Evaporative Passive Cooling Designs For Buildings

Zeynab Emdadi, Ali Maleki, Mojtaba Azizi and Nilofar Asim

ABSTRACT

Building energy consumption will likely increase in the future due to enhanced living standards and greater use of air-conditioning. This article reviews the technologies associated with evaporative passive cooling including roof surface evaporative cooling, evaporative cooling walls, and downdraft evaporative cooling in buildings. Our intent is to attract architects and building engineers to the energy-saving benefits of incorporating passive evaporative cooling in building designs.

INTRODUCTION

The building sector accounts for more than 40% of total global energy consumption [1]. Excessive energy use can be detrimental to the environment and exacerbate climate change, particularly in warmer climates. The energies used in buildings, encompassing ventilation, heating, and cooling systems account for over 60% of total building energy consumption [2]. Researchers should assess the micro-climatological conditions at building sites and detail comfort requirements under transient conditions during the cooling seasons.

It is important to advance passive and hybrid cooling systems, and materials to improve the technologies used in building envelope designs [3]. Wind is an important and available source of renewable energy. It provides excellent indoor environmental quality, comfort, plus a healthy and hygienic indoor climate [4]. Evaporative cooling systems require less input energy than mechanical pressure frameworks [5]. Researchers have considered both direct and indirect evaporative cooling systems [6]. By using direct evaporative cooling, air is simultaneously cooled and humidified. With indirect evaporative, the ambient air is cooled without being humidified [7]. This article reviews the technologies associated with passive cooling dissipation techniques that reduce the cooling requirements for buildings and their respective contributions towards the improvement of environmental quality.

Air conditioning systems can be sources of indoor air quality problems, mostly via condensate trays and cooling coils contaminated by organic dust, which could result in mold development in fan housings. Dirty filters could also result in contamination problems, while cooling towers can disperse *Legionella pneumophila* and other viruses [8,9].

OVERVIEW ON EXISTING DESIGNS

The principles associated with solar radiation and heat on roof-cooling systems are detailed in Figure 1. The amount of heat lost to the atmosphere from evaporation reduces roof temperatures. In tropical climates, such as those of India, solar radiation results in the overheating of roof areas. This can be mitigated by spraying water over water-retentive roof materials.

Roof Surface Evaporative Cooling (RSEC)

A damp roof surface allows water to evaporate and be absorbed by unsaturated ambient air. Evaporation results in the absorption of latent heat from a surface, reducing its temperature and subsequent heat gain. Wet roofs 104°F (40°C) can be maintained at temperatures below that of the ambient air 131°F (55°C). However, this requires large quantities of water, making implementation difficult in arid regions [10]. Cheikh et al. proposed an evaporative-reflective roof to passively cool buildings in hot and arid climates [11]. The proposed roof is composed of a concrete ceiling over a rock bed within a water pool. It forms a layer of air that separates the surroundings from an aluminum plate. The external surface is coated with a white titanium-based pigment, which maximizes daytime reflectivity; at night, the aluminum sheets are cooled to temperatures lower than the rock bed rock and water layer. This occurs as water evaporates from roof areas.

Evaporative cooling occurs during nights, since buildings dissipate heat to their surroundings. The release of heat is enhanced by spraying water on the roofs. This reduces the need for water the following morning because the system utilizes less than half of the water at night for cooling purposes. Such designs emphasize the use of natural lighting to illuminate deep and hard-to-reach spaces, subsequently reducing the dependency on artificial lighting (see Figure 2) [13].

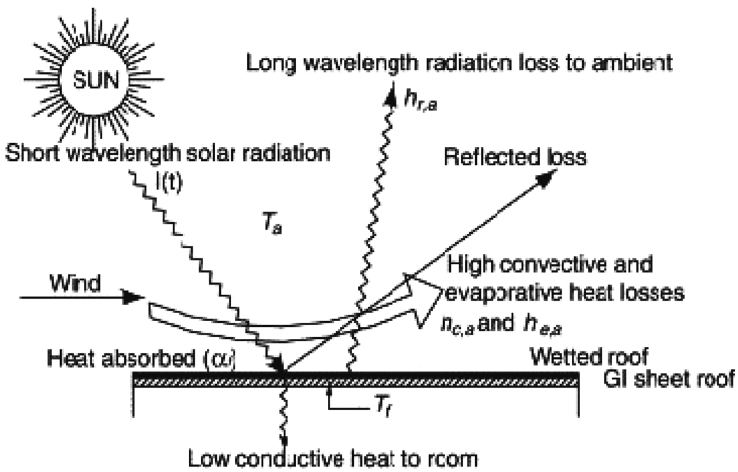

Figure 1. Distribution of solar radiation and transfer of roof heat with evaporative cooling [12].

