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Passive Downdraught Evaporative Cooling

I. Concept and Precedents

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Key Words

Passive downdraught evaporative cooling · Energy · Ventilation

Abstract

This is the first of a series of four papers that describe a 3-year EU-funded research project into the application of passive downdraught evaporative cooling to non-domestic buildings. In this paper various evaporative cooling techniques are reviewed. By spraying fine droplets of water at the top of atria, a downdraught of air cooled by evaporation can be produced. Such direct evaporative cooling using an evaporation tower appears to be a suitable approach for partly displacing the need for air-conditioning in hot, dry climates. It can satisfy fresh air requirements and reduce or eliminate demand for mechanical cooling. Examples of this cooling technique in Southern Europe and the Middle East have already demonstrated its operation and potential energy savings. However, limitations, primarily due to control of the system, have been identified. This introductory paper presents the theoretical basis of evaporative cooling, reviews some historical precedents, and discusses their relative strengths and weaknesses. Three further papers in this series will disseminate the main findings of the project.

Introduction

Concern about environmental degradation has b increasing steadily over the past 40 years [1]. One co quence of this was the 1997 Kyoto Agreement, wh called for a 20% reduction in the 1990 levels of car dioxide (CO_2) emissions by the year 2010. Buildings alleged to contribute approximately one third of the (and two fifths of the oxides of sulphur and nitrogen (S and NO_x) emissions globally [2] and non-industrial buildings consume 43% of all energy produced [3]. Con quently, they represent a priority area for EU mem states to meet their post-Kyoto commitments.

A survey of over 1,000 public and commercial bu ings in Greece [4] has shown that non-air-conditio buildings typically consume up to 44% less energy annu ly than their air-conditioned counterparts. Similar tre can be expected for other Southern European and s rounding countries with similar climates. Given that el tricity is the predominant energy source for air-conditi ing plant, which in primary energy terms is far more en ronmentally important than direct fossil fuel combusti the application of passive cooling techniques may b potent means for reducing environmental emissions. E porative cooling has great potential in this respect [5].

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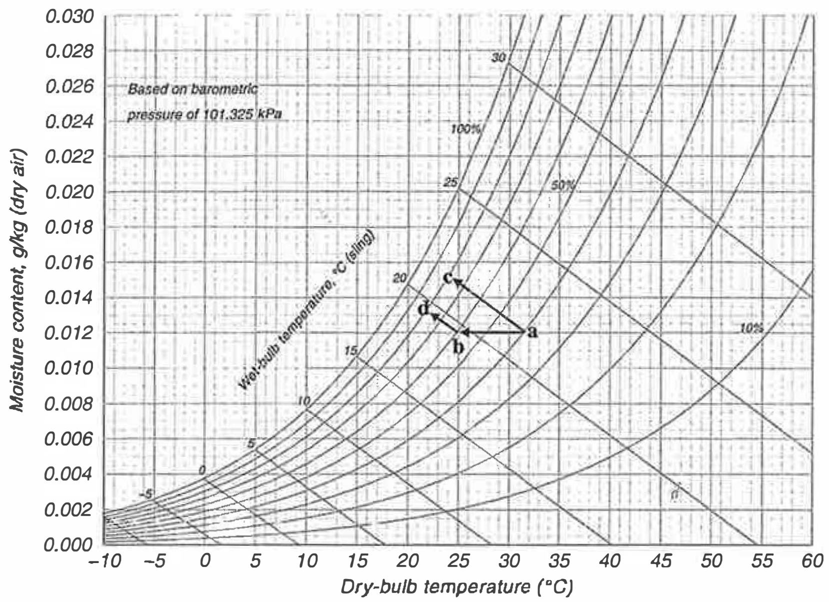

Fig. 1. Psychrometric chart showing evaporative cooling processes.

