Passive Downdraught Evaporative Cooling Applied on Existing Fabric: Using Traditional Chimney as Case Study in Portugal

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ABSTRACT: The objective of this paper is to investigate the use of Passive Downdraught Evaporative Cooling (PDEC) in existing fabric. A PDEC shower system was introduced on an existing brick chimney traditionally used for summer ventilation through chimney effect and the device was analyzed as case study. The methodology of this study was separated in two parts. First part reports a field experiment of the device and includes measurements of Relative Humidity (RH), Temperature (T) and Air Speed (AS) inside both PDEC and adjacent room. Second part complements field reports with the use of Thermal, Computer Fluid Dynamics (CFD) and Mathematical models. The Thermal Model (TM) was created according to building fabric and measurements of the field report. CFD modelling was combined with the TM to evaluate predicted Air Movement (AM), AS, T and RH beside all the room geometry and fabric, including chimney. The balance of intake air and exhaust air to minimize concentration of water inside room and chimney was also analyzed. Mathematical models, CFD and TM were combined to improve traditional chimney and PDEC cooling performance according to different number of occupants.

Keywords: PDEC, refurbishments, field report, thermal, CFD and mathematical model.

1. INTRODUCTION

PDEC originates from the vernacular architecture of the Middle East and it has been the object of great interest worldwide since 70´s energy crises. Several experiments have been carried out, namely by Givoni [1], Brian Ford [2] and Pearlmuter and al [3], to extend its effectiveness to both outdoors and indoors for uses such as domestic, offices and refurbishments.

The device consists of single or multiple towers equipped with a water/vapour supply placed on the top. During the constant injection of water, droplets descend through the tower and conditions close to saturation along its length. Cool air descends the tower and exits at its base where it is delivered to the adjacent spaces.

The concept is based on the relatively large amount of energy required to convert water from its liquid to gaseous form within a local thermal imbalance with subsequence differences in air density. This leads to the movement of air from a zone of high pressure, where air is hot and less dense (top of the tower) to a zone of lower pressure, where air is colder and denser (bottom of the tower).

PDEC is specially useful in hot-dry climates and it has several advantages: it is an adiabatic process because there is no addition or extraction of energy (heat) from the system, therefore, it can be completely passive; it supplies ambient air with moisture raising the RH levels, thus improving the thermal comfort and reducing problems resulting from low RH; it is a quite flexible system that can be easily adapted to new and existing constructions.

Whenever applied to existing fabric, PDEC depends not only on the cooling power required but also on the existing fabric limitations, namely architectural form and envelope materials. The combination of these factors is essential to define a DEC strategy and often a system can not be totally passive. For instance, when a shower system needs to be placed at low height PDEC based on free convection can result in discomfort. People may get wet from not evaporated water droplets. The addition of a fan increases the length of time before water droplets reach the ground, helping them to fully evaporate and eventually switch from a downdraught passive mode to a mechanical one, thus becoming a hybrid system.

However, even on a hybrid or mechanical DEC system, energy savings are quite high and energy consumption low enough to warrant its application to an existing fabric. This can help productivity in hot-dry areas where often the poorest population lives. Therefore, the system can also offer an economical benefit.

2. PHYSICAL PROCESS

Evaporative cooling is a physical process that occurs when water evaporates within a stream of ambient air without a supply of external heat, resulting in the drop of the Dry Bulb Temperature (DBT), increase of the RH while the Wet Bulb Temperature (WBT) remains approximately constant. The capacity of air to hold vapour is indicated by its DBT and RH.

Traditionally, the temperature drops to 2-3 °C above WBT [4].

Evaporative cooling occurs due to the principle of latent heat of vaporization that is the amount of "hidden energy" that is required to convert a unit of mass water from its liquid to its gaseous/vapour phase. The transfer of heat energy from ambient air to water to support the phase change is the process that reduces ambient air temperature. The latent energy required to evaporate more water is supplied by the surrounding air, so the later is cooled.

One gram of water that is evaporated without external heat extracts about 2519 J of the ambient air [3]. The heat transfer tends to increase the droplet temperature, whereas the latent energy absorbed by the vapour (during mass transfer) decreases the droplet. Water droplet evaporation occurs in 2 stages: first it is cooled to the equilibrium temperature, and then its radius decreases [5]. Equilibrium is reached when the droplet is cooled at the WBT.

