PASSIVE COOLING DISSIPATION TECHNIQUES FOR BUILDINGS AND OTHER STRUCTURES: THE STATE OF THE ART

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Abstract

Passive cooling in the built environment is now reaching is phase of maturity. Passive cooling is achieved by the use of techniques for solar and heat control, heat amortization and heat dissipation. Modulation of heat gain deals with the thermal storage capacity of the building structure, while heat dissipation techniques deal with the potential for disposal of excess heat of the building to an environmental sink of lower temperature, like the ground, water, and ambient air or sky. The aim of the present paper is to underline and review the recent state of the art technologies for passive cooling dissipation techniques in the built environment and their contribution in the improvement of the indoor environmental quality as well as in the reduction of cooling needs. The paper starts with a short introduction in passive cooling and continues with the analysis of advanced heat dissipation techniques such as ground cooling, evaporative cooling, and night ventilation in the built environment. The various technologies are compared versus their contribution to energy efficiency and users' comfort. Future trends and prospects are discussed.

Keywords: passive cooling, heat dissipation, ground cooling, evaporative cooling, ventilative cooling

1 INTRODUCTION

Buildings present a very high energy consumption compared to the other economic sectors. Although percentages vary from country to country, buildings are responsible for about 30-45% of the global energy demand. As a result of the application of very intensive energy savings' measures and technologies, the thermal performance of buildings during the winter period has been tremendously improved mainly in the developed world. On the contrary, because of the increasing standards of life, the affordability of air conditioning, the universalization of modern architecture and also the temperature increase in the urban environment and the global climatic change, the energy needs for cooling have increased in a rather dramatic way (Antinucci et al. 1992).

The serious penetration of air conditioning has an important impact on the absolute energy consumption of buildings. Studies have shown that refrigeration and air conditioning are responsible for about 15 % of the total electricity consumption in the world(Confederation of International Contractors' Associations 2002), while in Europe air conditioning increases in average the total energy consumption of commercial buildings to about 40 kWh/m2/y (Dascalaki and Santamouris 2002; Sfakianaki et al. 2011).

Passive cooling is a multilayered and multidisciplinary process. A framework that is widely accepted for passive cooling is under the frame of three steps: Prevention of heat gains, modulation of heat gains and heat dissipation. Important research has been carried out on the field of passive cooling of buildings. Existing experience has shown that passive cooling provides excellent thermal comfort and indoor air quality, together with very low energy consumption. New materials, systems and techniques have been developed, applied and are now commercially available (Santamouris et al. 2007). In parallel, passive cooling techniques and systems are extensively used in outdoor spaces to improve local microclimate and fight urban heat island (Gaitani, Mihalakakou, and Santamouris 2007; Santamouris et al. 2012; Santamouris, Synnefa, and Karlessi 2011).

Heat dissipation techniques deal with the disposal of the excess heat of a building to a sink characterized by lower temperature, like the ambient air, the water, the ground and the sky.

Effective dissipation of the excess heat depends on two main pre-conditions: a) The availability of a proper environmental heat sink with sufficient temperature difference for the transfer of heat and b) the efficient thermal coupling between the building and the sink.

The present paper aims to present the state of the art on heat dissipation passive cooling techniques. The main scientific and technical developments on ground, ventilative and evaporative cooling are presented and discussed. Examples of application are presented while the main future priorities are discussed.

2 THE USE OF THE GROUND AS A HEAT SINK

It is well known that the temperature of the ground at a depth of about 2.5 to 3 m remains fairly constant and low around the year(Mihalakakou, Santamouris, and Asimakopoulos 1992; Mihalakakou 1997). The idea to dissipate the excess heat from a building to a natural sink like the ground is known from the ancient time (Santamouris and Assimakopoulos 1997). The most common technique to couple buildings and other structures with the ground is the use of underground air tunnels, known as earth to air heat exchangers (EATHE). Earth to air heat exchangers consist of pipes which are buried in the soil while an air circulation system forces the air through the pipes and eventually mixes it with the indoor air of the building or the agricultural greenhouse.

