THE DESIGN AND CONTROL OF BUILDINGS WITH PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING

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ABSTRACT This paper describes part of an EC funded Joule project in which computer simulation has been used to investigate the viability of applying passive downdraught evaporative cooling (PDEC) to non-domestic buildings in hot dry climates. Using analytical techniques, CFD and thermal simulation, the performance-driven anatomy of PDEC buildings has been elucidated and engineering sizing methods have been developed. It is concluded that PDEC should formulate part of an holistic and carefully integrated solution. Its success is contingent upon the need to obviate wind and for many locations mechanical cooling support should be specified to ensure year-around occupant comfort. Nevertheless, water consumption is sufficiently low and energy savings are sufficiently high to warrant its increased application.

1 Introduction

Non air-conditioned buildings consume significantly less energy than their air-conditioned counterparts. Evaporative cooling, which uses latent heat of vapourisation - the energy required to convert unit mass of water from its liquid to its vapour state - to reduce space temperatures, can thus be a potent means for reducing energy use in hot dry climates.

The principal of employing evaporation for natural cooling has its roots in the vernacular architecture of hot dry middle-eastern climates in which a wind scoop was used to channel air to pass over a wetted mat or pool of water. Cunningham and Thompson (1986) employed this technique in the fabrication of a lightweight domestic-scale test building, which also incorporated a solar chimney to extract vitiated air. Although significant temperature reductions were achieved, the cooling output was limited by a low air exchange rate.

To eliminate the pressure drop caused by friction between ambient air and the wetted surface, whilst increasing the air-water contact area - which was generally restricted to the high level perimeter surfaces of the tower - a method of spraying droplets of water directly into the airstream was developed. Alvarez et al (1991) used this technique to cool the Seville Expo '92 Avenue of the Americas. Its success led ultimately to the inclusion of a tower within an office building atrium in Israel by Pearlmutter et al (1996). This project focussed upon increasing the flows of evaporatively cooled air. Wind catchers were used to maximise the airflow rates through the tower, but large-bore shower heads were used to encourage evaporation. Consequently, much of the sprayed water was collected within a pool at the base of the tower, although ambient temperature reductions of 10-15°C and a cooling potential of 30-40 kW were achieved.

The present project was conceived to extend the application of PDEC by enabling the supply of cooled air to multiple floors, implying the need for full evaporation early in the descent of the air through the tower. For an overview of this EC Joule project see Bowman et al (1997).

2 Physical principles

At the micro scale, each droplet (a few microns in diameter) experiences (in a non-saturated environment) heat, mass and momentum transfer processes (Rodriguez et al, 1991): (i) the temperature gradient at the droplet-air interface provokes a net heat transfer from the air to the droplet surface, if the air is warmer than the droplet, (ii) vapour near the water surface diffuses to the non-saturated air, (iii) if there is relative movement between the droplet and surrounding air, a transfer of momentum occurs between them and the rate of heat and mass transfer tends to increase. The physical action of water droplets descending through the tower therefore accelerates the cooling process.

The heat transfer tends to increase the droplet temperature, whereas the latent energy absorbed by the vapour (during mass transfer) decrease the droplet temperature. Equilibrium is reached when the droplet is cooled to the wet bulb temperature. The latent energy required to evaporate more water, reducing the droplet size, is supplied by the surrounding air, so the latter is cooled. Thus, water droplet evaporation occurs in two stages. First it is cooled to the equilibrium temperature, then its radius decreases.

At the macro scale, momentum is transferred from the sprays to the air in their immediate vicinity. Droplets descend through the tower, such that with a constant injection of water, conditions close to saturation persist throughout its length. Momentum coupled with buoyancy forces, due to a relative density difference between ambient and the evaporatively cooled air, causes the cooled air to descend the tower and exit at its base from where it is delivered to the adjacent spaces. Replacement ambient air is entrained at the head of the tower. The exchange rate of air through the tower increases proportionally with the square root of the temperature difference between ambient air and air within the tower, which in turn depends on the air wet bulb temperature (and the water injection rate into the airstream).