Figure 2. The night sky system which produces chilled water for the building's mechanical systems is shown in spray mode (photo by Paul Sterbezt).

Passive Evaporative Cooling Wall (PECW)

From the perspective of energy consumption, passive cooling is suitable for the evaporative cooling of materials on building surfaces. It has recently been applied to urban environmental design solutions. It helps cool surfaces during the summer (such as building walls and fences), and is ubiquitous in outdoor or semi outdoor locations.

Both He et al. and Naticchia et al. proposed water evaporative walls, which includes ventilated walls sprayed with water within the ventilated layer and the utilization of latent heat via the evaporation of water [14,15]. This subsequently cools the surroundings by intercepting thermal fluxes [15]. Evaporative wall cooling is conducted via multiple approaches, such as water absorption in transwall systems composed of plastic bags packed with a water–dye solution [16]. Ghiabaklou and Ballinger proposed a system that is applicable for cooling apartments in low-rise and multi-story buildings using a water cascade linked to balconies of individual units [17]. In these applications, water drips vertically over materials, such as nylons and other filaments, maximizing the exposed surface areas to the passing water. Water is pumped through a reservoir, and the air passing through the system is simultaneously cooled and humidified. If water-to-air contact is adequate to equilibrate the exit air, the temperature will be saturated to a level equal to the temperature of the wet bulb exiting air. However, the system requires that the supply water level be maintained since the evaporated water is removed.

An alternative air-conditioning system is the air window which uses intensive evaporation (see Figure 3). It focuses on ventilation, cooling and heating a system within a single block, which compresses a domestic system that uses energy at levels that is three to four times that of traditional vapor compression air conditioning systems. These are composed of porous polymeric materials and require water and a fan [18,19].

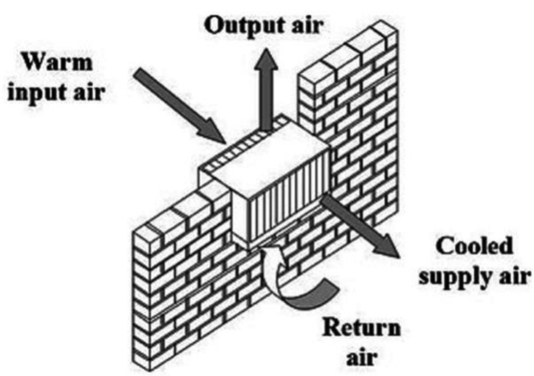

Figure 3. Air window system [19].

A semi-indirect evaporative cooling system uses hollow masonry units to provide a conduit to supply air to the cooled primary system. Air contacts the water droplets on the porous surfaces of the external masonry, enhancing heat and mass transfer (see Figure 4). Recent equipment designs avoid the risks associated with aerosols, as they are capable of eliminating pathogens [20].

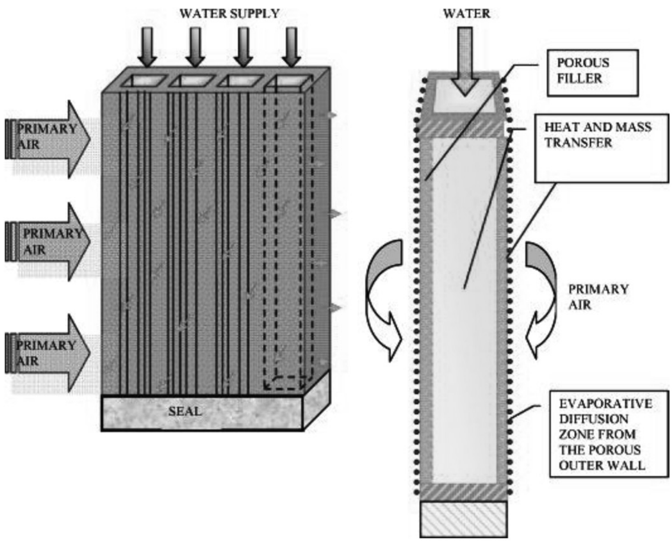

Figure 4. Semi-indirect evaporative cooling system showing hollow brick operation [21].