The energy consumed in the process of water evaporation can be utilized in two different ways to cool a building. One is by the direct evaporative cooling of the outdoor air, which is then introduced into the building. That is the case of downdraught evaporative cooling when gravity accelerates the evaporation process.

The other is by an indirect way, which is cooling a building element (wall, roof, etc) that transmits coolness to the interior by radiation. Both systems can be passive or use mechanical means.

When the system uses only passive means, and the local thermal imbalance is caused by "free convection", it is considered passive downdraught. The movement of air inside an evaporative cool tower may occur as a result of a "forced convection", produced when air is driven by mechanical means (such as an electric fan) to increase circulation.

3. PDEC INERTIAL SHOWER APPLIED TO EXISTING FABRIC

PDEC tower should always be considered a part of a holistic and integrated environmental strategy. In both new constructions and refurbishments, environmental strategy should consider passive tools appropriate to the specific climate. In a hot dry region, with well-insulated envelope, high thermal mass, or proper shading, the tower itself can be used without PDEC to cool throw stack-effect especially useful for natural ventilation and night cooling. This can even help delaying use of PDEC in the morning hours.

Finishing is also important: if a PDEC system is integrated in an existing structure made from porous materials, like a brick chimney or an impermeable material like plastic, it should cover the contact surface to increase its effectiveness between water and air.

4. MOURA´S TRADITIONAL CHIMNEY

The use of chimneys was particular successful in obtaining cooling by stack effect in Moura (38º13N:07º13W), a small village in the southeast of Portugal. Chimneys have inclusively a separate system to act as a fireplace smoke extract. These chimneys are the result of a strong Arabic influence in the village, and several beautiful examples can still be seen, especially in housing.

Although its architectural importance has both utilitarian and aesthetical aspects, these chimneys are either being demolished or maintained only as decorative elements; its cooling effect substituted by air conditioning systems. Due to its architectural form resembling a tower, it seems obvious to install an evaporative cooling device in the traditional chimneys, improving cooling performance of the building.

The chimney object of the case study is located on the first floor of *ATENEU MOURENSE*, a small cultural centre in Moura. The building was probably erected in 19th century as a rich farmer's house, and can be described as a typical noble two story urban house.

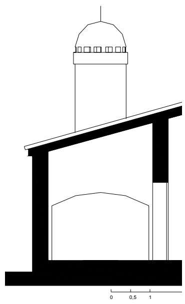

Figure 1 and Figure 2: Section of the adjacent room of chimney and photo of the exterior of the chimney

Internal and external walls are 60 cm thick, made from adobe and finished with lime.
The chimney has a cylinder shape measuring 4,8 m in height (measured from the floor of the room) and 0,9 m in diameter. It is located on the first floor adjacent to a room with approximately 19 m^2 floor area and 63 m^3 of volume. The room has tree old wooden doors (two interior and one exterior), and one north-facing window with single glazing and aluminum frame.
The chimney walls are in adobe, 0,30 m thick. On the upper limit there are a few openings. There is no lime rendering on it.
The chimney is adjacent to a fireplace that has its own smoke conduct. This confirms its use as a ventilation tower producing coolness by stack effect.

5. FIELD REPORT

An evaporative system project within the chimney was designed according to the experiments made by Givoni and Pearlmutter et al. It included 2 small showers with fine spray, placed 4, 5 m above floor plan, and a pond placed on the bottom of the chimney. A pump would recirculate the water. Water flow was estimated at 14 l/min and air speed at 0, 7 m/s (Figure 3).

A fan was placed near the showers helping to distribute water droplets in the air stream. Also, a plastic net covered the interior of the chimney. The system worked continuously for approximately 5 hours (the number of hours considered necessary for performance testing).

Due to practical reasons, the pump was excluded, and water was provided directly from the shower. A single shower was placed 4,5 m high above floor plan, with coarse water. The water was provided from an existing tap on the exterior that could be easily controllable. The water flow rate was 10,5 l/min.

The fan and the plastic net were also excluded. This was mainly because of the use of coarse water instead of fine spray thus increasing the air speed due to free convection which reduced contact time between water and the interior walls of the chimney. It also reduced the risk of air contamination from dirt on the chimney walls.

