Chapter 8
Ventilative Cooling in Combination with Other Natural Cooling Solutions: Direct Evaporative Cooling—DEC

Giacomo Chiesa and David Pearlmutter

Abstract This chapter analyses the potential combination of ventilative cooling solutions with direct evaporative cooling (DEC) systems. The focus is on passive downdraught evaporative cooling (PDEC) towers, whose performance is described based on the analysis of monitored results. The main design aspects of PDEC towers are explained, including basic relationships and support tools for system optimization. A series of case studies is reported, illustrating different integration strategies and providing a series of examples for designers. Finally, a simulation-based approach to analysing the local potential of PDEC to reduce thermal discomfort in naturally ventilated buildings is introduced, providing a method by which DEC systems can be integrated in building projects from the early-design phases.

8.1 Introduction

Ventilative cooling, such as controlled natural ventilation (CNV), is a strategy to consistently reduce the amount of energy required for space cooling and ventilation (IAQ—indoor air quality) by exploiting natural cooling potential due to heat gain dissipation thanks to air temperature differences between environmental and internal air and considering convective exchanges with air and the human body. Unfortunately, in some locations environmental air temperature in the summer period is higher than comfort thresholds, reducing the local potential of ventilative cooling techniques. Nevertheless, the possibility to adopt CNV or hybrid ventilation in combination with additional heat sinks may constitute a valid challenge to increase the potential of ventilative cooling systems and the number of application hours. Prominent among these strategies are evaporative cooling solutions, which are based on

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the fact that significant quantities of sensible heat are converted to latent heat during the process of water evaporation [1].

Evaporative cooling is a traditional cooling technique in dry and hot locations, with historical examples having been reported from as far back as ancient Egypt and Persia [2]. The wide variety of historical applications includes elements such as fountains, artificial grottos and nymphaea, water basins, open canals, and sprayers [3]. It is possible to consider, for example, the internal evaporative system in the Ziza palace in Palermo, Italy, or a similar system in Red Fort, Delhi, India, or even the 'canòpo' spaces of Roman villas in which water basins are linked with water fountain games—e.g. Villa Adriano in Tivoli, Italy. Furthermore, several Renaissance and Baroque villas used large fountain systems—such as the Neptune Fountain and the Water Organ in Villa d'Este, Tivoli, Italy—or artificial Grottos and nymphaeum spaces with water tanks and small fountains—such as the nymphaeum of Villa Giulia in Rome, Italy, or the Grotto of Thetis, Versailles, France.

The contemporary application of evaporative cooling systems for space cooling can be traced to two separated origins in the U.S., as documented by [4] and described in [5]. On the one hand, there was a need in the eastern states for cold humid air in textile buildings, and this led to the use of water sprayers as direct way to reduce air temperatures—creating the basis for air cleaning systems that became widespread in a range of industrial applications. On the other hand, indirect as well as direct evaporative cooling systems were developed in the hot-arid southwest and by 1930 had been implemented in Arizona and California for both residential and tertiary buildings. In parallel, the publication of psychrometric tables in the early 1900s by the U.S. Weather Bureau opened the way for the scientific definition of evaporative cooling base expressions (i.e. Carrier's paper of 1911) [6].

The adoption of evaporative cooling in mechanical systems since the beginning of the 20th century is reflected in U.S. patents on evaporative coolers, such as that of Stuart W. Cramer in 1906 for air conditioning textile spaces. It is still the basis for various direct and indirect HVAC-integrated technologies (see for example the review on solar cooling reported in [7], including both evaporative and desiccant air conditioning systems). Prominent among low-energy mechanical systems is the example of the "desert cooler" commercialized in the 1920's [8], in which a primary airflow is directly humidified by passing through a wet pad evaporator. In contrast, several indirect evaporative solutions are used in mechanical cooling systems, including those which are coupled with fan coil distribution systems, thanks to the integration of an evaporative chiller in order to cool a fluid that is further used to cool spaces.

This chapter focuses on passive evaporative cooling systems, which can be divided into direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) solutions—see for example Fig. 8.1. Considering the overall theme of the book, emphasis is placed on techniques connected with ventilative cooling and consequently on DEC systems such passive downdraught evaporative cooling (PDEC) towers. Among IEC solutions, however, it is possible to mention "psychrometric" roof ponds in which a shaded and naturally ventilated water layer can reduce the internal temperatures of the coupled space to values near to the ambient wet bulb temperature—see for example [9].

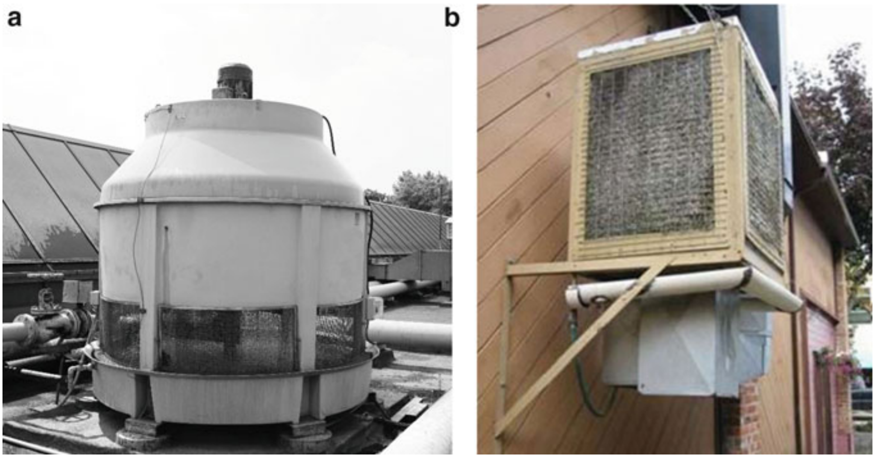

Fig. 8.1 **a** an indirect evaporative cooling (IEC) chiller; **b** a direct evaporative cooling (DEC) system (known as a "desert cooler" or "swamp cooler")

The chapter is structured as follows.

Section 7.2 describes in detail the physical principles of DEC (adiabatic humidification), including the use of graphical representation on a psychrometric chart. Different types of DEC systems are described (e.g. shower towers, misting towers, cooling towers, porous media, etc.), defining the main characteristics and functioning principles. Furthermore, the main calculation approaches, including simplified regression formulas and specific tools, are described and briefly compared. Moreover, the main design issues connected to the dimensions of DEC systems in specific contexts and building integration strategies are defined. Finally, a simplified design approach is suggested. Section 7.3 describes specific methodologies for calculating the local potential of passive downdraught evaporative cooling systems for reducing the environmental air temperature and improving the potential of natural controlled ventilation solutions. This analysis is based on the local climate conditions, and is applied to a large set of locations to highlight those sites in which DEC may have a high potential without the need for pre-dehumidification treatments of the external air. Finally, Sect. 7.4 provides a brief concluding summary of the chapter.