He et al. developed a PECW using porous ceramics, which was selected due to the capillary force that allows for the absorption of water to a level that exceeds 51 inches (130 cm) when the lower ends are submerged [22]. The proposed PECW have features that allow the passage of wind, which helps reduce temperature via evaporating water absorbed by the submerged porous materials [14]. PECW has an area that is shaded from direct and reflected solar radiation, and its surface can be cooled via evaporation (see Figure 5). The capillary action of the porous material exceeds 39 inches (1 m), thus eliminating the need for a pump.

The evaporative cooling system is semi-indirect and porous. It is composed of two unrelated air flows sectioned by a ceramic barrier: an outdoor air flow to be cooled, and a return air flow that comes into direct contact with water in a cooling tower. One type, detailed in Figure 6, uses a porous ceramic pipe cooler for evaporative recovery. The

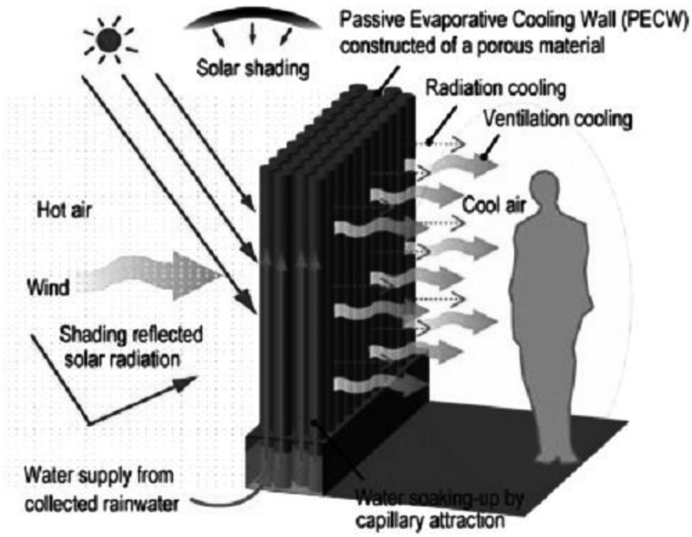

Figure 5. Passive evaporative cooling wall using porous materials [14].

pores of the ceramics prevent the transmission of contaminates as water evaporates from air [7]. Its economic and technical factors make it effective and viable [19].

Maerefat and Haghighi installed a solar chimney on an evaporative cooling system to decrease its energy consumption [18]. It uses a cooling cavity, whereby water is sprayed onto the wall. This forms

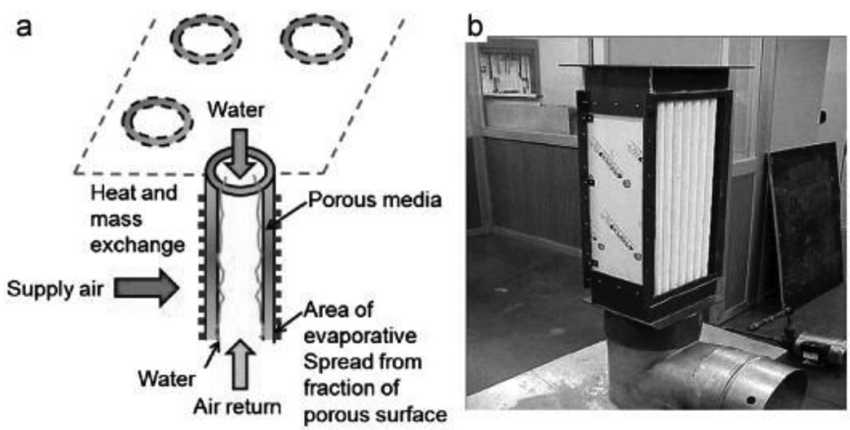

Figure 6. Porous ceramic pipes semi-indirect evaporative cooler: a) principle of heat and mass transfer, and b) experimental prototype [19].

a thin film of water over both the wall and air passages. Solar radiation then heats the air within the room passing through the chimney, creating a natural draft. This results in air circulation within the solar chimney, conditioned spaces and the cooling cavity. The resulting air circulation propels air through the cooling cavity via the wetted cool surfaces. Both cooling and ventilation are provided using solar energy during daylight hours.