The performance of the EATHE system varies as a function of its characteristics such as the length and the diameter of the pipe, the air flow rate, the depth where the system is buried, the thermal characteristics of the soil, the pipes' material, etc. (Jacovides, Santamouris, and Mihalakakou 1996; Mihalakakou, Santamouris, and Asimakopoulos 1994b, 1994c)

Hundreds of studies have been performed in order to develop models able to predict the efficiency of the earth to air heat exchangers, to analyse the experimental performance of pilot applications and to report the global performance of real scale case studies. At the initial stage of the research many problems associated to the use of ground pipes were reported. Most of them dealt with the accumulation of water inside the tubes, problems of indoor air quality, lack of efficient and dynamic control during the operation, etc. However, recent applications have overcome efficiently the initial barriers and given the quality and the quantity of the available actual knowledge and information, it may be concluded that EATHE is a very mature and quite efficient technology. Evaluation of many real case studies described in (Anon 1997), has shown that for moderate climates the seasonal energy performance of the EATHE systems is close to 8-10 kWh/m2 of ground coupling area, while the peak cooling capacity at air temperature close to 32 °C is estimated at 45 W/m2 of ground coupling area.Many applications of earth to air heat exchangers are available around the world and several scientific works have been published reporting design data and monitoring results. Existing works refer either to the use of EATHE systems in buildings or agricultural greenhouses. It is evident that the degree of information provided for each case is different and is almost impossible to homogenize the results or extract comparative conclusions. However, it is important to collect all available information, classify it and report the major results and conclusions from each project. In the following sections, data and results from 30 building projects and twenty agricultural greenhouse applications of EATHE are given.

Almost twenty different publications have been identified reporting application of EATHE systems in agricultural greenhouses. Review of 14 agricultural greenhouses equipped with earth to air heat exchangers is given in (Santamouris, Mihalakakou, Balaras, et al. 1995). The characteristics of the reported greenhouses are given in Table 3. The used earth to air heat exchangers were buried at depths varying between 50 and 200 cm. The heat exchangers are constructed using plastic, aluminium or concrete pipes. The projects have been monitored and information on the winter performance of the used systems is given in (Santamouris, Mihalakakou, Balaras, et al. 1995).

A system of earth to air heat exchangers consisting of 20 pipes buried at 2m depth and 15 long has been installed in an agricultural greenhouse of 150 m2 in Greece, (Mavroyanopoulos and Kyritsis 1986). The greenhouse was monitored only during the winter period where the EATHE system had an important contribution. In another experiment described in (Hollmuller 2001), 24 PVC pipes of 11 m length running at 80 cm below the ground have been installed in an experimental greenhouse in Switzerland. Data on the cooling potential of the system are not given.

Tenths of models have been developed to predict the thermal performance of earth to air heat exchangers. Proposed models are either deterministic where the thermal problem is described through appropriate equations as well as data driven where intelligent techniques like neural networks are used to predict the exit temperature from the exchanger, based on training of the models with appropriate experimental data. Deterministic models may be analytical or numerical. Analytical models propose algebraic equations to predict mainly the exit temperature from the exchangers, while analytical models are usually transient and propose a set of differential equations that describe heat and mass transfer phenomena. Numerical models may be of one, two or three dimensions. According to (Tittelein, Achard, and Wurtz 2009), numerical models may be classified as type A or type B. In type A models it is considered that part of the ground is influenced by the exchanger, while in type B models the whole geometrical area is considered. In the following sections the main models proposed are described and reviewed.

Heat transfer phenomena related to EATHE involves mainly a full analysis of the conduction phenomena in the ground and convection phenomena inside the pipe. A complete description of the proposed models to consider heat conduction in the ground is given in (Zoras 2009).

A comparative analysis of nine simulation models to predict the thermal performance of earth to air heat exchangers is given in (van de Brake 2008). It is found that the models described in (Hollmuller 2001) and (Mihalakakou, Santamouris, and Asimakopoulos 1994a) are validated and found to be accurate within 1% of existing published data.

A new methodology to calculate the contribution of earth to air heat exchangers to buildings is proposed in (Santamouris, Mihalakakou, Argiriou, et al. 1995).

