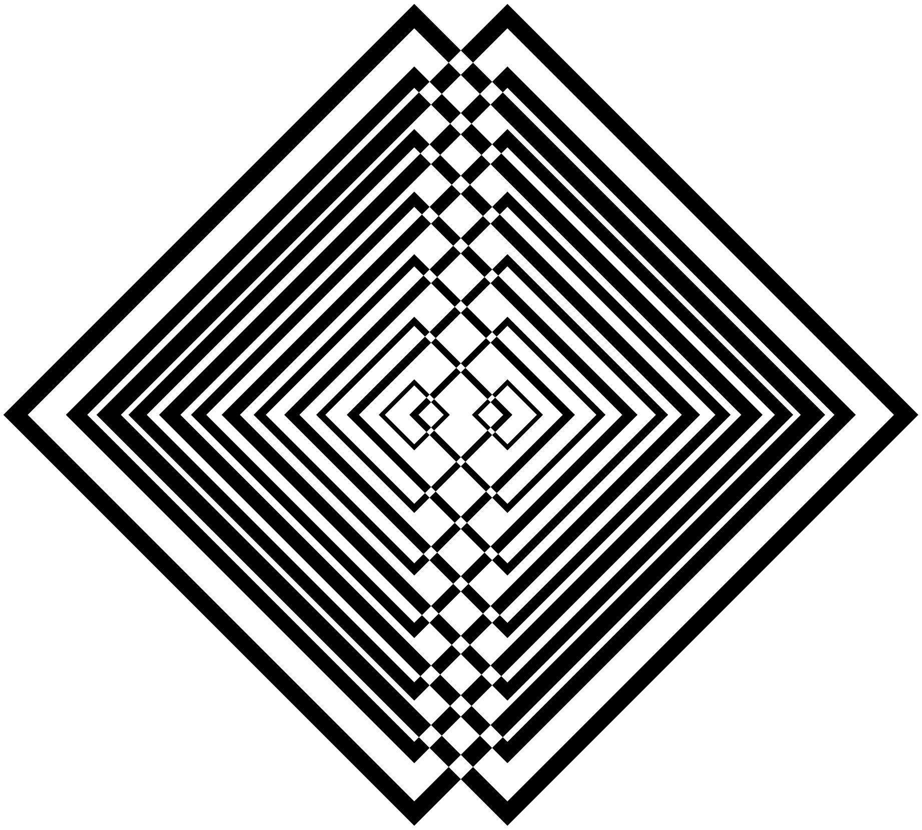
A HOLISTIC REVIEW OF THE PERFORMANCE OF THE PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING SYSTEM AS A PARTIAL SUBSTITUTE TO AIR CONDITIONING IN HOT AND DRY CLIMATES



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ABSTRACT

The objective of this paper is to review the functioning of the passive downdraft evaporative cooling system in vernacular as well as contemporary architecture and suggest appropriate means of integrating it with air-conditioning in order to offset the inherent drawbacks of both the systems. The methodology adopted to achieve this objective was revisiting the fundamental principles of the conventional PDEC in order to summarise the advantages and shortcomings in the functioning of PDEC in contemporary buildings and analyse the pros and cons of PDEC through energy simulation exercises. The major findings of the paper include an analysis of the contributions of some of the major parameters towards the performance of PDEC which offer an insight into the possible improvements in the performance of PDEC through innovations and their repercussions.

Key words: *Passive, Cooling, Downdraft, Energy, Evaporation*

1. Introduction

With the growing awareness of reducing the energy consumption in buildings, conscious attempts are being made to improve the energy efficiency of the conventional air-conditioning system, which has been established to be the largest contributor to operational energy consumption in buildings. In addition, air conditioning has also proven to be a major contributor to HFC and CO2 emissions. Post-COVID, the healthiness of the conventional air conditioning system is being questioned, on account of the large percentage of recycled air used and a school of thought has even started questioning the need for air conditioning for human comfort on account of the risk that it poses to human health in a pandemic situation. As part of the international efforts towards reduction in energy consumption and GHG emissions, various organisations have been increasingly emphasising the need for re-introducing proven passive air-cooling techniques for thermal comfort in building design, which have been part of the rich vernacular architectural traditions in our country as well as other parts of the world.

While significant research and advancements have been made in the field of conventional air-conditioning, the comparative degree of research and development on passive air-cooling techniques has been much lesser, and the architectural profession, as well as the science of air-conditioning, has not advanced much on this front. Wherever passive cooling techniques have been incorporated into contemporary architecture, the results have indicated a significant reduction in energy consumption. However, these techniques have not been able to offer completely satisfactory solutions in respect of achieving the desired comfort conditions on account of their limitations and lack of adequate research. Besides, the functioning of these techniques is heavily dependent on external climatic conditions and there is a need, therefore, to look at the integration of active and passive energy-saving measures in order to achieve the best results.

This paper focuses on Passive Downdraught Evaporative Cooling (PDEC), a passive cooling technique used very effectively for achieving indoor thermal comfort in the vernacular architecture of hot and dry climatic regions all over the world. The paper seeks to take an overview of the origin of the PDEC system, its suitability as a substitute for conventional air-conditioning, the role played by different parameters towards its effective functioning and the significant improvements carried out in the original system over the years.