Passive Downdraft Evaporative Cooling

Traditional passive down draft evaporative cooling (PDEC) systems have been used in the Middle East (i.e., Iran and Turkey) for centuries to improve natural ventilation and thermal performance [24]. Wind catchers redirect outside air into water-filled porous pots, and the temperature of air entering the building decreases due to evaporation.

Improved forms of evaporative cooling such as PDEC technology are viable alternatives to traditional mechanical cooling systems [25]. No specialized terminology for this PDEC technology is currently available. *PDEC tower* is a representative term for this particular type of component. Its application is named based on its structure, evaporative devices, and geographical locations [25]. The performance of passive cooling needs to be enhanced and validated for multiple climatic settings [24].

Many studies identify the parameters influencing the performance of PDEC towers. Ford et al. divided this technology into passive downdraft cooling (wind tower), active downdraft cooling, and hybrid downdraft cooling [26]. Hybrid downdraft cooling applications encompass passive and active downdraft cooling systems, rendering them usable for both hot–arid and warm–humid climates. While generally used for hot–arid climates, PDEC systems are complex and result in poor thermal comfort and insufficient cooling [27-30]. Applications involving PDEC are categorized based on their respective evaporative devices: a wind tower using a PDEC tower with pad and a PDEC tower with a spray [25]. PDEC towers equipped with sprays are most efficient for building cooling. The efficiency of catching wind and controlling the thermal performance of PDEC towers equipped with a sprayers exceeds that of multiple wind catchers and water drops, allowing PDEC towers to function despite variable weather conditions [25].

Wind Tower

A wind tower is the simplest form of PDEC technology without evaporative devices. It consists of a shaft, a wind catcher at the top of the shaft, a vertical baffle wall in the middle of shaft, and an opening at the bottom. Wind towers are fully passive systems [31]. They are also comfortable, multi-functional, economical, and capable of maintaining constant air temperature [31-33]. However, their shortcomings include: 1) the possibility of the presence of pollutants or insects; 2) the possibility of airflow loss through other openings in towers with more than two openings; 3) insufficient cooling capacity; 4) need for evaporative devices; and 5) dependency on the weather conditions [25,34]. Wind catchers are categorized into three primary groups: vernacular, modern, and super modern. Figure 7 shows a traditional building with passive cooling technology.

Modern wind catchers are comprised of dampers, sensors, and an adjustable ceiling ventilator known as a mono-draft. They are usually automatic, with mechanisms that control the flow of temperature, humidity, air flow, noise level, and CO_2 based on spatial needs [36,37]. These wind catchers provide interior natural ventilation and lighting using an integrated and energy-free system (see Figure 8) [38].

Modern wind catchers have been incorporated in the conceptual design of a 125-story building (see Figure 9). The design is aerodynamic, and can absorb wind [40]. The building's foundation sits on a revolving plate, allowing its position to channel the wind to the top and activate wind turbine generators to produce electricity for cooling and ventilation [40].

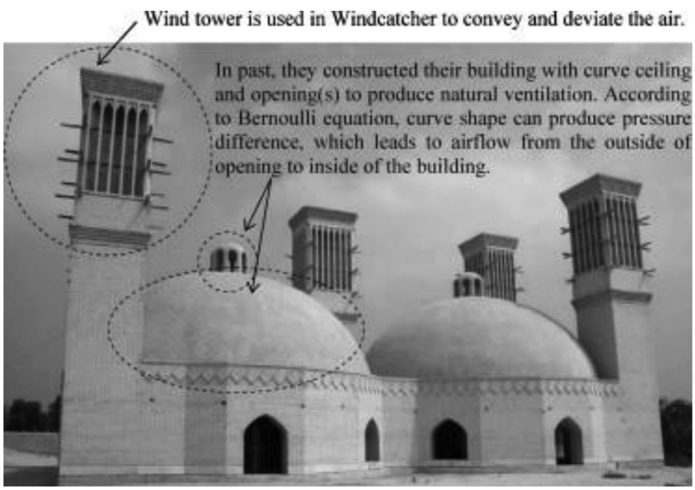

Figure 7. Traditional building with natural cooling characteristics [35].

