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Passive downdraught evaporative cooling system integration in existing residential building typologies: a case study

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Abstract

This paper analyses the integration of a passive downdraught evaporative cooling (PDEC) system in existing residential buildings through a case study, an existing 3-storey building located in a small city near Turin. This study was focused on the technological integration of a PDEC system in residential buildings rather than on its actual applicability, which proved to be very low to Turin's climate. Three main aspects are considered: a) a matrix of PDEC systems integration related to building typologies; b) the results of a laboratory testing in site conditions for evaluating the performance of PDEC systems and correctly dimensioning the evaporative tower; c) the design of an integrated PDEC-Building solution, showing that the described approach can be applied to existing designed buildings.

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Keywords: passive downdraught evaporative cooling; passive cooling; building system integration; PDEC monitoring

1. Introduction

This paper deals with the integration of a passive downdraught evaporative cooling (PDEC) system in existing buildings. A direct evaporative cooling technique such as the PDEC's is a well-known strategy for reducing the cooling demand in hot-dry climates, while indirect evaporative cooling systems or dehumidification-evaporation solar cooling systems [1] can reach good performance results also in mid-temperate climatic conditions [2, 3, 4, 5]. The expected reduction in cooling energy needs due to the use of PDEC systems in European cities was calculated to be between 25 to 85% according to local conditions [5]. Furthermore, the applicability of PDEC systems to the existing European residential building blocks was estimated as more than 70% [6].

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This paper presents the results of a study on the integration of PDEC systems in existing residential buildings carried out through a typological analysis and an application to an actual case study. The climate characteristics of the case study site, necessarily selected close to the testing laboratory location, are more suitable for the application of indirect evaporative cooling or solar dehumidification-evaporation systems than for PDEC due to high humidity of the external air in the summer period. Nevertheless, the study's results were worth to be published for their importance in setting a method to assess the potentiality for technological integration of the PDEC system in residential buildings with construction and layout characteristics typical of Northern Italy and, by extension, of Central Europe. In the first part of this paper (§ 2), a matrix of different integration possibilities was developed by comparing the list of PDEC solutions derived from [5, 7, 8] to a classification of the principal building typologies used in urban areas of Northern Italy and Central Europe. In a second part (see § 3), a case study is described, consisting of a design solution for integrating a PDEC system in an existing 3-storey residential building composed of three blocks and localized in the Municipality of Beinasco (TO). This case study includes both a laboratory testing on a PDEC tower installed in the LaSTIn lab (Laboratory on Systems for Technology Innovation, Department of Architecture and Design, Politecnico di Torino) and the development of a design solution for integrating PDEC towers in the existing building. The laboratory testing was performed to study the functioning of the system in similar climatic condition of the building site in order to correctly dimension it.

2. Typological integration of PDEC systems in residential buildings

Building typologies, PDEC systems and building integration of PDEC are classified. A matrix of different integration strategies is presented in par. 2.2. and based on classes defined in par. 2.1.

2.1. PDEC classification in relation to building typologies

Based on the knowledge of the existing residential building stock in Turin's metropolitan area, it is possible to identify the following five categories of building shape/structure.

- Isolated buildings, i.e. residential single or double family buildings. This category includes isolated buildings with possible attached garage and/or warehouse and a garden.
- Terrace houses, i.e. row buildings composed of several single family two-storey houses placed side by side, hence with one (at the ends of the row) or two (within the row) blind facades shared with the adjacent house/s and the other two façades with opposite compass orientations.
- Courtyard buildings, i.e. multi-storey buildings aggregated around a common, usually rectangular, courtyard.
- Tower buildings, i.e. multi-storey buildings with predominant vertical dimension and a square or circular plan comprising, generally, three-four apartment per floor exposed to all compass orientations.
- Row buildings, i.e. multi-storey buildings with predominant longitudinal dimension. Apartments have one or two exposures (except the ones at the ends-of-the-row) with access from various staircases directly or through corridors. In old low-income building types, still present in Turin, access to the apartments occurs through long balconies called "ballatoi".

