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# Analysing the performance of passive cooling system in Buildings: designing natural solution to summer cooling loads and Architectural Interventions

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***Abstract:*** *The continued rapid growth of construction industry and demand of energy raises a number of persistent questions and problems and demands for solution. Passive design responds to local climate and site conditions in order to maximize the comfort and health of building users while minimizing energy use. The key to designing a passive building is to take best advantage of the local climate. Passive cooling refers to a building design approach that focuses on heat gain control and heat dissipation in a building in order to improve the indoor thermal comfort with low or nil energy consumption. Passive cooling systems use non-mechanical methods to maintain a comfortable indoor temperature and are a key factor in extenuating the impact of buildings on the environment. The energy consumption in buildings is very much with the anticipation to further increase because of improving standards of leaving and the increase of world population. Air conditioning use has increasingly penetrated the market during the last few years and quite enough to contribute in the rise of absolute energy consumption. This paper reviews and analyses the performance of various passive cooling systems and their role in providing thermal comfort and its significance in energy conservation with the help of Architectural interventions.*

***Keywords:****Cooling Mechanisms, Passive Cooling, Passive cooling systems designing, and Architectural Interventions*

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## I. INTRODUCTION

There has been a drastic increase in the use of air conditioning system for cooling the buildings all around the world. The last decade has witnessed a severe energy crisis in developing countries especially during summer season primarily due to cooling load requirements of buildings. Increasing consumption of energy has led to environmental pollution resulting in global warming and ozone layer depletion. Passive cooling systems use non-mechanical methods to maintain a comfortable indoor temperature and are a key factor in extenuating the impact of buildings on the environment. Passive cooling techniques can reduce the peak-up cooling load in buildings, and reduce the size of the air conditioning equipment and the period for which it is generally required. According to Adnot, J. et al. [1], In Europe and worldwide the energy consumption for the cooling of buildings is increasing dramatically. Studies like "Energy Efficiency and Certification of Central Air Conditioners" (EECCAC) and "Energy Efficiency of Room Air Conditioners" (EERAC) predict a four-fold growth of energy demand for cooling between 1990 and 2020 in the EU 15.

*Annual cooling energy demand in the EU-15*

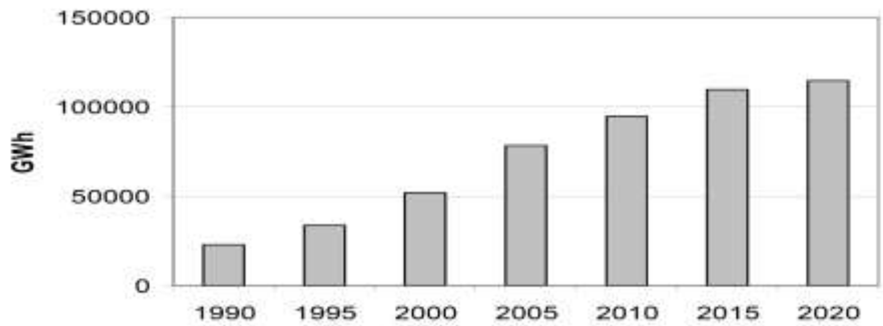


**Figure 1:** Estimated increase of cooling energy in the EU-15 from 1990 to 2020

The reasons for this development are manifold. As main causes can be identified:

- ✓ Inefficient building design (e.g. orientation and size of transparent building elements)
- ✓ Increase of internal loads (IT-equipment, lighting)
- ✓ Climate change aspects (increase of outdoor temperatures in the summer period)
- ✓ Tightened requirements on indoor comfort (e.g. caused by standardization and building directives, comfort claims by occupants)
- ✓ Misconduct of the occupants (misappropriate ventilation by occupants in the cooling period)

The energy consumption in buildings is very much with the anticipation to further increase because of improving standards of leaving and the increase of world population. Air conditioning use has increasingly penetrated the market during the last few years and quite enough to contribute in the rise of absolute energy consumption.

According to the World Watch Institute, buildings consume about 40% of the world's energy production. As a result, buildings are involved in producing about 40% of the sulfur dioxide and nitrogen oxides that cause acid rain and contribute to smog formation. Building energy use also produces 33% of all annual carbon dioxide emissions, significantly contributing to the climate changes brought about by the accumulation of this heat-trapping gas.