8.2 Direct Evaporative Cooling Systems: Main Principles

As mentioned previously, evaporative cooling systems can be divided into two types: direct and indirect. Direct evaporative cooling (DEC) is based on the direct evaporation of water into the primary airflow, while the indirect evaporative cooling (IEC) utilizes the evaporative cooling of a secondary fluid that exchanges sensible heat with the primary airflow. While direct solutions imply the increase of the absolute humidity of the treated air, indirect systems may avoid this—thereby lowering the dry bulb temperature of the treated air without increasing its moisture content (e.g. [10]). Considering the applicability of DEC for ventilative cooling purposes, this section focuses mainly on direct solutions. The physical principles of DEC systems are introduced in Sect. 7.2.1, followed by a survey of system types (Sect. 7.2.2), simple calculation approaches (Sect. 7.2.3), and design issues (Sect. 7.2.4).

8.2.1 DEC Physical Principles

Direct evaporative cooling solutions are based on the introduction of water into an airflow in order to saturate the air by evaporation (converting liquid water to gaseous vapour) and consequently reducing the temperature of the air stream and/or of the wet surface. It should be emphasized that this process, also called adiabatic saturation, does not change the total thermal energy of the system. The water vapour embodies latent heat, and may, in fact, condense—causing an inverse temperature trend. Even if the moisture content—also known as the absolute humidity or mixing ratio (measured in grams of water vapour per kilogram of dry air)—is small in comparison to other components of the air, this moisture is essential in atmospheric processes [1]. The absolute humidity ranges from 0 g/kg to a maximum value which varies in relation to air temperature and pressure levels. A commonly used index to define the amount of water vapour referring to this range is the relative humidity (RH) which is a percentage describing the amount of water vapour in the air with respect to the saturation water vapour quantity (100% RH) at the same dry bulb temperature (DBT).

Other essential variables in psychrometric studies are the (a) the dew point temperature, which corresponds to the temperature to which air at a fixed moist moisture content has to be sensibly cooled in order to reach 100% RH, and (2) the wet bulb temperature (WBT), which is the minimal temperature that can be reached with an adiabatic (i.e. fixed enthalpy) saturation process, cooling the air solely by the addition of water vapour through evaporation. At both of these points the air becomes saturated, resulting in the condensation of water vapour into liquid water. The cooling of air to its WBT reflects the fact that DEC is an isenthalpic process—see also [11]. Figure 8.2 shows these variables on a simplified version of a psychrometric chart based on Carrier studies—for an advanced description of physical processes in evaporation and desiccant processes see [12].

Considering these basic principles, it is possible to describe the effect of a DEC system as an adiabatic cooling process, “moving” the condition of the air along a line of constant enthalpy on the psychrometric chart (Fig. *). Under specific environmental conditions, a DEC system can convert the thermal state of the air into one that is considered comfortable—a state that can be visualized as the passing of this line of constant enthalpy through the “comfort zone” [13]. Figure 8.3 describes this process with a simple graphical representation of the phenomenon (Fig. 8.3a), and the plotting of monitored points representing the condition of the air before and after

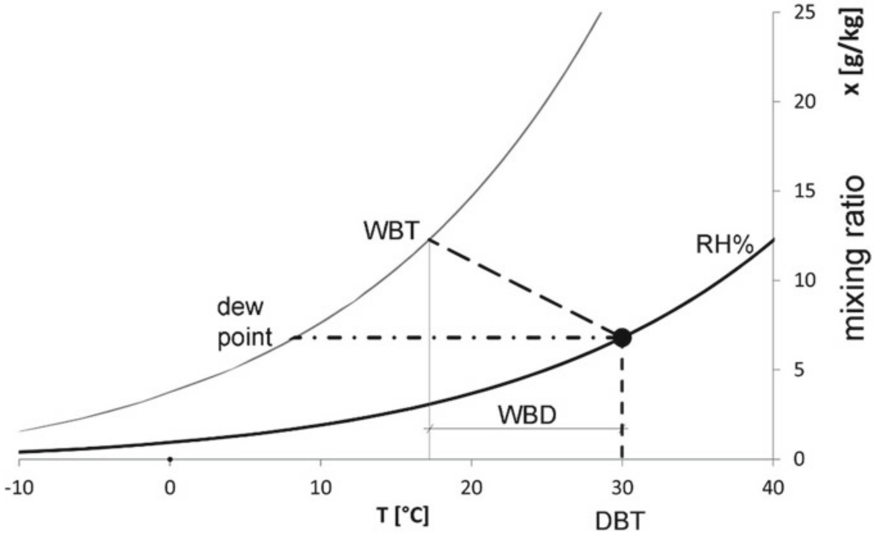

Fig. 8.2 Principal variables reported in a schematic representation of a psychrometric chart. WBT = wet bulb temperature, DBT = dry bulb temperature, WBD = wet bulb depression

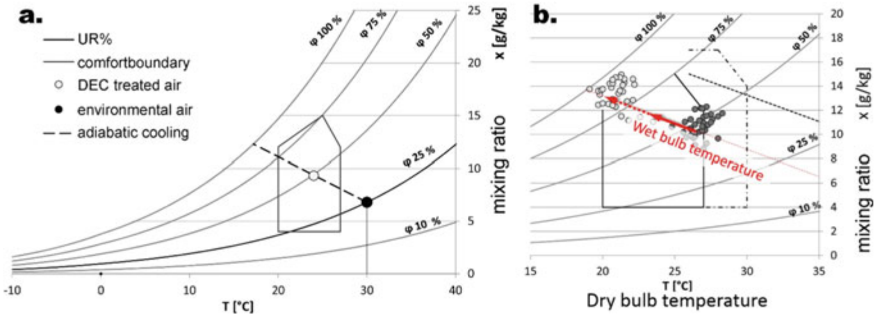

Fig. 8.3 **a** adiabatic cooling principles and DEC potential in reaching comfort; **b** the same principle illustrated by monitored data from an experimental DEC tower (inlet and outlet conditions), PoliTO, Turin

treatment in a PDEC tower (Fig. 8.3b). This basic approach was also used to define the applicability of DEC in bioclimatic comfort charts such as that of Givoni-Milne [14, 15].

Considering ventilative cooling applications, DEC is principally linked to desert coolers to treat intake air to be distributed in internal spaces, or to PDEC solutions in which little or no mechanical means are used to circulate the air—which is achieved instead through passive buoyancy forces [16, 17]. The expected effect of a PDEC tower in cooling an air flow is represented in Fig. 8.4. The graph illustrates the ambient air's DBT and corresponding WBT, as well as the temperature of the air after a passive DEC treatment.