A PDEC system is characterised by a buoyancy-driven downdraught air movement due to an air temperature drop caused by water evaporation. PDEC systems can be classified in two ways: technological and typological. In the former, four categories are considered related to the used water-spraying system: wet pad; shower tower (coarse sprayers); misting tower (atomizer nozzles); and porous media [5, 9]. In the latter, four different positions of the PDEC system in relation to the building are foreseen, based on Ref. [5]: central atrium (open), central atrium (closed), attached PDEC tower and detached PDEC tower [5]. They are described as follows.

- Central atrium (open) – e.g. the Malta Stock Exchange, Malta. This type of PDEC position implies a central space where there is no discontinuity between the occupied spaces and the space where downdraught cooling by evaporation occurs.

- Central atrium (closed) – e.g. the Torrent Research building, Ahmedabad, India. This type of PDEC position implies a central airshaft or a skylight well, within which cooled airflow is downdraught and distributed to the occupied spaces through window openings or vents.
- Attached PDEC tower – e.g. the auditorium of the C II Centre of Bangalore, India. It is a PDEC tower attached to the building wall and can serve one or more spaces.
- Detached PDEC tower – e.g. the C II Centre of Hyderabad, India. It is an external PDEC tower independent from the building, but localised nearby and connected by an underground tunnel or a horizontal channel.

2.2. A matrix of PDEC building typological integration

A combination of the above-described building types with the technological and typological PDEC classification allows for developing a matrix of possible PDEC-building integration as shown in Fig. 1. This matrix can be used in a preliminary design phase such as the building programming.

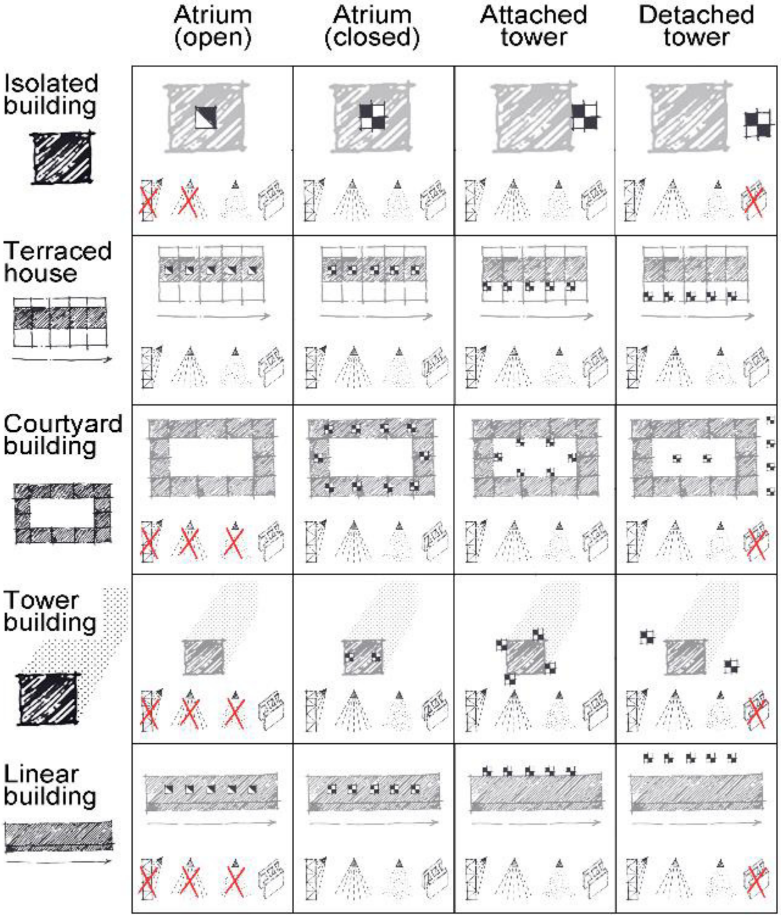

Fig. 1. A matrix of PDEC-building integration combining PDEC techniques (shown by icons, from left: wet pad, shower tower, misting tower, porous medium) and positioning with residential building typologies (a red cross means that the indicated technique is not suitable).