2. Objectives & Methodology

The objective of this paper is to review the functioning of the passive downdraft evaporative cooling system in vernacular as well as contemporary architecture and suggest appropriate means of integrating it with air-conditioning in order to offset the inherent drawbacks of both the systems.

a) Revisit the fundamental principles of the functioning of PDEC and its successful applications in vernacular architecture.
b) Enumerate the drawbacks of air-conditioning in today's scenario.
c) Critically evaluate the advantages and shortcomings of using PDEC as a partial substitute for conventional air conditioning in contemporary buildings, through case studies and energy simulations.
d) Evaluate the effectiveness of the different innovations and improvisations carried out in PDEC over the years to overcome its shortcomings.
e) Suggest a way forward in terms of integrating PDEC and conventional air conditioning to obtain the best results.

The methodology adopted to achieve this objective is:

a) revisit the fundamental principles of the conventional PDEC
b) summarise the advantages and shortcomings in the functioning of PDEC in contemporary buildings
c) analyse the pros and cons of PDEC through energy simulation exercises.

3. The functioning principles behind PDEC

PDEC works on the basic concept of evaporative cooling in hot and dry climatic areas, utilising the fact of high latent heat required by water for evaporation. It captures the dry winds that flow at a certain height in hot and dry climatic regions, by blocking the path of the wind, and densifying it by adding moisture to it. In the process, it utilises the principle of buoyancy for inducing air movement by natural means rather than relying on fans as mechanical means. This densified, moist, unsaturated and cooled wind is led downwards and into the living areas by wind towers, absorbs heat from human bodies, walls, floors and ceilings and equipment and becomes rarefied in the process. The rarefied air is then directed to exit outdoors, either through the PDEC itself or through a solar chimney used in conjunction with PDEC. These parallel and complementary movements of air columns create an air cycle, which performs three primary functions :

a) it brings down the indoor ambient temperatures to within the adaptive comfort range with the minimum use of energy
b) it ensures effective air movement, successfully resulting in the movement of large volumes of air without the requirement of fans

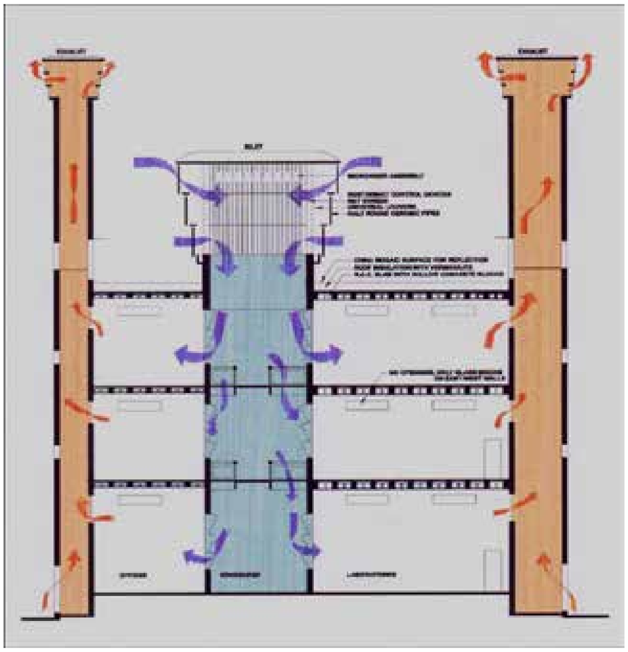

Figure 1: Air Flow patterns in a conventional PDEC
(Source: Thomas & Baird, 2004)

c) it increases indoor RH to within the comfort range; often the RH exceeds the comfort range
d) circulates fresh air to the occupants with minimum energy consumption (Figure 1).

4. Applications of PDEC in vernacular Architecture

The origin of using PDEC for evaporative cooling lies in the vernacular architecture of Egypt, from where it subsequently spread eastwards through the Middle East and Iran to north India with the Mughal empire, and westwards across North Africa to southern Spain (Ford, 2012). Taking advantage of the hot high-speed winds that blow unobstructed above the building skylines, wind catchers were used to capture the wind and direct it over porous water pots, causing evaporation and bringing a drop in temperature as a result of latent heat of vaporization (ibid). (see Figure 2)

The wind catcher contributed toward three important parameters of thermal comfort:
a) lowering the indoor ambient temperatures
b) ensuring an adequate number of air changes
c) increasing the indoor RH to more comfortable levels corresponding to the indoor ambient temperature.

Thus, while the dry bulb temperature falls, and the relative humidity increases, the wet bulb temperature remains more or less constant. There are two ways in which the passive cooling of the air can take place:
a) by means of direct evaporative cooling whereby the air coming in direct contact with moisture
b) by means of indirect evaporative cooling whereby the air coming in contact with the walls and roofs of the structure whose surface and core temperature is much lower than the air temperature.