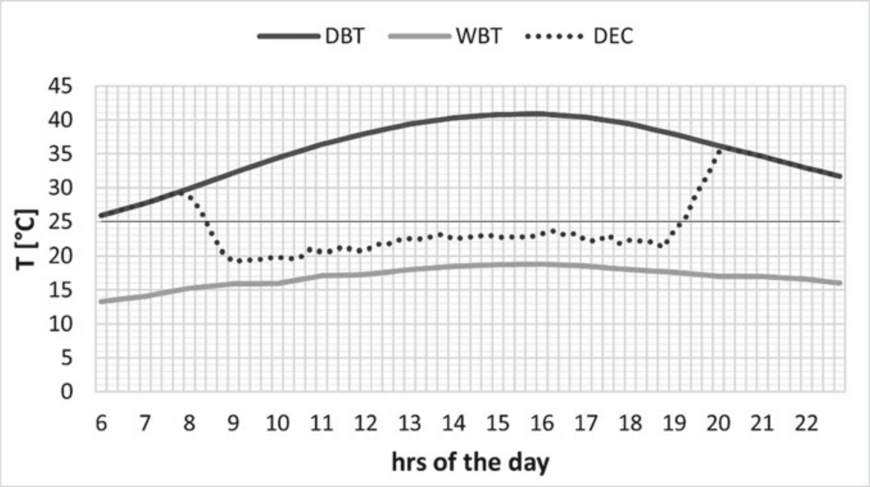

Fig. 8.4 Expected DEC treatment effect on environmental air for ventilative cooling purposes—typical climate conditions (Meteonorm v7.11 TMY), 21st June in Tucson, Arizona, considering a PDEC effectiveness around 0.8

8.2.2 PDEC System Types

Passive downdraught evaporative solutions may be classified according to the technological systems used for the evaporation of water in the treated airflow. According to Ford et al. [18], it is possible to identify four PDEC types: i. cool tower (wet pad); ii. shower tower (nozzle); iii. Misting tower (nebulizer); iv. porous media. Furthermore, a fifth type was also defined including hybrid systems in which an evaporative chiller located on the upper part of a building indirectly cools the air and consequently activates a natural downdraught, cooling the spaces below. The indirect approach allows for potential installations even under humid climate conditions (see for example commercial solutions such as Gravivent® or G-Therm®).

Nevertheless, focusing on direct systems, it is possible to divide PDEC solutions into two main classes: the first in which water is directly injected into an airflow—(e.g. shower and misting towers), and the second in which air passes through or close to a surface which is maintained in a moist condition—i.e. direct evaporation from wetted surfaces.

In the first case, nozzles or sprayers are needed, with or without water recirculation. In the second case, some solutions are nozzle-based (e.g. cool towers), while others (e.g. some porous media systems, such as the external columns of the Spain Pavilion at Zaragoza EXPO 2008) can be based on water basins and capillarity or on thin-layers of water flushing on porous surfaces.

Considering direct evaporation from moist surfaces, one of the most commercially diffused PDEC systems is the cool tower: a system based on *wet pads*. In this solution, the water is sprayed on a pad that can be made from treated cellulose.

The primary airflow comes in contact with this pad, which acts as an evaporative exchanger. Several commercial wet pad solutions are presently on the market, in some cases coupled with fans to increase the airflow. Examples of PDEC wet pad towers are Cunningham and Thompson's experimental tower at the University of Arizona (1986) [8, 19], the Visitor centre at Zion National Park, Utah, U.S. [18], the MOMRA Environmental Rowdah project in Riyadh, Saudi Arabia [20] and the office building housing the headquarters of Botswana Technology Centre, South Africa [21]. Figure 8.5 illustrates a sample scheme of a cool tower system.

In contrast, *porous media* are systems in which materials such as porous ceramic surfaces are maintained in a saturated condition while exposed to the primary airflow, in order to reduce the air DBT thanks to evaporation. Several bioclimatic archetypes of this technique may be found in traditional Indian, Greek and Arabian buildings. Recent examples can also be seen, such as the above-mentioned Spanish pavilion at the EXPO of Zaragoza. This technique may allow for the operation of DEC systems even when the quality of the water is poor.

Direct spray systems work in a similar manner, by using water nozzles to evaporate water in the primary airflow. Nozzles are located at the top of the PDEC tower, generating a vertical downdraught airflow (negative buoyancy forces). The treated airstream flows down naturally, due to the progressive reduction in DBT and high relative density, the increase in its humidity ratio, and due to motion transfer between un-evaporated drops and the airflow—see the equations reported in [1]. Mechanical fans may be used to increase the volumetric flow rate of treated air, in accordance with IAQ (Indoor air quality) and cooling requirements. Figure 8.6a shows a sample functional scheme of a nozzle-based PDEC system. A water collection system can be used for the recirculation of non-evaporated water. In addition to systems with a

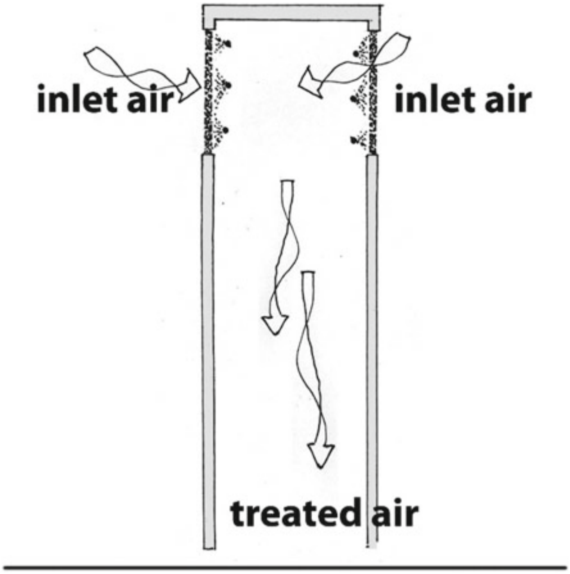

Fig. 8.5 Sample scheme of a cool tower system

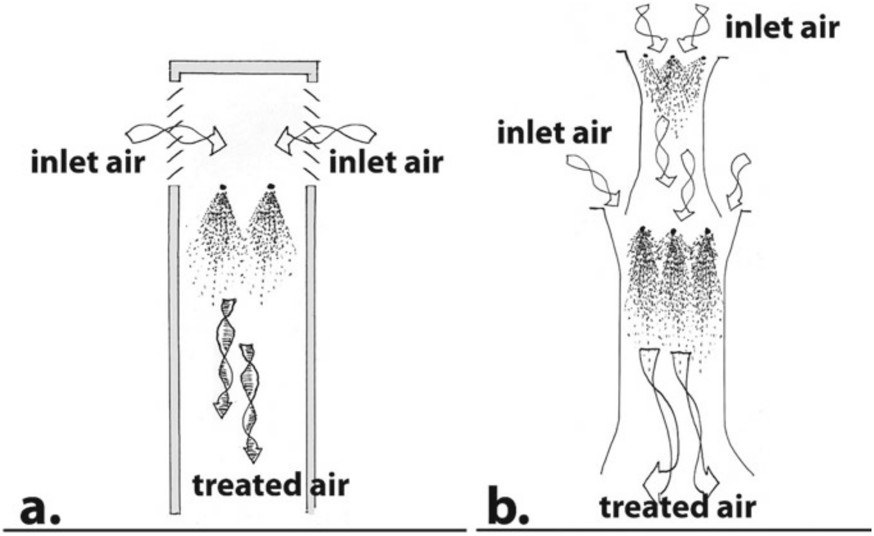

Fig. 8.6 **a** Sample scheme of a direct spray system; **b** sample scheme of a multi-stage spray tower system

single evaporator line, additional solutions have been investigated including a two-stage spray lines disposed vertically [9, 22]—see the sample scheme reported in Fig. 8.6b.

Among direct spay systems, misters and nebulizers generate water drops with smaller diameters, and if correctly designed can allow for full evaporation of the sprayed water—reducing the amount of water waste and the connected risk for legionella [23]. Small drops in fact accelerate the evaporation process due to their larger surface to volume ratio and hence their larger area of contact with the air. Furthermore, when misting towers are used, lower distances are needed between the tower inlet and the outlet openings connecting the PDEC tower with the space to be cooled [18]. Evaporation occurs, in fact, in the first few meters in height. However, this type of nozzle generally requires pumps working at higher pressure than those used in shower towers and is more susceptible to clogging. These towers may also show a lower effectiveness, not fully covering the WBD, even if they are designed to modulate water flows with respect to environmental conditions [1, 24].

