An Approach to Integrating Passive Cooling Devices in Buildings

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ABSTRACT. This paper surveys the state of integration of passive cooling devices in buildings. This survey illustrates the fact that there are no general prescriptions for the integration in the design of passive cooling devices. Further the present paper does not intend to propose general prescriptions for the integration of cooling devices in design but only to illustrate a number of existing problems.

1. INTRODUCTION

These last years most efforts were directed at obtaining energy savings by application of passive solar heating and/or rational use of heating energy. The state of the art of passive cooling devices regarding their integration in buildings was a minor concern in most of the works presented. Hence the authors tried to analyze physical phenomena in order to reduce heat losses by heating processes. The importance of heating was also imposed by most of the north European Countries after the first oil crisis; an illustration of that way of thinking is the building loads evaluation method (i.e. the method 5000) proposed in the European Passive Solar Handbook [1], which does not consider the warm period of the year, i.e. all warm months from June to September are not included in the method.

The continuous increase of the demand for air conditioning devices and a better approach of the energy needs of buildings in the Mediterranean countries changed that situation. Today passive cooling concepts are studied in detail and a great effort is made to apply on a large scale passive cooling systems and to estimate the performance of such systems.

Passive cooling devices can be classified in five categories which differ from one another in the physical phenomena at the basis of cooling processes. These categories are: Solar cooling, Radiative Cooling, Convective cooling, Evaporative cooling and use of thermal inertia of earth.An additional process, helpful for the cooling of buildings, involves the use of shade to avoid the overheating of buildings, either by construction devices or through the use of plants. Other devices such as solar chimneys (used to accelerate ventilation processes without using fans) will be considered as integral part of solar cooling in this paper. Possibilities for the future applications of vegetation will be discussed later.

Passive cooling devices are usually studied at the level of architectural design. In passive systems all functions (i.e. collection, storage and distribution) have to be carried out by the building elements themselves and construction materials have to be specially chosen to this effect. The cost of heating and cooling with passive systems thus increases because of the extra cost of the materials required that replace conventional building materials, Agrwal [2].

Most of the problems encountered in utilizing passive cooling devices arise from the fact that the energy supply is intermittent on a diurnal scale, i.e. radiative cooling is efficient only during the night -when the demand is greatest the supply is nil. As a consequence of this intermittence thermal inertia, i.e. the capacity to storing energy has to be incorporated into the systems as an integral part of the overall building, Agrwal [2]. A further consequence of this intermittence the systems need either interventions by occupants at specific time periods or complicated automatisms which make them non antagonistic with conventional energy applications as long the oil prices remain at today's low levels.

Traditional architecture was able to integrate passive cooling devices in buildings, as for instance by the various methods used to avoid overheating of buildings in the Mediterranean countries. These solutions were not very different in conception from the passive cooling devices of today. They seem to be very different only because they were based on the local technology levels and on a completely different understanding of thermal comfort. The conception of buildings in the warm regions of Greece, Italy and Spain is an example illustrating these propositions. The buildings were constructed with massive walls (i.e. elements with a large thermal inertia), narrow and high openings (facilitating natural ventilation and so disposed as to intensify cross ventilation), closed with massive blinds during the day, which were opened only after the sunset, with well "insulated" roofs (composed of a great number of mud layers covered with dried seaweed and tiles). All openings were closed during the day, except the kitchen, and opened after sunset. As a ritual after sunset the irrigation of court yards, when water was available, was used to accelerate by evaporative cooling the depression of the temperature of the ambiance. Sheltered buildings (i.e. use of the thermal inertia of the earth) were imposed by the great lack of space rather than from cooling needs. For this reason most buildings of that kind present physiological discomfort for most inhabitants, as will be discussed later.

This paper surveys the state of integration of passive cooling devices in buildings. It illustrates the fact that there are no general prescriptions of design integration of passive cooling devices, because a building type may have a dominant concern which in another building type or under different climatic conditions may be a minor concern. The present paper does not intend to propose general prescriptions of design integration of cooling devices but only to illustrate a number of existing problems.

2. RADIATIVE COOLING

The principle introduced in most studies until today is illustrated by the proposition by Givoni [3], that "any element that sees the sky loses heat by emission of long wave radiation". That principle introduces a heat sink in all heating or passive heating applications and specially in greenhouses where covers partly transparent to long wave thermal radiation are used, Whillier [4], Hassan [5], Hollands et all [6], Chandra et all [7], Chandra [8], Chandra et all [9], Delwich et all [10], Silva et all [11], Silva et all [12], Nijskens et all [13], Papadakis et all [14] and Papadakis et all [15]. All these studies have a common point which is expressed by the numerical calculation of the sky temperature by using a number of different models Isdo [16], Kimball et all [17]. The effect of cooling by night-sky radiation is further used in calculations of night-sky radiators (i.e. radiating surfaces covered with materials partly transparent to long-wave thermal radiation) and a number of calculation methods are proposed to this effect, Kimball [18].