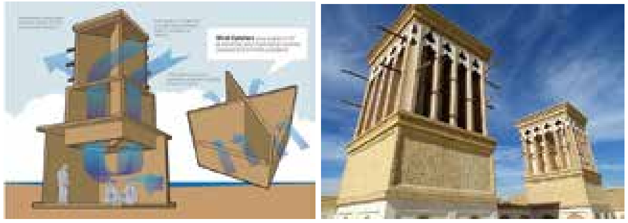

Figure 2: PDEC in vernacular Architecture of Middle East
(Source: Elborombaly & Prieto, 2015)

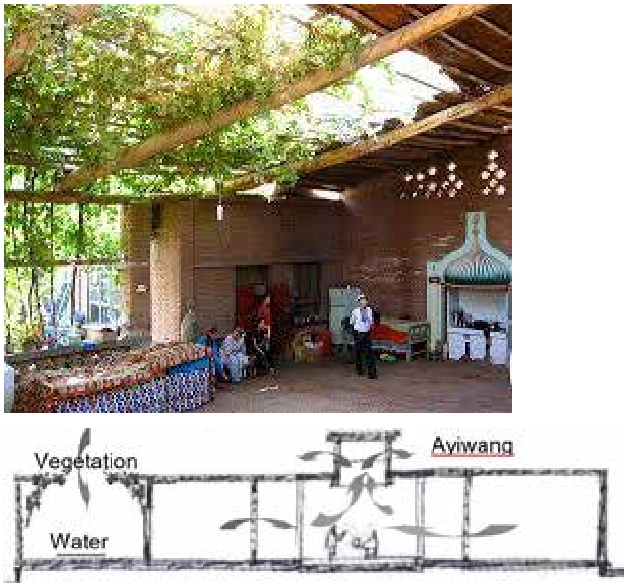

Figure 3: PDEC in vernacular Architecture of China
(Source: Xuan & Lv, 2017)

In the latter case, the diurnal difference between the indoor and outdoor temperatures which gets maximised by afternoon is 'dampened' by the thermal mass of the stone or earth masonry, and the air is further cooled by the evaporation of water in the ventilation airflow path. The design of these buildings involved an empirically based understanding of how to exploit ambient heat sinks to promote thermal comfort (de Melo & Guedes, 2006). The use of PDEC has also been found in the northwest regions of Gansu, Xinjiang and the Ningxia provinces of China, which are primarily hot and dry climatic regions. In these regions, the concept of PDEC is utilised in the form of a light well called 'a yi wang', which induces indoor air movement as well as a reduction in indoor temperatures (Xuan & Lv, 2017) (Figure 3)

5. PDEC as a partial substitute to conventional air conditioning- a critical evaluation

An evaluation of PDEC's performance by means of case studies and energy modelling yields some important results. For the purpose of this paper, the following five case studies and literature studies have been considered:

a. Case Study: Torrent Research Laboratories, Ahmedabad (Hot and Dry climatic zone), India

One of the finest successful applications of the concept of PDEC is Torrent Research Laboratories in Ahmedabad, a hot and dry climatic zone, where PDEC has been used in conjunction with conventional air conditioning. Out of a total of six laboratories and office blocks comprising a built-up area of 20,000 sqm, four laboratories are being cooled with PDEC, constituting about 72% of the total built-up area (see Figure 4). Some important results (Thomas & Baird, 2004) with respect to the comfort conditions and energy consumption in these laboratories as observed over a period of time are as follows :

i) Internal maximum temperatures were found to be about 5 degrees lower than the average external temperatures.
ii) Internal maximum temperatures were found to be about 12-14 degrees lower than the peak external temperatures. Temperatures of 29-30 degrees have been achieved when the external temperatures touched 43-44 degrees peak summer temperatures. This is very close to the recommended indoor temperature for mixed ventilation mode buildings as per ECBC 2017, which prescribes that the indoor operative temperature for mixed-mode buildings should be = (0.28 x outdoor temperature) + 17.87.
iii) Indoor temperature fluctuations were in the range of 4 degrees over a twenty-four-hour period when the fluctuations in external temperatures were in the range of 14-17 degrees, thus indicating greater stabilisation of indoor temperature than the external temperature.
iv) Number of air changes was found to be in the range of 6-9 per hour, which is as per the range of recommended air changes as per NBC 2016, which prescribes that the number of air changes should range from 6 to 15 for naturally ventilated laboratories.
v) The total annual average energy consumption by all the buildings per sqm of built-up area, using the mixed-mode ventilation system (Air conditioning + PDEC) was found to be approximate 54 kWh/m^2, as against the average figure of 280-500 kWh/m^2 for air-conditioned office buildings in India. This is much below the figure of 140 kWh/m2 laid out for fully air-conditioned buildings in India by ECBC 2017. It needs to be highlighted that besides savings in energy on account of air-conditioning, the use of PDEC also leads to significant savings in the electrical energy used by fans which, on an average, constitutes about 25-35% of the total electrical energy in office buildings (Ford, 2012).
vi) However, this energy-saving needs to be offset against the energy consumption by pumps on account of pumping of water to the top of the PDEC tower for which no average figures exist.
vii) It was established by a survey carried out on the occupants of the building that, on a scale of 1 to 7, health and productivity received a rating of 4.7, thus indicating a reasonable degree of comfort and satisfaction from the point of view of the user.
viii) The performance of the system and the indoor comfort conditions deteriorated when the outdoor and indoor relative humidity increased. The system started losing its effectiveness when the external relative humidity increased, and there are recorded instances where it created a sensation of discomfort for the occupants during the humid season.