Figure 8. Examples of mono-draft wind catchers [39].

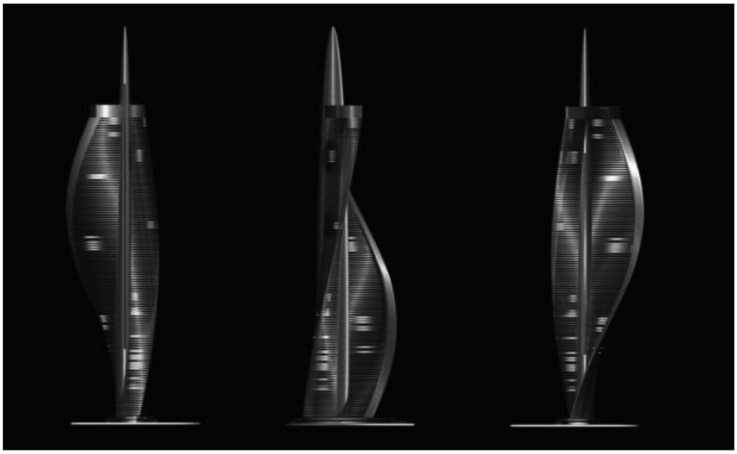

Figure 9. Conceptual design for a wind catcher tower [40].

PDEC Tower with Evaporative Devices

PDEC systems, using evaporative devices such as porous mediums and sprays have been developed and integrated into buildings to improve the cooling capacity of wind towers. These components are modified wind towers. PDEC systems are similar to traditional wind towers and include an additional evaporative device that induces a large temperature drop. Typical components include an evaporative device, such as wetted pads or sprays at the top, a shaft, a wind catcher, openings at the bottom, and a water tank or reservoir (Figure 10) [25].

Studies have indicated that the hardness of the water and microbiological contamination could create problems [42,43]. Noise and the large volumes of water consumption can be an issue in areas with high wind velocities [43-45].

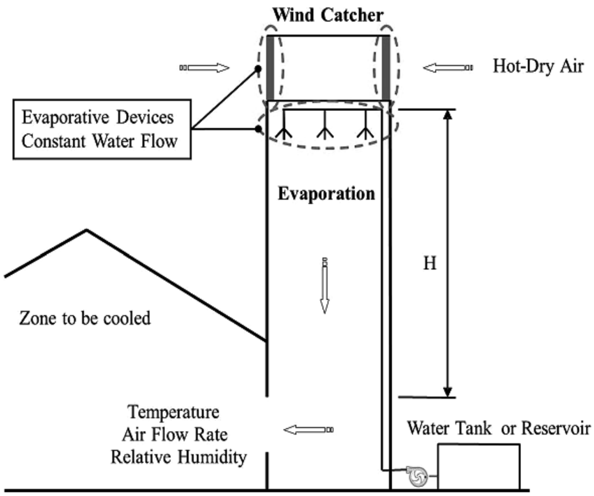

Figure 10. Configuration of PDEC tower with evaporative devices [41].

PDEC Towers with Pad

New designs mitigate traditional disadvantages, such as dust and low performance. One design that is suitable in windy areas uses one-way dampers in its tower head and a wetted column in its tower. Designs suitable in areas with less wind exposure use evaporative cooling pads at the tower entrance [46]. A newly designed PDEC tower with a pad has been installed at Zion National Park's visitors center in Utah (Figure 11). Torcellini et al. evaluated the passive cooling strategies of the PDEC tower with an evaporative pad and natural ventilation via clerestory windows [47].

Potential weaknesses of PDEC towers with pad include the high-pressure drop and short lifecycle of the pads [48]. Other problems include the need for a shading device to avoid water loss due to solar radiation and the inability to position the pads ideally to capture the prevailing winds [25].

