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Review

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.

Contents

1. Introduction

Construction is one of the most important significant economic sectors worldwide and represents a global world's annual close to $3 trillion. This corresponds almost to 10% of the global economy [1]. However, as reported by the United Nations [2], more than one billion of people live in squats, slums and inappropriate houses, while in many cities in the less developed world between one to two third of the population live in overcrowded poor quality houses [3,4].

Buildings present a very high energy consumption compared to the other economic sectors. Although percentages vary from

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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 [5].

Heat island has a very serious impact on the energy consumption for cooling purposes. Heat island is the most documented phenomenon of climatic change and increases highly urban temperatures [6]. Furthermore, the phenomenon increases the cooling energy consumption of buildings and the peak electricity demand [7–10], intensify the thermal stress in urban areas [11], worsen air quality as the rate of photochemical ozone production is accelerated because of the higher urban temperatures [12], and increases considerably the ecological footprint of cities [13]. In parallel, as heat island is mainly presented in dense populated areas, it has a serious impact on indoor comfort conditions in low income housing and increases considerably the energy needs to achieve basic comfort conditions in summer [14,15].

Global climatic change has also a serious impact on the energy consumption of the buildings sector for cooling purposes. Recent research has shown that because of the expected serious future temperature increase, the energy demand of the buildings sector in Greece could decrease by about 50% while the corresponding energy consumption for cooling could increase by 248% until 2100 [16].

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[17], while in Europe air conditioning increases in average the total energy consumption of commercial buildings to about 40 kWh/m^2/y [18,19].

Apart of the energy systems, air conditioning may be an important source of indoor air quality problems. Condensate trays and cooling coils may be contaminated by organic dust. This may cause fungal and mould growth in fans. Also, dirty filters may cause important contamination problems, while cooling towers may cause spread of Legionelea [20,21].

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 [22]. In parallel, passive cooling techniques and systems are extensively used in outdoor spaces to improve local microclimate and fight urban heat island [23–25].

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.

Three main processes of heat dissipation have been well studied and developed: (a) Ground cooling based on the coupling of buildings with the ground; (b) Convective or ventilative cooling based on the use of ambient air; (c) Evaporative cooling using the water as a heat sink. Radiative cooling processes using the sky as a heat sink, have been proposed, however have not gained important acceptance from the scientific and the technical world.

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 [26,27]. The idea to dissipate the excess heat from a building to a natural sink like the ground is known from the ancient time [28]. 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. [29–31]

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 [32], has shown that for moderate climates the seasonal energy performance of the EATHE systems is close to 8–10 kWh/m^2 of ground coupling area, while the peak cooling capacity at air temperature close to 32 °C is estimated at 45 W/m^2 of ground coupling area.

The present section aims to present the existing knowledge and advancement on the use and performance of EATHE systems. The known applications in buildings and agricultural greenhouses are reported in an organized way while the progress on modelling and simulation of the systems is also analysed.

2.1. Existing applications of earth to air heat exchangers to provide passive cooling

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. In Tables 2 and 3, the characteristics of the building and greenhouse projects are reported respectively.

2.1.1. *Using EATHE in buildings*

Earth to air heat exchangers have been applied in various types of buildings. The following section describes the characteristics of nine offices, nine residential, five educational, two production and one commercial, multifunctional, athletic centre, hospital and care home projects. Most of the projects have been monitored; however the provided degree of information varies considerably between the different projects. The reported efficiency of the EATHE systems varies as a function of the design characteristics and in particular, the number of pipes, their length and depth and the global management and use of the energy system.

The application of earth to air heat exchangers in an office building is Belgium is described in [33]. The building has a surface around 2000 m^2. The used earth to air heat exchanger includes two concrete pipes of 80 cm internal diameter and 40 m length, buried at depths 3 and 5 m, respectively. The pipes are connected to the ventilation system of the building and used for preheating and precooling purposes. Monitoring of the building has shown that the maximum supply air from the buried pipes never exceeds 22 °C. In parallel, it is found that earth to air heat exchangers decrease the discomfort hours in the office by 20–30% during the whole summer period.

The application of earth to air heat exchangers in three office buildings in Germany is described in [34]. In the first office, Netz AG (Hamm), 26 buried exchangers were designed for an air flow of 12,000 m^3/h. The surface of the building was close to 6000 m^2. The length of the pipes varied between 67 to 107 m. During the summer period when the ambient temperature was above 30 °C, the exit temperature in the exchanger was close to 18 °C. The outlet air temperature was always between 20 and 5 °C. The specific energy gains were calculated close to 13.5 kWh/m^2/year.

In the second office, Fraunhofer ISE, seven exchangers offering a total flow of 9000 m^3/h, were buried at 2 m depth. The surface of the building was 13,150 m^2. The length of the pipes was around 95 m. When the ambient air during summer was close to 36 °C, the exit temperature from the exchangers was around 24 °C. The specific energy gains were calculated close to 23.8 kWh/m^2/year.

Finally, in the third office, Lamparter, two pipes are buried at 2.3 m depth offering a total flow of 1100 m^3/h. The surface of the building was 1000 m^2. The length of the pipes was 90 m. When the ambient air during summer was above to 30 °C, the exit temperature from the exchangers was around 20 °C. The specific energy gains were calculated close to 12.1 kWh/m^2/year.

The application of four earth to air heat exchangers of 32 m length buried at 1.5 m depth at an office building in Marburg in Germany is described in [35] and [36], [37]. The total flow through the pipes was 3100 m^3/h. The cooling energy contribution of the exchangers was quite low and close to 1.5 kWh/m^2/year.

The application of earth to air heat exchangers in an office building of the University of Siegen, GIT, in Germany is described in [35] and [38]. The total surface of the building was 3243 m^2. The final energy use of the building was close to 70 kWh/m^2/y. Another similar application is described in [35] and [39], in the UBA building in Germany. The surface of the building was 32,384 m^2, and the earth to air heat exchanger used to precondition the outside air through over 5 km of tubes. The final primary energy of the building was 73.1 kWh/m^2/y.

Five horizontal earth–brine heat exchangers having a length of 100 m each are installed at 1.2 m depth and are used to heat and cool an office building of 833 m^2 in Germany [40]. Monitoring of the building has shown that the maximum heat dissipation per meter of tube was 8 W, while the COP of the ETAHE for cooling was 18.

Two polyethylene pipes having a length of 90 m and buried at 2.80 m depth, are used to supply cooling to an office building of 1488 m^2 in Germany [41]. The EATHE system is monitored for about three years and it is found that the temperature drop in the pipes was close to 10 °C while the COP of the system was measured between 35 and 50.

The use of EATHE in a commercial building, Schwerzenbacherhof, near Zurich, Switzerland, of 8050 m^2 is described in [42–46]. The exchangers are buried at 6 m depth while the system consists of 43 parallel high density pipes of 23 m length. The ground system is activated during the summer when the outdoor air temperature exceeded 22 °C. Monitoring of the buildings has shown that the EATHE system provides about 1/3 of total cooling demand.

Three ground heat exchangers have been used in the educational building of FH BRS University Dortmund in Germany [35] and [47]. The length of each pipe was 75 m, and was buried at 3.8 m depth. The total usable surface of the building was 16,000 m^2. The building was monitored and it is found that the air circulated through the pipes decreased its temperature up to 7 K compared to the ambient temperature. The specific contribution of the earth to air heat exchangers varied between 10 and 16 kWh/m^2/year.

An horizontal 1.5 m × 2 m concrete intake duct buried approximately 1.5 m below the ground surface was used to heat and cool an educational building in Norway, (Media School) [46,48–51]. The total surface of the building was 1001 m^2. Monitoring has shown that the EATHE system covers all cooling needs of the building. In another educational building in Norway, the Jaer primary school, the ETAHE system consisted of two parts: a prefabricated concrete pipe (20 m length and 1.6 m diameter) and a rectangular cast-in-place concrete duct (35 m length, 2 m width, and 3 m height) with a total surface area of about 450 m^2 [46,48–52]. The surface of the building is 850 m^2. Monitoring of the building has shown that the buried pipes cover the cooling needs and provide acceptable indoor air quality.

The application of almost 28 buried pipes in a school in Italy is described in [53]. The pipes' length was 70 m and were buried at 2.6 m. The building was not monitored but simulation results show that the average cooling contribution of each pipe was close to 760 kWh/m^2/y.

Four ground pipes buried at 1.5 m depth are used to provide cooling to the Philosophical school of the University of Ioannina, Greece [54,55]. The building has a surface of 4100 m^2. The system was monitored and is found that the EATHE system provides 33 kWh/m^2/year for cooling purposes.

Two production buildings equipped with earth to air heat exchangers in Germany are reported in [56]. The Huebner building of the University Hannover, having a surface of 2122 m^2 and the Surtec University Darmstadt, Passive House Institute with a surface of 4423 m^2. The final energy consumption of the buildings was close to 100 kWh/m^2/y and 73 kWh/m^2/y, respectively

The application of an earth to air heat exchanger to a hospital building in India is described in [56]. The total length of the heat exchanger – tunnel system was 3.66 × 4.57 m to 0.91 × 0.91 m. The monitoring of the system showed that when the maximum ambient temperature was close to 42 °C, the maximum air temperature at the exit of the tubes was close to 25.5 °C. It was concluded that an 80 m long tunnel of 2.05 × 1.4 m cross-sectional area can cool seven rooms of approximately 16 m^2 floor area.