In contrast, shower towers use a relatively coarse spray generated by nozzles characterized to produce a larger drop size. This system typically has a higher effectiveness than misting towers, but large quantities of residual non-evaporated water have to be collected at the base of the tower, resulting in a large risk for bacteria proliferation. A sample misting tower system is the one installed in the Malta Stock Exchange (a hybrid system), while an example of a shower tower (combining a range of sprayer types with different drop sizes) is the one installed at the Blaustein Centre for Desert Studies in Israel—see Fig. 8.7. Further examples are the shower tower in the Miele Showroom at Johannesburg in South Africa [25], and the shower towers

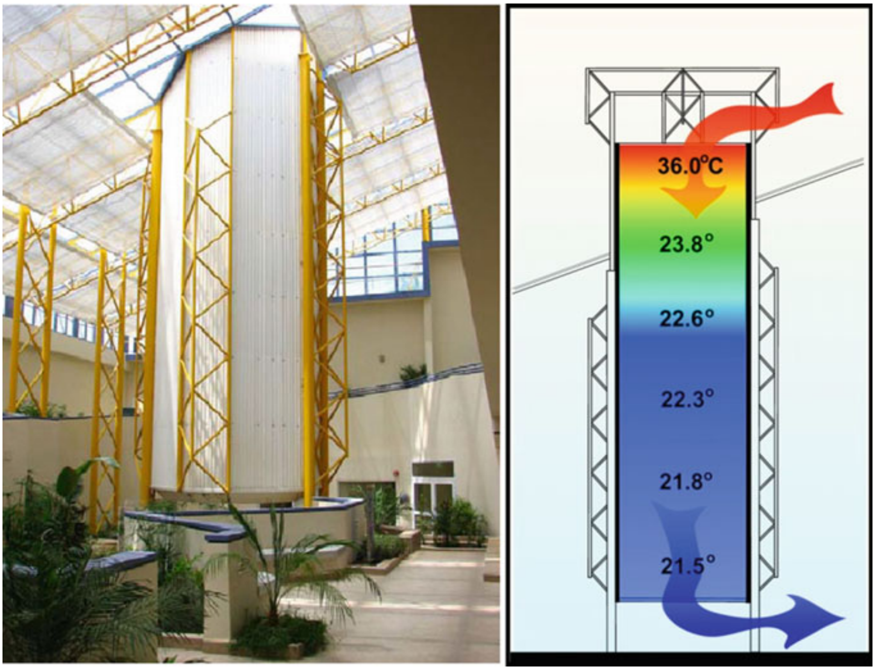

Fig. 8.7 The shower tower in the atrium of the Blaustein International Centre for Desert Studies in Israel (Photo courtesy of D. Pearlmutter) with schematic cross-section showing typical temperature profile

at the Council House office building in Melbourne, Australia. Figure 8.8 illustrates monitored data from a PDEC tower installed in a University laboratory, PoliTo, Turin, Italy equipped with a shower system [26].

8.2.3 DEC Simple Calculation Approaches

In order to simulate DEC systems for design purposes, different calculation approaches are possible. In particular, advanced simulations may be performed using CFD (Computation Fluid Dynamics) software [28], but such modelling requires specialized knowledge and incurs high computational costs when fully adopted in small/medium building solutions—see also the discussion in [29, 30]. Furthermore, the CFD simulation of an enthalpy exchange requires additional capabilities related to ventilative cooling, which are not provided in every commercial software package [28]. For this reason, the present chapter describes a number of documented calculation methodologies that have been recently validated using experimental data [23, 30].

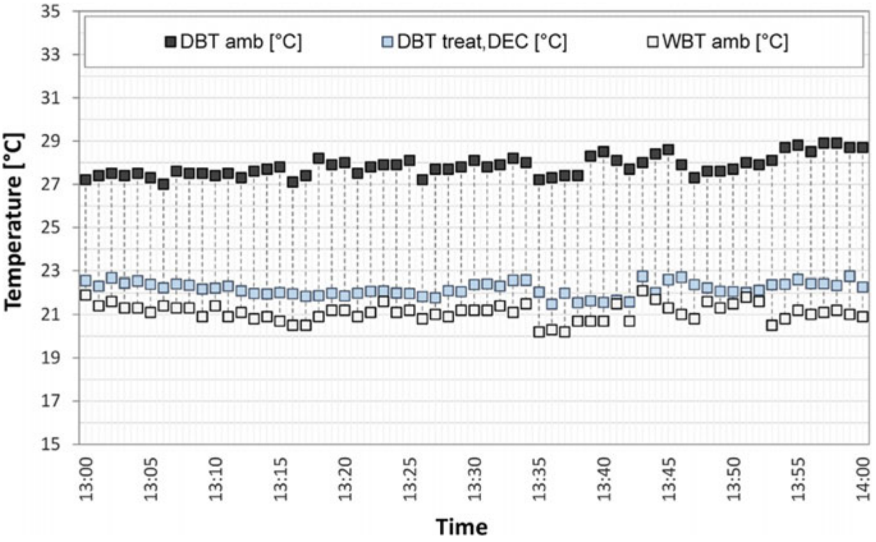

Fig. 8.8 Sample monitored values of inlet and outlet DBT (shower tower), and calculated WBT using the Stull expression [27]

Several studies have been reported in the literature about the development of simple calculation approaches to estimate the temperature (and the humidity ratio or RH) of an airflow following a DEC treatment. In particular, one of the more effective expressions to simply evaluate the potential of a PDEC tower is given in Eq. (8.1), as originally reported by Givoni [8, 31, 32] and based on analyses performed on the cool tower installed in an experimental building at the University of Arizona in Tucson [19]. This specific formula is also at the base of DEC simulation in EnergyPlus, and in particular is used in the CelDekPad module—see [33, 34]. Although Eq. (8.1) was developed for cool towers, it is possible to use it to predict the effects of shower and misting towers, as demonstrated with experimental data [26, 30].

$$DBT_{tr.air} = DBT_{in.air} - \varepsilon \cdot (DBT_{in.air} - WBT_{in.air}) \tag{8.1}$$

where the subscripts $DBT_{\mathrm{in.air}}$ and $DBT_{\mathrm{tr.air}}$ refer respectively to the psychrometric condition of the air entering the PDEC system (inlet) and to the condition of the outlet airflow after a PDEC treatment. The coefficient ε is the DEC effectiveness, a value representing the correlation between the inlet-outlet dry bulb temperature (DBT) difference and the environmental WBD, which represents the DEC potential—see Eq. (8.2). This relation is a synthetic index of a given PDEC's performance, and it is function of tower design configuration, site, and environmental conditions. As was suggested by Givoni, the DEC effectiveness of a system can be calculated using an early short-term monitoring. DEC effectiveness is, in fact, the slope of a linear regression line passing through the origin evaluating the difference in DBT between inlet and treated air plotted as a function of the correspondent WBD [8]. This calculation approach is especially useful when installing a new system in a given location, in order to correctly dimension it. In fact it is possible to make preliminary tests with a simple tube tower at an adjacent site to optimise the local effectiveness, and use this value to define the expected outlet conditions of a treated airflow using TMY (typical meteorological year) hourly data—see in particular the detailed approach described in [26]. Nevertheless, as was suggested in several studies [8, 30], a preliminary DEC effectiveness between 0.7 and 0.8 can be assumed as a general reference for early-design purposes.

$$\varepsilon = \frac{DBT_{in.air} - DBT_{tr.air}}{WBD_{in.air}} \tag{8.2}$$

Further expressions have also been developed based on experimental data. For example, Givoni [8, 35] developed an equation—see Eq. (8.3)—to calculate the expected outlet DBT by a shower PDEC tower. This equation also includes the water flow and the tower height, which are essential parameters for the definition of direct spray systems especially when no preliminary monitored data are available to calculate a more specific DEC effectiveness.

$$DBT_{tr.air} = DBT_{in.air} - WBD_{in.air}(1 - exp(-\varepsilon \cdot H))(1 - exp(-0.15 \cdot WF)) \tag{8.3}$$

where H is the tower height [m] and WF the rate of water flow [l/min].