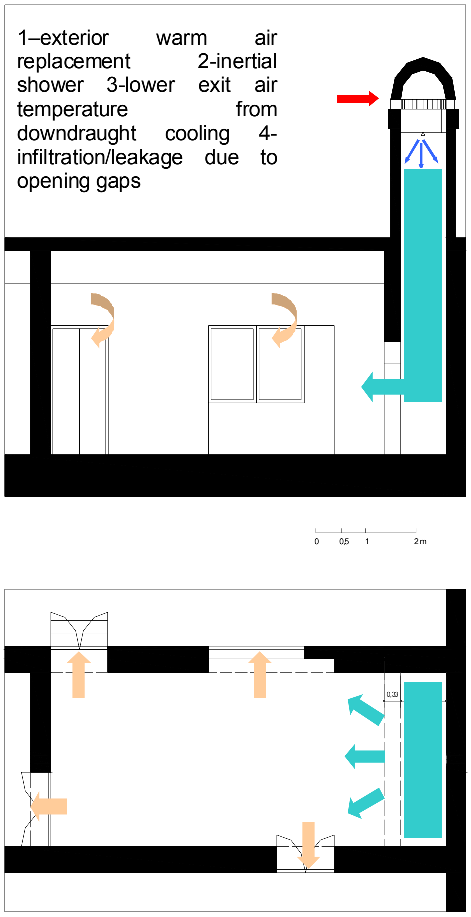

Figure 3: Section and Plan of the chimney and adjacent room (not on scale)

Water did not circulate continuously in order to avoid flood problems and the shower operated for only a few minutes. Also, PDEC configuration ended up being less detailed than initially thought. Testing conditions were not ideal, especially due to the use of course instead of fine spray.

5.1 Measurements

The measurements took place in the 6th of August, every hour, between 11:30 and 15:30 [6]. The room´s exterior and interior atmospheric conditions are registered on row 1 and 2 of Table 1. The drop of temperature and relative humidity registered at 12:30, is due to a breeze.

Table 1: Measurements

	Measured Parameters / time (hour)	11:30	12:30	13:30	14:30	15:30
1	Exterior conditions					
1.1	Air Flow Velocity (m/s)	0,15	0,3	0,2	0,15	0,15
1.2	Dry Bulb Temperature (ºC)	40	37,1	42,3	41,8	40,7
1.3	Relative Humidity (%)	19,7	23,4	14,2	15,5	17,2
2	Room conditions before evaporative cooling shower					
2.1	Air Flow Velocity (m/s)	0,2	0,15	0,15	0,2	0,2
2.2	Chimney Temperature (ºC)	31,2	28	31,5	32,3	33,6
2.3	Chimney Relative Humidity (%)	46,7	53,6	43,7	39,8	34,8
2.4	Room Temperature (ºC)	28,8	27,9	30,4	30,8	32,6
2.5	Room Relative Humidity (%)	48,5	50,3	42,2	39,6	31,9
3	Room conditions after evaporative cooling shower					
3.1	Air Flow Velocity (m/s)	0,5	0,6	0,6	0,6	0,5
3.2	Chimney Temperature (ºC)	26,5	25,5	22,0	26,6	23,4
3.3	Chimney Relative Humidity (%)	62	79,7	95,5	74	94,2
3.4	Room Temperature (ºC)	26,6	25,3	22,2	25,2	23,7
3.5	Room Relative Humidity (%)	56,6	75	91,7	78,6	92

Results show that after the shower system was activated, both exit air temperature and RH were not stable on the measured periods. Temperature ranged from 22 ºC to 26.6ºC and RH from 62 % to 95.5 %. Graphic 6.1 shows that there is a relation between temperature and RH, i.e., the higher humidity corresponds to lower exit air temperature. According to Graphic 6.2, room conditions after PDEC are very close to saturation, i.e., air cannot hold more moisture. Also, line of enthalpy is not absolutely constant, therefore WBT changes slightly.

To validate the experiments measured values, the outdoors climatic data and chimney physical properties were first tested on Givoni´s inertial shower mathematical model. Values obtained are very similar with the ones measured, except for those registered at 13:30. The differential is more than 4ºC, when the remaining is approximately 0.5ºC.

5.2 Summaries

Mouras chimney had several problems for use indoors, either needing some refinements or being only compatible for outdoors. It is important to note that although PDEC was activated every hour thus not providing continuous cooling, results are quite similar to those observed on other experiments, namely Givoni´s.

When Moura´s chimney PDEC was activated, it produced very high values of relative humidity (more than 90 %), especially in the first minutes of operation. Such high humidity can lead to surface condensation, creating the risk of mold growth or other moisture problems. Therefore, temperature depression of the chimney should be controlled so that relative humidity should not exceed 70 % [7] in all zones.