Concept and Methods

Evaporative cooling occurs as a consequence of the latent heat of vaporisation, that is, the amount of energy that is required to convert unit mass of water from its liquid to its gaseous/vapour phase ($\sim$2,260 kJ·kg^{-1}). This is appreciably greater than the specific heat required to raise the temperature of unit mass of water (4.18 kJ·kg^{-1}·K^{-1}). In evaporative cooling, the energy is supplied by ambient air whose heat content and capacity to hold vapour are indicated by its dry bulb temperature and relative humidity (the ratio of the partial pressure of superheated water vapour in moist air to the partial pressure of saturated water vapour at the same temperature). The transfer of heat energy from ambient air to water supports the phase change process and so reduces the temperature of the ambient air.

The branch of physics dealing with the thermodynamic properties of humid air is called psychrometry (from the Greek words *psychros* 'cold' and *metro* 'measure'. Regarding the application of evaporative cooling to buildings, five process categories have emerged: (i) passive indirect, (ii) active indirect, (iii) direct, (iv) active direct, and (v) two-stage. These are best described with the help of a psychrometric chart (fig. 1).

Passive Indirect Evaporative Cooling

The passive indirect approach involves the transfer of heat by conduction from a solid to a water source, which is cooled by evaporation to ambient air. The ceiling (or internal walls), cooled by conduction, then acts as a radiant/convective cooling panel, such that the space temperature is cooled without any resultant increase in absolute humidity (fig. 1, line a–b) and can be supplemented with comfort cooling by ceiling fans. Examples of this approach include:

(i) A shaded water pond over an uninsulated (except in winter) roof. The pond's water temperature follows closely the ambient average wet bulb temperature (the equivalent dry bulb temperature which results from humidifying air, at a given temperature and humidity, until saturation), with some elevation and swing that depends on the depth of water in the pond [6].

(ii) Roof sprinkling or roof spray cooling. This involves spraying droplets or a thin mist of moisture over the roof which extract sensible heat directly from the roof surface and ambient air for evaporation.

(iii) Moving water film. This involves maintaining a film of water flowing across the roof of a building, or down its facade as with the UK pavilion at the Seville Expo '92 [7]. In this way the increased relative velocity at the air-water interface enhances the evaporative process.

Active Indirect Evaporative Cooling

Ambient air is passed through the primary circuit of a tube, flat plate or rotary heat exchanger and evaporatively cooled due to contact with the wetted heat exchanger lining. Target zone air, which passes through the secondary circuit, then transfers heat through the cooled heat exchanger surfaces. This is picked up and rejected by the ambient 'scavenger air' in the primary circuit [8], such that the primary circuit exit air temperature is close to the secondary circuit inlet temperature as opposed to the ambient wet bulb temperature. Cooling is therefore delivered by convection as opposed to conduction to the target zone, again with no absolute humidity increase (fig. 1, line a–b).

Direct Evaporative Cooling

The direct approach involves the evaporation of water droplets in the air-stream which serves the target zone. There are numerous examples of this application, including:

(i) 'Evapotranspiration' – the process by which vegetation transpires moisture during the daytime to reject sensible heat gain. A typical deciduous tree loses about 1,500 kg of water by evaporation during a hot sunny day, which causes a corresponding 33.8 GJ of cooling. Likewise, an acre of grass can transfer in excess of 50 GJ [9].

(ii) Water features, including fountains, sprays, ponds and pools. An example is the domestic courtyard pool found in many vernacular homes of hot dry climates which is used to maintain a thermally stratified reservoir of cool daytime air [10].

(iii) The evaporative tower. This vernacular architectural concept traditionally involved the wetting of pads or placing of water-filled porous jars at the top of a chimney. Ambient air is cooled by evaporation. The density difference between the cooled and ambient air causes a downflow that ventilates the attached building. Air temperatures at the tower outlet are typically only 2°C higher than the ambient wet bulb temperature.

With this technique, the addition of water vapour increases the latent heat of the air-vapour mixture, but as the process is adiabatic, this increase is offset by a sensible heat reduction and a consequent lowering of the dry bulb temperature of the target zone air. In other words, the air state moves along a constant enthalpy or wet bulb temperature line (fig. 1, line a–c). Consequently, for the same dry bulb temperature reduction, direct evaporative cooling entails higher relative and absolute humidities than with the indirect approach.

