AIR-CONDITIONING: ENERGY CONSUMPTION AND ENVIRONMENTAL QUALITY

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Contents

Summary

The article discusses some major steps in the design of air-conditioning installations. It considers the existing penetration of air-condition equipment and the major characteristics of the market, and discusses the impact of urbanization on the cooling demand of buildings. It focuses in particular on the impact of temperature increase of cities on the cooling load of urban buildings, the increased peak electricity load, and the decrease in the efficiency of air-conditioning. The problem of appropriate climatic data for design is raised. The third part of the article presents strategies to decrease or eliminate the cooling load of buildings. These techniques, known as passive cooling techniques, are mainly based on solar control and heat avoidance methods, amortization of heat load techniques, and heat dissipation techniques. The results of applying these techniques in buildings are given. Another part of the article discusses possible improvements in the technology of room air-conditioners as well as expected improvements in their efficiency

The last part of the article discusses possible solutions to be considered during the rehabilitation of buildings. Existing case studies are presented. Techniques to reduce the cooling load of the building as well as their energy conservation potential are presented.

In parallel, possible rehabilitation techniques to improve the efficiency of HVAC systems in different types of buildings are presented.

1. Introduction

The development in the 1930s of inexpensive, reliable, Carnot cycle refrigeration systems, using electrically driven compressors, has made cooling widely feasible. During recent decades, air-conditioning has become widespread in residential and commercial constructions. Annual purchases of air-conditioning equipment had exceeded the $20 billion mark by the end of the 1980s (Predicasts, 1987), while the world trade in air-conditioning and industrial refrigeration equipment more than tripled in real terms from 1976 to 1985 (United Nations, 1985).

The increase of family income in Europe and elsewhere has made the use of air-conditioning systems highly popular. Annual purchases of air-conditioners in Greece have increased approximately 900 percent during the last four years, while sales of air-conditioners in Italy, Spain, and Portugal have risen similarly (Santamouris, 1990).

The impact of air-conditioner usage on electricity demand is a serious problem for many developed countries. Peak electricity loads oblige utilities to build additional power plants in order to satisfy the demand, thus increasing the average cost of electricity. This has become a serious problem for many European countries (Santamouris, 1991), as well as for the United States, where the total electric peak load induced by air-conditioning is estimated to be equal to 38 percent of the non-coincident peak load (Adrews, 1987).

This article discusses some major aspects of the use of air-conditioning installations. Section 2 of the article discusses the needs for air-conditioning and ways to reduce the energy consumption of buildings for cooling purposes, Section 3 discusses the existing penetration of air-conditioning equipment mainly in Europe and the major characteristics of the market. The third part discusses the impact of urbanization on the cooling demand of buildings.

In Section 4, the impact of temperature increase of cities on the cooling load of urban buildings, and the increased peak electricity load, as well as the decreased efficiency of air-conditioning are discussed, and the problem of appropriate climatic data for design is raised. Section 5 discusses possible improvements in the technology of room air-conditioners as well the expected improvements in their efficiency, and the main aspects of demand size management techniques. The later sections discuss aspects related to the mechanical and natural ventilation of buildings and its impact on the energy efficiency of buildings and indoor air quality.

Finally, the very last part of the article discusses possible solutions to be considered during the rehabilitation of buildings. Existing case studies are presented. Techniques to reduce the cooling load of the building as well as their energy conservation potential are presented. In parallel, possible rehabilitation techniques to improve the efficiency of the HVAC systems in different types of buildings are presented.

2. Techniques to Reduce the Use of Air-Conditioning

The environmental quality of indoor spaces is the result of a compromise between the building physics applied during the design of the building, energy consumption, and outdoor conditions. Indoor environmental quality can be seen as a combination of acceptable indoor air quality together with satisfactory thermal, visual, and acoustic comfort conditions.

Although indoor air quality is almost a direct function of the outdoor environmental quality, comfort in general is a more complex notion dealing with the physiological and psychological well-being of the inhabitants, and not necessarily the result of some thermal and visual parameters. The interrelation of all parameters defining indoor environmental quality seen from a "systemic" view permits us to describe and better understand the complexity of the procedures taking place in a building. According to such a view, the outdoor environment (forming a subsystem of the whole system-building) determines its stability and offers the inputs that define the epistemological and praxeological spaces of the inhabitant as well as of the buildings control. Actions decided and executed either under the form of natural control of the occupants, or the technical control of an intelligence system, can be seen as the functional and structural adaptation of the system-building to the inputs coming from the outdoor subsystem. Addressing successful solutions to counterbalance the effects of increased energy consumption for cooling in buildings is a necessary condition for the future. Possible solutions involve amongst others:

