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Auxiliary Environmental Control in Passively Cooled Buildings

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ABSTRACT. The need for auxiliary heating and cooling systems in European buildings is established on the basis of building physics and climatic conditions, emphasizing that cooling systems may not be needed in most regions if there are no large internal gains and the building envelope is well designed, through the use of bioclimatic design principles. Occupant attitudes and the consequences upon indoor environmental quality are also compared for the cases of actively and naturally controlled buildings. Ways to optimize the energy and functional efficiencies of mechanical cooling systems are then discussed, including the cooling-producing equipment, distribution networks and control strategies. Finally, the major difficulties that now exist in modelling, sizing and designing HVAC systems are also presented, pointing out some topics for future research and standardization.

1. INTRODUCTION

Auxiliary systems for indoor environmental control, from the simplest fireplace to the most sophisticated heating, ventilating and airconditioning computer-controlled system, are present in the vast majority of the building stock, whatever the type of, or the use for the buildings. Their need is seldom questioned, but the best type or size for a particular application is often debatable, especially when energy efficiency considerations come into play. This debate becomes more important in buildings where bioclimatic design procedures are adopted, as their dynamic thermal behaviour is usually more sensitive to interactions with any active control systems that might be functioning within it, particularly, once again, if it desired to take the most advantage of passive solar.

In this text, prior to discussing the auxiliary systems themselves and the critical issues that can now be raised in terms of their design and energy efficiency, the need for such systems will be critically evaluated or, better yet, bound by a set of objective parameters. Cooling will naturally receive most of the attention.

2. THE NEED FOR ADDITIONAL HEATING AND COOLING

Auxiliary energy inputs to an indoor space serve the purpose of keeping the indoor environment, i.e., temperature and, in some cases, humidity, within a range around desired setpoints. The amount of auxiliary energy needed at a certain moment is the balance of all the thermal exchanges from the building envelope to the indoor air and the magnitude of the available indoor heat sources, as shown in Fig.1 and eqn.(1):

$$\dot{Q}_{aux} = \dot{Q}_{ge} + \dot{Q}_{gi} + \dot{Q}_{gv} \qquad (1)$$

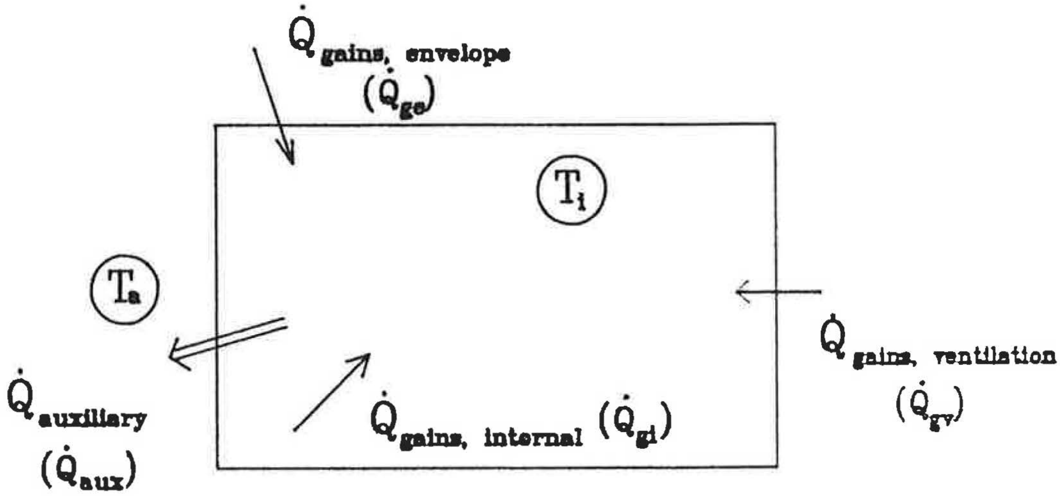

Fig.1 - Instantaneous Space Heat Balance

The two envelope terms ($\dot{Q}_{ge}$ and $\dot{Q}_{gv}$) can be either positive (gains) or negative (losses). If the gains exceed the losses cooling is required to maintain a constant indoor temperature T_i. Conversely, if losses exceed the gains, $\dot{Q}_{aux}$ becomes negative and heating is therefore required.