3. The case study

3.1. Case study description

An existing residential building compound located in the Municipality of Beinasco (TO), designed by the ArTech Studio of arch. Giancarlo Pavoni, was selected as case study for assessing the potentiality of installing PDEC systems for summer cooling in a technologically and architecturally integrated way. The case study is a 3-storey row-building composed of four semi-detached blocks with a slightly different orientation around an average South-West's. This building, erected in 2013, was conceived since the first design phase as a bioclimatic architecture with U_{values} for both opaque and transparent envelop components set to values lower than the ones prescribed by the Italian energy code. The building compound includes 24 residential units (apartments) of different dimensions. The different orientation of the four blocks leaves empty "corner-shape" spaces between the end-walls of each block, that were used for proposing the installation of the PDEC towers and connected equipment. In order to dimension correctly the PDEC system, a prototype PDEC tower was constructed in the LaSTIn and its performance monitored during a summer period. The monitoring phase is described in par. 3.2., the dimensioning of the PDEC system for the case study building is described in par. 3.3., and its integration to it is defined in par. 3.4.

3.2. Laboratory testing of the PDEC system

The testing PDEC tower installed in the LaSTIn was monitored between July and August 2015. The main objective was to assess the performance of the system in real climate conditions in order to obtain reliable values of outlet air temperature and airflow rate that could be used for dimensioning the PDEC system designed for the case study building.

The experimental system is composed of the following elements.

Main hardware

- A tower constituted by a PVC tube generally used in drainage systems with a diameter of 400 mm and a height of 3 m. This "tower" was installed adjacent to the laboratory's external wall and fixed to an existing structure with its base elevated by 1.5 m above grade in order to allow measuring and positioning of a collecting basin for the not evaporated water.
- The evaporative hydraulic system. The used nozzle is a plastic full cone nebulizer used in agriculture (micronebulizzatore Geolia), positioned at 20 cm from the top entrance of the tube. This is a very low cost nozzle (less than 1€), easy to be found and replaced. It worked at the local aqueduct conditions (measured water flow of 17.74 l/h) with a spray angle of 30°.

Monitoring sensors

1. Datalogger TESTO 480;
2. Telescopic hot bulb ø 3mm air velocity sensor , for measuring the inlet air velocity (velocity measurement range 0…10.00 m/s; accuracy ±0.03 m/s);
3. High precision waterproof temperature sensor pt100 (precision ±0.15 °C measurement range 0…+100 °C; resolution 0.01 °C), used for measuring the outlet air temperature. The sensor was protected by the non-evaporated water flow according to the methodology described in [10];
4. High precision sensor of humidity and temperature (RH% 0…100%, accuracy ±1.0% in RH 0…90% and ±1.4% in RH 90…100%; temperature -20…+70°C, precision ±0.2 °C between +15…30°C and ±0.5°C for other temperatures), used for measuring the inlet air.

The tested PDEC system is of a shower tower type, where non-evaporated medium-size water drops increase the airflow by motion transfer (see Fig. 2).

Data collection and recording was carried out in real time by using the software "PC Testo EasyClimate" developed by TESTO. The inlet Wet Bulb Temperature (T_{WB}) was automatically calculated by the software using the following expression:

$$T_{WB} = T_{DB} \cdot \mathrm{atan}\left(0.151\,977(RH\% + 8.313\,659)^{1/2}\right) + \mathrm{atan}(T_{DB} + RH\%) - \mathrm{atan}(RH\% - 1.676\,331) + 0.003\,918\,38(RH\%)^{3/2} \cdot \mathrm{atan}(0.023\,101 \cdot RH\%) - 4.686\,035 \quad (1)$$

Where the T_{DB} is the dry bulb temperature and the RH% is the relative humidity, both measured by the sensor.