- The improvement of the ambient microclimate in the urban environment involving the use of more appropriate materials, increased use of green areas, use of cool sinks for heat dissipation, appropriate layout of urban canopies, and so on, to counterbalance the effects of temperature increase.
- The adaptation of buildings to the specific environmental conditions of cities in order to efficiently incorporate solar and energy saving measures, and counterbalance the radical changes and transformations of the radiative, thermal, moisture, and aerodynamic characteristics of the urban environment. This incorporates appropriate sizing and placing of the building openings to enhance airflow and natural ventilation, and use of passive cooling techniques to decrease cooling energy consumption and improve thermal comfort.
- The use of advanced air-conditioning equipment for individual buildings designed to operate optimally in urban conditions. This involves systems with optimized COP curves for the specific temperature and humidity conditions, systems using advanced inverters, intelligent control, and so on.
- The use of centralized or semi-centralized production, management, and distribution cooling networks (district cooling), together with the use of demand side management actions such as local or remote cycling.

None of the above can be seen as isolated areas of concern. The interrelated nature of the parameters defining the efficiency of the performance of buildings during the summer requires that practical actions undertaken at the various levels should be part of an integrated approach.

2.1. Passive Cooling Techniques

In particular, application of passive cooling techniques in buildings has been proved to be extremely effective and can contribute highly to decrease the cooling load of buildings. These techniques can be classified in three main categories:

- Techniques that aim to protect the building from solar radiation and prevent ambient heat. Protection from heat gains may involve the following measures: landscaping, and the use of outdoor and semi-outdoor spaces, building form, layout and external finishing, solar control and shading of building surfaces, thermal insulation, control of internal gains, and so on.
- Techniques aiming to modulate heat gains. Modulation of heat gain has to do with the capacity for heat storage in the building structure. This delay strategy can provide attenuation of peaks in cooling load and modulation of internal temperature with heat discharge at a later time. The larger the swings in outdoor temperature are, the more important the effect of such storage capacity is. The cycle of heat storage and discharge must be combined with means of heat dissipation, so that the discharge phase does not add to overheating.
- Heat dissipation techniques. These techniques deal with the potential for disposal of excess heat by natural means. Dissipation of the excess heat depends on two main conditions: first, the availability of an appropriate environmental heat sink for the heat to be rejected, and second, the appropriate thermal coupling and sufficient temperature differences for the transfers of heat from indoor spaces to sink. The main processes of heat dissipation techniques are radiative cooling using as heat sink the sky, evaporative cooling using as sink the air and water, convective cooling, using as sink the air and ground cooling based on the use of the soil. Heat dissipation techniques are generally climate dependent. Mechanical devices may assist heat transfer as a means of overcoming low temperature differences or other limitations.

Recent developments achieved through the PASCOOL research project of the Commission have permitted the development of appropriate systems and techniques ready to be applied in buildings. The PASCOOL research project of the European Community, aimed to develop techniques, tools, and design guidelines in order to promote passive cooling applications in buildings. The project is based on an extensive experimental program that has allowed us to better understand phenomena related to passive cooling processes in buildings. The major results of the program include:

- Experimentally validated tools describing natural ventilation conditions in buildings like the multizone air flow model PASSPORT-Air and the CP-Calc method to predict pressure coefficients around buildings.
- Thermal comfort assessments and criteria as presented in the previous section.
- Experimentally validated solar control algorithms.
- Experimental and theoretical studies and algorithms describing the role of thermal mass in free running and air-conditioned buildings as well as to predict the impact of night cooling techniques as a function of thermal mass.
- A validated version of the PC simulation tool Passport Plus including algorithms for natural ventilation, solar control and comfort.

- Algorithms and tools to assess the cooling potential of natural cooling techniques (evaporative, radiative, ground coupled), and a European Atlas on the potential of natural cooling techniques in southern Europe.
- Test Reference Summer climatic files for selected South European locations.
- A design handbook including all the developed guidelines.
- A computerized handbook to provide on line help and information during the design stage.

Although the results achieved by PASCOOL are very important and produce a first significant advance to passive cooling in Europe, serious further work needs to be done towards the better understanding of comfort and energy related phenomena during summer in buildings. Research efforts should focus on the development of appropriate comfort criteria and models for summer under transient conditions, as well as on the application of passive cooling techniques in urban environments. Aspects related to micro climate and urban climates are extremely important and determine energy consumption for cooling purposes. At the same time, the results of the European "ZEPHYR" competition, focusing on passive cooling applications in buildings, have shown that there is a very serious need for simple design tools and information and dissemination procedures concerning the application of passive cooling techniques in buildings.