Also, water particles did not fully evaporate before reaching the ground. People placed near the chimney could easily get wet from not evaporated water droplets. Evaporation depends upon droplet diameter and length of time water stays within the air stream. Therefore water droplet should be small enough or the distance from the sprays to the openings great enough to guarantee total evaporation. Since height of the shower could not be maximized because cooling source was placed on the top of it, a fine spray mist of water (like filtered micronisers) should have been used instead.

Finally, exit airflow of 0.7 m/s rate was far above than the 0.25 m/s recommended avoiding unpleasant draughts.

6. MODELLING

Since field-testing had several limitations to produce valid data, it seemed important to create a thermal and a dynamical model of the PDEC tower and adjacent rooms to investigate cooling performance of the system. There are few programs that allow a PDEC simulation because there is the need to recognize top-down airflows and driven forces. PDEC are often described as “reverse chimneys” because the column of cool air falls.

Therefore, although the cooling source from a plant may be placed at the same height of any evaporative cooling device, the air temperature will be continuously increase so that the exit temperature is higher than the cooling source (plant). Also, when the cooling source is placed in the exit opening with a temperature similar to the evaporative cooling system, the air temperature will increase inside the chimney and a pressure zone may occur when in contact with outside air.

Both situations are the opposite of the downdraught evaporative cooling effect. However, internal conditions can be reproduced according to an occupancy pattern (number of users of the space/building, heat gains from people, machinery, etc) and physical properties of the construction (envelope, heat losses from envelope, etc) in a thermal model of the PDEC chimney and adjacent room. This model can be combined with a CFD program that analyses how airflow rates from PDEC supply coolness into the adjacent room. Finally, mathematical models developed and validated by authors such as Givoni can be used to define limitations of Moura´s Chimney cooling power, depending on the number of occupants that can be supplied under comfortable parameters.

6.1 Thermal Model

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (%)	Humidity Lower Limit (%)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)	Include solar in MRT (y/n)?
25.0	18.0	0.0	0.0	100.0	0.0	0.0	0.0	Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1	10	16	0.0	SIZE
2				
3				
4				

	Radiant Prop.	View Coefft.
Heating	0.000	0.248
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	10	1.000	0.000	0.000	0.000	0.000	0.000	0.000
2	9	1.000	1.000	0.000	20.000	10.000	0.000	0.000
3	5	1.000	0.000	0.000	0.000	0.000	0.000	0.000

Figure 4: Input TAS parameters

TAS 8.4 was used to create a thermal model with an envelope similar to Moura´s chimney and adjacent room. It was tested according to the weather profile of the experimental day (6th of August) with input data from 4 people (Figure 4).

The program does not include Moura´s weather data, so a place with similar climatic conditions was used: Phoenix, Arizona, USA because of its hot dry climate and similar latitude [8]. Also, the test day was not the 6th of August but 29th of July, more similar to the climate parameters measured on the experiment day. Output data was similar to those verified on the field report.

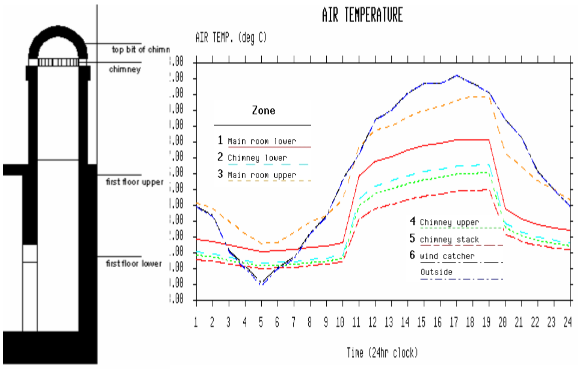

Figure 5 : Temperatures according to zones

6.2 Computer Fluid Dynamics (CFD) Model

CFD does not simulate cooling systems where driven forces and cooled air occur in the same pressure zone, therefore heat transport does not correspond to air movement inside the cooling chimney. The downdraught evaporative cooling should be on the bottom of the tower. However, a CFD can be very efficient to ensure that exit air speed and temperatures are precisely distributed within a space. This is specially important to identify eventual stagnant zones where air does not flow and temperature gradients are higher than 3k in the neck zone [9].