The simplified principle given above, that a surface radiating to the sky without any protection, loses heat in contact with the ambient air, reduces in fact the effectiveness of cooling systems. This is because the surface is heated from the ambient air through natural convection and for this reason limited temperature depressions are obtained against ambient air temperature, i.e. up to 4 or 5 ^{o}C in humid regions and up to 5 or 7 ^{o}C in arid regions, Givoni [3]. Further the influence of water vapor contained in the ambient air, of clouds and of air pollutants is very important so that the experimental acquisition of sky radiation (specially night-sky radiation in the 8-14 Ìm atmospheric window band) should be necessarily monitored, Papadakis [19].

Today a number of elaborate models and techniques are proposed which seem to give more satisfactory results Agrawal [2], Givoni [3], Matsuta [20], Frangoudakis et all [21], Frangoudakis et all [22], Frangoudakis et all [23], Ayoob [24] and Balcomb [25]. In all these works the major obstacle to the use of radiative cooling devices is the solar radiation incidence during the day. The horizontal orientation of radiating surfaces (orientation presenting the highest view factor with the sky, i.e. providing the highest heat flow) presents the highest solar radiation incidence during summer, Balcomb [25]. Two different strategies are proposed by the authors to face this obstacle: The first strategy is based on the conception of "hybrid heating-cooling systems", which have double circuits, i.e. solar heating of a medium during the day and cooling by another medium during the night (in most cases heating of domestic water and cooling of water to be circulated). The second strategy is based on the unique function of the system, i.e. only heating in winter and only cooling in summer. That strategy needs in its application automatisms to avoid the exposure of the radiating surface during the night and during the day respectively.

Finally integration of radiative cooling devices in buildings presents a number of theoretical and technical problems of a different kind. This concerns both of the above mentioned devices, i.e. radiative heating-cooling and radiative cooling devices. The problems which have to be solved are: Theoretical models for predicting quantitatively the performance by the application of the systems in a full size house; storage of heat in winter and summer; maintenance of the systems and automatisms.

3. EVAPORATIVE COOLING

In arid regions the water evaporation process is used to cool directly the outdoor air which is introduced in the building (in humid regions the process has no applicability). Such systems are operated during the day when a large quantity of hot air is to be cooled and in some cases hot air is driven by using solar chimneys. From a physiological point of view this method of cooling is not acceptable as the cooled indoor air becomes excessively humid and a high rate of air flow is necessary for effective cooling. That causes large variations in air speed, i.e. sensation of thermal discomfort and further a sensation of suffocation within the cooled buildings. This method of cooling is limited to the regions where ample water in quantities of 0.3 to 0.5 m3/dwelling unit is available and where outdoor humidity of air is very low, Agrawal [2].

Building elements can also be cooled indirectly by evaporation (i.e. the element is irrigated). They thenserve as heat sinks and absorb heat from the interior of the building, or dissipate in this manner the heat absorbed by incidence of solar radiation. That technique of evaporative cooling does not elevate indoor air vapor content. That technique is similar to that of shaded water ponds which also serve as cold storage.

An indirect evaporative process is also the irrigation of earth around the building when no vegetation is present, or more irrigation of earth covered with gravel, which lower the earth surface temperature and create a sensation of thermal comfort in arid regions. Green grass or vegetation around the building provide also evaporative precooling of ambient air which is later introduced in the building, Givoni [3] and Balcomb [25].

Integration of evaporative cooling in buildings presents the same theoretical and technical problems, exposed above for radiative cooling and involves in addition the necessity of predicting instantaneous comfort sensations, Fanger [26], Olgay [27] and Givoni [28]. By cooling directly by evaporation the outdoor air the additional problem of condensation of water vapor on inner surfaces of building elements has to be faced and that because the surface temperature of the elements is under the dew point of the indoor air, dew point which is very close to the indoor air temperature of humid air.

The most significant problem present in any application of evaporative cooling is in fact the availability of water. It is important to underline that arid regions, which are most appropriate for evaporative cooling applications, are arid exactly because water is not available. In the best situations limited quantities of water are available and those quantities have other many important uses, which are very distant from that of evaporative cooling.