3 Modelling techniques

At the micro-scale, the three dimensional energy, mass and momentum conservation equations must be solved in conjunction with a particle tracking routine. In this way both the momentum and buoyancy forces and the evaporation processes can be precisely simulated. This was achieved using the general-purpose computational fluid dynamics code, CFX-3D.

Because PDEC consumes water it is desirable to exploit alternative passive cooling techniques to minimise the extent of PDEC operation. This is best achieved with night cooling of exposed thermal mass and by reducing daytime ventilation to the minimum whilst maintaining acceptable indoor air quality, when ambient temperature exceeds internal temperature. In this respect PDEC buildings should exhibit a succession of operating modes, each inheriting passive cooling benefits from the former. For example night cooling delays the start of PDEC and passes on cooler fabric temperatures. These thermodynamic and airflow interactions can only be predicted using a dynamic thermal simulation program with simultaneous solution of the mass flow domain and control imposed upon airflow openings. This was achieved using ESP-r (Clarke et al, 1998). Macro-scale evaporative cooling was emulated, by dynamically cooling a spray zone at the head of an atrium to 70% of the ambient wet bulb temperature depression.

These complementary modelling techniques provide a detailed and comprehensive view of the performance of PDEC design proposals. They have been applied to design and dissect the performance of a hypothetical office development located in Seville, Spain.

4 Anatomy of a PDEC building

To optimise the benefits from preceding modes of operation, and in particular from night cooling, an exposed high thermal capacity structural fabric should be specified. There should also be some form of ventilation tower serving the occupied spaces with some means for entraining ambient air, cooling it using sprays and exhausting contaminated air (Fig.1a). CIBSE (1997) recommend that for stack-driven airflow, which pervades when there is no cooling demand, the depth (from façade to stack) should not exceed five times the floor-to-ceiling height. This ensures that surface resistances do not excessively constrict airflow openings (Fig.1b).