Eleven pipes buried at 2 m depth have been used to provide heating and cooling to an 80 beds care home in Frejus, France [57]. The total surface of the building was 3950 m^2 and the EATHE system is used to cool the dining room of 380 m^2. Monitoring of the building has shown that the system delivered an initial cooling power of 14 kW at 2 m^3/s air flow-rate and of 9.5 kW at 1 m^3/s air flow-rate. In summer, cooling power values of typically 5 kW were observed after one to three days of uninterrupted use.

A ground cooling system composed by buried pipes of 40 m length, buried at 4 m depth, is installed in a building named "CircoLab", which is a multi-functional facility with corporate, conference, recreational, cultural and community functionalities [57]. The surface of the building was 382 m^2. Monitoring of the system has shown that the exit temperature from the buried pipes was almost 5 °C lower than the ambient temperature.

Six pipes buried at 3 m depth were used to cool an athletic centre in the major Athens area in Greece [58]. The length of the pipes varied between 40–57 m. The building was not monitored, but thermal simulations have shown that the EATHE system covered almost the 60% of the cooling needs.

The use of earth to air heat exchangers in a multi-storey passive house building in Romania, (AMVIC PH), is reported in [56]. The ground exchangers consisted of two parallel drums of external diameter 400 mm buried at 3.5 m depth. The drums were connected by eight pipes and their length is 30.8 m and 5 m, respectively. Monitoring showed that when the ambient temperature was 32 °C the temperature at the exit of the pipes was close to 26 °C.

A ground heat exchanger buried at 1.5 m depth composed of 6 parallel lines of 11 m each was connected to an experimental building in New Delhi, India [59]. The air was circulated to the pipes and then used for ventilation purposes. Monitoring and simulation analysis has shown that the annual energy conservation potential of the exchanger was close to 10,320 kWh, while the average seasonal energy efficiency for cooling was 2.9.

Two earth to air heat exchangers having a length of 74 m and buried at 2.5 m were connected to a house in India [60]. Monitoring of the pipes system has shown that when the ambient temperature was 42 °C the exit temperature of the ground exchangers was close to 27 °C.

The application of an earth to air heat exchanger in a passive house in France is described in [61]. The pipes are buried at 1.6 m and have a length of 30 m. The system is connected to a building of 132 m^2, and was used for ventilation and cooling purposes. The project is not monitored but simulation results show that the use of the EATHE reduces the cooling degree days from 56 to 22. Another application of ETAHE in residential buildings in France is described in [62]. An exchanger of almost 40 m long was buried at 2.5 m depth. The exchanger was connected to the house to provide ventilation, while a similar building not connected to EATHE was monitored as well. It is found that when the ambient temperature was 37 °C, the exit temperature from the exchangers was 24 °C. In parallel, the building connected to the EATHE was almost 3 °C lower temperature than the same building not associated to an exchanger.

The application of a ground exchanger of 39 m length buried at 2 m depth and connected to a residential building of 33 m^2 in France is described in [63]. It is reported that the used exchanger improves considerably comfort conditions during summer, while it keeps the indoor temperature of the house below 27 °C without the use of air conditioning systems.

An experimental application of a 48 m long pipe buried at a depth from 2.6 to 3.2 m in a small building in Italy is described in [53]. The project was monitored and it is reported that the temperature difference between the inlet and the outlet of the pipe during the summer period was close to 10 °C.

The results of a European demonstration project aiming to integrate EATHE systems in buildings is described in [57]. In particular two ground pipes are used to provide heating and cooling in each of 6 residential buildings in Portugal. The pipes were 25 m long. Monitoring has shown that during the summer period the temperature of the air circulated inside the pipes was reduced by 8 °C.

2.1.2. Using EATHE in agricultural greenhouses

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 [64]. 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 [64].

An agricultural greenhouse of 1000 m^2 equipped with five earth to air heat exchangers is described in [65]. The greenhouse is located in Greece. Five tubes of 30 m length have been buried at 1.5 m depth. Monitoring of the greenhouse has shown that the temperature reduction inside the tubes during the summer period was almost 10 K.

The installation of 26 non-perforated, corrugated buried plastic drainage pipes in a greenhouse in Canada of almost 80 m^2 is described in [66,67]. Two rows of 13 pipes, 10.5 m long, were buried at 450 mm and 750 mm depth respectively. Monitoring of the system has shown that the temperature drop inside the pipes was between 3–4 K.

An experimental application of EATHE in an agricultural greenhouse of 24 m^2 in India is described in [68–70]. The exchanger was buried at the depth of 1 m and was 39 m long. Monitoring of the greenhouse has shown that its temperature was 3–5 °C lower in summer when the ground system was in use.

A system of earth to air heat exchangers consisting of 20 pipes buried at 2 m depth and 15 long has been installed in an agricultural greenhouse of 150 m^2 in Greece [71]. The greenhouse was monitored only during the winter period where the EATHE system had an important contribution. In another experiment described in [72], 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.

A pipe of 47 m length was buried at 3 m depth in an experimental greenhouse of 48.1 m^2 in Turkey [73–75]. The daily maximum cooling coefficient of performances (COP) value of the system was measured close to 15.8. The total average COP in the experimental period was close to 10.0.

2.2. Modelling the performance of earth to air heat exchangers

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 [76], 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. The main characteristics of the considered models are given in Table 1.

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 [77].

The performance of eight simplified numerical and analytical models presented during the 1980s to predict the exit temperature of EATHE [78–85] is evaluated in [86]. All models are applied in a single and not a multi pipe configuration. As mentioned, most of the models predict a quite similar exit temperature for the earth to air heat exchangers. Some details about the considered models are

Table 1
Characteristics of the proposed models to simulate the performance of EATHE.

Reference	Type of model	Dimensions	Single or multi-pipe	Validation
Deterministic—Analytical Models				
[87]	Analytical Steady State	One Dimensional	One Pipe	Successful Validation data are not provided
[99]	Analytical Transient	One Dimensional	One pipe	Successful Validation against existing experimental data.
[102]	Analytical Transient	Three dimensional	One pipe	Validation data are not provided
[88]	Analytical Steady State	One dimensional	One pipe	Successful Validation against a parametric prediction model
[89]	Parametrical Analytical Model	One dimensional	One pipe	Successful Validation against existing experimental data.
[79]	Analytical model	One dimensional	One pipe	Successful Validation against existing experimental data.
[82]	Analytical model	One dimensional	One pipe	
[84]	Analytical model	One dimensional	One pipe	
[90], [91]	Analytical model	One dimensional	One pipe	Successful Validation against existing experimental data, (52)
[93]	Analytical model	One dimensional	One pipe	
Deterministic Numerical Models				
[78]	Numerical Model	One dimensional	One pipe	
[80]	Numerical Model	One dimensional	One pipe	
[81]	Numerical Model	One dimensional	One pipe	
[83]	Numerical Model	One dimensional	One pipe	
[85]	Numerical Model	One dimensional	One pipe	
[63]	Numerical Model	One dimensional	One pipe	Successful Validation against existing experimental data.
[97]	Numerical Transient	Two Dimensional		Validation data are not provided
[76]	Numerical Transient	Two Dimensional	Multi-pipe	Successful Validation against a detailed numerical model
[109]	Numerical Transient	Two Dimensional	One pipe	Successful Validation against existing experimental data
[98]	Numerical Transient	Two Dimensional	Single pipe	Successful Validation against a detailed numerical model
[95]	Numerical Transient	Three Dimensional		Validation against real experimental data. Maximum difference between experimental and theoretical values: 5%
[96]	Numerical Transient	Three dimensional	Multi pipe	Successful Validation against existing experimental data. The mean difference between the theoretical and experimental data was 0.7 °C in winter and 0.6 °C in summer
[100]	Commercial CFD tool. Numerical Transient.	Not reported		Validation against real experimental data. Maximum difference between experimental and theoretical values: 15%
[101]	Commercial CFD tool. Numerical Transient.	Not reported		Successful Validation of the convective model against data collected in an experimental room
[72]	Numerical Transient	Not reported	Multi pipe	Successful Validation against existing experimental data.
Data Driven Models				
[98]	Data Driven – Neural Network		Single Pipe	Successful Validation against a detailed numerical model
[103]	Data Driven – Genetic Algorithm		Single Pipe	Successful Validation against a detailed numerical model

given in Table 1. An one dimensional analytical steady state method to calculate the performance of buried pipes is presented in [87]. The authors developed a relation that links the thermal efficiency with the pressure drop inside the exchanger. In parallel, a graphical method to determine the length and the diameter of the pipes is provided. The paper did not include any validation exercise against experimental data.

An analytical predictive model is also presented in [88]. The system is modelled as two coupled heat transfer processes, convection inside the pipe and conduction between the pipes and the ground. The proposed model was validated against parametric prediction models and a good agreement is reported.