Figure 4a: Torrent Research Laboratories, Ahmedabad
(Source: Thomas & Baird, 2004)

Figure 4b: Plan of Torrent Research Laboratories, Ahmedabad
(Source: Thomas & Baird, 2004)

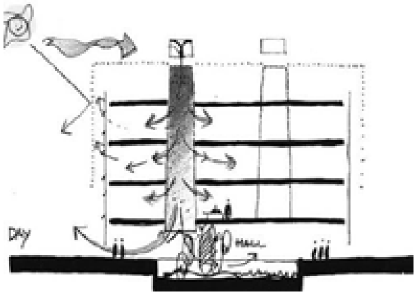

Figure 5: Daytime functioning of PDEC in office building in Catania
(Source: Kamal, 2016)

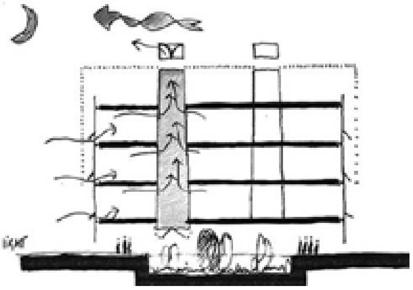

Figure 6: Night time functioning of PDEC in office building in Catania
(Source: Kamal, 2016)

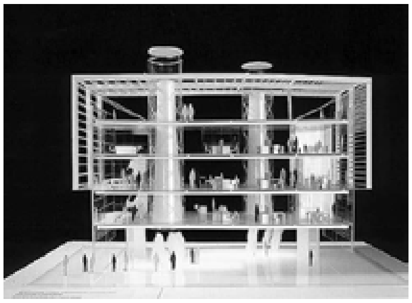

Figure 7: Office Building in Catania, Italy by Mario Cucinella Architects.
(Source: Kamal, 2016)

b. Energy Simulation Study: Office Building in Catania, Italy
Mario Cucinella Architects proposed a design for a four-storeyed office building in Catania, Italy, consisting of nine 3m diameter glazed cylindrical PDEC towers, which would rise above the roof by about 6 m. External air would enter the towers via high level openings and, after circulating through the building, exit through the double-skin façade. The towers also served the purpose of nighttime ventilation and bringing the daylight into a deep plan space (Elizabeth and Ford, 1999). (Figure.5, 6 and 7).

Thermal analysis of the building was undertaken by ESII using PASSPORT-Plus in which a PDEC tower model had been incorporated and the CFD program FLUENT. The following inferences were drawn from the thermal simulation analysis:

i) The tower height should be 6m above the building roof
ii) Acceptable indoor thermal comfort conditions could be created with PDEC, with the external temperature being 29ºC and an internal heat load of 30.7 W/m2
iii) However, it was observed that comfort conditions could not be created throughout the year with PDEC alone, and it had to be supported by a mechanical cooling system.
iv) An annual saving of 27% could be achieved by using PDEC in combination with Air-conditioning in comparison with a fully air-conditioned building.
v) The water demand for PDEC cooling was equivalent to 10 litres per person per day

c. Case Study: N.I.I.T, Neemrana (Hot and Dry climatic zone), India
Another successful example of an institutional building located in a hot and dry climatic zone having achieved acceptable indoor thermal conditions through a judicious combination of earth air tunnel system, PDEC, solar chimney and air conditioning is N.I.I.T, Neemrana, Rajasthan. (Figure 8). Important observations from the studies carried out by the Architects prior to deciding on PDEC are as follows (Gupta, n.d.) :

i) PDEC alone would not be able to control dust and humidity. This necessitated the need to have a mixed-mode ventilation system.
ii) In several buildings using PDEC both for ingress of fresh air and egress of stale air, quite often the indoor spaces did not receive an adequate quantum of air circulation and the required frequency of air changes, thereby resulting in the decision to combine PDEC with solar chimney.
iii) In line with the concept of adaptive comfort as advocated by ASHRAE 55, the designers decided to set the indoor comfort temperature range to between 28-30 degrees C, breaking away from the conventionally used comfort temperature range of 23-26 degrees C, with humidity at 65% (+/-10%). This has also been a contributing factor to achieving the desired indoor comfort conditions.
iv) Post-construction, some important outcomes of the use of PDEC are as follows:
   a) The building has been able to achieve an EPI of 33 kWh/sqm/year as against the ECBC stipulated norm of 140 kWh/sqm/year.
   b) However, as a disadvantage, winter heating is not possible through this system.
   c) The air circulation through PDEC varies its direction of flow as per the external weather conditions.

When the outdoor temperature is higher than the indoor temperature, (for instance in the summer afternoons), subject to a minimum external air movement, the PDEC tower will draw the external air downwards into the internal areas as a reverse stack effect. On the contrary, when the indoor temperatures are higher than the outdoor temperatures, (for instance in the early mornings and late evenings), the stack effect forces the indoor air, warmed due to the absorption of thermal energy from indoors, to rise through the PDEC and exit outside.

d. Energy simulation exercise: Office building in Seville, Spain (Hot and dry climatic zone)
An energy simulation exercise was carried out for a hypothetical office building comprising PDEC in Seville, Spain, a hot and dry climatic zone, to predict the possible results in terms of Atrium comfort conditions and energy efficiency. (Figure 9). Some important results (Robinson, et al, 2004) of the energy simulation exercise are as follows:

Figure 8: N.I.I.T Neemrana Campus with PDEC and peripheral exhaust shafts
(Source: Gupta, 2014)