The method is based on the principle of balance point temperature and is validated using TRNSYS simulations. The method may be used as an hourly based simplified simulation accurate model to design the coupling of buildings with EATHE and size their specific quantitative characteristics. The method is further extended to couple buildings with both EATHE and night ventilation techniques. The basic characteristics of the method are similar as in (Santamouris, Mihalakakou, Argiriou, et al. 1995). The new extended method is validated against detailed simulations performed with TRNSYS.

Research described in (Misra et al. 2012) has evaluated the performance of EATHE when coupled with the condenser of a conventional air conditioning system. The experiment has been carried out in India and comprised a 60 m long horizontal cylindrical PVC pipe buried at 3.7 m depth. The air at the exit of the exchanger was either directly circulated in a room together with the air from a conventional air conditioner or it was used for cooling the condenser tubes of an 1.5 TR window air conditioner. The experiment It was found that when the air is used to cool the condenser the achieved energy conservation was close to 18 %, while when both system supplied in parallel the room, the corresponding energy saving was around 6 %.

3 EVAPORATIVE COOLING

Evaporative cooling is extensively used as a passive cooling technique in the built environment. The air movement over a wetted surface causes some of the water to evaporate. This evaporation results in a reduced temperature and an increased vapour content in the air. The increase of the surface area increases the evaporation, resulting in a significant cooling effect. There are two basic types of evaporative air cooling techniques:

- The direct evaporative coolers that are commonly used for residential buildings. In this type of evaporative cooling the reduction of temperature is followed by an increase of moisture content.
- The indirect systems where the evaporative cooling is delivered across a heat exchanger, which keeps the cool moist air separated from the room. This system does not cause an increase of the air humidity.

The limit of the evaporative cooling potential is given by the wet bulb temperature of the air to be cooled. Some researchers (Givoni 1992), (Evyatar 2007) though indicate that this theoretical limit is rarely reached and that the maximum output of the most evaporative coolers is at least 2°C warmer than the wet bulb. Therefore the climatic criterion for the applicability of evaporative cooling is the ambient wet bulb temperature.

Direct evaporative cooling is the simplest and oldest form of air conditioning. It is performed using a fan to draw hot outside air into the building by passing it from an evaporative pad (see Figure 2). Direct evaporative cooling is quite simple and cheap commonly used for residential applications to cool the air by increasing its moisture content of the air (Bom et al. 1999). Typical commercial evaporative coolers have an effectiveness of 50-70%.

Since the major drawback for DEC is the wet bulb temperature limitation, research efforts the last decades are mainly focusing on the improvement of the DEC's effectiveness by various configurations targeting to expand their application in more humid climates.

For the improvement of DEC's effectiveness the following alternatives are proposed in chronological order:

- Water falls over films proposed by Giabaklou et al (Giabaklou and Ballinger 1996) while exposing maximum surface area to the passing air flow.
- The use of micronisers is proposed for the Passive Down-draught Evaporative Cooling (PDEC) configuration studied by (Bowman et al. 2000) and (Robinson et al. 2004).
- An evapo-reflective roof to reduce passive cooling in buildings for hot arid climates has been proposed in (Ben Cheikh and Bouchair 2004).
- A direct evaporative cooler that operates either with natural wind flow or with wind catchers is described in (Qiu and Riffat 2006).
- Water evaporative walls are proposed in (Naticchia et al. 2010) and (He and Hoyano 2010) on 2010 and 2011.
- A wet porous cooling plate as a building wall is proposed in (Chen and Liu 2010; Chen 2011) where cooling is performed via evaporation of the porous material.

Therefore direct evaporative cooling can be considered a very effective solution for hot and arid climatic conditions. When humidity is increased other evaporative cooling configurations can be a viable solution.

For hot humid climates the indoor temperature conditions should be kept lower than outdoors. In these regions where usually the outdoor temperature fluctuations are small and the humidity is considerably high throughout the whole day, direct evaporative cooling is not effective. The indirect evaporative coolers (IEC) can be an alternative option.