PDEC Towers with Spray Systems

There are advanced designs for PDEC towers with spray systems. Dai et al. proposed a passive cooling system for humid climates that uses a solar chimney with an adsorption cooling system [49]. The increased ventilation rates cool interior spaces while keeping humidity levels constant. The air flow rate is a function of the efficiency of the evaporative cooling device, tower height, cross section, resistance to air

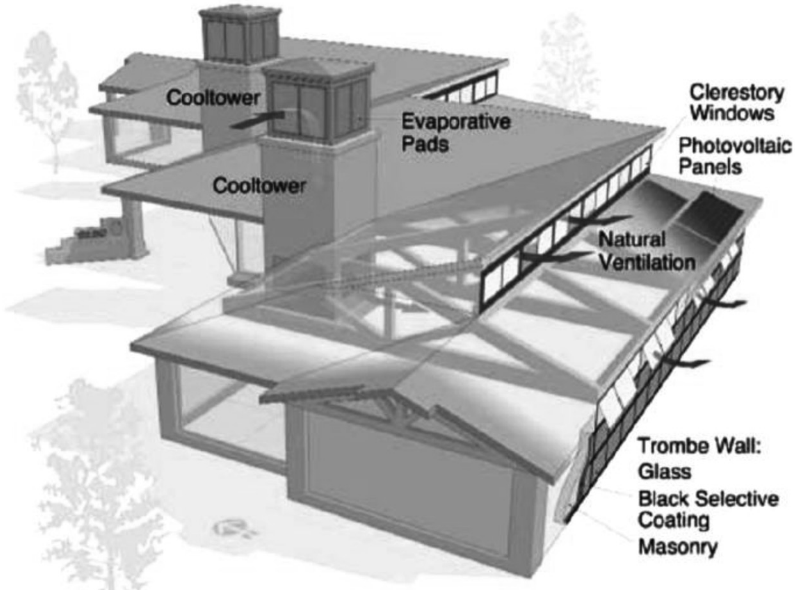

Figure 11. Energy-efficient features of the visitors center at Zion National Park (courtesy of the National Renewable Energy Laboratory) [47].

flow in the cooling device, tower, and structure (if any) into which air is discharged [50]. The Torrent Research Centre in Ahmedabad has a PDEC system (see Figure 12) which decreases the ambient temperature by about 57°F (14°C) and air changes by a minimum of six per hour. Ford et al. monitored the performance of this building and proved that the system is economically efficient [51]. He concluded that the main variables, such as the type of wind catcher and the size of water drops, influence the cooling performance of the spray PDEC tower.

An example of the use of a PDEC tower system in India is the Inspector General of Police (IGP) Complex in Gulbarga, Karnataka, constructed in 2005 (Figure 13). Data indicated that temperature drops during a period of March through May were about 55°F (13°C). The simple payback period compared to an equivalent air-conditioned building was estimated to be roughly five years [25].

The IGP Office complex uses a PDEC system which passes air over multiple layers of water trapped in the wind tower. This cools the water, which is then channeled to the interior of the buildings, similar to earth tunnel (cool tube) air-conditioning systems.

Figure 12. Torrent Research Centre passive down draft evaporative cooling, Ahmedabad (photo courtesy: Abhikram) [52].

Figure 13. Inspector General of Police Complex, Gulbarga was the first naturally ventilated LEED Gold building in India (photo by Jiten Prajapati) [53].

The spray PDEC tower system is capable of providing superior cooling capabilities. There have been efforts to maximize the performance of these devices using comprehensive analyses [25].

CONCLUSIONS

Buildings are major consumers of total primary energy. Passive cooling technologies can decrease their energy consumption. The use passive cooling is becoming more widespread due to the enhancements in materials and designs. This article explores passive evaporative cooling concepts being used roofs, walls and downdraft locations for building applications. Down draft wind catchers are regarded as innovative, as they use evaporative cooling for large or semi-enclosed areas, such as courtyards, particularly in arid regions. For current architectural practice, it is essential for architects and building engineers to include passive cooling mechanisms in buildings as an inherent part of a building's design. This helps decrease the dependency on mechanical systems for thermal comfort and mitigates environmental problems from excessive consumption of energy.

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