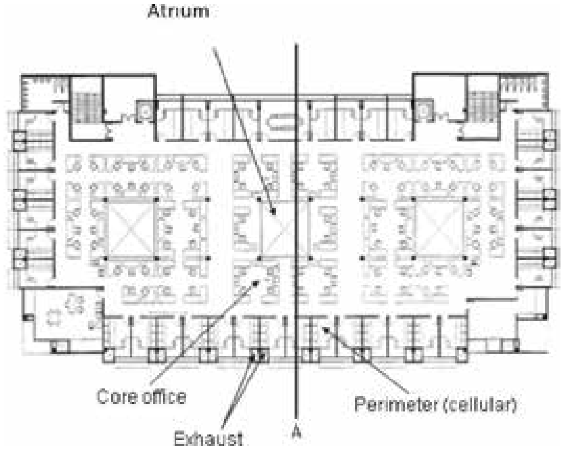

Figure 9: Typical floor plan of a hypothetical PDEC building design -Atriums act as wind towers and the peripheral shafts as solar chimneys
(Source: Robinson, et al, 2004)

i) Taking 26 degrees C as the upper limit for indoor comfortable temperatures, PDEC alone would be insufficient to provide the required comfort conditions for the entire year. Even after augmenting PDEC with additional thermal control measures such as night venting, low thermal gains and increased airflow volume from PDEC, temperatures exceeding 26 degrees were observed in the core areas for about 200 occupied hours.
ii) This in turn resulted in overheating of perimeter zone areas, which turned out to be warmer than the core areas by about two degrees. The overheating was observed to last for about 400 hours.
iii) The extent of annual overheating even after optimizing the PDEC performance and activating night ventilation exceeded the comfort criteria by a significant margin.
iv) PDEC has so far not proven its effectiveness in achieving the desired comfort conditions without some form of mechanical support. However, in spite of the necessity of mechanical cooling to supplement the functioning of PDEC, there are proven substantial Co2 and energy savings in the use of PDEC vs. mechanical cooling.
v) It is possible to stabilise the indoor thermal environment to some extent along with achieving substantial energy savings for cooling by appropriately balancing the air flows and close monitoring of PDEC operations.
vi) A comparison of the primary energy consumption, Co2 requirements and water consumption per floor area between PDEC cooling and air-conditioning results in the following important observations are shown in Table 1.
    - Savings of about 76% in the primary energy consumption compared to air conditioning are possible with cooling set-point of 26 degrees C and low internal heat gains.
    - Savings of about 83 % in the primary energy consumption compared to air conditioning are possible with cooling set-point of 26 degrees C and high internal heat gains. This is on account of the significant increase in primary energy consumption due to higher internal thermal gains, even though the set point temperature remains the same. Thus, as the internal thermal gains increase, maintaining the same cooling set point temperature of 26 degrees C, the primary energy required for cooling and the water consumption increase significantly.
    - Savings of about 50 % in the primary energy consumption compared to air conditioning are possible with cooling set-point of 24 degrees C and low internal heat gains
    - Similar savings in Co2 consumption are also highlighted in the table
    - It is possible to achieve sufficiently high airflow rates indoors without relying on external wind speeds. With an appropriate balancing of openings and moderation of airflow, it is possible to maintain indoor thermal stability along with substantial energy savings.
    - The primary energy requirement for cooling and the water consumption increases significantly with the increase in the internal heat load.

However, all the above-mentioned results cannot be said to be completely accurate, as these are derived from simulation exercises, which are based on various assumptions such as airflow resistance, external conditions, mixing of air masses, indoor adaptive comfort and surface convective coefficients and these need to be applied to actual buildings to get an accurate picture.

e. Energy simulation exercise: School building in Sacramento, California, (Warm and Humid climatic zone), U.S.A

i) An energy simulation exercise was carried out for a hypothetical school building comprising of PDEC, in Sacramento, California, (a warm and humid climatic zone with a large variation in relative humidity), to predict the possible results in terms of comfort conditions and energy efficiency, consisting of two scenarios: a) a base case scenario using the conventional air -conditioning and b) a scenario using PDEC. (Kang & Strand, 2016). Some important results of the exercise are as follows:
ii) A reduction of 95.5% in the energy required for cooling was achieved by using PDEC for indoor comfort as compared to air conditioning. The energy consumed was 179.34MJ as against the requirement of 3994.59MJ for air conditioning. This is partly on account of the energy savings on account of non-use of fans. These figures include the energy required for pumping the water.
iii) The PDEC systems consumed a large volume of water, up to 356.11m3, as compared to 1.5 m3 consumed by conventional air conditioning.
iv) A sharp rise and drop in relative humidity coupled with variations in the ambient wet-bulb temperatures was observed both at the start of PDEC operation and in the evenings. Relative humidity of 40% was observed between 11 am (when the PDEC started functioning) and 2 pm. The Relative humidity increased up to nearly 80% at 4PM in all spaces in Sacramento due to increase of water requirements to meet cooling loads that significantly increased. The relative humidity started dropping at 6 pm, along with ambient temperature decreasing from 23.9 degrees C to 20.9 degrees C. Thus, it turned out that inappropriately designed PDEC towers can significantly increase indoor humidity level, resulting in excessive water consumption.
v) Overcooling of indoor spaces was observed during early morning hours.
vi) The indoor temperatures achieved by using PDEC were more consistent than those achieved by using air-conditioning.
vii) The results of energy simulation have shown that PDEC system having the required controls was able to maintain the indoor thermal comfort level within a reasonable range, while PDEC system without these controls displayed considerable variation in the indoor thermal comfort levels.