All these energy terms are dynamic in nature due to outdoor climatic influences and to interactions with thermal storage in the building mass, as will be discussed later on with more detail. But it is useful to also analyze the heat balance in terms of integrated means over a sufficiently long period of time, as this will allow a meaningfull insight towards establishing the need of auxiliary energy systems. Indeed, the ultimate aim of bioclimatic design is the "zero energy" house, i.e., a house where no auxiliary energy would be needed. Then, realizing that

$$Q_{gv} = V \rho C_p \; (T_a - T_i) \qquad (2)$$

eqn.(1) can be rewritten in terms of the mean indoor temperature that can be naturally obtained if no auxiliary energy is available:

$$T_i = T_a + \frac{Q_{gi} + Q_{ge}}{V \rho C_p} \qquad (3)$$

If buildings are massive, indoor thermal storage ensures that T_i is relatively constant during a certain period, slowly evolving towards new average values as the intensity of the Q_{gi} and Q_{ge} terms changes. Conversely, the absence of a significant amount of thermal mass will result in important fluctuations of the indoor environment.

Eqn.(3) shows that the mean indoor temperature is always higher than the mean outdoor ambient temperature, because Q_{gi} is always positive and

Q_{ge}, in the absence of passive or active refrigeration systems, is either positive or, in the limiting case, zero: absence of solar gains and $T_i = T_a$ (Q_{ge} can only be negative if, through refrigeration, $T_i < T_a$). This fact leads to a first, very important distinction between auxiliary heating and auxiliary cooling:

- Nowhere in continental Europe, the warmer southern Mediterranean zones included, is the mean outdoor temperature sufficiently close to the comfort zone (18-22°C) during the colder periods in winter [1] to avoid the need of auxiliary heating systems.

  Heating could only be avoided in the presence of a very large (Q_{ge} + Q_{gi}) term, which is not practical most of the time.

  Of course, going towards lower latitudes, outside Europe, there are regions where the mean outdoor temperature is close to or within the comfort range, In those regions, auxiliary systems can then be avoided if bioclimatic design principles are successfuly adopted.

- Conversely, in most regions in continental Europe the mean outdoor temperatures never reach the comfort zone (24-26°C) during the warmer summer periods [1]. This range is approched or surpassed only in a narrow region along the southern Mediterranean coastal line. In the most northern regions, temperatures are even too low to even approach the 24-26°C range unless high internal or solar gains are available.

  Therefore, in most of Europe, it is possible to design buildings that, in the absence of significant internal loads, may naturally reach indoor comfort during summer without any auxiliary mechanical devices. Of course, the envelope loads must be small and sufficient thermal inertia must be present to ensure that the indoor temperature remains relatively constant and close to the previously defined comfortable mean.

  If the outdoor climate is too humid, auxiliary systems for environmental control shall also be necessary.

So, while heating systems are recognized as unconditionally necessary anywhere in Europe, refrigeration systems must be critically looked at in most places and, in general, they should be avoided.

There is, of course, a major assumption in this conclusion: even with sufficient indoor thermal inertia, temperature fluctuations, most of the time of the same order of magnitude as achieved with active controlled systems, but sometimes a little larger, will be present. Moreover, during sequences of hot days, when the mean outdoor temperature approaches or reaches the 24-26°C range, the indoor temperature may reach or even go slightly above the accepted higher limits of the comfort range. A tollerance for such fluctuations must thus exist. If precise indoor environmental control is demanded at all times, then it will be very difficult, maybe even impossible, to avoid mechanical refrigeration. It is a matter of mental attitude, but it is also a matter of balancing a short and small incovenience with the substancial savings that result from not installing and operating such mechanical systems. This tollerance can anyhow be paralleled with the acceptance of larger fluctuations in indoor temperature during the heating season in passive solar buildings, which are widely described as acceptable by their occupants - e.g., most buildings in CEC's project Monitor brochure series [2].