Although Eqs. (8.1) and (8.3) are based on DEC effectiveness, it is also possible to estimate the treated DBT by using adapted expressions, which are independent of this specific value [30]. In particular, Eq. (8.4) [8] and Eq. (8.5) [35] report two alternative expressions for Eq. 8.3 (shower tower) whose definition was based on experimental data analysis. These expressions are principally conceived for early-design purposes, and the calculation approach can be coupled with EnergyPlus [35].

$$DBT_{tr.air} = DBT_{in.air} - WBD_{in.air}(1 - exp(-0.8 \cdot H))(1 - exp(-0.15 \cdot WF)) \tag{8.4}$$

where the DEC effectiveness is assumed as 0.8, a value that was demonstrated to be a correct indicator for early design purposes of PDEC towers on different experimental databases and for different expressions—such as Eqs. (8.1), (8.3), (8.4) and (8.5)—with a statistical accuracy of 86% based on different indicators (MBE, RMSE, U95, TT, R^2) [30].

$$DBT_{tr.air} = DBT_{in.air} - (0.9 \cdot WBD_{in.air} \cdot (1 - exp(-1.5 \cdot H)) \cdot (1 - exp(-0.15 \cdot WF))) \tag{8.5}$$

The same study mentioned before suggested that the equation with the highest statistical relevance is Eq. (8.1) for all PDEC cases considered (cool, shower/misting tower), followed by Eq. (8.5) for shower/misting towers.

By knowing the inlet and outlet temperatures and the inlet humidity, it is possible to calculate the humidity ratio or the RH of the outlet airflow considering psychrometric expressions for adiabatic cooling transformation—inlet and outlet air have the same WBT. This approach may be followed to check if outlet air RH is out of the comfort boundary, or to define control systems (DEC activation or mixing system coupling treated and external air) to modulate the PDEC functioning. This is especially important during the evaluation of a system's climatic potential, to avoid overestimation of PDEC applicability—e.g. see the specific calculation approach described in [36].

Additionally, dedicated models to simulate DEC systems have been developed for dynamic energy modeling software such as ESP-r [37], TRNSYS [38], DOE2 [39] and EnergyPlus [33].

Finally, there is also specific software devoted to simulating the effect of PDEC towers for architectural design purposes, e.g. [40, 41]. One example is the PHDC Air Flow tool, developed in the 6th EU framework for research and development project 'Passive and Hybrid Downdraught Cooling (PHDC)' [18], which is based on a multi-zone loop method. The software enables calculation of the air flow generated by the PDEC, the DBT and RH of the outlet air, and the specific flow in PDEC-connected living spaces positioned at different floors. The PDEC systems considered are cool towers (wet pad), shower and misting towers. The obtained values are a function of tower height, the type of wind catcher at the top of the tower (if any), specific nozzle characteristics, the potential presence of an exhaust tower, and floor height and space length (up to four floors can be simulated in the same run in order to check relative results). The distributed version of the software makes a single calculation, based on input data representating internal and environmental starting conditions (outdoor and indoor DBT and RH, wind speed, and height above sea level).

8.2.4 DEC Design Issues

This section investigates some major aspects to be considered in PDEC tower design. First are some of the aspects connected to the evaporative systems, such as nozzle types and bacterial prevention strategies, and these are followed by some of the issues connected to building integration schemes and simple design recommendations.

Main design aspects that may influence the performance of a PDEC tower are related to physical and morpho-technological issues. Considering physical aspects, it is important to remember the wind pressure at the PDEC inlet mount; air specific weight, which varies during evaporation, and motion transfer. Morphological and technological aspects include tower geometry (e.g. height and cross-section area), aerodynamic behaviour of the system, water flow (l/min and distribution), sprayer types, and sprayer numbers and their geometrical distribution—see also [17, 30, 42, 43].

Firstly, as was mentioned in Sect. 11.2.2, it is evident that the choice of the nozzle type is an essential aspect to be considered in PDEC tower design. Research by Guetta [44] compared different available types of nozzle, and as expected, a higher working pressure increased the required power of the pump—it but also decreased the water drop diameter and surface area as well as the volumetric flow rate. Of course fine nozzles show a higher risk of clogging, even if smaller drops may help reduce the time for fully evaporating the sprayed water in the tower system. Conversely, if full evaporation is not needed the system may work at lower pressure with larger drops, reducing maintenance and operational costs. A summary report of these outputs was also included in [1].

In addition, since various types of nozzles are present on the market, especially for pressurized water flow using pumps, the following spray characteristics should be analysed—see also [23, 45].

- The spray angle, which expresses the coverage area considering the tower height;
- The type of cone (e.g. full cone, semi-full cone, hollow cone, flat spray, or air atomizing);
- The nozzle shape (e.g. round, squared, rectangular);
- The number of orifices for single nozzle (e.g. single, multiple);
- The operation pressure at the inlet of the sprayer (e.g. from water district pressure, to high pressure industrial systems);
- The water flow rate at the chosen pressure;
- The size of water drops for a fixed water flow and pressure;
- If given, the Sauter diameter of water drops (D_{32}—see [1]);
- If given, the total surface area of sprayed drops per second;
- The characteristics of the adopted nozzle technology, including pressure, turbulence, and deflection (such as in spiral nozzles) or atomization (by combining water with compressed air).

A second aspect to be taken into account is the risk of microorganism formation (e.g. bacteria, fungi and algae) in the water, especially for preventing legionellosis [46]—see also ANSI/ASHRAE Standard 188-2018 [47]. This is one of the major potential hazards in PDEC system operation, especially where water is not fully evaporated [48]. Several standards and codes of practice include specific aspects to control and prevent the risk for Legionella, especially for large cooling towers in evaporative chillers [49]. A number of specific considerations are especially relevant for PDEC system design. Firstly, water temperature has to be carefully controlled in order to prevent bacteria formation, which principally occurs above 20 °C and below 60 °C—for Legionella the risky domain is 20–45 °C [50]. Secondly, the use of biocides is a highly recommended strategy, especially in combination with water filtering to reduce the presence of potential nutrition particles [51, 52]. Thirdly, the nozzle spray angle may be determined so as to minimize the amount of non-evaporated water reaching the internal surfaces of the PDEC tower and the bottom area outside the collection basin [1]. Fourthly, the usage of drift eliminators is suggested to reduce the amount of water drops remaining in the treated airflow when directed to living space [52]. Furthermore, when PDEC systems are directly spraying in a living space, e.g. in atrium zones, people have to be protected from direct exposure to excessive water spray.