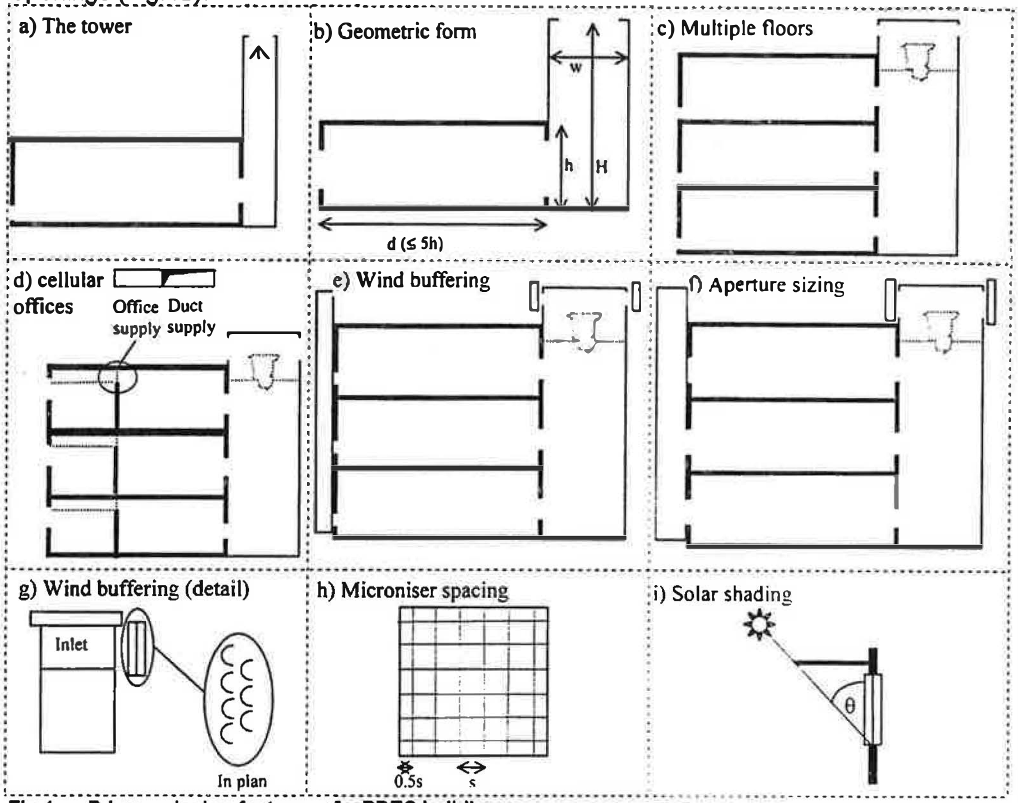


Fig.1 Primary design features of a PDEC building

To assure its uptake within the office sector this concept must be capable of serving multiple floors of potentially deep and cellularised buildings (Figs.1c & 1d). This may be achieved with a series of vertical towers that open onto each floor. If appropriately shaded, these may also supply daylight to the core areas of a building. For good daylighting a tower width to height (w:H) ratio of 0.6-1:1 has been suggested (Hastings, 1994). Ducts may also be installed within the occupied space to channel relatively uncontaminated (thermal / gaseous) air to perimeter cellular offices.

To avoid spray risk the air-borne water particles must fully evaporate before reaching the uppermost tower opening. The likelihood that a droplet will entirely evaporate depends upon droplet diameter and the length of time that the water stays within the airstream, which itself depends upon ambient wet bulb temperature, ambient and internal dry bulb temperature, tower height and the presence of wind forces. Therefore, droplet size should be small enough and the distance from the sprays to the openings great enough to guarantee total evaporation. Sufficiently small droplet diameters can be achieved with micronisers, provided that the water is appropriately filtered. Mitigating wind effects is more difficult.

The objective of tower wind buffering (Fig.1g) is to prevent axial forces from pushing the water plume, which extends from the underside of the micronisers, towards the tower perimeter. It should also avoid enhanced airflow velocities in the vicinity of the micronisers from increasing the plume length (Fig.2a). Façade buffering aims to prevent occupant control (i.e., opening windows) from causing thermal contamination due to ventilation heat gains when ambient temperatures are high and from disrupting internal airflow characteristics (Fig. 2b). This is achieved by opening façade vents into an exhaust stack (Fig.1e).

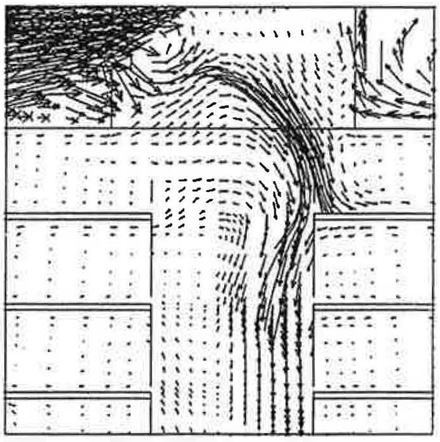


Fig.2a CFD prediction showing effects of axial and downward forces upon water plume integrity

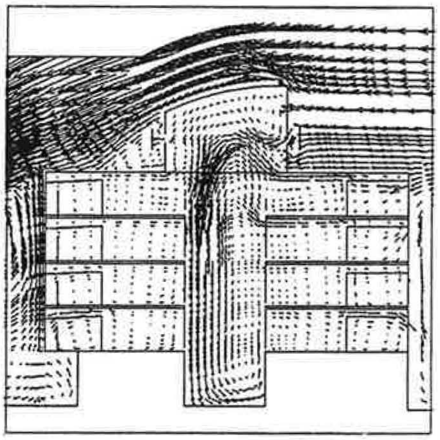


Fig.2b CFD prediction showing ambient air ingress and disrupted flow due to façade openings