It is also necessary to realize that active cooling systems are not always problem-free. Indoor air quality has received a lot of attention in the recent years due to problems such as Sick Building Syndrome, Building-Related Illness, Legionnaire's Disease, etc. [3-4]. One must then wonder if, once again, a small dose of thermal discomfort in naturally ventilated buildings might not be a better alternative to buildings that are more precisely controlled by forced-air environmental systems that may exactly be the main source of those problems: e.g., Fanger and his coworkers established that the systems themselves may contribute with a major portion of the indoor air pollution sources in many buildings [5]. Although these problems can be overcome through good design and maintenance, and by supplying appropriate levels of fresh air to the spaces, all these measures are costly and indicate that mechanical cooling should be used only when the internal loads are too intense and the building would otherwise be uncomfortable without refrigeration.

As a last idea on this topic, the concept of zoning the building can be used as a last resort to separate spaces where the temperature must be precisely controlled from those where fluctuations are tollerable [6]. Smaller mechanical systems are therefore possible for the more demanding spaces, while the others can be designed for free-floating regime.

3. THE SIZE OF AUXILIARY COOLING SYSTEMS

When auxiliary cooling systems are needed, as discussed in the previous section, then its size should be reduced to the absolute possible minimum to ensure energy conservation. This reduction should be made both in terms of peak needs (installed power) and integrated seasonal needs (energy consumption).

The major responsibility for accomplishing these objectives lies with the architect, because, as shown by eqn.(1), the term that can be better controlled is Q_{ge}, i.e., the gains through the envelope. The internal and ventilation gains, Q_{gi} and Q_{gv}, respectively, are mostly imposed by the types of activities and occupancy that occur inside the building. The only exception is the lighting component, where, once more, an intelligent design of the envelope to provide sufficient daylighting can substantially reduce electrical lighting needs [7]. In parallel, the electrical design must also be carefully thought of, to take full advantage of daylighting, turning on electrical power only as strictly required to provide the desired illumination levels, making use of concepts such as task lighting and continuous illumination level control, as opposed to general lighting and on/off switching [8].

To reduce the gains through the envelope, the architect should follow a checklist that includes:

. building form and orientation;
. envelope insulation;
. use of light colours, particularly in the roof;
. glazing area and orientation (east and west should be reduced to a minimum);
. efficient (total) shading of all glazings, preferably from the outside.

Shading can be, if necessary, combined with tinted or reflective glass to achieve the mandatory low values of shading coefficient in each glazing.

The most critical of all these items is, no doubt, the last one.

Solar gains, if significant, are the major contributor to the envelope gains and, often, unshaded or badly shaded glazings lead to total loads that conventional air-conditioning systems cannot satisfactorily handle, particularly in small spaces.

Peak installed power can be further reduced if massive construction is adopted. Mass introduces a larger delay factor in heat conduction through the envelope, and delays the release of solar and internal gains to the indoor air towards later in the day, thereby offsetting part of the load towards hours with a lesser load and contributing to a flater load diagram. Fig.2 shows such an example, for solar gains through unshaded SW glass on July 21st at 40ºN latitude, for buildings with low and high inertia [9].