IEC usually incorporates an air to air heat exchanger to remove heat from the air without adding moisture. In IEC the hot outside air is passed through a series of horizontal tubes that are wetted on the outside. A secondary air stream blows over the outside of the coils and exhausts the warm, moist air to the outdoors. The outside air is cooled without adding moisture as it passes through the tubes. Indirect evaporative cooling typically has an effectiveness of almost 75%. There are various configurations that can increase effectiveness even higher than 100%, i.e. cooling the supply air to a level below the wet-bulb temperature.

An evolution of the simple DEC is the so called two stage evaporative cooling (Bourne 2004) as depicted in Figure 4. The two stage evaporative coolers pre-cool the air before it goes through the evaporative pad. The overall system has 70% effectiveness for its indirect part and 90% effectiveness for the direct part (Anon 2007) while the relative humidity of the cool air is between 50-70%. Two-stage evaporative coolers can reduce energy consumption by 60% to 75%.

Significant research efforts for the improvement of DEC's effectiveness are performed by various researchers the last decade.

Based on the above, indirect evaporative cooling techniques can be low energy solutions for medium and large buildings where passive cooling techniques cannot reach the required comfort conditions (Belding and Delmas 1997; Costelloe and Finn 2007; Elzaidabi 2009; Joudi and Mehdi 2000; Kim et al. 2011; Navon and Arkin 1994). Such systems require energy for the fan power for the air flow. On the one hand this fan power can be up to 20% less due to lower air velocities required and on the other hand the main reduction of the energy demand is attributed to the replacement of the conventional air conditioning system. Based on future projections performed in (Smith and Harpham 2010) and (Hanby and Smith 2012) climate change will deteriorate the energy demand for cooling in areas which are less vulnerable nowadays and the dependence on mechanical cooling will be increased. This research showed that the evaporative cooling and especially the IEC are suitable solutions for more extreme conditions due to increase in wet bulb temperature depression. The projections are tested under the UK climatic conditions and it is proved by simulations that the 'drier' UK climate provides an opportunity to offset the impact of increased cooling demands through wider application of indirect evaporative coolers.

Based on the state of the art review, evaporative cooling is a viable and attractive passive cooling technique for various climatic conditions while a considerable effort is put in the improvement of systems' effectiveness and applicability (Navon and Arkin 1994). Moreover there is a significant environmental and economic benefit in using EC over conventional air conditioning due to the it's increased energy efficiency.

4 VENTILATION AS A PASSIVE COOLING TECHNIQUE

Night ventilation or nocturnal convective cooling exploits the cold night air to cool down the building's absorbed heat gains during daytime and reduce the daytime temperature rise. Night ventilation can either be driven by natural forces – i.e. stack or wind pressure difference, or may be sometimes supported by a small fan power to provide sufficient airflow at times when the natural forces are weak. As a consequence, temperature peaks are reduced or even postponed. The efficiency of the technique is mainly based on the relative difference between the outdoor and indoor temperatures during the night period. However, for a given place, the cooling potential of night ventilation techniques depends on the air flow rate, the thermal capacity of the building and the appropriate coupling of the thermal mass and the air flow.

Various studies prove night ventilation effectiveness. In (Givoni 1991, 1992) Givoni argues that the night ventilation technique is efficient particularly for arid regions where day time ventilation is insufficient to ensure thermal comfort. Kolokotroni and Aronis in (Kolokotroni and Aronis 1999) introduce some variables for the building such as building mass, glazing ratio, solar and internal gains, orientation and demonstrate that the optimization of the building design for night ventilation according to these parameters can cause an abatement of about 20-25% of the air conditioning energy consumption. The effectiveness of night ventilation techniques is determined by the prevailing climatic conditions, the microclimate, the building characteristics and the location. The outdoor temperature, the relative humidity and the wind speed are the environmental parameters that influence the successful application of night ventilation techniques (Geros et al. 2005; Santamouris et al. 1996).