Considering building integration issues, it was demonstrated that between 62 and 82% of existing buildings in southern Europe allow for PDEC system integration [53], for a consequent reduction in cooling energy needs in the range 25–85% [18]. In order to define potential integration schemes, PDEC systems can be classified according to either typology (see Sect. 7.2.2) or building integration mode. Four main integration classes were suggested by Ford et al. [18] in accordance with the position of the PDEC tower relative to buildings and open spaces. Figure 8.9 illustrates these integration modes (see also [54]) that can be defined as: i. attached PDEC tower, such as in the Council House 2 in Melbourne, Australia; ii. detached/isolated PDEC tower, in which the tower has an independent structure and is connected to living spaces by ducts, e.g. Hyderabad centre C II, India; iii. internal closed tower, in which the tower is centrally located in relation to internal spaces, and the system is closed and connected by dampers or other openings to the cooled spaces, e.g. the Torrent research centre at Ahmedabad, India; iv. Internal open tower, in which the PDEC system is integrated in the building, e.g. in an atrium, and directly connected with cooled spaces. In the latter case, dedicated spaces for the collection of un-evaporated water have to be taken into account in the design of the system.

A simplified approach to PDEC integration was recently reported in [26] including a typological table that combines PDEC classes with typical building typologies (i.e. isolated, terraced, courtyard, tower, and linear buildings). The main aspects to be considered for PDEC integration are related to technological and operational concerns, such as the need to avoid the exposure of people and living space to unevaporated water flows, and to architectural concerns such as the visual and aesthetic harmony with existing or newly designed surroundings. In particular, for a central open system, it is suggested to either use cool towers or misting systems or to consider shower towers if a sufficient part of the space is available as a water collecting basin. In this sense, an open tower may be useful in a large building with public open spaces, while in a single building its application is limited in terms of required space

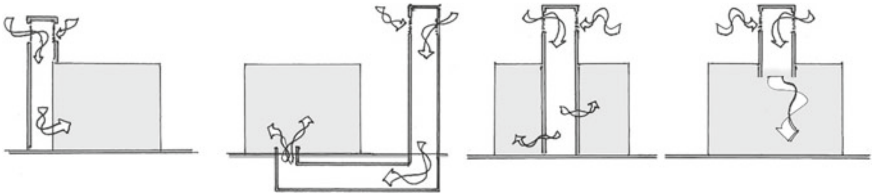

Fig. 8.9 Sample schemes of PDEC tower integration in buildings

and aesthetic impact. For multi-storey residential buildings, attached systems may result in easier integration, even if detached solutions (more useful for tertiary and public buildings, considering the possibility to integrate the system with the existing mechanical ventilation system) or central closed towers may also be considered if, for example, a cavedium (a small atrium to allow ventilation) is present.

Considering tower early-design dimensioning, a simplified approach may be defined, considering the following steps [26]:

- Definition of the airflow rate, which is the higher of two possible values: (1) the rate required for IAQ purposes, based on standard recommendations (see also [55]), and (2) the rate required for cooling purposes, considering the thermal heat to be dissipated and the expected primary airflow temperature. For ventilation, see the simplified formula reported in [56, 57] (Eq. 8.6), that can be adapted for PDEC system by considering the treated airflow temperature, calculated according to the equations reported in Sect. 11.2.3:

$$q_{need-cool} = H/(c_{air}\rho_{air}(\vartheta_{in} - \vartheta_{amb})) \tag{8.6}$$

where H represents hourly heat gains of the space to be cooled on a daily average, c_{air} and ρ_{air} are respectively the heat capacity and density of air, and ϑ_{in} and ϑ_{amb} are the daily average internal and environmental (or PDEC treated) air temperatures.

- Calculation of the minimal required PDEC section area to dimension the tower system, e.g. by using the following (Eq. 8.7):

$$A_{min-PDEC} = q_{need}/C_d\sqrt{(\vartheta_{comf} + 273)/(\Delta\vartheta \cdot g \cdot h)} \tag{8.7}$$

  where C_d is the PDEC tower discharge coefficient, ϑ_{comf} the target comfort, $\Delta\vartheta$ the average difference between the inlet and treated air temperatures, g is gravitational acceleration and h the tower height.
- Definition of the minimal section area of the opening connecting the PDEC tower with living spaces, e.g. by adopting Eq. (8.8):

$$A_{op} = q_{need}/(C_d \cdot v) \tag{8.8}$$

  where the discharge coefficient C_d refers to the connecting opening, and v is the airflow velocity.

Of course advanced calculations are needed for large installations and detailed design stages. In any case, the potential of a PDEC system for increasing the ventilative cooling applicability is connected to the reduction of the airflow temperature, when the airstream remains in the RH comfort boundaries, for higher heat gain dissipation potential.

8.2.5 Local Climatic Potential of PDEC

DEC systems, such as the majority of passive cooling solutions, show a local specific applicability [58, 59]. This section briefly reports some of the indices available for quantifying this applicability together with an application of some of them to define the geo-climatic potential of PDEC solutions in the extended Mediterranean Basin area.

As mentioned above in Sect. 7.2.4, DEC applicability is related to specific morpho-technological aspects and design choices related to the installed PDEC system. However, even before any design decisions are taken the local potential of DEC is limited by the geo-climatic conditions, since it is a function of the wet-bulb depression (WBD), with the wet-bulb temperature (WBT) representing the theoretical minimal temperature that can be reached by adiabatic cooling alone (Sect. 7.2.1). Different methodologies have been developed to analyse this local climatic DEC potential, including tools and KPIs (Key Performance Indicators). Among such tools is the Ventilative Cooling Potential Tool, which was recently developed under the IEA EBC Annex 62. This application calculates the balance heating temperature of a space unit in a given location and furthermore defines the number of hours in which ventilative cooling is supporting comfort conditions together with the number of additional comfort hours due to DEC operation when the environmental air is above the thermal balance threshold [60, 61]. Among KPIs, a priority classification ranging from Very Low to Very High combines the average seasonal WBD and the average seasonal difference between ambient air and the comfort threshold (e.g. 25 °C or 26 °C) considering cooling hours. This approach was described in [62, 63] and recently was applied to generate a priority map in U.S. [64], while was compared to other approaches considering China locations [36] around the Mediterranean Region [65, 66]. Nevertheless, in addition to averaging indicators, other approaches have been introduced in literature, considering for example cumulative indicators, based on hourly or sub-hourly analyses. One of these approaches focuses on the expected reduction in climatic cooling energy needs, by calculating the residual amount of cooling degree hours (CDH_{res}) in comparison to the environmental (no DEC) amount of CDH in the same location—see also [23, 67, 68]. This approach allows one to consider the virtual effect of a PDEC system in treating the air and consequently reduce the cooling needs by heat gain dissipation. The well-known cooling degree hour (CDH) index, a daily version of CDD (Cooling Degree Day), is based on Eq. (8.9), in compliance with ISO 15927-6:2007 [69]:

$$CDH = \sum_{h=1}^{n} \left\{ \begin{matrix} \vartheta_{amb,h} - \vartheta_{tr} & \Rightarrow \vartheta_{amb,h} > \vartheta_{tr} \\ 0 & \Rightarrow \vartheta_{amb,h} \leq \vartheta_{tr} \end{matrix} \right\} \quad (8.9)$$

where n is the number of hours (h) in the analysed period (e.g. from June to August or, considering the extended summer season from May to October); $\vartheta_{amb,h}$ is the ambient temperature of hour h; and ϑ_{tr} is the calculation threshold. This last value can be calculated as the balance temperature above which it is needed to cool a specific space, or assuming standard values such as 26 °C [70], 25 °C [62], 22 °C [71], 18.3 °C [72] or 15.5 °C [73]. The CDH_{res} index combines the calculation of the expected PDEC treated temperature with the equations reported in Sect. 7.2.3, considering a virtual tower activation when the environmental CDH is higher than zero [68].