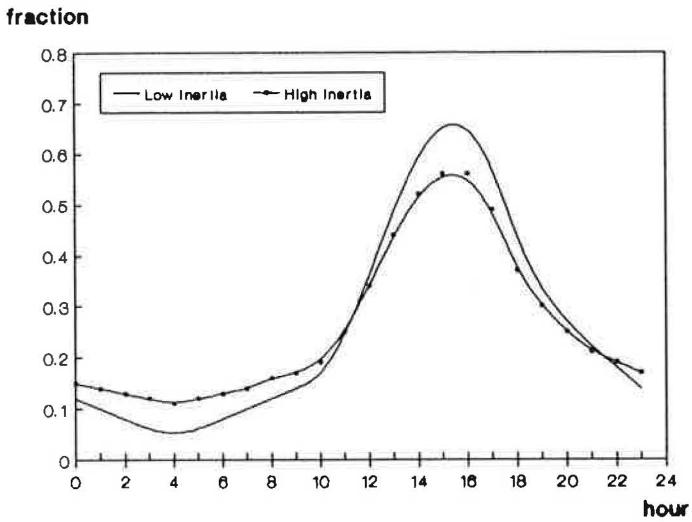

Fig.2 - Air-conditioning load from unshaded SW glazings [9].

In addition to a reduction in the size of the installed HVAC equipment, these will operate, on average, closer to peak power, thereby also ensuring a better efficiency. Both these effects may contribute to significant savings over the life of the system.

In retrospect, by comparing the concepts described in this and in the previous sections, it is possible to conclude that the measures that can achieve a smaller, more energy-efficent air-conditioning system are basically the same as those described for trying to design buildings that do not need air-conditioning: load-avoidance and internal mass. These two major guiding principles cannot be overemphasized, and they must be ingrained into the design process of every architect, at least for building design in the warmer, southern European regions.

Once all these "passive" measures to reduce the size of, or ultimately eliminate, the airconditioning system have been taken, it is the job of the systems´ designer to reach an energy and cost-efficient solution for that building. A number of sistems´ related issues will be dealt with in the next section, but one that concerns itself directly with system size shall be addressed first: oversizing. As a rule, to take uncertainties and a limited expansion capability into consideration, designers have a tendency to oversize the installed power of the HVAC system. This invariably leads to a reduction of the average energy-efficiency of the system over the cooling season, because the equipment will be operating on a yet smaller part-load mode. This tendency should be fought, e.g. through standardization of load-calculating procedures which would limit the designers´ options and responsibility, and through normative rulings that would place legal limits on the amount of allowable oversizing. Otherwise, the reduction accomplished by careful architectural design may be partly or totally wiped out by a bad systems´ design.

4. THE DESIGN OF AIR-CONDITIONING SYSTEMS

The energy and functional efficiencies of an HVAC system depend on details that go beyond its size, as discussed in the previous section. These factors can be grouped into three main categories:

a) Cooling equipment COP - Identical amounts of delivered energy can be produced with different amounts of primary energy. The COP of refrigeration machines can vary in a relatively wide range, depending on the quality of manufacturing and the type of refrigeration cycle used (e.g., single or multiple stage vapor-compression or absorption cycles with different refrigerant mixtures) [10]. In addition, absorption cycles, even if with a lower COP, may consume less primary energy if heat can be produced from a low-grade source. Conversely, the compression work required by the other type of cycle is generally produced with low efficiency.

The rated COP of every equipment is based on steady-state full-power periods. During start-up, and during part-load operation, when the equipment cycles on and off, the operating COP may be significantly lower. It is thus imperative to maximize the average seasonal COP of the refrigeration equipment by trying to reduce part-load and cycling. To achieve these objectives, there are two relatively easy and cost-effective measures that can be adopted in systems´ design:

- ice or cold water storage tanks can allow sizing the refrigeration equipment for a smaller peak power, allowing for the storage system to supply the peak needs from energy produced during the periods when requirements are smaller.
  The disavantage of this solution is the large size and cost of the storage tank. As a compromise, a smaller size storage tank can act as buffer, supplying the building loads and being recharged by the refrigeration equipment, but guaranteeing minimum consecutive operating periods that ensure high COPs. In this latter case, peak installed power will be the same as without storage.

- total refrigeration power can be divided into stages, such that only the needed power is switched on, for a longer period, once again resulting in higher COPs.

The cost-effectiveness of these measures increases with size, which reduces their potential use when consciencious architectural design is present, as it should. As the loads decrease, there are less savings to compensate the required investments and payback periods increase. So, another important consequence of sound thermal architectural design is the simplification of the most appropriate HVAC system for a particular building.