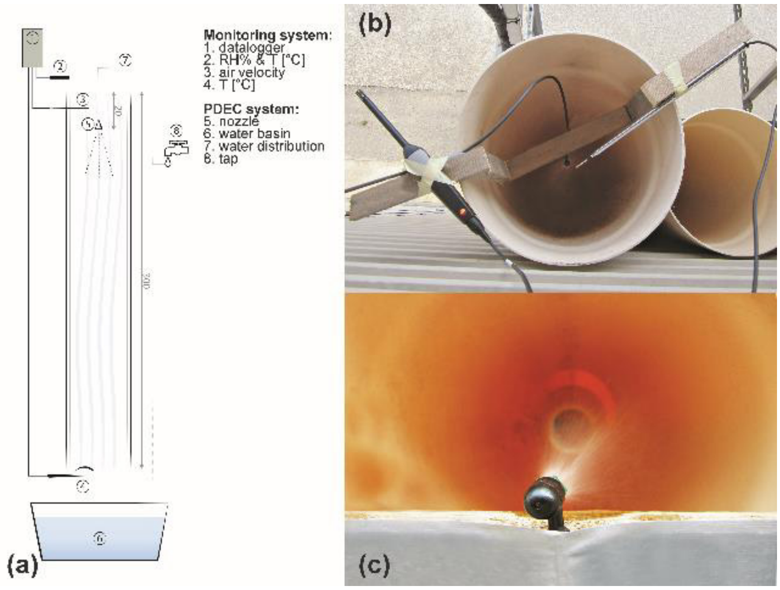

Fig. 2. (a) the monitored PDEC system; (b) upper part of the PDEC tower with sensors; (c) the spraying nozzle.

Data were collected during five days (30th and 31st of July 2015 and 5th-6th and 7th of August 2015) from morning to the late afternoon. During these days, a high wet bulb depression (WBD) was measured and the PDEC tower was able to reduce inlet air temperature by 8 to 11 °C. The effectiveness of the system in reaching the theoretical limit of evaporative cooling represented by T_{WB} can be calculated using the following expression [11]:

$$\varepsilon_{WBD} = \left(T_{in,DB} - T_{out,DB}\right)/\left(T_{in,DB} - T_{in,WB}\right) \quad (2)$$

Where subscript $_{in}$ refers to inlet values and subscript $_{out}$ to outlet ones.

The ε_{WBD} is function of several environmental conditions and varied between 62% to 88%. The temperature of outlet air can be calculated using the following expression developed by Givoni [7, 12] and compared to others' in a recent work [11]:

$$T_{out,DB} = T_{in,WB} * slope\left(T_{in,DB} - T_{in,WB}\right) \quad (3)$$

Where the slope coefficient is calculated for each tower system and location by elaborating a monitored dataset as described in [7, 11]. In the present study, slope was assumed to be 0.84. The graph of Fig. 3 shows a good match between data monitored in the 5th of August and the calculated ones.

Water consumption in a PDEC system is function of the type of nozzle. An average amount of 17.74 l/h of water sprayed by the monitored nozzle was measured, while the amount of not evaporated water collected in the water basin was 17.09 l/h, with a relevant water consumption by evaporation of only 0.65 l/h. Due to this high amount of not evaporated water, a recirculation system was foreseen in the PDEC tower designed for the case study in order to increase its efficiency and sustainability. With water recirculation, an estimate of PDEC system water consumption could reach 10 litres every 3 days.

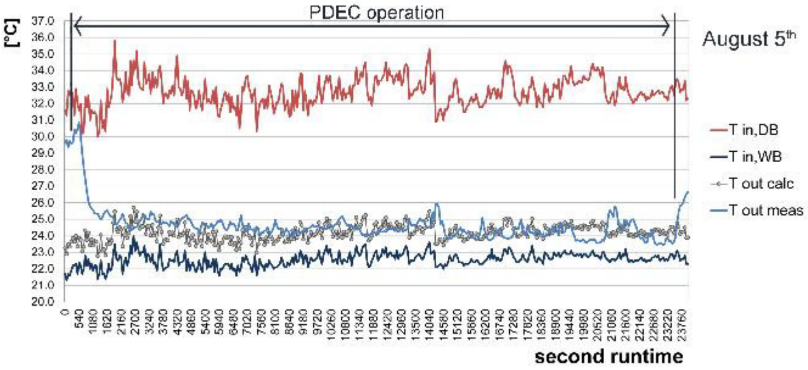

Fig. 3. Monitored and calculated data – 5th august 2015.