Before the invention of mechanical refrigeration, ingenious use was made of the many means of cooling (e.g. damp cloths hung in draughts created by the connective stack effect in buildings). So dwellings and life styles were developed to make best possible use of these sources of cooling. The introduction of mechanical refrigeration permitted not only the ability to increase the likelihood of achieving complete thermal comfort for more extended periods, but also a great deal of flexibility in building design, and simultaneously led to changes in life style and work habits. However, increasingly, the use of a 'higher technology' resulted in natural-cooling systems being ignored. Now with the growing realization of the rapid depletion of non-renewable energy sources and of the adverse environmental impacts of fossil-fuel dissipating processes, it is accepted that it is foolish to continue consuming vast amounts of non-renewable fuels for the air-conditioning of buildings, when our ancestors achieved thermal comfort by natural means. Hence to reduce the emission of greenhouse gases, caused by fossil fuels to power the cooling requirement of the buildings has stimulated the interest towards adoption of passive cooling techniques for buildings.

## II. COOLING MECHANISMS

There are different cooling systems available for electronics and power systems whose applications depend on different factors. Required cooling capacity, physical confinements, environmental conditions, cost and compatibility requirements are some of the most important criteria that can determine which method to use for a particular system. Cooling methods in general can be categorized in two major groups; active cooling and passive cooling. Active methods are the ones in which a power source is required to run the cooling system. There are different types of active cooling mechanisms, such as fan-assisted cooling, spray cooling, refrigeration cycles, jet-impingement cooling, and electro-wetting cooling. Each of these methods has its own range of applicability in term of heat dissipation capacity. Among mentioned methods, two-phase cooling mechanisms due to very large value of boiling latent heat of coolant have much higher capacity than single-phase methods. In most of the high and ultrahigh heat flux systems single phase methods do not meet the requirements and two phases should be implemented.

Another major group of cooling systems are passive methods which do not require a power source to operate. These methods have generally less heat dissipation capacity compared to active ones but they are widely preferred for electronic and power electronic devices since they provide low-cost, no parasitic power, quiet operation and reliable cooling solutions. Due to the absence of moving parts in most of the passive cooling systems, they do not need regular maintenance and are very reliable. The most important component of a passive-cooled system is heat sink which is in direct contact with the ambient. Such passive techniques are drawing more attention because they are "green" and air is the most accessible coolant, particularly for applications in hostile environments, e.g. contaminated air, vibrations, noise, and humidity. Other components of such systems may include heat spreaders, heat pipes, and thermal energy storage systems that may include phase change materials (PCM).

## III. PASSIVE COOLING IN BUILDINGS

Controlling the heat, a building gain from its environment is what passive cooling is all about. It is also what passive heating is about, and the relation between those two functions is crucial. Keeping unwanted heat out in the summer and drawing it in during winter are issues that should—in fact, must—be addressed hand in hand, for the simple reason that in either case the design of the building itself is the climate-control mechanism.

There are designers, it should be noted, who define passive cooling systems as strategies which literally introduce coolness into a building without mechanical assistance, a definition that excludes design strategies which stop heat before it can enter and become part of the cooling load. While it's a definition that has real meaning, especially in its opposition to active mechanical cooling strategies, even its proponents agree that controlling heat gain is the essential first step in any attempt to cool buildings naturally, passively, through designs itself.

If controlling heat gain is the first step in a passive cooling venture, then the adjunct corollary is learning as much as possible about the climatic conditions on site that produce unwanted heat, and a critical tool in that learning process may soon be on the way.

Building design approach that focuses on heat gain control and heat dissipation in a building in order to improve the indoor thermal comfort with low or nil energy consumption Santamouris & Asimakoupolos [21]. This approach works either by preventing heat from entering the interior (heat gain prevention) or by removing heat from the building (natural cooling) Limb 1998 [15]. Natural cooling utilizes on-site energy, available from the natural environment, combined with the architectural design of building components (e.g. building envelope), rather than mechanical systems to dissipate heat Niles, Philip, Kenneth, & Haggard [19]. Therefore, natural cooling depends not only on the architectural design of the building but how it uses the local site natural resources as heat sinks (i.e. everything that absorbs or dissipates heat). Examples of on-site heat sinks are the upper atmosphere (night sky), the outdoor air (wind), and the earth/soil.

Passive cooling covers all natural processes and techniques of heat dissipation and modulation without the use of energy Santamouris & Asimakoupolos [21]. Some authors consider that minor and simple mechanical systems (e.g. pumps and economizers) can be integrated in passive cooling techniques, as long they are used to enhance the effectiveness of the natural cooling process Givoni & Baruch [8]. Such applications are also called 'hybrid cooling systems' Santamouris & Asimakoupolos [21]. The passive cooling system can be grouped in two main categories:

- ✓ Preventative systems that aims to provide protection and/or prevention of external and internal heat gains.
- ✓ Modulation and heat dissipation systems allow the building to store and dissipate heat gain through the transfer of heat from heat sinks to the climate. This technique can be the result of thermal mass or natural cooling.