Santamouris et al (Santamouris, Sfakianaki, and Pavlou 2010) pointed out that the application of night ventilation techniques to residential buildings may lead to a decrease of cooling loads almost 40 kWh/m^2/y with an average contribution of 12 kWh/m^2/y. In urban areas though, the Urban Heat Island (UHI) phenomenon deteriorates quality of life and has a direct impact on the energy demand, the environmental conditions and, consequently, on ventilation effectiveness. The increased urban temperatures (Livada et al. 2002; Livada, Santamouris, and

Assimakopoulos 2007) exacerbate the cooling load of buildings, increase the peak electricity demand for cooling, decrease the efficiency of air conditioners,(Cartalis et al. 2001; Santamouris et al. 2001) and create an emerge necessity for passive cooling.

To better understand the relative phenomena and also quantify the impact of night ventilation techniques, important experimental and theoretical research has been carried out (Santamouris et al. 2010). Various studies are performed reporting the contribution of night ventilation to passive cooling either in real buildings or in test experimental conditions. Moreover a series of simulation studies can be found targeting to the quantification of night ventilation in the reduction of cooling demand together with improvement of indoor comfort.

Based on the above, night ventilation can be categorized based on the type of study, i.e. simulation based or experimental based as well as based on the building types studied.

Ventilative cooling is studied for various building types including offices, residential, industrial, etc. The aim of the present section is to review the applicability of night ventilation for various dwellings.A significant number of studies are focusing on the energy efficiency and applicability of night ventilation cooling in office buildings under various climatic conditions (Blondeau, Spérandio, and Allard 1997) showed a reduction of diurnal variation from 1.5 to 2°C, resulting in a significant comfort improvement for the occupants. The same results can be found by Birtles et al (Birtles, Kolokotroni, and Perera 1996) in London region.

An office building in Germany is monitored versus its ventilation in (Pfafferott, Herkel, and Wambsganß 2004). Adequate thermal insulation and moderate window dimensions guarantee a low heating and cooling energy demand. Two buildings (the Institute of Criminology building and the English Faculty building) with night-time natural ventilation strategies in Cambridge, UK, were selected for a pilot field study. The buildings were designed by architects Allies + Morrison (London, UK) with engineers Buro Happold (London, UK)(Yun and Steemers 2010).

Therefore night ventilative cooling is a very effective method to reduce the air conditioning demand for office buildings and improve thermal comfort during daytime regardless the climatic conditions. In order to increase the night ventilation cooling performance and ensure that the required window opening will be performed on a regular basis, the night ventilation strategy should be integrated to the office buildings energy management system and control if applicable.

Regarding residential buildings the following studies are found: The ventilation effectiveness is studied in (Golneshan and Yaghoubi 1990) regarding the residential buildings of Iran. The effectiveness of night ventilation technique for residential buildings in hot-humid climate of Malaysia is analysed in (Kubota, Chyee, and Ahmad 2009).Two hundred fourteen air conditioned residential buildings using night ventilation techniques have been analysed in (Santamouris et al. 2010). Based on the above residential buildings' energy efficiency can be considerably enhanced by night ventilation strategies and minimise the use of air conditioning. Moreover the specific passive cooling technique can contribute to an improvement of indoor thermal comfort for low income households where the air conditioning is not an option due to economic restrictions.

5 CONCLUSIONS

The energy consumption of the buildings is quite high and may increase considerably in the future because of the improving standards of life and increasing penetration of air conditioning.

Urban climate change and heat island effect is another important source enhancing the use of air conditioning and increasing peak electricity demand. .

Important research has been carried out that has resulted in the development of alternative to air conditioning systems, techniques and materials. The proposed technologies, known as passive cooling can provide comfort in non-air conditioned buildings and decrease considerably the cooling load of thermostatically controlled buildings. In parallel, passive cooling techniques and systems may be used to improve the outdoor urban environment and fight heat island.

The proposed technologies have been tested in demonstration and real scale applications with excellent results. The efficiency of the proposed passive cooling systems is found to be high while their environmental quality is excellent. Expected energy savings may reach 70 % compared to a conventional air conditioned building while substantial improvements have been measured in outdoor spaces.. Based on the research developments many of the proposed systems and in particular the heat dissipation systems have been commercialised and are available to the public.It is evident that further research is necessary in order to optimise the existing systems and develop new ones.

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