Finally, one note to stress that refrigerating equipment has been undergoing in recent times a major change to replace ozone-harming refrigerants by other more suitable alternatives. Although these changes may result in lower COPs in the short term, it is a price worth paying and, in the long run, COPs are expected to once again equal those that were previously available.

b) Ventilation - Fresh air for providing adequate indoor air quality is figured into the calculation of the needed system power. This total may however be misleading if the fresh air distribution inside the building is not well designed, i.e., if the fresh air is not circulated through where it is really needed. This concerns, first, the distribution amongst the various spaces inside the building, and, second, the distribution within each space.

If the distribution among the various spaces is not proportional to the real needs - as often occurs, because supply air is proportional to design loads in constant flowrate systems and to actual loads in VAV systems - indoor air quality is affected where not enough fresh air is supplied. To correct this, the occupants or the systems' troubleshooter usually increase fresh air supply rates to the whole building, with the ensuing increase in energy consumption [11].

Within each space, supply and exhaust grilles must be conveniently selected to ensure that the fresh air goes through the occupied space, i.e., the portion of the space where occupants really are: from the floor up to a height of about 2m. This is best characterized by the concept of "Ventilation Effectiveness" [12,13]. Once again, a low ventilation effectiveness will result in the bypass of a large portion of the supply air directly to the exhaust grilles. Thus, to ensure thermal comfort and indoor air quality, either the air supply is increased, or the room thermostat is set at a lower temperature in summer, or both.

Operating costs can also be reduced if the fresh air intake is circulated through an energy recovery system. These systems are generally cost-effective in winter, but may be too costly just for summer.

c) Control - A bad control strategy can completely destroy any savings that may be achieved through all the previously discussed measures. Modern techniques based on microprocessors can, on the other hand, optimize systems operations and significantly improve overall efficiency. Issues such as optimized ventilation control, proportional to real occupancy needs [14], optimized economizer cycle to make the best possible use of free-cooling whenever cool outside air is available [15], optimized use of the thermal inertia, switching the system on an off before occupancy starts and ends to dilute start-up peaks and to take advantage of stored energy at day-end [16], thermal storage "loading" along predicted needs for heating or cooling as a function of weather forecasts [17], optimized lighting control for taking full advantage of daylighting, load management, etc., can be integrated into packages that may be very cost-effective particularly in large buildings [18]. While this could be described as what is commonly called "intelligent building" technology, it does not have to be carried to the limit, and simpler controls can be thought of for simpler applications where all these functions would not be needed nor desired.

In the context of sections 2 and 3, it is fair to stress that control strategies that try to optimize the interaction between thermal inertia and the HVAC system should receive carefull consideration. Thus, free-cooling (economizer cycle) and start-up and shut-down times for daytime only systems are very important factors in the design of the system.

These topics tried to describe how the mechanical systems' designer also plays a decisive role upon the energy performance of a building, when architectural measures, by themselves, cannot guarantee indoor comfort during summer.

5. THE MAIN OBSTACLES TO SUCCESSFUL DESIGNS

The sequential design process that was sketched in the previous sections has two main phases:

- Architectural design, leading to the final decision whether auxiliary heating and cooling systems are necessary;
- Systems design, when systems have been recognized as necessary for a particular building.

There are major hurdles that need to be overcome in each of the two phases.

First and foremost, the architect and the whole design team must be aware of building physics and of the consequences that their decisions may have upon the thermal performance of the building. They must be knowledgeable and must consciously desire to reduce the loads and do without additional cooling. This calls for further emphasis on education, both in the architectural schools and through technology transfer programs directed at practicing professionals.