**3.1 Preventatives**

Protection from or prevention of heat gains encompasses all the design techniques that minimizes the impact of solar heat gains through the building's envelope and of internal heat gains that is generated inside the building due occupancy and equipment. It includes the following design techniques:Santamouris & Asimakoupolos [21].

**3.1.1 Microclimate and site design**

By taking into account the local climate and the site context, specific cooling strategies can be selected to apply which are the most appropriate for preventing overheating through the envelope of the building. The microclimate can play a huge role in determining the most favorable building location by analyzing the combined availability of sun and wind. The bioclimatic chart, the solar diagram and the wind rose are relevant analysis tools in the application of this technique Brown; Dekay, Mark [5].

**3.1.2 Solar control**

A properly designed shading system can effectively contribute to minimizing the solar heat gains. Shading both transparent and opaque surfaces of the building envelope will minimize the amount of solar radiation that induces overheating in both indoor spaces and building's structure. By shading the building structure, the heat gain captured through the windows and envelope will be reduced.

**3.1.3 Building form and layout**

Building orientation and an optimized distribution of interior spaces can prevent overheating. Rooms can be zoned within the buildings in order to reject sources of internal heat gain and/or allocating heat gains where they can be useful, considering the different activities of the building. For example, creating a flat, horizontal plan will increase the effectiveness of cross-ventilation across the plan. Locating the zones vertically can take advantage of temperature stratification. Typically, building zones in the upper levels are warmer than the lower zones due to stratification. Vertical zoning of spaces and activities uses this temperature stratification to accommodate zone uses according to their temperature requirementsSantamouris & Asimakoupolos [21]. Form factor (i.e. the ratio between volume and surface) also plays a major role in the building's energy and thermal profile. This ratio can be used to shape the building form to the specific local climate. For example, more compact forms tend to preserve more heat than less compact forms because the ratio of the internal loads to envelope area is significant Caldas [6] and Caldas, Santos [7].

### 3.1.4 Thermal insulation

Insulation in the building's envelope will decrease the amount of heat transferred by radiation through the facades. This principle applies both to the opaque (walls and roof) and transparent surfaces (windows) of the envelope. Since roofs could be a larger contributor to the interior heat load, especially in lighter constructions (e.g. building and workshops with roof made out of metal structures), providing thermal insulation can effectively decrease heat transfer from the roof.

### 3.1.5 Behavioral and occupancy patterns

Some building management policies such as limiting the amount of people in a given area of the building can also contribute effectively to the minimization of heat gains inside a building. Building occupants can also contribute to indoor overheating prevention by: shutting off the lights and equipment of unoccupied spaces, operating shading when necessary to reduce solar heat gains through windows, or dress lighter in order to adapt better to the indoor environment by increasing their thermal comfort tolerance.

### 3.1.6 Internal gain control

More energy-efficient lighting and electronic equipment tend to release less energy thus contributing to less internal heat loads inside the space.A passive solar design involves the use of natural processes for heating or cooling to achieve balanced interior conditions. The flow of energy in passive design is by natural means: radiation, conduction, or convection without using any electrical device. Maintaining a comfortable environment within a building in a hot climate relies on reducing the rate of heat gains into the building and encouraging the removal of excess heat from the building. To prevent heat from entering into the building or to remove once it has entered is the underlying principle for accomplishing cooling in passive cooling concepts. This depends on two conditions: the availability of a heat sink which is at a lower temperature than indoor air, and the promotion of heat transfer towards the sink. Environmental heat sinks are:

- ✓ Outdoor air (heat transfer mainly by convection through openings)
- ✓ Water (heat transfer by evaporation inside and / or outside the building envelope)
- ✓ The (night) sky (heat transfer by long wave radiation through the roof and/or other surface adjacent to a building
- ✓ Ground (heat transfer by conduction through the building envelope)

The important cooling systems like shading, Insulation, Induced ventilation, Radiative cooling, Evaporative cooling, Earth coupling, andDesiccant cooling, are discussed in details:

## IV. PASSIVE COOLING SYSTEMS DESIGNING NATURAL SOLUTION AND ARCHITECTURAL INTERVENTIONS

### 4.1 Solar shading

Among all other solar passive cooling systems, solar shading is relevant to thermal cooling of buildings especially in a developing country owing to their cost effectiveness and easy to implement. A properly designed shading system can effectively contribute to minimizing the solar heat gains. Shading both transparent and opaque surfaces of the building envelope will minimize the amount of solar radiation that induces overheating in both indoor spaces and building's structure. By shading the building structure, the heat gain captured through the windows and envelope will be reduced.