An analytical parametrical prediction model for the calculation of the exit air temperature from EATHE is also proposed in [89]. Four variables are considered to calculate the performance of the earth to air heat exchangers: tube length (L), tube radius (r), velocity of the air inside the tube (V) and depth of the pipe below the earth surface (D). The model was validated against experimental data as well as predictions from a detailed numerical model for the thermal performance of the earth tube system.

Another analytical simplified model to optimize the use of EATHE is described in [90] and [91] GAEA (Graphische Auslegung von Erdwärme Austauschern). The model is designed for one pipe application and is successfully validated against experimental data [92]. In [93] an analytical model assuming an undisturbed temperature of the earth surface in contact with the ETAHE pipe is described. According to [94], the model is simple estimation method, and does not account for heat transfer in the soil and other processes in EATHEs.

A three dimensional transient numerical model, is developed and described in [95]. The model considers heat and mass transfer phenomena and is validated against experimental data collected from an EATHE installed in an agricultural greenhouse. A very good agreement between the numerical and the experimental data has been achieved. The maximum reported difference is about 5%. A second three dimensional transient numerical model is also described in [96]. The model can be used for the evaluation of the thermal performance of multiple-pipe EATHE. Using the detailed numerical model, simple analytical approximate expressions have been developed and proposed. The numerical model is validated against experimental data and is found that the mean difference between the theoretical and experimental data was 0.7 °C in winter and 0.6 °C in summer.

A two dimensional numerical transient model that permits to compute the ground temperature at the surface and at various depths as well as the exit temperature of the air form the heat exchangers is described in [97]. The model is applied in the simulation of the energy system of the Pirmasens PH building, (Rhineland Palatinate, Germany) however no validation data are given. A second two dimensional transient numerical model to predict the performance of EATHE is presented in [88]. Superposition techniques were used to analyse the influence of the ground surface temperature on the soil temperature at any point in the pipe vicinity. The model is validated against an extensive set of experimental data and a very good agreement is reported. A third two dimensional numerical model is also described in [76]. The model is based on the use of convolutive response factor algorithm. The validation is performed against a three dimensional detailed numerical simulation model where a very good agreement between the two codes has been found. Finally, a fourth, two dimensional transient numerical model is presented in [98]. The model accounts for humidity variations of the air, natural thermal stratification of the soil, latent and sensible heat transfer. The model was successfully validated against experimental data.

A single dimensional transient analytical model to predict the performance of EATHE is proposed in [99]. Based on the results obtained, a simplified analytical model is proposed as well. The models are validated against existing experimental data and the agreement was satisfactory. A numerical one dimensional transient model is also described in [63]. The model is successfully validated against experimental data.

The use of the commercial Computational Fluid Dynamics software FLUENT to predict the temperature distribution inside earth to air heat exchangers is described in [100]. The obtained data have been compared against experimental data collected through the application of EATHE in a building in Southern Brazil. It is reported that the maximum difference between the theoretical and experimental results was not exceeded 15%. A second use of CFD models, (Fluent), to predict the performance of large rectangular EATHE is described in [101]. The accuracy of the proposed method to calculate convective heat transfer is validated against data collected in an experimental chamber.

An explicit numerical simulation model to simulate sensible and latent heat thermal processes in EATHE is described in [72]. The tool is connected to the TRNSYS software and is able to simulate multiple pipes. The proposed algorithms are validated against existing experimental data collected from an agricultural greenhouse equipped with earth to air heat exchangers.

A model to calculate the performance of EATHE using eight steady state equations together with six equations describing the heat fluxes perpendicular to the soil elements, one equation describing the heat flux perpendicular to the soil – environment interface and finally one equation that describes the heat flux between the soil and the pipe is described in [102]. Validation data are not provided.

Data driven techniques to predict mainly the exit temperature from EATHE were also developed and are available for use. A neural network model to estimate the hourly variation of the exit air temperature has been developed and described in [98]. The method is based on the use of back propagation techniques and uses as inputs, ground temperatures, air temperature, relative humidity, ground temperature at burial depth, air mass flow rate and tunnel length. The predictions of the model were compared against the transient numerical model described in [98], and it is found that the data driven model is in agreement with the deterministic one. A second data driven model based on the use of genetic algorithms to optimize the design of EATHE is described in [103]. The proposed model is compared against the transient deterministic model described in [98], with successful results.

Additional models on the calculation of the performance of earth to air heat exchangers are described in [42,104–107].

A comparative analysis of nine simulation models to predict the thermal performance of earth to air heat exchangers is given in [108]. It is found that the models described in [72] and [109] are validated and found to be accurate within 1% of existing published data.

2.3. Coupling the buildings with earth to air heat exchangers

A new methodology to calculate the contribution of earth to air heat exchangers to buildings is proposed in [110].

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 [110]. The new extended method is validated against detailed simulations performed with TRNSYS.

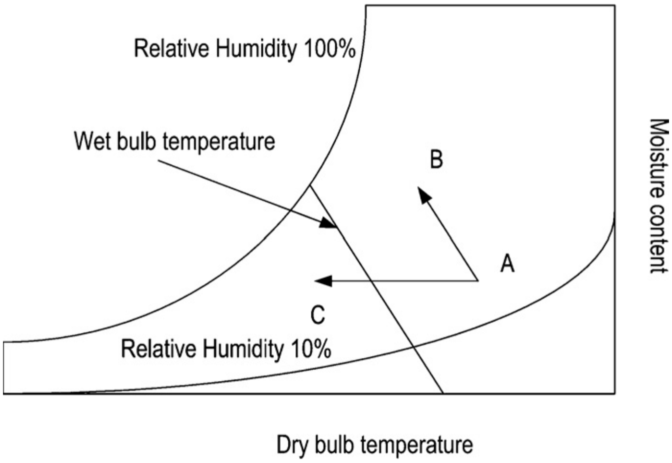

Fig. 1. The direct (DEC-Line AB) and indirect (IEC-Line AC) evaporative cooling process.

Research described in [111] 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%.

Analysis of the above can be found in Tables 1–3 where more references are discussed [112–125].

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 (Fig. 1).

The limit of the evaporative cooling potential is given by the wet bulb temperature of the air to be cooled. Some researchers [126,127] 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.

The state of the art review in the following sections is based on the categorization of evaporative cooling to direct and indirect. Finally a third section is added to include hybrid systems such as

Table 2
Characteristics of the Building projects where EATHE systems are used.

Reference	Country/region	Type of building	Surface of building	Characteristics of EATHE	Results
[33]	Belgium	Office	$\sim$2000 m^2	Two buried at 3 and 5 m	The maximum supply air from the buried pipes never exceeds 22 °C. In parallel, it is found that earth to air heat exchangers decrease the discomfort hours in the office by 20–30% during the whole summer period.
[34]	Germany	Office	$\sim$6000 m^2	26 buried exchangers at 2–4 m depth, for an air flow of 12,000 m^3/h	When the ambient temperature was above 30 °C, the exit temperature was close to 18 °C. The outlet air temperature was always between 20 and 5 °C. The specific energy gains were close to 13.5 kWh/m^2/year.
[34]	Germany	Office	$\sim$13,150 m^2	7 buried exchangers at 2 m depth, for an air flow of 9000 m^3/h	When the ambient temperature was above 36 °C, the exit temperature was close to 24 °C. The specific energy gains were close to 23.8 kWh/m^2/year.
[34]	Germany	Office	$\sim$1000 m^2	2 buried exchangers at 2.3 m depth, for an air flow of 1100 m^3/h	When the ambient temperature was above 30 °C, the exit temperature from the exchangers was around 20 °C. The specific energy gains were calculated close to 12.1 kWh/m^2/year
[35,36,112]	Germany	Office	$\sim$1948 m^2	3 buried exchangers at 1.5 m depth, for an air flow of 3100 m^3/h	The specific energy gains were calculated close to 1.5 kWh/m^2/year
[35,38]	Germany	Office	$\sim$3243 m^2	–	The final energy use of the building was close to 70 kWh/m^2/y
[40]	Germany	Office	$\sim$833 m^2	Five horizontal earth–brine heat exchangers having a length of 100 m each are installed at 1.2 m depth	The maximum heat dissipation per meter of tube was 8 W, while the COP of the ETAHE for cooling was 18.
[41]	Germany	Office	$\sim$1488 m^2	Two polyethylene pipes having a length of 90 m and buried at 2.80 m depth	The temperature drop in the pipes was close to 10 °C while the COP of the system was measured between 35 and 50.
[35]	Germany	Office	$\sim$32,384 m^2	5000 m	The final primary energy use of the building was close to 73 kWh/m^2/y
[42–46]	Switzerland	Commercial	8050 m^2	The exchangers are buried at 6 m depth, the system consists of 43 parallel pipes of 23 m length	Monitoring of the buildings has shown that the ETAHE system provides about 1/3 of total cooling demand
[35,47]	Germany	Educational	$\sim$16,000 m^2	5000 m	The air circulated through the pipes decreased its temperature up to 7 K compared to the ambient temperature. The specific contribution of the earth to air heat exchangers varied between 10 to 16 kWh/m^2/year.
[46,51]	Norway	Educational	1010 m^2	An horizontal 1.5 m × 2 m concrete intake duct buried 1.5 m below the ground surface	Monitoring has shown that the EATHE system covers all cooling needs of the building.
[46,52]	Norway	Educational	850 m^2	It consists of two parts: a prefabricated concrete pipe (20 m length and 1.6 m diameter) and a rectangular cast-in-place concrete duct (35 m length, 2 m width, and 3 m height) with a total surface area of about 450 m^2	Monitoring of the building has shown that the buried pipes cover the cooling needs and provide acceptable indoor air quality.
[53]	Italy	Educational	–	28 buried pipes of 70 m length buried at 2.6 m	The building was not monitored but simulation results show that the average cooling contribution of each pipe was close to 760 kWh/m^2/y
[54,55]	Greece	Educational	4100 m^2	Four ground pipes buried at 1.5 m depth	The EATHE system provides 33 kWh/m^2/year for cooling purposes
[35]	Germany	Production	2122 m^2	–	Final energy consumption around to 73 kWh/m^2/y
[57]	Italy	Multi functional	382 m^2	buried pipes of 40 m length, buried at 4 m depth	The exit temperature from the buried pipes was almost 5 °C lower than the ambient temperature.
[58]	Greece	Athletic Center	–	Six pipes buried at 3 m depth. The length of the pipes varied between 40–57 m	The building was not monitored, but thermal simulations have shown that the EATHE system covers almost the 60% of the cooling needs of the building.
[113]	India	Hospital	–	80 m	When the maximum ambient temperature was close to 42 °C, the maximum air temperature at the exit of the tubes was 25.5 °C. An 80-m-long tunnel of 2.05 × 1.4 m cross-sectional area can cool seven rooms of approx. 16 m^2 floor area.
[57]	France	Care Home	380/3950 m^2	Eleven pipes buried at 2 m depth	The system delivered an initial cooling power of 14 kW at 2 m^3/s air flow-rate and of 9.5 kW at 1 m^3/s air flow-rate. In summer, cooling power values of typically 5 kW were observed after one to three days of uninterrupted use.
[56]	Romania	Passive House	–	Two parallel drums buried at 3.5 m depth. Are connected by eight pipes and their length is 30.8 m and 5 m, respectively.	When the ambient temperature was 32 °C the temperature at the exit of the pipes was close to 26 °C
[60]	India	House	–	Two earth to air heat exchangers having a length of 74 m and buried at 2.5 m	When the ambient temperature was 42 °C the exit temperature of the ground exchangers was close to 27 °C.