4. CONVECTIVE COOLING

Natural or forced ventilation constitutes the usual passive cooling device. That is the most natural passive cooling device which provides a sensation of comfort not only by depression of indoor air temperature but also by accelerating the evaporation of human perspiration. That is why simple air movements without significant temperature difference between indoor and outdoor air cause a sensation of comfort during the hottest days of the year. Cross ventilation is very effective but sometimes causes a sensation of discomfort at high air speed rates. The natural night temperature depression gives the possibility to cool the indoor of buildings through forced night ventilation. About 3 air changes/h provide a good perception of comfort, i.e. no particular perception of warmth or coolness, Silvestrini et al [29]. A number of 10-15 air changes/hour provide the lowest cooling energy consumption for a building, Silvestrini et all [29], heat is extracted from the walls of the building through convection and the stored coolness avoids a rapid indoor air temperature increase the following day. During the nights when the outdoor temperature decreases under 20 ^{o}C forced night ventilation provides discomfort through undercooling, Silvestrini et all [29].

Natural or forced ventilation supplies fresh air from outdoors, but in most of the big cities of today the outdoor air is more polluted than the indoor air, i.e. the outdoor air is charged with all usual city pollutants and that means that it is less appropriate for respiration then the indoor air which contains only human residues, Hollowell et all [30], Moschandreas [31] and Woods et all [32]. But that also means additional difficulty in applying ventilation in a great number of cities of today without prevention, i.e. filtering, cleaning etc of the ambient air.

Integration of convective cooling, i.e. natural ventilation processes presents most theoretical and practical problems. Natural ventilation is today very difficult to study theoretically. Experimental visualization of air flow photographed in water tanks, Diaz et all [33], or in wind channels answers some of the questions posed. The solutions obtained until today for the three dimensional Navier-Stokes equations are not yet completely satisfactory and the energy equations are not yet solved in a manner permitting to include these solutions in simulation methods of the thermal performance of buildings, Laudner [34]. Further the existing wind data today are given in form of daisies of monthly mean values. Very few of hourly data are given for restricted places and there is no satisfactory correlations between wind speed and direction and natural ventilation or infiltrations in buildings, Roset et all [35].

5. EARTH THERMAL INERTIA

Earth integrated buildings, earth shelter protection of buildings or geotectural design become important as passive building concepts based on the practically infinite thermal inertia of the earth. The techniques used are quite simple to understand, i.e. buried walls and/or earth covered roofs or more buildings directly dug in the appropriate rocks or the earth (vaulted structures).

Earth thermal inertia can be also used in conventional buildings with a number of techniques as well as high conductive walls which are heat sinks for the building indoor (providing important heat losses in winter), Givoni [3], or earth-air exchangers which can be considered as passive systems because only fans have to be used to move outside air through pipes (which are buried in the earth) and/or to drive the indoor air to the outdoor of the building. These last systems are very useful as heating systems in the winter when relatively low indoor temperature is needed or as outdoor air preheating systems or as heat recovering systems (recovering energy from the air driven to the outdoor of the building).

Integration of earth thermal inertia in passive cooling strategies would be possible after a number of theoretical and technical problems are solved, such as: Theoretical models for predicting quantitatively the thermal performance of full size sheltered buildings, the avoidance of surface and subsurface water intrusion in the building, of dampness and dankness, the intensification of the poor natural ventilation, the avoidance of psychological discomfort due to the lack of optical communication with the outside and to the lack of natural light, Wright [36]. The practically infinite thermal inertia of the earth provides finally a self-regulated in temperature and comfort indoor environment of the sheltered building, which is not in comformity with the current comfort concepts Andreadaki [37].

Integration of earth-air exchangers seem to be immediately possible although a number of theoretical problems have to be solved in the future. Some practical problems are already dealt with by using systems of that kind in agriculture, R. W. Spengler et all [38], Bansal [39], Boulard et all [40], Walker et all [41]. The lack of theoretical models for predicting quantitatively the performance of the application of such systems in a full size house remains the major problem.

6. SOLAR COOLING

Most of known solar cooling devices are (with the exception of solar chimneys) clearly active cooling systems. Some examples are given here after to illustrate this proposition.

The solar absorption cooling units are based on the technology of refrigeration by absorption where the generator of the chemical solution (usually NH_3-H_2O or LiBr-H_2O) is heated by using hot water which is heated by a solar collector instead of a conventional heating unit using fuel or gas, Agrawal [2].

Solar dehumidification and evaporative cooling units are based on the properties of desiccant materials, which have affinity for water vapor. The most frequently used desiccant materials are either molecular sieve or silica gel. Outdoor air is dehumidified and then further cooled by direct water evaporation processes. The desiccant material is regenerated in a chamber by the use of hot air from a solar collector, Agrawal [2].