This geo-climatic index was compared with results of dynamic energy simulations using EnergyPlus considering a large set of locations (60) in the Mediterranean Region and a large number of design and operational variations for sensitivity analysis (night ventilation, wall insulation level, internal heat gains, thermal mass, roof insulation and window orientation) [66]. Results showed a very good correspondence between the simulated effect of DEC in reducing the indoor discomfort intensity in comparison to the cases without DEC, when analysed using the CIDH index (Cooling Internal Degree Hour, which is an adaptation of CDH for internal conditions) and the reduction of the environmental CDH due to DEC (CDH_{res}). The coefficient of correlation between CDH and CIDH was demonstrated to be quite high ($R^2 = 0.956$ without DEC and $R^2 = 0.903$ with DEC), confirming the significance of the indices used. Secondly, the R^2 value when internal and climatic reduction of the original CDH due to DEC were compared (climate $\text{CDH-CDH}_{\text{res}}$ vs. building $\text{CIDH}_{\text{noDEC}}\text{-CIDH}_{\text{DEC}}$) was found to be 0.953, demonstrating the high correlation level between the climatic CDH_{res} approach and the related building conditions. This analysis suggests that the most statistically representative DEC effectiveness for CDH_{res} analyses is 0.6.

Another hourly approach to define the local geo-climatic applicability of DEC is the effect that a PDEC tower is expected to have on the number of discomfort hours for free-running buildings. In this case, the reference number of climatic discomfort hours is compared to that expected when DEC systems are activated. The DEC effect can be estimated by using one of the expressions reported above in Sect. 7.2.3, while the comfort-hour threshold can be defined by using temperature-based indicators (e.g. fixed or adaptive thresholds) or comfort boundaries including temperature and humidity, such as in well-known bioclimatic approaches (e.g. Givoni-Milne [14, 15] or Olgyay [74]). Recently, a comparison similar to the one conducted for CDH_{res} was performed by analysing the DEC effect on the number of discomfort hours of a free-running office building, with and without DEC, simulated in EnergyPlus, and the corresponding number of discomfort hours at the geo-climatic level (before any building definition), with or without DEC [66]. The comfort boundaries were assumed by ASHRAE 55-1992—see also [65] and its representation in Fig. 8.10.

This study shows a very good correlation between the simulated building conditions and the geo-climatic KPI. The highest DEC effectiveness in terms of the discomfort-hour index was demonstrated to be in the 0.6–0.8 domain. Firstly, the correlation between building discomfort hours plotted as a function of climate discomfort hours had an R^2 of 0.924 without DEC and 0.917 with DEC (effectiveness = 0.6), and of 0.896 for a DEC effectiveness of 0.8. Secondly, the percentage reduction in discomfort hours due to DEC in buildings plotted as function of the climate results shows an R^2 of 0.749 for DEC effectiveness 0.8 and 0.790 for an effectiveness 0.6 [66].

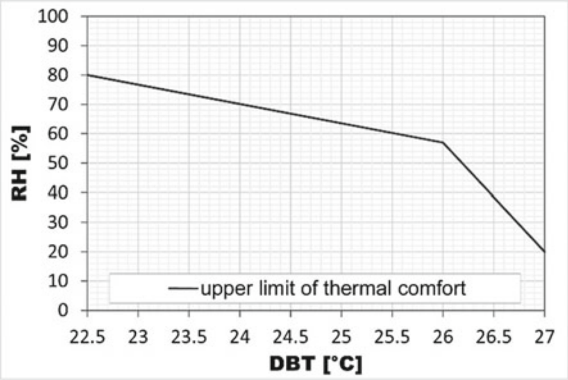

Fig. 8.10 The adapted ASHRAE upper comfort boundary for defining the number of discomfort hours

In order to underline the importance of studying the local potential of DEC, an application of two KPIs (CDH_{res} and the number of discomfort hours) is presented here. A total of 100 locations were selected in the extended Mediterranean Region and their TMY (Typical Meteorological Year) climate data files were generated using Meteonorm 7.11 [75]. The map in Fig. 8.11 plots the selected set of locations. In terms of the Köppen-Geiger climate zone classification [76], the chosen locations include zones Bw, Bs, Cf and Cs.

A reference threshold temperature of 25 °C was assumed for the calculation of CDH and CDH_{res}, assuming a precautionary PDEC effectiveness of 0.6 and using Eq. (8.1) to estimate the PDEC treated air conditions in an extended summer period