Table 2 (*Continued*)

Reference	Country/region	Type of building	Surface of building	Characteristics of EATHE	Results
[61]	France	House	132 m^2	The pipes are buried at 1.6 m and have a length of 30 m	The project is not monitored but simulation results show that the use of the EATHE reduces the cooling degree days from 56 to 22.
[62]	France	House	–	The pipe is buried at 2.5 m and have a length of almost 40 m	When the ambient temperature was 37 °C, the exit temperature from the exchangers was 24. In parallel, the building connected to the EATHE was almost 3 °C of lower temperature than the same building not associated to an exchanger.
[63]	France	House	39 m^2	The pipe is buried at 2 m and have a length of almost 39 m	The exchanger improves considerably comfort conditions during summer, while it keeps the indoor temperature of the house below 27 °C without the use of air conditioning systems.
[53]	Italy	House	–	48 m long pipe buried at a depth from 2.6 to 3.2 m	the temperature difference between the inlet and the outlet of the pipe during the summer period it was close to 10 °C.
[57]	Portugal	House	–	2 pipes of 25 m length	During the summer period the temperature of the air circulated inside the pipes was reduced by 8 °C
[100]	Brazil	House	~30 m^2	Two pipes at 2 m and one at 0.5 m depth	Exchangers buried at 2 m depth have the potential to decrease indoor temperatures up to 3 K during the summer period
[59]	India	House		One pipe of 6 parallel lines of 11 m each buried at 1.5 m depth	The annual energy conservation potential of the exchanger was close to 10,320 kWh, while the average seasonal energy efficiency for cooling was 2.9.

two stage DEC-IEC, three stage evaporative coolers, and combination of evaporative cooling with other technologies [128–132].

3.1. *Direct evaporative cooling techniques*

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 Fig. 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 [133]. Typical commercial evaporative coolers have an effectiveness of 50–70%. The DEC's effectiveness describes the performance of the system by measuring how closely the supply air temperature leaving the evaporative cooler approaches the outdoor wet-bulb temperature:

$$n = \frac{T_{db-enter} - T_{db-supply}}{T_{db-enter} - T_{wb-enter}}$$

where n: the effectiveness of the DEC; $T_{\text{db-enter}}$: the dry bulb temperature of the air (usually outdoor) entering the DEC; $T_{\text{db-supply}}$: the dry bulb temperature exiting the DEC; $T_{\text{wb-enter}}$: the wet bulb temperature of the air (usually outdoor) entering the DEC.

Since the major drawback for DEC is the wet bulb temperature limitation, research efforts the last decades are mainly focusing on

Table 3
Characteristics of the EATHE systems.

Reference	Country	Surface of the Greenhouse	Characteristics of the EATHE system	Results
[65]	Greece	1000 m^2	Five tubes of 30 m length have been buried at 1.5 m depth.	Monitoring of the greenhouse has shown that the temperature reduction inside the tubes during the summer period was almost 10 K
[114]	Turkey	835 m^2	Plastic pipes buried at 50 cm deep	–
[115]	Canada	100 m^2	Plastic pipes buried at 45 and 65 cm deep	–
[116]	Italy	200 m^2	Concrete pipes buried at 40 cm deep	–
[117]	France	176 m^2	Concrete pipes buried at 40 and 80 cm deep	–
[118]	Canada	72 m^2	Plastic pipes buried at 30 and 60 cm deep	–
[119]	France	1470 m^2	45 cm deep	–
[120]	Russia	–	Plastic pipes buried at 40 cm deep	–
[121]	France	3000 m^2	Plastic pipes buried at 80 cm deep	–
[122]	Italy	1000 m^2	Concrete Pipes	–
[122]	UK	1000 m^2	Concrete Pipes	–
[123]	Japan	1736 m^2	Plastic pipes buried at 50 and 90 cm deep	–
[125]	Greece	150 m^2	Aluminium pipes buried at 200 cm deep	–
[26]	France	58 m^2	Plastic pipes buried at 200 and 210 cm deep	–
[79]	Greece	1000 m^2	Plastic pipes buried at 150 cm deep	–
[66,67]	Canada	80 m^2	26 non-perforated, corrugated buried plastic drainage pipes. Two rows of 13 pipes, 10.5 m long, were buried at 450 mm and 750 mm depths, respectively	Monitoring of the system has shown that the temperature drop inside the pipes was between 3–4 K
[69,70,124]	India	24 m^2	The exchanger was buried at the depth of 1 m and was 39 m long.	Monitoring has shown that its temperature was 3–5 °C lower in summer when the ground system was in use
[71]	Greece	150 m^2	20 pipes buried at 2 m depth and 15 long	–
[72]	Switzerland	–	PVC pipes of 11 m length running at 80 cm below the ground	–
[73–75]	Turkey	48 m^2	A pipe of 47 m length was buried at 3 m depth	The daily maximum cooling coefficient of performance was close to 15.8. The total average COP was 10.0.

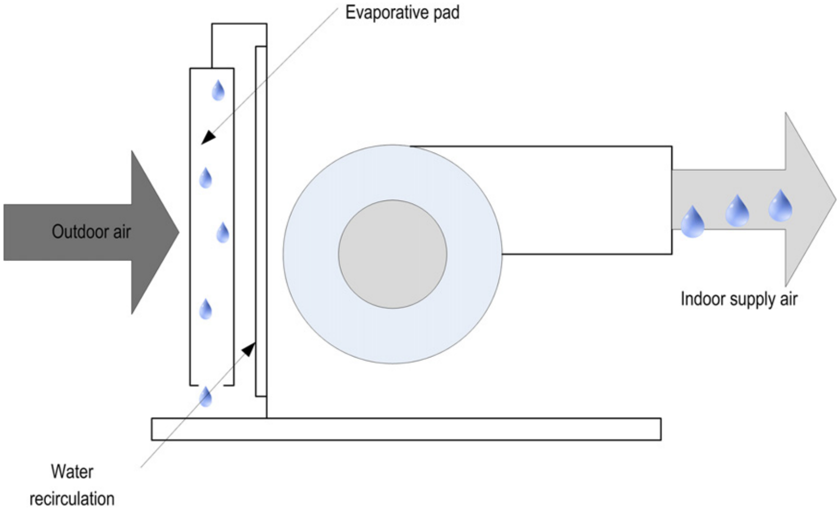

Fig. 2. The direct evaporative cooling.