6. A summary of the significant advantages and drawbacks of PDEC and their co-relation with major parameters

PDEC has successfully demonstrated its capacity to improve indoor thermal conditions in hot and dry climates by means of effective reduction of indoor temperatures, adequate air movement and enhanced humidity. However, the most significant shortcoming of PDEC is its incapacity to perform efficiently when the external relative humidity increases. Many of the hot and dry climatic zones in our country have a short warm and humid season, during which the effectiveness of PDEC as a stand-alone system has proven to be insufficient to achieve the desired indoor thermal comfort conditions. There is no option in the current PDEC system for exercising control over humidity. Other disadvantages of PDEC include a) the risk of micro bacterial contamination and blockage of the water nozzles, b) lack of effectiveness in terms of controlling pollution, as compared to air-conditioning. A detailed explanation of the three major means by which PDEC achieves indoor comfort, namely a) reduction in the indoor ambient temperatures, b) ensuring the required number of air changes and c) increasing the RH to the desired levels, is as follows:

i) The quantum of reduction in the indoor ambient temperatures is dependent on the extent of evaporative cooling, the magnitude of indoor air speeds and the specific heat of the building materials used. Water droplet size is the most critical factor that affects the extent of evaporative cooling. The use of wetted pads originates from vernacular architecture. In a study carried out by Pearlmutter et al., the results confirmed that a finer water droplet led to a greater temperature reduction and cooling capacity compared to wetted pads. (Etzion, et al, 1997)

ii) The same has also been established in case of Torrent Research Laboratories, Ahmedabad. The second most important parameter that impacts the quantum of reduction in the indoor temperature is Water flow rate. The results obtained from the simulation studies by Kang and Strand (2009) have shown that both the flow rate as well as the temperature of the air exiting from PDEC is directly impacted by the water flow rate.

iii) Achieving the desired number of indoor air changes by using PDEC has been established to depend on :
    a) external wind velocity
    b) adequate means of air exhaust
    c) height of the tower
    d) angle of incidence of the wind on the tower face
    e) area of the wetted pads.

    The efficiency of PDEC in conditions with a low velocity of external winds has been found to be low. The higher the tower, the greater are the pressure differences between the top and bottom of the tower, and a high-pressure difference significantly contributes to inducing air movement. Results of energy modelling carried out by Kang & Strand (2016) has established that the most effective height of the PDEC tower is between two to three times the width of the tower cross section, and there is no scientific evidence to suggest that its' minimum height should be maintained as 15 m, which is a misconception.

iv) Their research has also established that the height of towers has a linear relationship to air volume flow rate. The higher the external wind speed, the greater is the rate of extraction of the volume of air from indoors. Their research has further established that, for the same area of cross section of the tower, the performance of PDEC is directly proportional to the air mass flow rate, which, in turn, has a direct relationship with temperature reduction. For the same area of cross section, a lower flow rate of the air mass led to a greater extent of temperature reduction as observed by the same researchers. (Kang, 2016). However, as observed, this does not hold good when the cross-sectional area was altered. Although the efficiency of PDEC has been found to be low with low velocity external winds, it has been observed that, even with high velocity of external winds, there have been instances when some of the indoor spaces have been excluded from the indoor air circulation on account of inappropriate locations and sizes of exhaust outlets. The effective indoor circulation of air is not solely dependent on the indoor wind speed and also depends on the design of indoor air circulation. Another significant factor that contributes to the air circulation is the angle of incidence of wind at the entry and exit points from the tower. A scaled model of PDEC was tested for wind pressure coefficients and it was found that the angle of incidence was a determining factor for the wind pressure coefficients (Khan, et al, 2008).

v) It has been established that an increase in the indoor RH is dependent on a) Water flow rate and b) Droplet size. As established by Kang & Strand (2016), in order to achieve the required drop in indoor temperature and humidity without wasting water, the water flow rate should vary as per the outdoor conditions. Studies by Gokarakonda & and Kokogiannakis (2014) have established that, if the water flow rate in PDEC is adequately controlled, it is possible to use PDEC for air cooling in warm and humid climates as well (Kang & Strand, 2016). Simulation studies by Kang & Strand (2016) have established that smaller droplet sizes lead to an increase in the RH. It has also been observed that the efficiency of the system begins to drop when the droplet size exceeds a particular limit.

7. Innovations and Improvisations in PDEC system over the years:

Various innovations and improvisations have been carried out in PDEC to overcome some of its drawbacks. These include technological interventions as well as improvements in the design. Some of the significant modifications are as follows:

i) Use of Desiccant for dehumidifying the incoming air: A Desiccant system uses a desiccant material with low vapour pressure on its surface to reduce the absolute humidity of the air. When used in conjunction with the PDEC, a Desiccant system, therefore, can overcome the shortcomings of the PDEC system in operating in warm and humid climates. Besides, the Desiccant raises the temperature of the air in contact in the process of