Active Direct Evaporative Cooling

The principle is similar to that for active indirect cooling, with the exception that the evaporatively cooled air (due to contact with wetted pad surfaces) is delivered direct to the target zone, with no consequent heat exchanger efficiency losses. However, this efficiency improvement is offset by increased target zone humidity, which reduces the effectiveness of comfort cooling due to localised air movement.

Two-Stage Evaporative Cooling

This is a combination of active direct and indirect evaporative cooling which is generally used when the required dry bulb temperatures are lower than the previous methods can deliver. Generally, a single unit will first accommodate an indirect heat exchanger, which ambient air passes through en route to the direct evaporative cooler. The cooling process is depicted by line a–b–d in figure 1. This configuration may result in cooling losses due to condensation of the high humidity air when in contact with the heat exchanger surfaces. The increased cooling capacity of the unit is offset by the increased pressure drop and consequent fan power requirement.

Passive Downdraught Evaporative Cooling

The active methods of evaporative cooling, whilst having the potential to deliver satisfactory environmental conditions in climates with sufficiently low average wet bulb temperatures, have the disadvantage of consuming energy for fans and water pumps. In terms of minimising energy use therefore, it is preferable to choose more p sive solutions. Of the indirect methods, the roof p entails severe structural overheads, and requires sc form of thermal insulation for protection during wir months. The fabric wetting methods have no such o heads, but run the risk of mould growth as well as che cal damage if the water is not carefully filtered. There also efficiency losses in the method of cooling deliv and some form of predictive control may be necessary ensure that delivered cooling coincides with demand c to the inertia of thermally massive constructions. Of all these methods then, direct evaporative cooling offers t most rapid and efficient method of cooling delivery, th is little risk of damage to materials or any structural ov head, and energy consumption is either zero or negli ble.

Landscaping and water features, whilst producing d cernible cooling benefits, do so inefficiently, becau much of the achieved cooling is not delivered to the poi of need. These approaches are also independent of t built form of a proposed development, and so may acco pany any dedicated cooling strategy. Of the methods direct evaporative cooling, the evaporative tower a proach, or passive downdraught evaporative cooli (PDEC), would appear to offer the greatest potential dispense in part with the need for air-conditioning.

Physical Principles

In recent years, methods to improve the efficiency the vernacular evaporative tower concept have been d veloped. The most important of these relates to the meth od of encouraging evaporation. To eliminate the pressu drop caused by friction between ambient air and the we ted surface, whilst increasing the air-water contact area which was generally restricted to the high level perimete surfaces of the tower – a method of spraying fine droplet of water directly into the air-stream has been developed.

As part of a control loop to maintain certain preset con ditions within a target zone, micronisers will be switche on to commence PDEC. Fine droplets of water – in size o the order of several micrometers – are then propelled int the air-stream. At this micro scale, each droplet experi ences (in a non-saturated environment) heat, mass an momentum transfer processes [11]:

(i) The temperature gradient at the drop-air interfac provokes a net heat transfer from the air to the drop sur face, if the air is warmer than the drop.

(ii) Vapour near the water surface diffuses to the non saturated air.

(iii) If there is relative movement between the drop and surrounding air, a transfer of momentum occurs between them. This tends to increase the rate of heat and mass transfer. The physical action of water drops descending through the tower therefore accelerates the cooling process.

The heat transfer tends to increase the drop temperature, whereas the latent energy absorbed by the vapour (during mass transfer) decreases the drop temperature. Equilibrium is reached when the drop is cooled to the wet bulb temperature. The latent energy required to evaporate more water, so reducing the droplet size, is supplied by the surrounding air which is cooled. Thus, water droplet evaporation occurs in two stages. First it is cooled to the equilibrium temperature, then its radius decreases. The likelihood that a droplet will entirely evaporate under a given set of environmental conditions depends upon droplet diameter and the length of time that the water stays within the air-stream (which itself depends upon air temperature difference, tower height and the existence of axial forces due to wind). Therefore, droplet size should be small and the tower tall enough to guarantee total evaporation, whilst maximising the evaporative cooling achieved – by having a short enough tower to limit heat gains to the cooled air and a dense enough water spray to maximise latent heat exchange.