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. [134] while exposing maximum surface area to the passing air flow. This is achieved by allowing the water to fall vertically over nylon lines or other filaments, thus exposing the maximum surface area to the passing air flow. Through simulation results for, a semi-arid location in New South Wales Australia the evaporative cooling system proposed shows average relative humidity inside the building equal to 73.2% with average air velocity of 0.28 m/s and average temperature of 24.18 °C, which is close to the comfort range.
- The use of micronisers is proposed for the Passive Down-draught Evaporative Cooling (PDEC) configuration studied by [135] and [136]. The micronisers are located close to high level air inlets. The micronisers spray small droplets of water into the air. During droplets' evaporation, latent heat is extracted from the air leading to a reduction of the dry bulb temperature of the air. The relatively dense cool air then descends into the building and cools it.
- A direct evaporative cooling is studied for a room in Delhi in [137] and [138] using TRNSYS computer simulation from May until June while the rest of the summer period is excluded due to increased humidity. The aim of the study is to find the optimum combination of air flow rate and by pass flow rate in order to maintain indoor comfort within acceptable limits. The research showed that the humidity is very high when the air by pass rate is zero leading to uncomfortable conditions. Comfort is achieved by a bypass rate ranging between 20–40% while when the bypass rate is increased and the evaporation is decreased discomfort occurs due to higher temperatures. Moreover increased air change rate ranging from 5–10 ach can lead to a significant comfort improvement.
- Another DEC configuration consists of the use of porous ceramics as evaporators. Porous ceramic evaporators for direct evaporative cooling (DEC) are proposed by [139], [140] and [141]. In [139] a sensitivity analysis is performed in order to assess the cooling effect versus air humidity and temperature supply water pressure, and evaporators' layout within the duct. The research showed that the higher the porosity, the higher the cooling effect while a low porosity gives no measurable effects. Moreover the air flow over the ceramic evaporators and the surface area play a significant role for the cooling effect. The maximum cooling effect measured in [139] is almost 224 W/m^2 with high porosity ceramic evaporator placed in a stack four high with water supplied at 1.0 m head.
- An evapo-reflective roof to reduce passive cooling in buildings for hot arid climates has been proposed in [142]. The roof design consists of a concrete ceiling over which lies a bed of rocks in a water pool. Over this bed is an air gap separated from the external environment by an aluminium plate. The upper surface of this plate is painted with a white titanium-based pigment to increase reflection of a radiation to a maximum during the day. At night, the temperature of the aluminium sheet falls below the temperature of the rock bed mixed with water. Water vapour inside the roof condenses and cools the roof. Through simulations in Laghouat city in Algeria the evaporative reflective roof showed that it can reduce the internal room air temperatures during the day up to 8 °C in comparison to the air temperatures for a conventional roof over the room.
- A coupling of evaporative cooling with solar chimney is performed by [143]. A solar chimney is attached to a south-facing wall. The evaporative cooling is performed via a ceiling panel with the wet channel is adjacent to the room side. The air inside the solar chimney is heated by the solar radiation creating an upward flow due to the stack effect. This flow initiates also air movement inside the room. By connecting the air exit of the evaporative cooler with the inlet of the solar chimney, the air travels through the evaporative cooler before it flows into the solar chimney. The system is tested via simulation and shows that is capable of coping with a radiative cooling load which is in range of 40–50 W/m^2 while it can reduce the peak load by 10% by a quarter of the ceiling area in an office building in Japan is replaced by the proposed configuration.
- A direct evaporative cooler that operates either with natural wind flow or with wind catchers is described in [144]. In the examined system, the total evaporative water mass, the available cooling temperature and required cooling time are the parameters under investigation. Through simulation tests it is shown that 20 kg water and 26 min are needed to evaporate for 1 ton of water and to lower its temperature to the wet bulb temperature of ambient air.
- Another attempt to couple evaporative cooling system with a solar chimney appears in [145]. The evaporative cooling technique exploits a cooling cavity where circulating water is sprayed on the top of the wall. A thin film flows along the wall surfaces of

the air passage. The solar radiation heats up the room air flowing through the chimney, and the hot air generates the draft in the chimney. Thus air is circulated in the solar chimney, room and cooling cavity. The chimney effect forces the air to move through the cooling cavity with wetted cool surfaces. Therefore, both cooling and ventilation are provided during daytime by solar energy. Numerical analysis together with experiments show that even when the solar intensity is low (i.e. 200 W/m^2) and the ambient air temperature is up to of 40 °C the indoor thermal conditions are within acceptable range. Since optimum indoor conditions can be achieved when outdoor relative humidity is less than 50% the proposed system is suitable for hot and arid climate.

- Water evaporative walls are proposed in [146] and [141] on 2010 and 2011. The system proposed in [146] includes ventilated walls which are sprayed in the ventilated layer and it exploits the latent heat derived from the evaporation of water and uses it to cool by intercepting all the thermal flux coming from outdoors. Various spraying systems are tested using a prototype evaporative wall configuration which is compared with a conventional wall. When the sprayers are activated the air temperature in the ventilated chamber drops abruptly and is maintained lower than the benchmark ventilated wall by 10 °C during the evaporative effect. By increasing the number of sprays a more evaporative effect is reached with duration of slightly more than 1 h. The reduction in the peak temperature is 5 °C after the spraying.
- A wet porous cooling plate as a building wall is proposed in [147,148] where cooling is performed via evaporation of the porous material. The effect of the outdoor climatic conditions in the cooling effectiveness as well as the plate's thickness is studied using theoretical modelling and experimental set-up. Through the analysis an average temperature of about 5–8 °C below the ambient is achieved in the porous plate with a thickness of 10 mm, 25 mm and 50 mm. The lower the plate thickness the lower the temperature difference achieved indicating that the porous plate thickness should be carefully designed.

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. More configurations [149–158] and applications [159–168] are described in next sections and tabulated in Tables 4 and 5.

3.2. Indirect evaporative cooling

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 (Fig. 3). 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 [158] as depicted in Fig. 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 [169] 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. Some examples are:

- An indirect evaporative chilled was developed and tested in [170] and [141]. The specific evaporative system was applied in a building in Shihezi City, China. The COP of the cooling energy room (obtained divided by electricity consumption of the indirect evaporative cooler and the fresh air handling unit) reached 9.1 while the COP of the total systems (cooling energy room obtained divided by electricity consumption of all components in the system) reached 4.9, which saved more than 40% electricity compared with ordinary air conditioning systems.
- An IEC is tested in an experimental house, in Maracaibo, Venezuela by [171]. An IEC is installed on the ceiling of the bedroom. The system consists of water exposed to an air flow controlled by small fans, which keep its temperature close to the wet bulb temperature. A polyethylene film supports the water and allows a fast heat transmission rate from the bedroom to the water. A plastic sheet covers the 30–40 mm water pond, while limiting the air only through inlet and outlet vents. Finally the roof is painted externally in white colour and insulated with 10 mm polystyrene, which protects the water pond from solar overheating. For the specific case study in Maracaibo, the indoor temperature drop through the IEC is 0.9–1 °C comparing with no cooling system.
- Sub-wet bulb temperature IEC is examined by various researchers. The aim of such systems is to enable cooling below the wet bulb temperature of the ambient air. The concept presented by [172] is based on branching the working air from the product air, which is indirectly pre-cooled, before it is finally cooled and delivered. The concept is to reach the dew point of ambient air. The coolers analysed are three two-stage coolers (a counter flow, a parallel flow and a combined parallel-regenerative flow) and a single-stage counter flow regenerative cooler. The wet bulb cooling effectiveness for the examples studied is 1.26, 1.09 and 1.31 for the two-stage counter flow, parallel flow and combined parallel-regenerative cooler, respectively, and it is 1.16 for the single-stage counter flow regenerative cooler.
- The significance of the heat exchangers in the cooling efficiency of the IEC is analysed in [173,174]. Numerical analysis is performed in order to simulate cross- and counter-flow M cycle heat exchangers' operational and geometrical characteristics targeting to improve their cooling effectiveness while simultaneously reduce their size. Prototype heat exchangers are used together with a validated model to test the systems' performance. The counter-flow exchanger demonstrated better cooling effectiveness and 20% higher cooling capacity than the cross-flow system.

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 [153,170,175–178]. 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 [179] and [180] 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

Table 4
Evaporative cooling systems.