Where passive techniques are being considered as alternatives to air-conditioning the following are some of the primary benefits:

- Environmental benefits. There are important indirect environmental benefits associated with the reduction of the CFCs, and the reduction of pollution caused by the production of electricity.
- Indoor environmental quality and occupant health.
- Cost savings. These will include savings in capital, maintenance and running costs.
- Energy savings. The resulting savings in primary energy can be considerable.
- Reduced strain on national grids by reducing the peak electricity demand.
- Simplicity, ease of operation. These are common characteristics but may vary between different processes and techniques.

Thermal comfort of buildings is a well-researched area. However, our existing knowledge of comfort covers a small part of environmental conditions while it responds partly to personal and behavioral situations. The major part of the experiments has resulted in methods to predict thermal comfort under steady state conditions. The most well-known and widely accepted methods are the "Comfort Equation" proposed by Fanger, and the J. B. Pierce two-node model of human thermoregulation. On the basis of these models several steady state thermal comfort standards have been established during recent years.

However, because of the thermal interaction between the building shell, the occupants, and the heating and cooling system, steady state conditions are rarely encountered in practice. Thermal conditions in free floating buildings are far from steady, while important indoor fluctuations between 0.5 °C and 3.9 °C are found in a constant set point passive solar building as an effect of the control system. Knowledge of thermal comfort under transient conditions is still limited. A review on thermal comfort in transient conditions concludes, “results of thermal comfort experiments seem to be the only source of information on thermal acceptability in changing environmental conditions.”

Some of these experiments show an important discrepancy with the Fanger model, especially for the region where no mechanical conditioning is applied. The causes of discrepancy are summarized, and the review deals mainly with the temporal and spatial variation of the physical parameters. Based on their data Humphreys and Nicol have proposed an adaptive comfort model. Humphreys has demonstrated that for a group of people the comfort temperature is close to the average temperature they experience. Studies have shown, that by using a version of the model to set variable rather than static design temperatures, remarkable savings can be made in the energy needed for air-conditioning.

Developing Humphreys’s work, the Comfort group of PASCOOL, based at the Martin Centre, Cambridge University, in collaboration with University of Athens, has carried out field studies to understand the mechanisms by which people make themselves comfortable at higher temperatures. Important results have been obtained with the use of a specially designed personal monitoring instrumentation, questionnaires, and an observation procedure. Preliminary findings confirm that people are comfortable at much higher temperatures than expected. In one building 89 percent of inhabitants were satisfied with a mean operative room temperature of 30.5 °C. It is also confirmed that people take a number of adaptive actions to make themselves comfortable including moving to cooler parts of the room.

This was shown by the fact that temperatures recorded by the personal loggers were about 0.75 °C to 1.5 °C lower than average room temperature. Many changes to clothing and to the building controls were also detected. In 864 monitored hours there were 273 adjustments to building controls and 62 alterations to clothing. Although the metabolic rate was not monitored, it was shown by modeling and measurements of body movements using stroboscopic photography that quite modest changes in the speed that an action was carried out could reduce the average metabolic rate by about 10 to 20 percent. This is an important finding because it suggests that nominally identical tasks can be achieved for different expenditure of energy. Comfort research under transient conditions is very promising and can result in high energy savings. However, further field and theoretical studies are necessary in order to improve knowledge on this topic.

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Biographical Sketch

Matheos Santamouris was born in Athens in 1956. He acquired his Diploma of Physics at the University of Patras, Greece, in 1979, a Postgraduate Diploma, DEA on Energy Physics. Institute National Polytechnique de Grenoble, France in 1981, and a Ph.D. on Energy Physics at the University of Patras in 1986. He is Visiting Professor to the School of Architecture, Low Energy Unit, University of North London, UK, and Associate Professor at the Physics Department, University of Athens.

He has been a member of the Editorial Board and reviewer of the *International Journal of Solar Energy* since 1989, and of the *Annual European Directory of Sustainable and Energy Efficient Building* since 1993. He was a member of the Editorial Board of the journal *Sun at Work in Europe* (1989–91), and is a reviewer for a number of scientific journals. He has written and edited a range of books including, most recently, *Energy in the Urban Environment* (James and James, London, 2001), *Passive Solar Energy in Practice* (co-author) (James and James, London, 2001), and *Construire Sostenibile il Mediterraneo* (co-author) (ALINEA, Italy, 2001).