3.3. The PDEC system applied to the case study building

3.3.1. System dimensioning

Based on the collected data from testing, a simple method for pre-dimensioning the PDEC system to be designed for the case study was elaborated. One of the main variable to be defined was the tower's diameter, calculated through the following steps.

Firstly, the airflow rate needed for covering the cooling demand (q_{r-cool}) in two representative apartments amid the 24 residential units was calculated using the following equation [13]:

$$q_{r-cool} = \frac{H}{c_a \cdot \rho \cdot (t_i - t_e)} \qquad [\mathrm{m}^3/\mathrm{h}] \tag{4}$$

Where: H is the environmental heat power (solar and internal gains) calculated according to [13], c_a is the air thermal capacity (0.28 W/kg°C), ρ is the air density (1.2 kg/m^3), t_i is the internal air temperature (assumed as the average of the maximum temperature of summer months), t_e is the external air temperature, for which two assumptions were considered: a) t_e = average between maximum and minimum summer ambient temperature; b) t_e = average temperature of the air treated by the monitored PDEC system.

Secondly, the minimum required section area of the PDEC tower was calculated using the following expression [5]:

$$A = \frac{q}{C_d} \sqrt{\frac{(T_i + 273)}{\Delta T \cdot g \cdot h}} \qquad [\mathrm{m}^2] \tag{5}$$

Where T_i is the set point temperature, ΔT is the difference between tower's inlet and outlet air temperature, g is the acceleration of gravity, h the height of the tower (difference between the height of inlet and outlet openings), C_d is the discharge coefficient due to flow resistance of the tube (assumed as 0.9).

Thirdly, the net flow area of the vent connecting the PDEC system to the indoor environment was calculated using the following equation:

$$A_{\text{vent}} = \frac{q_{\text{r-cool}}}{C_d \times v} \qquad [\text{m}^2] \tag{6}$$

Where v is velocity of the downdraught airflow in the PDEC tower assumed as the average of the monitored air velocities in the laboratory testing (0.8 m/s). Table 1 reports the calculated values for the two chosen apartment units. The dimension of the tower used during testing is compatible to the requirement of unit B, while for unit A the needed tower's diameter is ≥ 470 mm. However, only one tube's diameter value of 500 mm was considered in the design of the PDEC system integrated in the case study building for both apartment units. Furthermore, the distance between a PDEC tower and its corresponding apartment was taken as a minimum in order to assure that the treated airflow could naturally reach the indoor environment.

Table 1. PDEC system dimensions (*calculated according to [5])

	Apt. A	Apt. B
Floor area [m^2]	66	46
Volume [m^3]	178.2	124.2
$q_{r\text{-}cool}$ [m^3/h]	391.1	235.1
ACH*	2.2	1.92
PDEC diameter [m]	0.47	0.36
A_{vent} [m]	0.17	0.1

A scheme of the designed PDEC system is shown in Fig. 4 (a).

