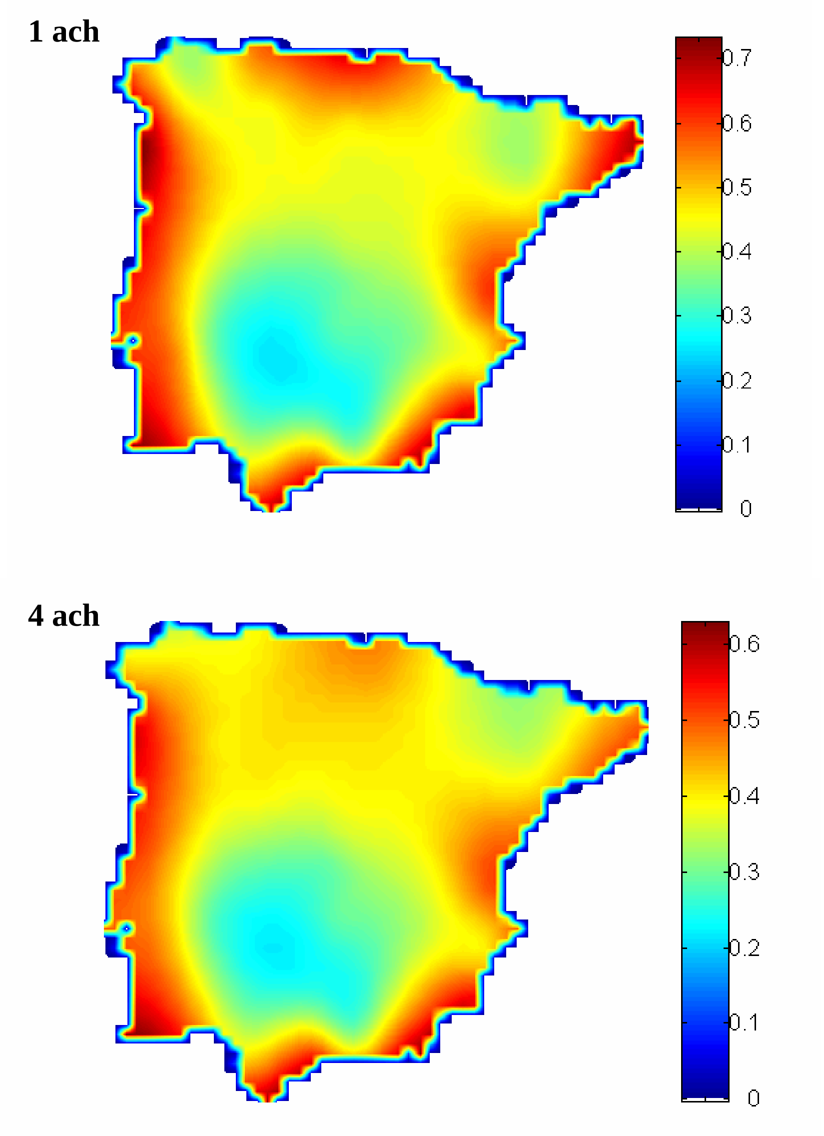

Figure 15: Total energy saving through the combination of free cooling and energy recovery device (1 & 4 ach)

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