AMBIENS is a CFD two dimensional Cartesian grid system, in which a transversal “slice” 1m tick including exit air from chimney, was modelled. The grid represents the computational cells that will be the basis of the simulation. Building elements were not placed reproducing reality thus maximizing output information to better understand indoors thermal comfort. Therefore window and outlets (corresponding to doors gaps) are placed in the same plan, although this does not happen in any 1m slice.

Features represented are:

a) one window
b) one cooling source (air inlet)
c) two door gaps (air inlet and air outlet)

Note that inlet air volume should equal outlet air volume.

Definitions of modelling included:

a) each pixel is equivalent to 0.1m height or width and $0.1m^2$ area
b) 4 pixels for each opening, equivalent to $0.41m^2$ assuming $2.5m^2$ in reality

Input data for modelling included:

a) 63m^3 of room volume

b) 2 ACH of infiltration, equivalent to 0.035m^3/s of Airflow Rate in the whole room, therefore 5.83 x 10 -3m^3/s in the “slice”

c) air speed of 1 pixel equivalent to 0.0075m/s at 0.6m/s or 8 pixels at 0.3m/s i.e., “slice” volume divided by area of each pixel

d) 0.6m/s definition of exit air speed, either 4 pixels

Temperature surface (obtained from TAS model) included:

roof - 34^o; floor - 31^{o}C; walls - 32^{o}C ; window - 40^{o}C

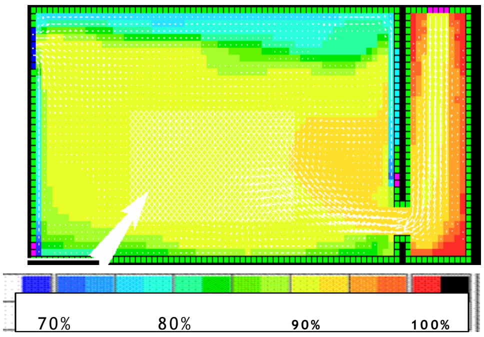

Figure 6 : Relative Humidity

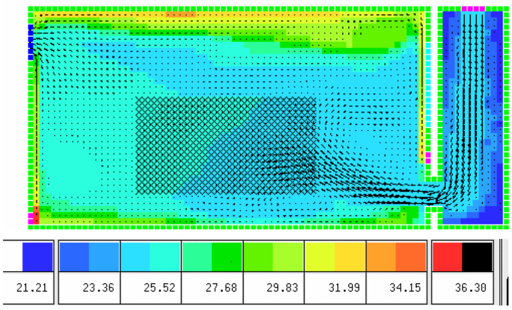

Figure 7: Temperature

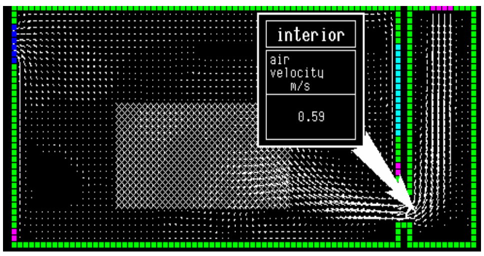

Figure 8 : Air Speed

6.3 Mathematical Models

To better evaluate cooling limits of the device PDEC + Chimney, two scenarios were established to be tested with mathematical models: i) with a medium occupancy, i.e., 15 people, and ii) maximum occupancy, i.e., 25 people. (Table 2).

Internal gains from 15 and 25 people were inputted in TAS model and used to evaluate cooling needs according to these occupancies.

Formulas used were:

Texit *= DBT – (DBT-WBT) x (1 -exp (-.8 x H)) x (1 - exp (-.15 x WF))* [10]

Flow *(m^3/hr) = 3600 x exit opening x speed*

P *= A x v x delta t x Cp x p* [11]

Table 2 : Input parameters

chimney 15 pp		
Cooling Power Required	**3,05**	**kW**
Cooling power delivered	4,36	kW
Minimum diameter of chimney	0,9	m
Minimum area of chimney	0,64	m2
Velocity of air flow	0,34	m/s
Outdoor temp	42	degC
Desired exit temp	26,5	degC
outdoor wetbulb temp	22	deg C
Indoor max RH%	70	%Rh
Water Flow Rate	10,6	l/min
Exit Opening	1,72	m2
Air flow rate	2142	m3/hr
ACH	34	
Abs Hum ambient air temp t	10	g/Kg
Abs hum max at that temp	18	g/Kg
Expected wet bulb depression	14	degC
Delivered power in ambient co	**3,05**	**kW**