At the macro scale then, momentum is transferred from the microniser spray to the air in the immediate vicinity of the micronisers. Droplets descend through the tower, so 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 volume exchanges of air through the tower increase proportionally with the temperature difference between ambient air and air within the tower, which in turn depends upon the wet bulb temperature of ambient air (as well as the rate at which water is injected into the air-stream).

Previous Applications

The principle of using evaporation to drive a cool downdraught descends from the vernacular architecture of hot dry Middle Eastern climates. For example, the traditional Middle Eastern wind scoop *(malqat* or *badgir)* was used to channel air to pass a wetted mat or pool of water [12]. Interest in this technique has recently been revitalised due to the pressing need to reduce energy use for cooling. However, modern designers frequently misapply vernacular concepts and the resultant buildings accommodate occupants with much higher comfort expectations. Prior to large-scale take-up therefore, a process of learning and refinement is required to engender confidence in the viability and effectiveness of the technique via simulation, experimentation and the development and testing of demonstration buildings [13].

The first reported modern application of PDEC is the domestic-scale lightweight test building of Cunningham and Thompson [14], which consisted of two towers at either end of an open occupied space with an attic above (fig. 2). Ambient air entered via one tower, which housed wetted pads close to the intake. The dense cooled air descended into the occupied zone at floor level. The heated, more buoyant air then passed through ceiling slots and was guided through a shallow attic (for fabric cooling). The driving force was then due to a solar chimney at the opposing end of the PDEC tower, through which warmed air exited. With a peak ambient dry bulb temperature of 40.5 °C and wet bulb temperature of 21.3 °C, air exited the tower at 23.8 °C at a rate of 30 ach^{-1} and maintained an average indoor temperature of 24.6 °C [6]. Givoni [6] also states that the indoor temperature during the hottest hours could be closer to the tower exit temperature in a high mass building with a smaller temperature swing.

Two parallel rows of six 30 m high towers (fig. 3) were developed to demonstrate the application of PDEC for urban microclimate cooling at Expo '92 in Seville [15]. These towers also demonstrated, for the first time, the use of micronisers to spray a fine mist. This optimises air-moisture contact for evaporation whilst minimising pressure losses. Finer regulation of cooling output can be achieved by controlling microniser output and large volume flows of cool air can be achieved during windless ambient conditions without natural or mechanical assistance. However, a fixed wind catcher, oriented in the prevailing wind direction, was installed to increase volume flows of cooled air for a higher net cooling output during windy days. A pool at the base of the towers captured the water that had not evaporated and recirculated it using a pump. A numerical model was also developed to size the required number of microniser nozzles for optimal cooling [11].

The Expo '92 towers set the precedent for two further applications of PDEC using evaporative sprays. The first was a laboratory model of a PDEC tower servicing an enclosed courtyard at UCLA [16]. As with the Expo