Reference	Type	Configuration	Cooling effect
[149]	Two stage DEC-IEC	A two-stage evaporative cooling experimental setup consisting of an indirect evaporative cooling stage (IEC) followed by a direct evaporative cooling stage (DEC).	The effectiveness of the two stage system is 108–111% while the IEC' effectiveness is 55–61%. 60% power savings
[132]	Hybrid system including DEC coupled with of nocturnal radiative cooling, cooling coil	The cold water is stored in a storage tank. During next day, hot outdoor air is pre-cooled by the cooling coil unit and then it enters the direct evaporative cooling unit.	The results obtained demonstrate that overall effectiveness of hybrid system is more than 100%
[150]	Hybrid ground-assisted DEC.	A ground circuit provides pre-cools the air and then a DEC cools the air even below its wet-bulb temperature.	The results obtained demonstrate that overall effectiveness of hybrid system is more than 100%
[151]	Chilled-water coil in conjunction with a DEC pad	A DEC is used as an additional component to air-handling unit	Using a DEC in conjunction with a chilled coil results to 35% energy savings comparing the chilled coil For a LEED rated building, this corresponds to four credits for energy conservation.
[152]	DEC	Testing the speed of frontal air, the dry-bulb temperature of frontal air, and the temperature of the incoming water versus cooling efficiency	DEC cooling efficiency increases with frontal air dry-bulb temperature and decreases with frontal air velocity and incoming water temperature correspondingly.
[153]	DEC/IEC	100% outdoor air system integrates DEC/IEC.	The proposed system shows a 16–25% less annual cooling coil load and an 80–87% reduced annual heating coil load with respect to a conventional variable air volume system.
[154]	Dew point evaporative cooling	5 ton rooftop unit with Heat exchanger and flow path arrangement, provide unhumidified air below wet bulb temperatures.	80% energy savings relative to a conventional vapor compression system.
[155]	Multi-step system of nocturnal radiative cooling and two-stage evaporative cooling	During the night, water is passed by the radiative panels and is stored. During the day, the stored cold water in the storage tank is used as coolant for a cooling coil unit and a two-stage evaporative cooler.	Higher effectiveness than conventional two-stage evaporative coolers. Energy savings 75 and 79% compared to mechanical vapor compression systems.
[156]	IEC by polycarbonate with a total heat exchange area of 6m2	Tested in laboratory while enabling different climatic conditions to a climatic chamber.	The heat transfer through the heat exchanger polycarbonate wall improves the overall effectiveness.
[135,136]	Passive Down-draught Evaporative Cooling (PDEC)	Micronisers that are located close to high level air inlets.	Savings between 50 and 83%-depending upon occupancy and set-point. Thermal comfort could not be achieved by PDEC only
[141,139,140]	DEC	Porous ceramic evaporators	–
[157]	DEC	Evaporative condenser for residential refrigerator was introduced. Sheets of cloth are wrapped around condenser to suck the water from a water basin by capillary effect.	The condenser temperature increases 0.45 °C for each degree increase in evaporator temperature when the air velocity is 2.5 m/s, and the ambient condition is 29 °C and the relative humidity is 37.5%.

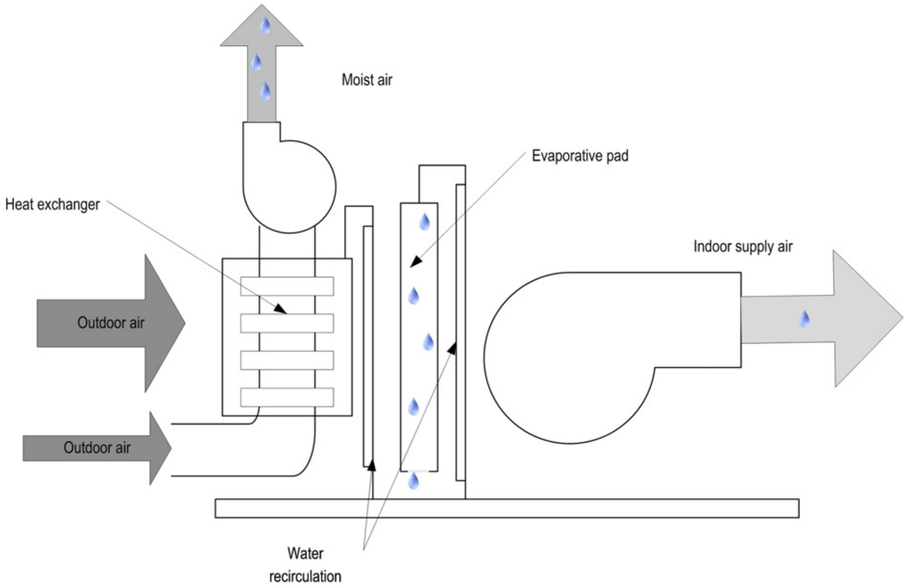

Fig. 3. DEC configuration.

Table 5
Evaporative cooling applications.

Reference	Type of application	Location	System	Cooling effect
[159]	University building	Sonoma, US	IEC/DEC the outside air is blown through DEC medium that reduces the dry-bulb temperature of the air. Then IEC pre-cools the primary air stream via an air-to-air exchanger.	–
[176]	Residential Building	Israel, hot and arid climate	Direct–Indirect Evapoartive cooling	The efficiency estimated as 0.8 for the DEC, and 0.9 for the DEC-IEC.
[160]	60 cities	India	DEC utilisation potential for comfort conditioning.	The central and north western regions of the country have high potential, while the coastal region, eastern and northern regions have poor potential.
[161]	University library building	Delhi, India	Coupling of direct and regenerative evaporative cooling technologies with water chiller system	12.09% and 15.69% energy conservation and PMV within comfort range for most of the year
[170]	Residential two storey building	Bagdad, Iraq	Indirect evaporative cooling. Testing the effectiveness of the plate heat exchanger employed for the indirect evaporative cooling stage and its effect upon the variation in the air flow rate.:	Consumption is reduced to fan operation and water pumping. The COP is increased versus a conventional VAV.
[129]	Various building types	Kuwait	DEC, IEC with cooling tower, two-stage IEC/DEC, three stage IEC/DEC-mechanical vapour compression	The higher EER was for IEC/DEC followed by DEC. 27–35% energy efficiency compared to mechanical vapour compression system.
[162]	Various building types	India, Australia	DEC and IEC	75% energy savings for all evapotive systems tested. Improved cpmfort by IEC versus DEC
[163]	Demo building	Shihezi, China	IEC	40% reduction in electricity.
[164]	Office	Beirut, Lebanon	DEC with split air conditioning system	Total daily reduction in the consumed energy of 5% in June and 4.5% in August.
[165]	Office	Sydney, Australia	Hybrid evaporative cooling coupled with HVAC	52% power savings can be obtained by this system while maintaining the predicted mean vote (PMV) between −1 to +1 for most of summer time
[166]	Office	Xinjiang, China	radiant air conditioning based on evaporative cooling	43% energy savings
[167]	Residential	US	Retrofitting the air conditioning condenser with a media pad evaporative cooler.	17–20% increase of system's performance and a decrease in diversified peak of 0.33 kW
[168]	Residential building	Mediterranean region	Testing in 500,000 Mediterranean residential buildings	Energy savings about 1084 GWh/year. Total avoided CO2 emission 637,873 ton. Payback period 2 years

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.

3.3. *Modelling the performance of evaporative cooling*

The various techniques used to model evaporative cooling processes by various researchers can be distinguished to numerical simulation [181] and soft computing techniques [182]. Some examples are:

- A simplified simulation model for both direct and indirect evaporative cooling passive buildings was developed in [183]. The model can be coupled with any type of building using thermal networks. The simplified simulation model assumes that the indoor air temperature is uniform while the temperature of the water is assumed to be equal to the wet bulb temperature of the

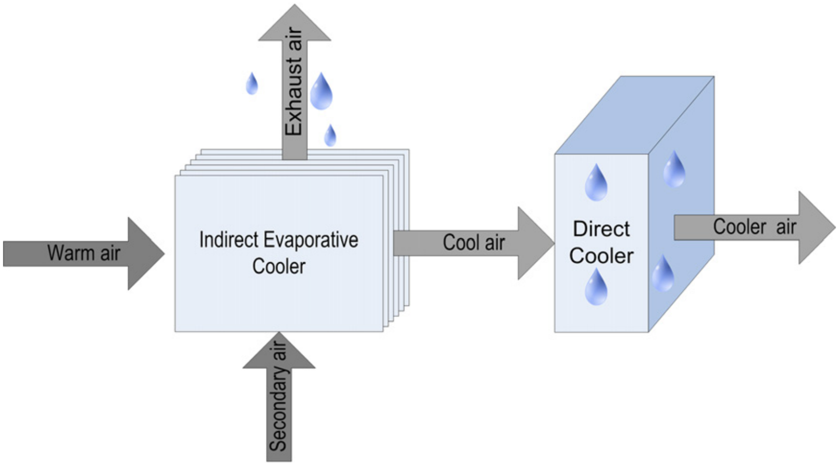

Fig. 4. Two stage evaporate cooling or IEC-DEC configuration.

air that enters the cooler. Finally the specific simulation program does not cover all types of control strategies for indirect evaporative cooling processes. Although there are limitations the model was extensively used to study the evaporative cooling techniques in Southern Africa.

- Artificial neural networks (ANNs) are used in [184] to predict the performance of a direct evaporative system. Using some of the experimental data for training, a three-layer feed-forward ANN model based on back propagation algorithm was developed. The predictions agreed well with the experimental values with correlation coefficients in the range of 0.969–0.993, mean relative errors in the range of 0.66–4.04%
- A modelling technique for the heat and mass transfer of evaporative devices is proposed in [132] that takes into account the surface wetting factor and the non-unity Lewis factor The analysis reveals that poor wetting degrades cooling efficiency and water flow rate should be enough low to keep the surface wet.

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 [176]. 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 [126,185] 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 [186] 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 [187,188].