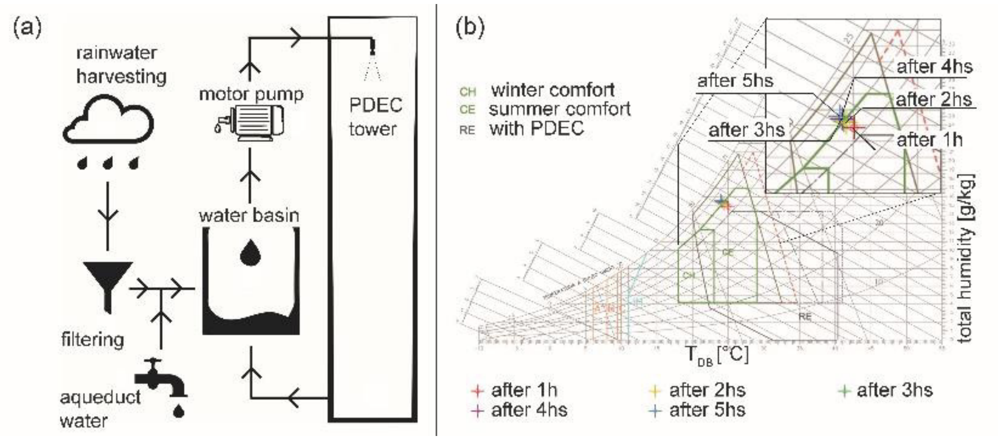

Fig. 4. (a) a scheme of the designed PDEC system; (b) calculated internal conditions plotted on a psychrometric chart.

3.3.2. System operation and performance assessment

The designed PDEC system is based on the nebulization of water in a series of towers. Each tower serves one single residential unit. The water used in the evaporation system is pumped from a tank positioned at the base of the system that can be filled using different methods:

- by connecting to the local water distribution system;
- by recycling the not-evaporated water during PDEC operation;
- by filtering the water collected in a rain harvesting system.

A simple balance was used for estimating approximately the air temperature and relative humidity of indoor spaces after a given period of time of PDEC operation. Equation 7 was used for calculating the indoor air temperature, while equation 8 allowed to estimate the indoor relative humidity:

$$(q_{r-cool} \times T) \times t_{PDEC} + V \times t_i = (V + q_{r-cool} \times T) \times t_x \tag{7}$$

$$(q_{r-cool} \times T) \times UR_{PDEC} + V \times UR_i = (V + q_{r-cool} \times T) \times UR_x \tag{8}$$

where: T is the period of operation (hours), V is the cooled volume, subscript $_x$ refers to the final environmental condition, subscript $_I$ to the starting environmental condition, and subscript $_{PDEC}$ to the PDEC airflow condition.

Results from equations (7) and (8) for a 5-hour period of PDEC operation in two apartments are reported in Table 2. Water flow is assumed as constant and equal to the average measured value. The following assumptions were made: outlet air temperature and relative humidity from the PDEC system are constant during the considered period and equal, respectively, to 23.6°C and 85%; starting indoor air temperature and relative humidity are equal, respectively, to 28°C and 50%.

Table 2. Values of indoor air temperature and relative humidity in two apartments after 5 hours of PDEC system operation (calculated according to [5])

	Apt. A					Apt. B				
Variables	1st hr.	2nd hr.	3rd hr.	4th hr.	5th hr.	1st hr.	2nd hr.	3rd hr.	4th hr.	5th hr.
Room T_{DB} [°C] – calc.	25	24.4	24.2	24.0	24.0	25.1	24.5	24.3	24.1	24.0
Room RH% – calc.	74.6	79.1	81.0	82.1	82.1	73.4	78.3	80.4	81.6	82.3

As shown in Fig. 4 b, the points combining the above-indicated air temperature and relative humidity values plotted on a psychrometric chart, fall slightly out of and Givoni's summer comfort boundaries starting from the second hour of PDEC operation. This result is due to the combined effect of high RH of both outdoor air and PDEC outflow. To avoid this discomfort condition, a different PDEC operation management was considered based on the following not necessarily alternative modes:

- setting a not-continuous PDEC operation schedule using a sensors-controlled system;
- varying the amount of water flow reaching the nozzles, by selecting the number of activated nozzles or changing the water pressure acting on the water pump;
- controlling the hygrometric characteristics of airflow. by mixing treated and untreated air