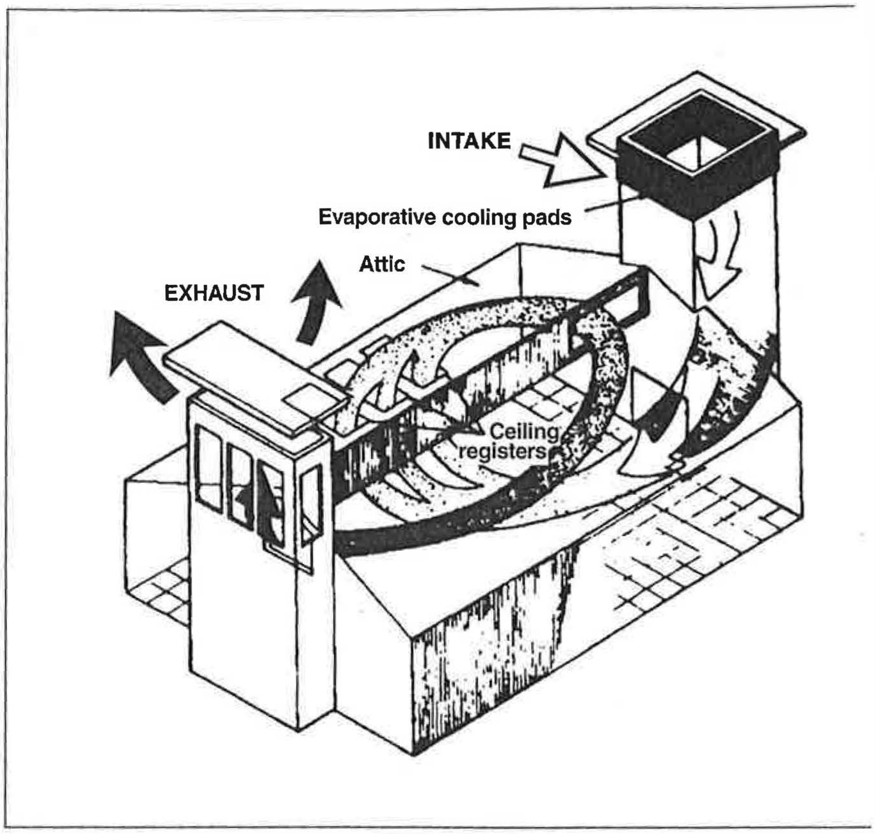

Fig. 2. Experimental building [14].

design, the tower consisted of three parts: a wind catcher, an evaporative column and a water pond. Evaporation was achieved using showerheads and collection using a bucket. Unfortunately, the results from this crude model were inconclusive. Nonetheless, Pearlmutter et al. [12] embraced the concept (of a PDEC tower within an enclosed courtyard) in their PDEC study which involved performance testing of a scale model and a full-scale tower incorporated into an existing office building together with refinements to the basic design. The project focussed on increasing the volume flow rates of evaporatively cooled air (to maximise cooling output) by studying wind catcher and microniser design. Furthermore, evaporation was achieved using relatively large bore showerheads. Consequently, much of the sprayed water did not evaporate and was collected in a pool at the base of the tower. Nonetheless, the project demonstrated reductions in delivered air temperature over ambient of 10–15°C and a cooling potential of 100–120 kW, with fan assistance to buoyancy-driven flow and that this could be improved with the use of curved deflectors. With buoyancy forces alone, the cooling potential was reduced to 30–40 kW, although the

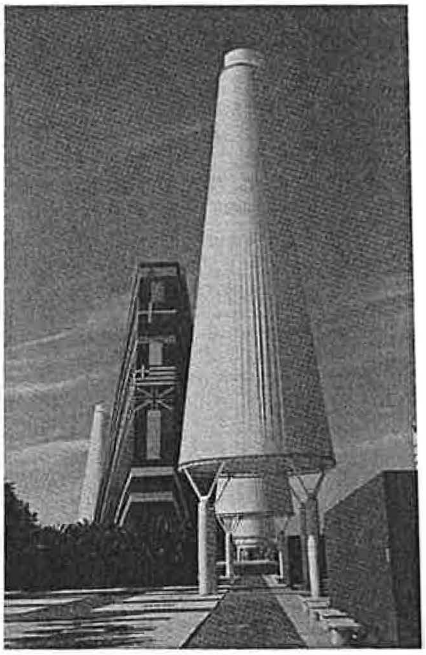

Fig. 3. Cooling towers at Expo '92, Seville.