chimney 25 pp		
Cooling Power Required from	**4,05**	**kw**
Cooling power delivered	5,8	kW
Minimum diameter of chimney	0,9	m
Minimum area of chimney	0,64	m2
Velocity of air flow	0,43	m/s
Outdoor temp	42	degC
Desired exit temp	25,5	degC
outdoor wetbulb temp	22	deg C
Indoor max RH%	70	%Rh
Water Flow Rate	11,9	l/min
Exit Opening	1,57	m2
Air flow rate	2402	m3/hr
ACH	38,1	
Abs Hum ambient air temp t	10	g/Kg
Abs hum max at that temp	18	g/Kg
Expected wet bulb depression	14	degC
Delivered power in ambient co	**4,06**	**kW**

6.4 Summaries

According to AMBIENS, air beside a window has a higher RH than the rest of the room, excluding the chimney since its surface has a higher temperature. (Figure 6). Here risk of condensation is higher. Also, air is distributed in a very satisfactory way within the room, and door gaps are important to help extract “old” air thus renewing the air and creating a replacement cycle (Figure 7). Therefore an exhaust (like a fan) should be placed on the opposite side of the chimney.

Moura´s PDEC chimney is capable of providing cooling power up to 25 people under comfortable parameters, namely exit air temperature (Figure 7) and speed, and RH. *Scenario 1* results show that since the shower is not very high, the system will always rely on a high water flow rate to achieve exit temperatures of about 25°C. This is true not only for this case but for all PDEC systems that use free convection.

Exit air openings can play an important role defining water flow rate. Results suggest that a system with a flexible size opening could be used to deliver the exact amount of cooling required, although this is not practical. Results also show that even though thermal comfort benefits from reducing on exit air speed, increase of temperature penalizes it. *Scenario 2* shows that by reducing the water flow rate by 2.5l/min, exit air temperature will increase 1°C.

Water consumption in *Scenario 1* and *2,* can be estimated as 0,08l/min and 0,105l/min, assuming there is a cooling delivering of 4,4Kw and 5,8Kw. If the system is used during 8 hours, it corresponds to an extreme water consumption of 38,4l and 50,6l per day. It is important to note that concerning domestic water consumption, typically a shower consumes 20-40 liters and a bath consumes 50-100 liters [10]. Therefore it is suggested that water should be used from domestic sources.

Regarding ventilation supply, the system is efficient since 25 people require approximately 13 ACH (assuming 8l per person per second), and the system can supply 38 ACH.

6.5 Recommendations

Some "Rules of thumb" can be used whenever DEC is applied to an existing structure:

1. Whenever there are limitations on architectural form concerning important aspects of PDEC systems (like shower height) there is the need to place a low power fan to increase length of time droplets stay within the air stream of the tower. Electricity to feed the fan can be produced by PV cells since in hot-arid regions solar radiation is traditionally very high.
2. There is the need to place a low power fan to extract "old air" produced indoors on the opposite side of the PDEC tower. Volume of inlet air should equal volume of extracted air. A PV can feed the fan.
3. Surfaces where PDEC occurs, an impermeable net or film is always needed to improve PDEC performance and reduce water consumption. This may require excellent detailing on junctions construction;
4. Control of RH to avoid condensation, mold growth and fabric deterioration is essential. One possible way is through the use of coils that supply air cooled by the PDEC system but with excess of humidity. This is considered indirect PDEC and requires another fan to remove humidity into the atmosphere.
5. Use of micronisers or nozzles to avoid unpleasant draughts caused by water droplets descending the tower.
6. Re-use of domestic water, since in the DEC inertial shower system any type of water can be used because evaporation occurs in free air stream.

7. CONCLUSION

Results show that the DEC system can hardly be totally passive whenever is applied to existing tower structures or refurbishments. To become totally passive, DEC system needs to be accurate in several aspects of physics of construction.

A hybrid or mechanical DEC system can provide building interiors with ambient comfort conditions mainly from early spring to early fall, but especially in summer with low energy consumption.

The energy required to run a fan to both re-circulate water and disperse water particles can be feed with a PV cell.

Energy savings per annum can be circa 6.000kWh, assuming a dense occupancy. It corresponds to money savings of 600 €/year [11]. The environmental benefit is a reduction in CO^2 emissions by 3120kg of CO^2.[12].

Therefore, the use of DEC towers should be promoted in traditional architecture. It benefits building heritage and also the poor population that inhabits these older buildings, enormously improving their health and quality of life.

ACKNOWLEDGEMENT

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