Santamouris et al. [189] 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 [190,191] exacerbate the cooling load of buildings, increase the peak electricity demand for cooling, decrease the efficiency of air conditioners, [7,10] 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 [189]. 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.

4.1. Ventilation experiments

As mentioned above the main experimental analysis is performed either using test cells or by real experimental data in case study buildings.

Additionally to the experimental works, numerous simulation based studies have been published reporting the theoretical performance of individual buildings or sensitivity and climatic analysis [192].

Specific monitoring studies in real buildings or test cells, are reported in [28,188,193–203]. Most of the studies conclude that the use of night ventilation in free floating buildings may decrease the next day peak indoor temperature up to 3 K. In parallel, when applied in air conditioned buildings, a considerable reduction of the peak cooling may be expected.

Test cells are developed by various researchers to contribute in the quantification of ventilation effectiveness. Some examples [204–207] are tabulated in Table 6.

4.2. Simulation based techniques

Night ventilation is a very attractive passive cooling technique as it improves thermal comfort by reducing the operational costs for air conditioning. Although the principles of night ventilation are very simple, the overall system is very difficult to design and control. Moreover it involves considerable uncertainties concerning its cooling potential and effectiveness (see Section 4.4). Therefore the optimization and evaluation of night ventilation design is a complicated procedure and only few cases could be measured on site. As a result the simulation techniques for naturally ventilated buildings are very important during the design phase and in the evaluation of advanced hybrid and innovative technologies.

Available design methods for night ventilation range from simple analytical and empirical methods to multi-zone and computational fluid dynamics (CFD) techniques [208–210].

Most analytical approaches are based on a conventional macroscopic approach that utilises the Bernoulli Equation for flow and opening [200]. This equation, which is based on the conservation of energy, is used to calculate air velocities through openings.

Network models are widely used for simulation of ventilation in multi zone buildings coupled with thermal flow analysis [210]. The network method is based on the application of the Bernoulli Equation to determine the pressure difference and hence flow rate across each opening in the flow network. Zones are interconnected by flow paths, such as cracks, windows, doors and shafts, to form a flow network. Network methods are able to take into account the effects of outdoor climate, the location and size of each opening, and stack, wind and mechanically driven ventilation.

Computational Fluid Dynamics are based on the Navier–Stokes equations. CFD simulation provides detailed distribution of air temperature, air velocity, contaminant concentration within the building and its surrounding areas. However, the application of CFD

Table 6
Test cells for ventilation experiments.

Name	Type of experiment	Experimental set-up	Results	Reference
–	Two cells (4m × 4 m × 3 m)	Two identical test cells are introduced to test night ventilation effectiveness combined with insulation.	Pitch insulation and ceiling insulation lower the daytime indoor temperature up to 0.8 °C and 0.6 °C respectively.	[204]
Passlink	Test Cell Greece	The cell has a removable south wall and roof with a Pseudo-Adiabatic Shell (PAS). The experiment tested a typical ventilated Wall' and an upgraded ventilated Wall'.		[205]
Test Room	Test room with a wooden construction insulated with 100 mm rock wool. The dimension are 2.64 m × 3.17 m × 2.93 m (width × length × height) resulting in a volume of 24.52 m^3.	With different configurations of the air in- and out-let openings of the test room, mixing and displacement ventilation are investigated in terms of night cooling. The room is equipped with temperature sensors network in various locations	The amount of heat discharged during night-time ventilation per unit floor area and cooling potential depending on the air change rate is estimated.	[206,207]

for natural ventilation prediction has been limited due to increased computational time and computer requirements. Building simulation tools facilitate energy efficient sustainable building design by providing rapid prediction of thermal comfort, indoor air flow of the building and better understanding of the consequences of ventilation for cooling. Another modelling software that is very frequently used is TRNSYS coupled with COMIS [211,212]. The specific technique is a combination of thermal modelling with air flow representation and is a very powerful tool for estimating thermal comfort coupled with indoor air quality.

Some examples of the various modelling approaches are:

- Breesch et al. [33] used TRNSYS-COMIS to model night ventilation with heat exchangers. The simulations are used to estimate the relative importance of the different techniques. The evaluation shows that passive cooling has an important impact on the thermal summer comfort in the building. The models are validated by experimental analysis.
- Flourentzou et al. [213] used Bernoulli equations to measure the discharge coefficients in night ventilation for passive cooling.
- Simplified parametric building models for night ventilation using energy balance equations are proposed by Pfafferot et al. [203,214]. The specific models are tested versus experimental data that include the indoor temperature and the temperature amplitude from measurements. Moreover a powerful building simulation tool, ESP-r can be also used for night ventilation (Pfafferot, 2003).
- An analysis for the determination of the reduction in the maximum indoor temperature compared with the maximum outside temperature ($T_{\max}$) was carried out using an hourly simulation model ENERGY to predict the thermal performance of the building [215]. The results obtained show that in the hot humid climate of Israel it is possible to achieve a reduction of 3–6 °C in a heavy constructed building without operating an air conditioning unit. The exact reduction achieved depends on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night. The simple design tool provides the conditions under which night ventilation and thermal mass are effective.
- Yun and Steemers [216] employed a regression model to develop predictive models of window-control for night-time naturally ventilated offices. Separate logistic analyses for various buildings are conducted as different behaviours in window-control are observed from the monitoring activities due to the different types of openings (i.e. tilt and turn windows and side-hung openings). The window-control models are divided into arrival, subsequent occupation period and departure. The indoor temperature, outdoor temperature and a combination of the two temperatures as driving variables for window-control behaviour are modelled.

Finally some examples for the use of CFD for night ventilation are listed below:

- Favarolo et al. in [217] analysed the impact on the airflow rate of the dimensions and position of a large rectangular opening and of the temperature difference between inside and outside air using CFD where experimental results are used for CFD validation and verification.
- Fraisse et al. in [218] studied the effectiveness of a ventilated wall to improve summer comfort in wood-frame houses using a CFD model where by integrating forced convection of the ventilated wall air gap the cooling potential and the benefit of installing obstacles is analysed.
- Manz et al. in [219] used computational fluid dynamics to model night ventilation in double skin facades. The computational procedure integrates three different types of models spectral optical model, computational fluid dynamics model and building energy simulation model in order to decrease computational time and complexity.

In the modelling of ventilation systems a recurring theme is the decision on how accurate the models should be and the trade-off being between accuracy, computational time and complexity. Detailed models such as detailed CFD analysis require a significant effort to set up the problem, even more time to solve it and when the solution has been obtained, uncertainties in various parameters may create errors in the solution. On the other hand more simplified models such as network models make some critical assumptions that depending on the problem and the degree of accuracy can be acceptable. Therefore in all cases modelling of ventilation is a balance between the needs of accuracy and efficiency.

4.3. Night ventilation on various building types

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:

- The analysis of night ventilation for office buildings during summer period is performed by Blondeau et al. [195] showing 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. [220] in London region.
- The predicted effectiveness of night ventilation in four buildings in UK is studied in [221,222]. A hybrid ventilation strategy, i.e., air conditioning during the day and natural ventilation during the night shows that energy savings of about 5% of the cooling

energy could be obtained in typical buildings and up to 40% in buildings optimized for maximum benefit from night ventilation compared to the same building without night ventilation. The suggested energy savings would occur without any compromise on the internal thermal environmental conditions.

- Moreover night ventilation for office buildings' thermal performance, required peak power loads and required daily cooling energy loads in office buildings in a moderately warm summer climate is studied in [223]. Offices without internal loads and with large loads were compared. The role of intensive night cooling in the warm Mediterranean climates is also analysed in [223]. In buildings without large internal loads, intensive night ventilation combined with regular cooling during working hours is the most efficient strategy for office buildings. Testing the night cooling in buildings with large internal loads, intensive night cooling enables the lowest internal mass temperatures and the lowest power loads throughout the whole working day. The peak power load is reduced by 13%.
- Gratia et al. in [224] studied the night ventilation potential for narrow offices in Belgium where single-sided day ventilation can reduce cooling needs by about 30% and cross night ventilation can reduce the cooling demand by 38%. This is explained by the weather conditions where the outside temperatures are rather low and that the period of ventilation is long.
- The suitability of night ventilation for office buildings with lightweight construction located in cold climates is analysed by [225]. Through simulation based approaches using EnergyPlus the indoor thermal environment and the energy consumption in typical office buildings in northern China are studied. The most important factors influencing night ventilation performance such as ventilation rates, ventilation duration, building mass and climatic conditions were evaluate. With night ventilation rate of 10 ach, the mean radiant temperature of the indoor surface decreased by up to 3.9 °C. The longer the duration of operation, the more efficient the night ventilation strategy becomes. The results show that more energy is saved in office buildings cooled by a night ventilation system in northern China than ones that do not employ this strategy.
- An office building in Germany is monitored versus its ventilation in [226]. Adequate thermal insulation and moderate window dimensions guarantee a low heating and cooling energy demand. A central atrium serves as a buffer zone for solar energy gains during the winter. In summer, solar loads are minimised by efficient shading systems and cross ventilation in the atrium roof. The ventilation strategy during working hours uses both natural (from the outside and the atrium) and mechanical ventilation in the offices. The multifunctional corridors are mechanically ventilated. The building's energy performance was monitored over 2 years with a high time resolution. Within the monitoring campaign, the energy demand for heating and ventilation, the internal loads caused by equipment, operative and intra-fabric temperatures, flow rates due to mechanical ventilation and local meteorological conditions were measured. The building is designed to achieve moderate summer indoor conditions. The percentage of working hours with operative temperatures above 25 °C is around 10%. Passive cooling by free night ventilation improves the thermal comfort without increasing the electricity demand. The presented methodology for data evaluation using simulation allows a deeper insight into the efficiency of night ventilation (e.g. air flow patterns, user behaviour, building characteristics, heat transfer and energy balance) and gives the possibility to improve ventilation strategies. Hybrid ventilation strategies have to be implemented carefully in order to avoid disturbance of the natural ventilation by additional, mechanically driven air flows. An adapted simulation model can be used for advanced control strategies based on weather forecasts.
- 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). Each building is comprised, in the main, of cellular offices, with one or two people per office, but also contains a small number of rooms for various other purposes. One of the key features of these buildings is the employment of a night-time ventilation strategy for space cooling. This is enabled by carefully designed windows that do not present security issues, thus allowing night-time natural ventilation. Therefore, the occupants in these building are free to keep windows open during the night when they leave the office at the end of each day [216].