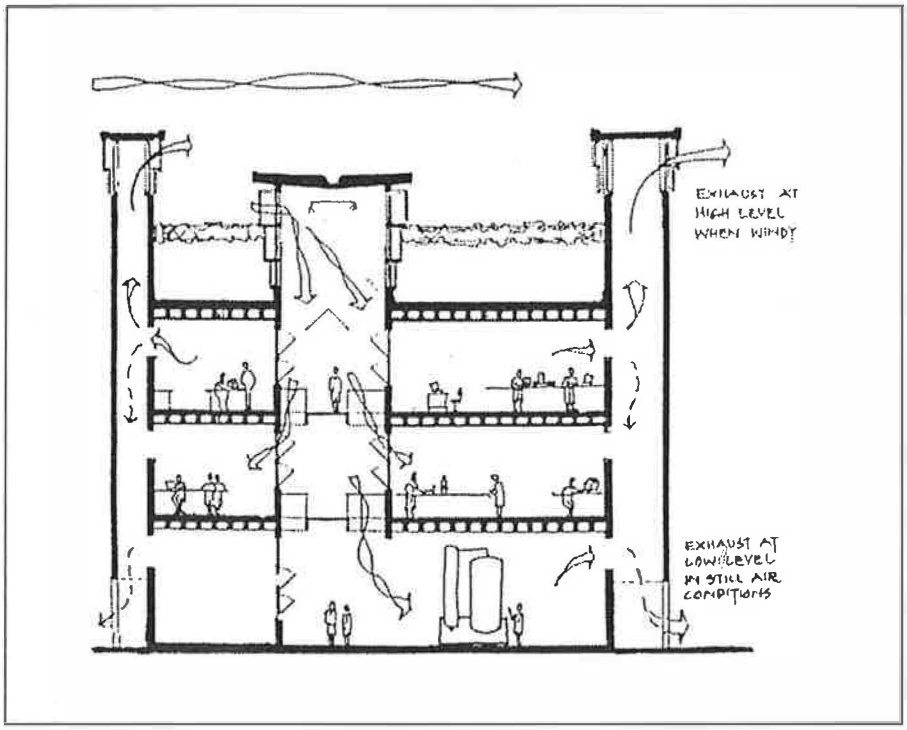

Fig. 4. Torrent Research Centre, cross section showing airflow (architects: Abhikram, with Brian Ford Associates).

temperature of the delivered air was only marginally lower. Although this study represented the first application of PDEC within a real office building, the authors' emphasis on maximising cooling output served to restrict the application of the technique to base-only outlet and protection of the base floor space using a pool.

Conversely, office buildings, which are considerably larger and more complex than their vernacular domestic counterparts, have multiple floors. As such they require delivery of cooled air from within the tower's structure, ideally, in atria fashion to provide a source of daylight. This is plausible given the finding of Pearlmutter et al. [12] that much of the air temperature reduction achieved by evaporative cooling is achieved within the first 1–2 m of the tower and that flows without mechanical or wind assistance can achieve large temperature reductions.

More recently, a 14,000 m^2 research and development centre for the Torrent Pharmaceutical Company was completed at Ahmedabad, India, making full use of PDEC features (fig. 4, 5). Initial experience suggests significant energy and cost savings. Subsequently, an EU-funded project was established to identify the optimal means for applying PDEC to complex, multiple-floor office buildings whilst maintaining modern occupant comfort requirements.

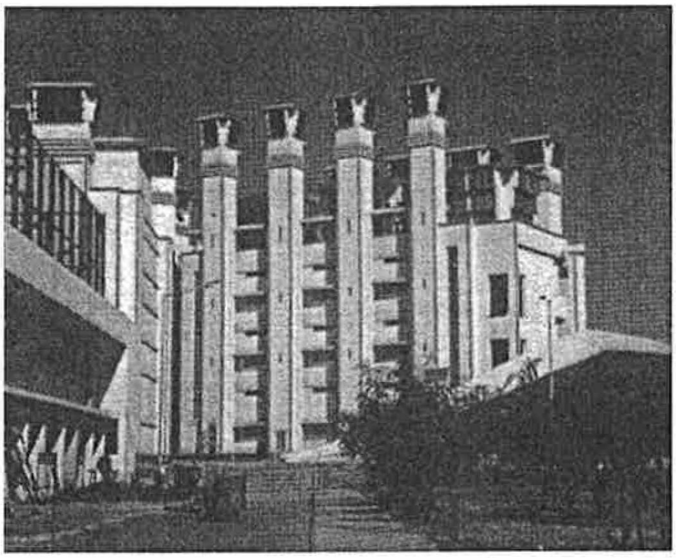

Fig. 5. Torrent Research Centre (architects: Abhikram, with Brian Ford Associates).

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