All the systems just described are not to be considered as passive cooling systems and will not be discussed further in the present paper. An exception is the conception of solar chimneys, which are in fact passive systems. Solar chimneys are nothing else than air solar collectors. The air is heated by solar radiation incidence and hot air is driven outside the building in summer. Well disposed low apertures assure the supply of outdoor fresh air. These systems are operated during the day when solar radiation is available.

Integration of solar chimneys in buildings presents not only the theoretical, technical and physiological problems mentioned with respect to convective cooling but also a number of specific problems as well, such as avoiding the overheating of parts of the building by residus heat (i.e. the solar chimneys have to be fully uncoupled from the building), etc.

7. SHADE AND VEGETATION

Natural or constructed shading devices were always used in the past to avoid overheating in summer and during the several months when incident solar radiation becomes important. The most effective devices are evidently the moving ones because the use of movable shading permits full solar radiation incidence in winter, so that heating is not disturbed.

A number of usual shading devices such as balconies etc, which are integral parts of the buildings have a negative influence on the buildings thermal performance because they constitute important thermal bridges and provide significant heat losses independently of the season. The negative influence of that kind of devices is more intensive during the heating period then during the cooling one. This is because, first, the loads of the building during the cooling period due to direct solar radiation are much more important then the losses from thermal bridges and, secondly, the thermal inertia of this kind of building elements (usually concrete elements under real unsteady state conditions) means a time lag of twelve to 18 hours for the peak of the losses to reach the interior surface of the elements, i.e. in the night when compensation by natural ventilation is possible.

Vertical shading devices are much in use in Mediterranean traditional architecture. Massive wooden blinds were used to cover the openings of the building but either venetian blinds or roll down sliding are preferable. This is because the non massive blinds not only reduce direct solar radiation incidence in the rooms but also reduce diffuse and reflected solar radiation (which also provide important overheating in the summer) providing comfortable day lighting in the interior of the buildings. Daylighting is qualitatively much better than any other lighting, Balcomb [25].

East and west oriented openings may be than effectively shaded by deciduous trees, since they admit about 50% of the solar gains in the spring and block the solar gains in autumn, Balcomb [25]. South openings can not be effectively shaded by deciduous trees; horizontal beds of grape vines are consequently more effective.

Significant depression of the outside surface temperature of exposed to the sun external walls could be obtained by a ventilated double skin, Fohry [42]. Analogous temperature depression is obtained by leaf covered external walls, which could provide an interesting reduction of cooling needs in summer, Holm [43]. The influence of deciduous and evergreen vegetation cover on exterior walls could be a method of retrofitting badly insulated light walls of existing buildings Holm [43] and this could be possible for high buildings because these plants can grow easily in pots. Finally vegetation around the building reduces the reflected solar radiation loads of the building and provide radiative precooling of ambient air.

Integration of shadowing and vegetation in buildings presents a number of theoretical and technical problems. Models for predicting quantitatively and qualitatively the efficiency of shading devices exist in great numbers but the use of these models is efficient only in heavy simulation methods calculating the thermal performance of buildings under real unsteady state conditions; simulation methods of that kind are still in development. Moreover vegetation can not be automatized and that means that use of vegetation as shading or evaporative ambient air precooling can be only under continuous human intervention to take care, irrigate and offer the indispensable services to the plants.

8. CONCLUSIONS

The above survey of integrating passive cooling devices in buildings shows that many theoretical and practical problems have to be faced before any large scale application of these technologies is possible. All the above mentioned technologies are still under study and the theoretical models developed need extensions or sometimes better formulation (convective cooling) in order to provide satisfactory solutions or for predicting qualitatively and quantitatively the performance of these passive cooling devices by their application in a full size house (storage of heat in winter and summer included).

Simulation methods for predicting time dependent thermal performance of buildings as function of the local climatic conditions (i.e. under real unsteady state conditions) are the tools for integrating passive cooling devices if these tools could be completed with the necessary additional models. But that kind of simulation methods is still in development and needs a long time experimental validation.

The applicability of each of the above presented passive cooling devices depends on the nature of the physical processes considered which may need resources which are lacking or may provide physiological or psychological discomfort and must therefor be handled with care.

Finally the major problem encountered in utilizing passive cooling devices ais that the energy supply is intermittent on a diurnal scale; this may be solved by utilizing more than one device in a complementary manner, i.e. the one supplying energy when the supply of the others is nil. Further passive cooling devices based on the local technology level and taking into account the diversity of climatic conditions and the diversity of building types and uses can offer to the European countries a regional and environment-friendly industrial research and development, which will provide passive cooling systems more competitive with the conventional energy applications, despite oil prices at today's low levels. The example of traditional architecture which was able to integrate passive cooling in buildings could be extended by using the advanced technology of our time.

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