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 [227] regarding the residential buildings of Iran. The study showed that that construction of east and west windows should be discouraged while increased air changes per hour ranging from 12 to 30 ach should be applied.
- The effectiveness of night ventilation technique for residential buildings in hot-humid climate of Malaysia is analysed in [201]. The effects of different natural ventilation strategies on indoor thermal environment for Malaysian terraced houses are evaluated based on the results of a full-scale field experiment. The results of field experiment indicated that the cooling effect of night ventilation is larger than those of the other ventilation strategies during the day and night. It was observed that the night ventilation technique lowered the peak indoor air temperature by 2.5 °C and reduced nocturnal air temperature by 2.0 °C on average, compared with the current window opening patterns, i.e. daytime ventilation.
- Night ventilation with solar chimneys is applied to social housing design for hot climates in Madrid in [228]. Storage chimneys – oriented to the west – collect solar gains during the afternoon while the surface temperatures of the concrete walls reach temperatures up to 50 °C. During collection the chimneys are closed. During night time when the ambient temperatures are down to around 20 °C the flaps at the top of the chimneys are opened and now the chimney effect of the collected heat sucks the exhaust air out of the apartments. The fresh cold night air enters through the east facade and runs through the flat, cooling down the thermal masses of the open walls and ceilings. Results of the simulation show that indoor temperature remains between 21–23 °C during night.
- Two hundred fourteen air conditioned residential buildings using night ventilation techniques have been analysed in [189]. The selected buildings present a very large spectrum of cooling needs and applied night air flow rates. It has been found that night ventilation applied to residential buildings may decrease the cooling load up to 40 kWh/m^2/y with an average contribution close to twelve, 12 kWh/m^2/y. The correlation between the cooling needs of the buildings and the energy contribution of night ventilation is found to be almost linear. In parallel, the uncertainty associated to the evaluation of the energy contribution of night ventilation decreases seriously for higher air flow rates.

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.Other building types are also studied versus the applicability of ventilation as a passive cooling technique:

- Night ventilation coupled with double skin facades for industrial archaeology buildings is studied in [229] showing using simulation techniques that at least 12% of energy can be reduced on yearly basis.
- A night ventilated library located in Ireland is considered and analysed in [230]. The building is modelled using ESP-r and the mean bias deviation between the predicted and experimental data is better than 0.45 °C for the dry bulb temperature. Examination of night ventilation rates indicated that increasing night ventilation up to 10 air changes per hour result to 1 °C reduction for medium gains and 2 °C reduction for high internal gains.
- Night ventilation and active cooling coupled operation strategy is studied for the large supermarkets in cold climates in China. The model on the thermal storage of the indoor goods is set up. Furthermore, based on the thermal balance of the whole room, the temperature change model is founded. The coupled operation process is simulated for the typical supermarket buildings. The overall energy consumption of the system is analysed. The result shows that the opening time, duration and air flow rate of night ventilation all affect the performance of active cooling. Active cooling will influence night ventilation too. It also turns out that the coupled operation leads to shorter operation time of active cooling. The various operation modes are given at different climatic conditions. Compared with the normal active cooling system, the coupled operation system can save energy at 2.99 kWh/(m^2 a) in cold climates in China while 3.24 kWh/(m^2 a) in Harbin [231].
- Three real buildings in Athens, Greece the two ones located in the suburban areas and the third one in the centre of Athens [199]. Measurement of indoor temperature as well as of the air flow rates, when night ventilation is applied is performed. Using simulation techniques, coupled with the experimental data. For high thermal mass, of night ventilation techniques, permits to decrease the next day peak indoor temperature, under free-floating conditions, by up to 3 °C. For low thermal mass under free-floating conditions, night ventilation techniques decrease the next day peak indoor temperature to about 0.2 °C, while the 24-h average reduction of the indoor air temperature is close to 0.4 °C.

4.4. *Ventilation effectiveness*

A number of studies are performed in order to better understand the techniques' effectiveness and to diminish uncertainties. Although night ventilation contributes to the reduction of cooling demand, the uncertainties in the prediction of thermal comfort restrain engineers from wide application of this technique.

- The heat transfer at the internal room surfaces is one of the uncertainties consider by the researchers [207]. The increased convection usually expected due to high air flow rates is hard to predict. Therefore an experiment was set up in a full scale test room showing that for low air flow rates displacement ventilation is more efficient than mixing ventilation. For higher air flow rates the air jet flowing along the ceiling has a significant effect, and mixing ventilation becomes more efficient. A design chart to estimate the performance of night-time cooling during an early stage of building design is developed.
- Another research that analyses the uncertainty of night cooling performance is performed in [232]. Since the performance of natural night ventilation highly depends on the external weather conditions and especially on the outdoor temperature the temperature rise that is noticed the last century has a strong impact on night ventilation's effectiveness. The researchers in [232] proposed a methodology to predict the performance of natural night ventilation using building energy simulation taking into account the uncertainties as inputs. The performance evaluation of natural night ventilation is based on uncertainty and sensitivity analysis. The uncertainty analysis showed that thermal conditions with single-sided night ventilation have the largest uncertainty while the uncertainty is reduced with passive stack and cross ventilation. The most significant parameters that affect thermal comfort are the internal heat gains, solar heat gain coefficient of the various blinds, internal convective heat transfer coefficient, thermophysical properties related to thermal mass, set-point temperatures controlling the natural night ventilation, the discharge coefficient $C_{\rm d}$ of the night ventilation opening and the wind pressure coefficients $C_{\rm p}$.
- The feasibility of passive cooling for newly built office buildings in the temperate climate of Belgium is assessed using the standardized adaptive comfort criteria [233]. The analysis is performed using Monte Carlo approach on all 320 building design variants with 100 runs for every building design variant using simple random sampling. The obtained accuracy of the calculated weighted exceeding hours as summer comfort criterion will be assessed to evaluate this number of runs. of the simulated weighted exceeding time for different building designs with varying insulation level, glazing-to-wall-ratio, glazing type and air tightness. The results indicate that it is possible to cool office buildings solely by diurnal manual window operation, even for highly insulated and air tight buildings. This requires minimizing heat gains to about 900 kJ/m^2 per working day during summer months. When a combination of diurnal window operation and night ventilation is available, limiting the heat gains to about 1500 kJ/m^2 per working day suffices. These target values can be achieved only when solar gains are minimized through sensible façade design.

Another critical point studied by various researchers is the impact and uncertainty of night ventilation due to poor outdoor environmental conditions and urban heat island phenomenon. To this end Geros et al. in [188] analysed the cooling potential of night ventilation in the urban context. The research is focused on ten urban canyons in the area of Athens, Greece where various environmental parameters are measured. The urban canyon geometry and the ambient temperature inside the canyon affect significantly the ability of the outdoor environment to play the role of a heat sink when night ventilation is applied. Additionally, the wind velocity is reduced inside urban canyons and wind direction is significantly modified reducing the indoor air flow caused by natural ventilation techniques. Therefore, in non-air-conditioned buildings where the effect of night ventilation concerns the reduction of the indoor temperature the next day, the dominated inside the canyons conditions reduce the efficiency of the technique, (on average up to 4 °C for the studied canyons).

Similar work is performed by Kolokotroni et al. [234] for the area of London. London has a well-documented urban heat island problem which is studied in the past by various researchers [192]. In the framework of Kolokotroni's study an urban office using night ventilation has 10% less cooling demand than a typical office while a suburban office where night ventilation is applied does not need extra mechanical cooling. During an extreme hot week, an optimised office in London would require 27% of the cooling needed by the reference office while in a rural location the value is 14%.

Other cities that night ventilation effectiveness is studied versus urban heat island include Nicosia, Cyprus [235], Chania, Crete [236], Shanghai [237], etc.

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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