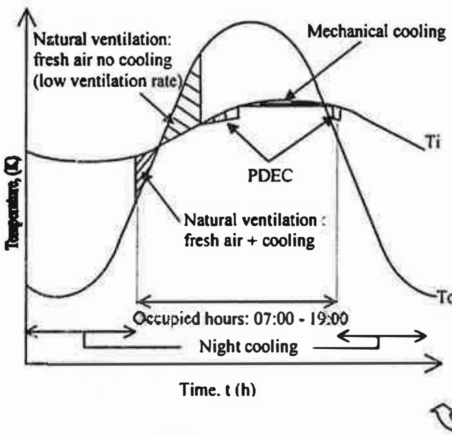
Within naturally ventilated and cooled buildings it is desirable to ensure that airflow rates are vertically and horizontally balanced to ensure uniform supplies of fresh and thermally treated air. Buoyancy driven airflow varies with the opening size and the magnitude of the buoyancy force. In natural ventilation mode the greatest stack pressure exists at the base of a tower and in PDEC mode, the base of the tower is subject to the greatest fluid pressure head. Since the smallest airflow opening represents the point of control, this should be located between the tower and the offices on the lowest floor. To achieve vertical balancing the tower-office openings should be proportionally increased on higher floors and each opening en-route to the exhaust shaft should be slightly larger still, for horizontal balancing (Fig.1f). The exhaust shaft should be the largest opening, since it serves all floors. However, because the air exiting from lower floors doesn't occupy the full stack height, the stack size can be proportionally reduced to ensure vertical and horizontal flow balancing.

To maximise evaporative cooling efficiency, micronisers should be placed as close together as possible without causing overlap between plumes – so prolonging their length. CFD analyses indicate that a spacing of about s = 0.3 m achieves optimal results (Fig.1h). Finally, conduction and shortwave radiation gains should be curtailed with low thermal transmittance fabric and good solar shading (Fig.1i). It is also important to thermally isolate the exhaust shaft from ambient conditions, to maintain the downdraught during PDEC operation.

5 Control issues

Following from the principles raised in section 3, five operating modes can be discerned by analysing diurnal ambient (To) and indoor (Ti) temperature swings in relation to each other (Fig.3a). At night, ventilation is encouraged for internal fabric cooling. Reasonably high airflow rates are also encouraged during occupancy whilst internal temperature exceeds ambient temperature. Subject to draught risk or when ambient temperature increases above internal temperature, airflows are reduced to the fresh air requirement. When temperatures reach a given setpoint PDEC is invoked and the supply of cooled air is increased until an absolute upper comfort limit is reached. At this point a switch occurs from passive downdraught *evaporative* (PDEC) to *mechanical* (PDMC) cooling, which uses the same air distribution system by placing cooling coils at the head of the tower (Fig.3b).

Algorithms have been designed to ensure that these five operating modes perform optimally when the sensor and actuator hardware (Fig.3b) has been connected to a Building Management System. However, it is interesting to consider the different possibilities for PDEC control.



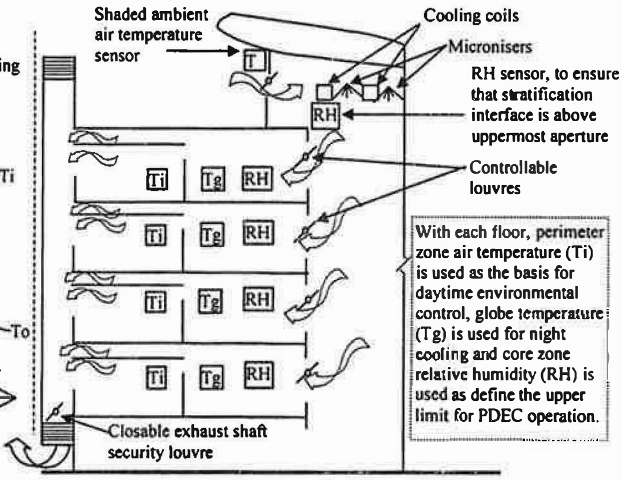
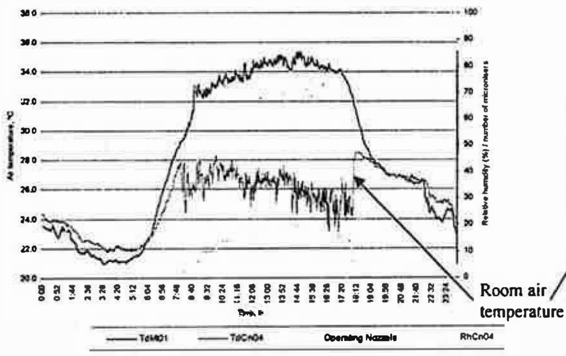


Fig.3a The four PDEC operating modes **Fig.3b Hardware distribution for effective control**

PDEC can be controlled by adjusting microniser (M) output, ventilation opening area (A) or by combining the two. With ventilation apertures at their maximum opening extent, quite subtle temperature differences can drive high air exchange rates. High ventilation rates deliver large cooling fluxes. This coarse control causes hunting, which entails large and rapid temperature fluctuations (a discomfort risk) particularly at the boundaries of PDEC operation (Fig.5a). Paradoxically, cooling efficiency is low as relatively cool air exits via the exhaust shaft and water consumption is high.