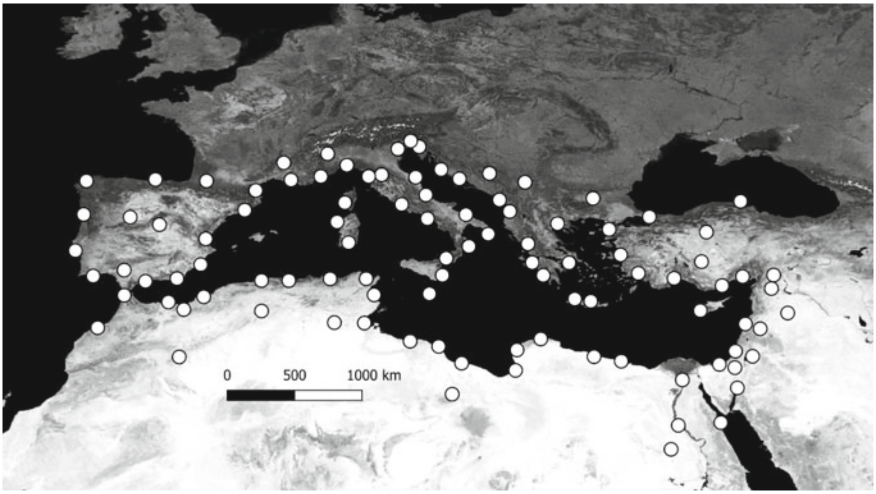

Fig. 8.11 The chosen set of location

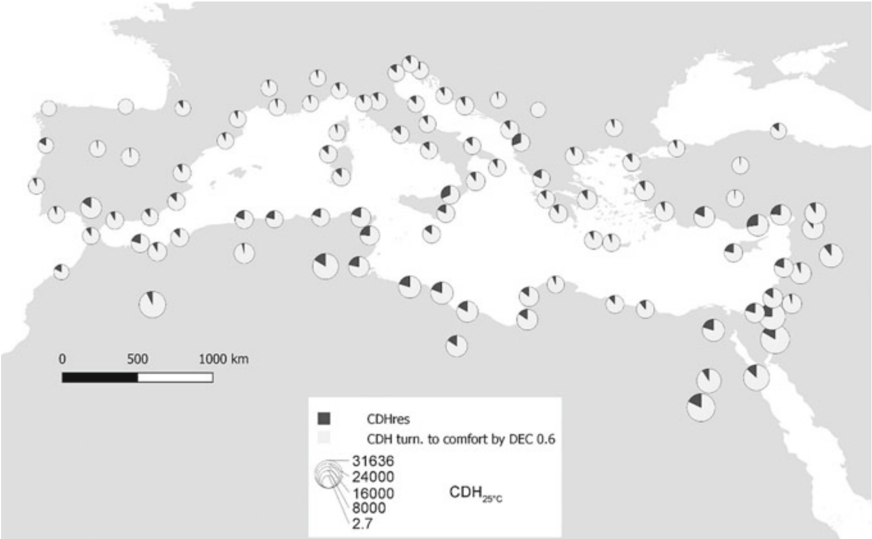

Fig. 8.12 Georeferenced distribution of the reduction in CDH due to DEC for the 100 considered locations. Area of pie charts are proportional to the original CDH, which varies from 2.7 to 31636

(from May to October). Based on calculations performed using a customized tool developed in Python [77], the map in Fig. 8.12 plots the geo-climatic applicability of DEC in reducing the climatic cooling needed in the Mediterranean Region. This map shows that while the general distribution of environmental CDH follows a trend related to latitude (with the exception of semi-mountainous locations), the potential of PDEC for reducing the local climatic cooling requirement is locally specific—see for example the difference between Messina and Syracuse in Sicily, or between the Algerian locations on the coast and in the desert. In general, however, the map shows that PDEC has a very high potential for reducing the original CDH values (as represented by the grey section of the pie charts). As expected, the highest potentialities are prominent in drier locations, such as in central Spain and the semi-desert areas of the Eastern Mediterranean—though PDEC applicability is also quite high in the coastal Mediterranean areas defined as Csa and Csb.

Furthermore, the same set of locations was analysed for discomfort hours both with and without DEC activation, adopting the comfort boundary shown in Fig. 8.10. Also in this case Eq. (8.1) was used to estimate the treated air temperature by a PDEC tower assuming the same precautionary effectiveness of 0.6. The relative humidity of the treated airflow was calculated considering psychrometric equations correlating the vapour pressure (Pv) and the saturated vapour pressure (Pvs) of the treated air. CETIAT tables were assumed to calculate the Pvs, while the Pv is function of the Pvs at WBT, the total pressure, the WBD and the psychrometric constant (0.000662). Results are shown in Fig. 8.13. This map classifies the 4416 seasonal hours in the

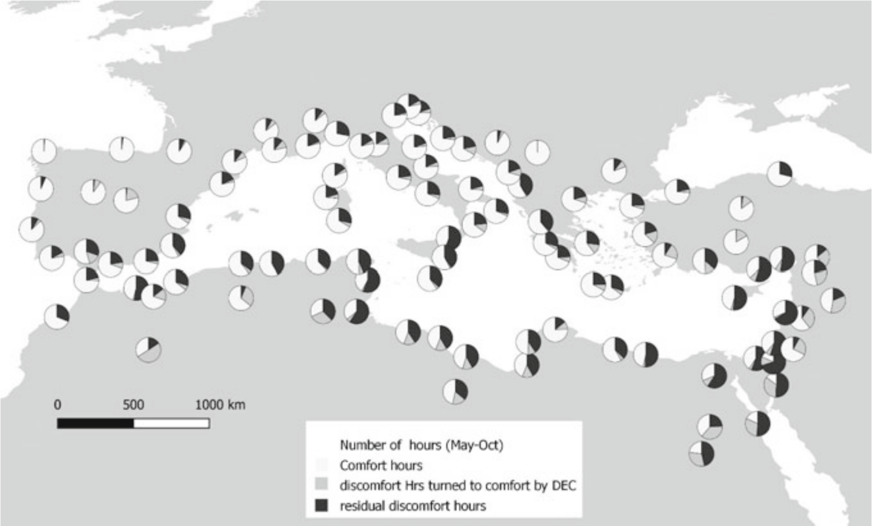

Fig. 8.13 Georeferenced distribution of the reduction in number of discomfort hours due to DEC for the 100 considered locations

extended summer period according to the relative proportion of hours with pre-existing climatic comfort, comfort only after application of PDEC, and residual discomfort even after a PDEC treatment. This breakdown is especially instructive for quantifying the increased potential of ventilative cooling due to a DEC pre-treatment under free-running conditions. The map highlights the fact that higher PDEC potentials are reached in: (i) dry and semi-desert areas, (ii) southern Mediterranean locations, with special regard to central areas such as in Libya, (iii) locations in central Spain, and iv) around the Aegean Sea.

The last two maps and Fig. 8.14 illustrate the extent to which DEC applicability is locally specific, reinforcing the findings of previous studies on the topic (e.g. [78, 79]). Nevertheless, either by adopting available maps or by using devoted KPIs, it is

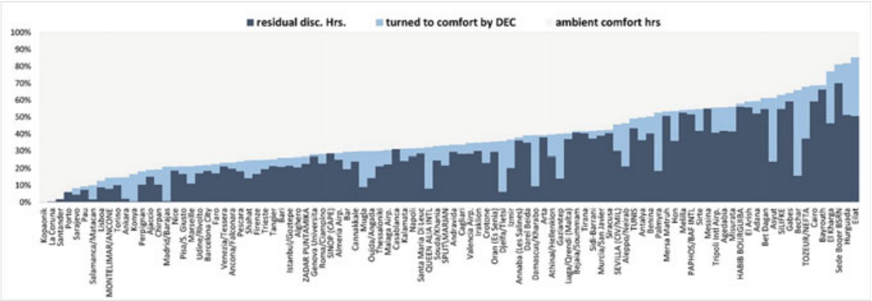

Fig. 8.14 Distribution of comfort hours, residual discomfort hours and ambient comfort hours turned to comfort for the considered set of locations

possible to estimate this geo-climatic potential even in the early stages of building design, and to decide whether PDEC systems represent a valid solution for the particular climatic location. If so, such solutions may significantly boost the ventilative cooling effect and its local applicability when external air temperature and humidity are above the critical comfort threshold.

8.3 Conclusions

This chapter describes basic physical and functional aspects of direct evaporative cooling systems, including different calculation models, and a method to define the climatic local potential of this low-energy ventilative cooling solution. Moreover, a potential applicability map was produced for the Mediterranean basin, based on 100 locations.

Additionally, early-design DEC issues are discussed, suggesting a simple approach for early dimensioning those systems including simple building integration schemes. The adoption of graphical representation tools, such as the Givoni chart, allows to make this approach feasible for both bioclimatic designers and engineers.

On the general point of view, this chapter underlines that DEC systems are valid solutions to increase the applicability and the cooling potential of ventilative cooling systems when ambient temperature conditions are hot and sufficiently dry. Nevertheless, the applicability of these systems requires continuous evaluation and maintenance in order to prevent the potential growth of bacteria and moulds.

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