Once past this first hurdle, others more technical in nature come up. The most important among these is, no doubt, the lack of appropriate friendly tools to evaluate architectural designs in terms of their thermal behaviour. Most of the available tools are not directed towards helping the designer decide whether an auxiliary system is needed or not. They are either too simple and thus of little help in this respect, or they are quite sophisticated, more like research tools, requiring a significant effort to master, and they cannot, therefore, be legitimately expected to be adopted as tools by even the best practicing designers. Moreover, the choice of which software to use is not clear for most people, as the results from the best known programs often disagree for the same cases [19].

An appropriate tool must clearly establish whether overheating will or will not be present, and the magnitude and frequency of the overheating in case it is present, and it must be simple to use. It must do so by simulation with either real or simulated weather data, or draw upon simpler heat balances of the spaces that must neverthless take inertia into account. These analyses must, in any case, be carried out in a nonsteady mode, because buildings without auxiliary systems operate in a free-floating regime. This unsteady mode of operation is inherently more difficult to simulate than when building are thermostatically controlled, because thermal mass is always difficult to model:

- When models rely on detailed simulation techniques based on nodal networks, e.g., ESP, thermal mass usually requires large numbers of nodes that complicate the model and lengthen the time necessary to obtain a solution;
- When models rely on transfer-functions or weighting factors like DOE or TRNSYS, there are no readily available transfer functions or weighting factors for heavy construction such as is typical in southern Europe. This limitation leads to load overestimation in the

simpler case of calculating heating and cooling loads in heavy buildings under thermostatic control, but it is almost unsurmountable if the building environment is in a free-floating regime.

This situation must be reversed, so that designers can be confident that their design will provide comfort without air-conditioning, or that they are able to define the right size HVAC system when it is deemed to be necessary. Lacking this certainty, designers will protect themselves and install HVAC systems even if they are not really needed. In many instances, they will even oversize them to be sure that there will be no complaints once the building is commissioned.

In the second phase, to design efficient HVAC systems, a major difficulty lies once again with the interaction with the building mass, i.e., with selecting the best control strategy to take full advantage of the peak load reducing capabilities of the thermal mass. If air-conditioning does not operate 24-hours a day, mass can also reduce total energy consumption if natural ventilation or forced air free-cooling are figured into the control strategy. Once again, this process is enhanced by simulation, and the same difficulties previously described in this section apply whenever mass comes into play.

There is clearly a need for models that may better describe the interaction between massive buildings and HVAC systems. Conversely, for light buildings and for the different parts of the mechanical systems, there is software capable of accurately predicting their performance, including features such as storage, equipment response, controls, etc. The most difficult aspects to model in those programs relate to air circulation. Issues such as ventilation effectiveness and air circulation inside enclosed spaces, stratification (particularly in spaces with high ceilings), infiltration and natural ventilation continue to be handled on a still very empiric basis. These are topics that still need further research to be incorporated on a more scientific basis into HVAC models and simulation codes, as well as into the design routines of practicing professionals.

6. CONCLUSIONS

The major points that were established in the previous sections can be summarized as follows:

1 - While auxiliary heating is generally necessary everywhere in Europe, auxiliary cooling may only be necessary in the warmest regions of southern Europe and when large internal loads exists as long as bioclimatic architectural design is adopted;

2 - The size of auxiliary cooling systems should be kept to a minimum;

3 - Auxiliary cooling systems design must be optimized to obtain an acceptable energy efficiency;

4 - The more successful the architect is in reducing loads, the more difficult it is to justify HVAC system sophistication;

5 - The main barrier to successful design of passively cooled buildings is the lack of simple design tools that designers can use to be certain that no cooling system is necessary;

6 - The simulation of thermal mass behaviour and the interaction with the indoor environment and with any existing HVAC systems need significant improvements.

Without this, the current tendency for increased energy consumption due to airconditioning use during the summer months will intensify [20]. The number of air-conditioning systems being installed is increasing rapidly, and this trend needs to be reversed. It has already changed the electrical consumption peak from winter to summer in many regions, and is about to do so in many others.

Passive cooling strategies, particularly in the early stages of architectural design, can significantly contribute to slowing or even reversing this situation, and an effort towards this goal should be a top priority, especially for southern European countries.

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