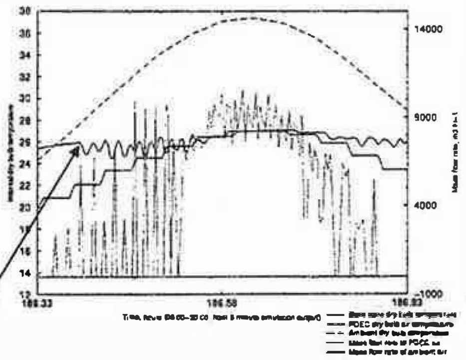


Fig.5a Microniser control: experimental results **Fig.5b Aperture control: simulation results**

Ventilation opening control implies that micronisers switch on and off to maintain a preset humidity, and ventilation apertures are progressively opened until they are at their maximum extent. However, at the boundaries of PDEC operation there may be a draught risk due to overcooling and there is yet again a risk of hunting (Fig.5b). Combined microniser-aperture control surmounts these problems by vastly increasing the number of control increments, i (to $\sum_i M . \sum_i A$). Cooling efficiency is also improved and water consumption is reduced.

6 Performance summary and concluding remarks

The principles described in sections 4 and 5 above formed the basis of a hypothetical 4880 m^2 treated floor area (TFA) office development in Seville. A $40m^2$ slice (consisting of a 6m x 4m perimeter zone and a 6m x 6m core zone) of one floor of this building, served by an $18m^2$ tower with airflow controlled by openings* (varying from $0.7m^2$ to $3.6m^2$) at the core-tower interface, was modelled using ESP-r. The model has also been tested with a lower discharge coefficient (0.15) and smaller openings# ($0.1m^2$ to $2.3m^2$) to examine the energy / water use and comfort implications of reduced airflow rates and inlet velocities (Table 1).

Table 1 Resource consumption for the two opening configurations

PDEC evaluation parameter	Large openings*	Small openings#
Maximum core zone air exchange rate, ach^{-1}	91.5	57.0
Core zone overheating, h > 27.5°C	136 (85)[1]	282 (176)
Perimeter zone overheating, h > 27.5°C	455 (313)	690 (571)
Hours of PDEC use, h > 26°C	1291	1292
Hours of perimeter zone mechanical cooling, h ≥ 28°C	571	804
Total annual water usage, m^3	680	415
Peak number of micronisers required	630	447
Peak mechanical cooling energy demand, kW	1330 (10.9)[2]	976 (8.0)
Total mechanical cooling energy consumption, MWh	106 (14.5)[3]	138 (18.9)

[1]based on hours (h) exceeding 28°C to compare with BRECSU (1995) target: temperatures may exceed 28°C for up to 5% of occupied year. [2]kW per slice. [3]$kWhm^{-2}$ TFA.

With no PDEC or night cooling support, this building has an annual delivered mechanical cooling energy requirement of 32.9 $kWhm^{-2}$TFA. PDEC therefore provides a 56% annual energy saving, or 18.4 $kWhm^{-2}$TFA. For this technique, which can be applied to occupied buildings with multiple floors, mechanical support is required to ensure comfort and delivered cooling output is more modest than Pearlmutter et al have achieved. Nevertheless, water consumption is sufficiently low and energy savings are sufficiently high for the technique to warrant serious consideration when designing for low energy use in hot dry climates.

An Energy and Environmental Design Guide for PDEC Buildings has been prepared. This describes more fully the physical principles of PDEC and the desirable attributes of a PDEC building together with optimal control algorithms, opening sizing techniques, simulation methods, thermal comfort issues and case study analyses. It is hoped that this will be published shortly. To determine the viability of PDEC in the early design phase, work is currently in progress to develop a simplified climatological design tool.

7 References

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