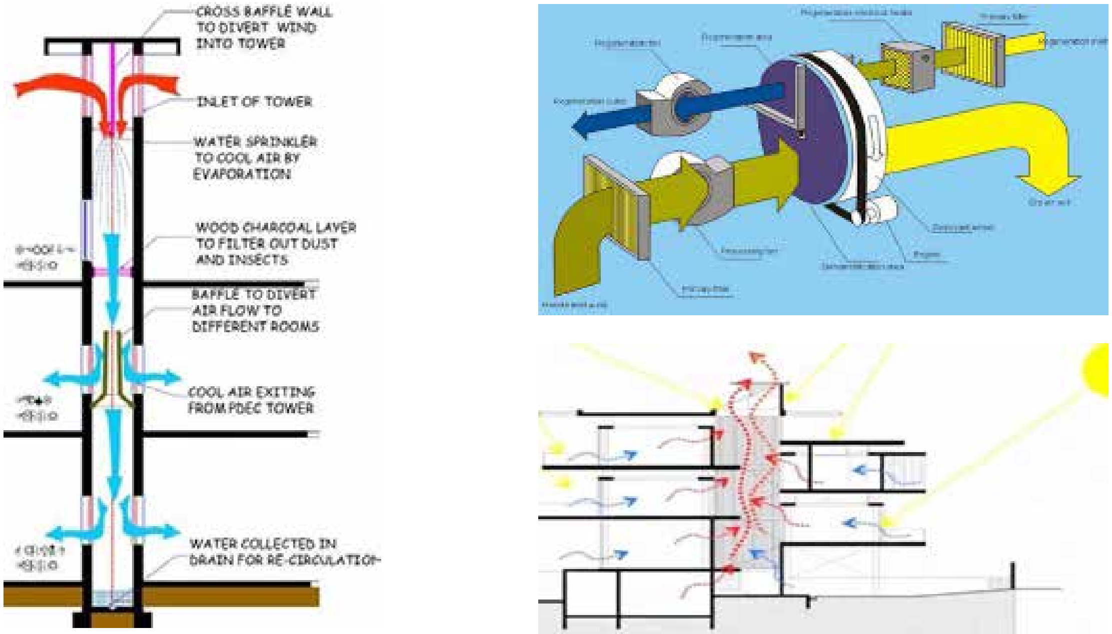

Figure 10: Typical combination of Desiccant with PDEC *(Source: Halid, et al, (2016)*

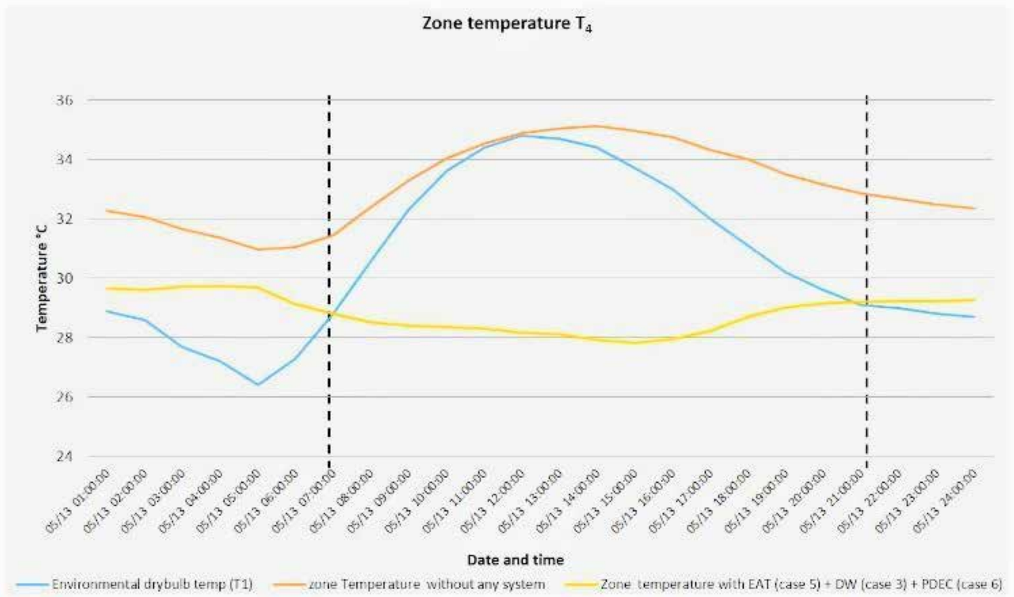

Figure 11: Reduction in internal Zone temperatures on account of Earth Air Tunnel + Desiccant + PDEC *(Source: Gokarakonda & Kokogiannakis, 2014)*

dehumidification to the advantage of the system. This rise in temperature augments the upward rise of buoyant air through the solar chimney, thus completing the air cycle. (Figure 10). This model has been successfully implemented in some projects worldwide.

ii) An energy modelling exercise was carried out by Gokarakonda & Kokogiannakis (2014) to infer the results of air cooling by using PDEC in combination with a desiccant dehumidifier and an Earth Air tunnel system for a typical dwelling unit in the warm and humid climate of Vishakhapatnam, where the peak summer temperatures touch 38 degrees C and the average relative humidity throughout the year is above 60%. The results showed that using the EAT+DW+PDEC system as against natural ventilation the following significant results were achieved:

iii) The peak indoor summer temperatures were reduced by about 8 °C

iv) The indoor relative humidity remained below 75%.

v) Use of PDEC in conjunction with Earth Air Tunnel. Energy simulation studies by Gokarakonda & Kokogiannakis (2014) established that, by using Earth Air Tunnel, it was possible to reduce the indoor temperatures and bring these within the comfort zone (see Figure 11).

vi) Replacement of the conventional PDEC with the double skin façade: Replacement of the conventional PDEC with the double skin façade acting as a wind tower has been successfully demonstrated in some buildings, including a multi storeyed building in Belgium, in which the façade is on the leeward side of the building similar to a wind tower surrounded by a region of negative pressure. Solar radiation falling on the façade augments the stack effect. (Gratia & de Herde, 2007).