3.3.3. PDEC technological and architectural integration

The existing building was analysed for finding residual spaces to locate the PDEC technical system units according to one of the solutions reported in the matrix of Fig. 1. The four-semi-detached blocks of the building leave three residual outside triangular spaces confined by walls without openings. These spaces are perfectly adapted for locating the PDEC system units dimensioned as in par. 3.3.1., and each serving one or two batteries of three vertically distributed apartments depending on their position, respectively, at the edge or in between blocks. Each PDEC technical system unit is of the type "detached tower" and comprises from three to six vertical tubes, depending on the position as mentioned above. Each tube, where nebulised water is sprayed at the top, supplies air through a horizontal duct to a single apartment to avoid interference between private space uses and relevant air quality. Air within each apartment is then exhausted naturally through vents positioned on the wall adjacent to the stairwell. The driving force is a stack effect caused by the pressure difference due to the difference in air density between the space connected to the PDEC system and the staircase shaft. The Each PDEC technical system unit is protected by a light metal wall structure on both sides of the triangular space, the apex and the open part not bounded by the building masonry walls Each tube has its own system for collecting the not-evaporated water. The bearing structure for the roof and metal walls of the PDEC technical system is composed of metal pillars and girders HEA. The external wall cladding is made of standard thin squared panels of weathering steel (COR-TEN) available in the market suggesting a solution that can be repeated elsewhere (see Fig. 6).

Fig. 5. The proposed building integration of the PDEC system.

These panels present an increasing transparency and lightness, from bottom to the top by means of laser-cut holes. These series of holes allow for air entering the technical space as well as reducing the weight of the wall. The roof covering of each PDEC technical system is not continuous but composed of mechanically movable louvers able to shade the underneath space meanwhile preventing rainwater penetration. The proposed cor-ten material is characterized by a brown colour fitting well to the existing building external texture and landscape context. On a compositional point of view, the proposed integration of the PDEC technical system to the building does not create a conflict with the actual building aspect but rather looks for harmonising technological and architectural characteristics (see Fig. 5).

4. Conclusions

The method here developed can help designers to include PDEC technical systems in existing buildings, even if it can be adapted in future for new building stocks. Main conclusions are:

- PDEC systems can be easily integrated in existing buildings without compromising visual and perceptive characteristics of architecture;
- Knowing the site-dependent and building-related indoor environmental requirements a PDEC system needs to comply with is important for dimensioning correctly the system since the pre-design phase;
- Even low cost nozzles working at low pressure can obtain good performance, even if the amount on not evaporated water is high. Recirculation pumps can be very useful for drastically reducing water consumptions.

Further investigations are planned with the aim of developing a database of PDEC potential applicability in different locations as well as assessing alternative solutions employing indirect evaporative cooling systems, possibly connected to low pressure heat exchangers [14], when climate conditions do not favour direct evaporative cooling.

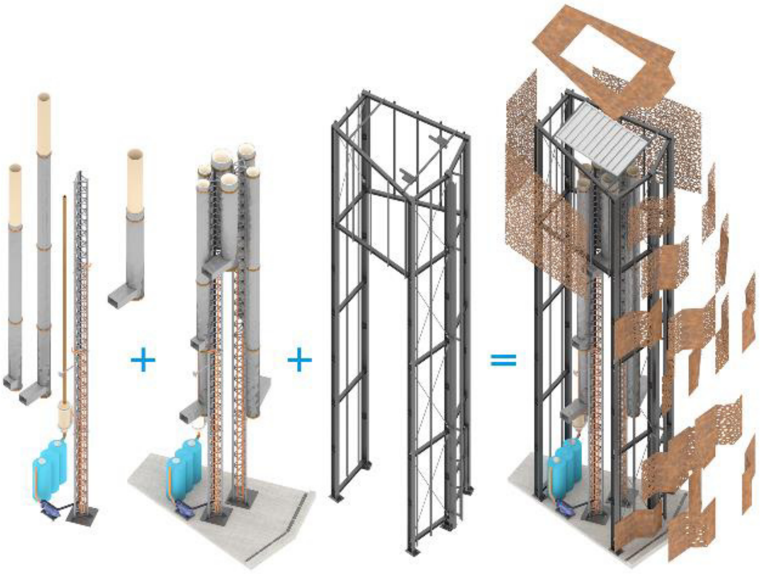

Fig. 6. The proposed PDEC system.

Acknowledgements

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