8. Conclusions and way forward

Though the concept of PDEC is based on sound climatic principles and has proven itself in the vernacular as well as contemporary architecture of various hot and dry climatic regions of the world, it, nevertheless suffers from some inherent drawbacks, the major ones being its incapacity to function under increased external humidity levels and the significant variations in its performance as per varying outdoor conditions. The results of energy modelling as well as the analysis of its performance in few implemented projects clearly establish the need to integrate PDEC with conventional air conditioning in order to get the best results for achieving adaptive comfort in buildings in predominantly hot and dry climatic regions. In order to overcome the constraint of the loss of its efficiency during humid external conditions, the use of desiccant dehumidifier in conjunction with PDEC could possibly be a workable option, though more work needs to be carried out in this regard. It is possible to use PDEC effectively in warm and humid climates if there are adequate in-built mechanisms to control the water flow. More in depth analysis needs to be carried out to study the inter-relationship between the different parameters that affect the performance of PDEC. Even though the mixed mode ventilation model consisting of PDEC and air conditioning has been recommended to be the ideal one, further research needs to be carried out with respect to deciding the quantum of indoor cooling to be carried out through air conditioning and PDEC respectively. There is strong requirement of carrying out further research on the contribution of all the contributing parameters, including their inter relationship with each other. As on today, there does not exist a validated mathematical model which takes into account these and other parameters, based on which a scientific design of the PDEC system can be carried out.

Table 1: **Comparison of whole building primary energy, Co2 and water consumption calculations**
(Source: Robinson, et al, 2004)

Set point temperature & Thermal gain	Primary energy		Co2 emissions		Water consumption
	Use (MWh)	Savings (%)	Use (tonnes)	Reduction (%)	(m3)
26 degrees C, low thermal gain	95	76	22	75	213
26 degrees C, high thermal gain	173	83	39	82	393
24 degrees C, low thermal gain	283	50	62	50	235

REFERENCES

1. de Melo, Ana Cláudia Martins & Guedes, Manuel Correia (2006), *Passive Downdraught Evaporative Cooling Applied on Existing Fabric: Using Traditional Chimney as Case Study in Portugal,* Proceedings of the 23rd Conference on Passive and Low Energy Architecture, Geneva.
2. Elborombaly, Hossam Hassan & Prieto, Luis Fernando Molina. (2015), Adaptation of Vernacular Designs for Contemporary Sustainable Architecture in Middle East and Neotropical Region, Asian Journal of Computer Science and Information Technology.
3. Etzion, Y.; Pearlmutter, D.; Erell, E. & Meir, I.A. (1997). *Adaptive Architecture: Integrating Low-Energy Technologies for Climate Control in the Desert.* Automation in Construction 6.5 (1997)
4. Ford, Brian (2012), *Downdraught Cooling: An Overview of Current Research and Practice,* Architectural Science Review, 55:4, 237-240.
5. Gokarakonda, Sriraj & Kokogiannakis, Georgios (2014). *Integrated Dehumidification and Downdraft Evaporative Cooling System for a Hot-Humid Climate.* University of Wollongong, Australia, Faculty of Engineering and Information Sciences -Papers: Part A.
6. Gupta, Vinod (2014) *Towards Building a Sustainable University Campus,* CES Conclave on Green Buildings.
7. Gratia, E.; de Herde, A. (2007), *Guidelines for Improving Natural Daytime Ventilation in an Office Building with a Double Skinned Facade,* Solar Energy 81 (4) 435–448.
8. Halid, Hazeeb; Azeem, Hafiz P.A.; Pradeep, S.J., Sankar, Sarath R.U. (2016), Experimental Analysis of Solid Desiccant Wheel Dehumidifier, *International Journal of Research in Mechanical Engineering,* Volume 4, Issue 3. pp. 104-109.
9. Kamal, Mohammad Arif. (2016) Assessment of Passive Downdraft Evaporative Cooling Technique for Environmental Sustainability in Buildings, International Journal of Research in Chemical, Metallurgical and Civil Engineering (IJRCMCE) Vol. 3, Issue 2. ISSN 2349-1442 EISSN 2349-1450
10. Kang, Daeho (2016). *Advances in the Application of Passive Down-Draft Evaporative Cooling Technology in the Cooling of Buildings.*
11. Kang, Daeho & Strand, Richard K. (2009), *Simulation of Passive Down-draft Evaporative PDEC Cooling Systems in Energy Plus,* Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland.
12. Kang,Daeho & Strand, Richard K. (2016), *Significance of Parameters Affecting the Performance of a Passive Down-Draft Evaporative Cooling (PDEC) Tower with a Spray System,* Publications and Research New York City College of Technology.
13. Khan, Naghman; Su, Yuehong & Riffat, Saffa B. (2008), *A Review on Wind Driven Ventilation Techniques,* Energy and Buildings, 40,1586–1604.
14. Robinson, D.; Lomas, K.J.; Cook M.J. & Eppel, H. (2004) *Passive Down-draught Evaporative Cooling: Thermal Modelling of an Office Building,* Indoor Built Environment. Pp.13:205–221.
15. Thomas, Leena & Baird, George (2004) *Post-occupancy Evaluation of Passive Downdraft Evaporative Cooling and Air-Conditioned Buildings at Torrent Research Centre, Ahmedabad, India.*
16. Xuan, H. & Lv, A.M. (2017), T*he Application of Downdraught Cooling in Vernacular Sky well Dwellings in China*- Proceedings of the International Conference on Environmental and Energy Engineering, IC3E 2017. DOI :10.1088/1755-1315/63/1/012037.

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