A country like Nigeria and other developing countries in North Africa and Middle-east region has witnessed a steep rise masonry houses with RCC roofs. However, the availability of electric power in the villages especially during summer is limited. These RCC roofs tend to make the indoor temperature very high around 41°C: This is due to high roof top temperature of around 65°C in arid regions. Solar shading with locally available materials like terracotta tiles, hay, inverted earthen pots, date palm branches etc. can reduce this temperature significantly.

Shading with tree reduces ambient temperature near outer wall by 2°C to 2.5°C. On an average a depression of six degrees centigrade in room temperature has been observed when solar shading systems are adopted Babsel, Hause, Minkel [3]. Kumar, Garg and Kaushik [12], evaluated the performance of solar passive cooling techniques such as solar shading, insulation of building components and air exchange rate. In their study they found that a decrease in the indoor temperature by about 2.5°C to 4.5°C is noticed for solar shading. Results modified with insulation and controlled air exchange rate showed a further decrease of 4.4°C to 6.8°C in room temperature. The analysis suggested that solar shading is quite useful to development of passive cooling system to maintain indoor room air temperature lower than the conventional building without shade.

**4.1.1 Shading by trees and vegetation**

Proper Landscaping can be one of the important factors for energy conservation in buildings. Vegetation and trees in particular, very effectively shade and reduce heat gain. Trees can be used with advantage to shade roof, walls and windows. Shading and evapotranspiration (the process by which a plant actively release water vapor) from trees can reduce surrounding air temperatures as much as 5°C. Different types of plants (trees, shrubs, vines) can be selected on the basis of their growth habit (tall, low, dense, light permeable) to provide the desired degree of shading for various window orientations and situations. The following points should be considered for summer shading Kamal [11]

- Deciduous trees and shrubs provide summer shade yet allow winter access. The best locations for deciduous trees are on the south and southwest side of the building. When these trees drop their leaves in the winter, sunlight can reach inside to heat the interiors.
- Trees with heavy foliage are very effective in obstructing the sun's rays and casting a dense shadow. Dense shade is cooler than filtered sunlight. High branching canopy trees can be used to shade the roof, walls and windows.
- Evergreen trees on the south and west sides afford the best protection from the setting summer sun and cold winter winds.
- Vertical shading is best for east and west walls and windows in summer, to protect from intense sun at low angles, e.g. screening by dense shrubs, trees, deciduous vines supported on a frame, shrubs used in combination with trees.
- Shading and insulation for walls can be provided by plants that adhere to the wall, such as English ivy, or by plants supported by the wall, such as jasmine.
- Horizontal shading is best for south-facing windows, e.g. deciduous vines (which lose foliage in the winter) such as ornamental grape or wisteria can be grown over a pergola for summer shading.

**4.1.2 Shading of Roof**

**4.1.2.1 Roof shading by solid cover.**

Shading the roof is a very important method of reducing heat gain. Roofs can be shaded by providing roof cover of concrete or plants or canvas or earthen pots etc. Shading provided by external means should not interfere with night-time cooling. A cover over the roof, made of concrete or galvanized iron sheets, provides protection from direct radiation. Disadvantage of this system is that it does not permit escaping of heat to the sky at night-time.

**4.1.2.2 Roof shading by plant cover.**

A cover of deciduous plants and creepers is a better alternative. Evaporation from the leaf surfaces brings down the temperature of the roof to a level than that of the daytime air temperature. At night, it is even lower than the sky temperature.

**4.1.2.3 Roof shading by earthen pots.**

Another inexpensive and effective device is a removable canvas cover mounted close to the roof. During daytime it prevents entry of heat and its removal at night, radiative cooling. Painting of the canvas white minimizes the radiative and conductive heat gain Gupta [9].

4.1.3 Shading by overhangs, louvers and awnings etc.

Well-designed sun control and shading devices, either as parts of a building or separately placed from a building facade, can dramatically reduce building peak heat gain and cooling requirements and improve the natural lighting quality of building interiors. The design of effective shading devices will depend on the solar orientation of a particular building facade. For example, simple fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high.

However, the same horizontal device is ineffective at blocking low afternoon sun from entering west facing windows during peak heat gain periods in the summer.

**4.2 Insulation**

Insulation in the building's envelope will decrease the amount of heat transferred by radiation through the facades. This principle applies both to the opaque (walls and roof) and transparent surfaces (windows) of the envelope. Since roofs could be a larger contributor to the interior heat load, especially in lighter constructions (e.g. building and workshops with roof made out of metal structures), providing thermal insulation can effectively decrease heat transfer from the roof.

The effect of insulation is to reduce heat gain and heat loss. The more insulation in a building exterior envelope, the less heat transferred into or out of the building due to temperature difference between the interior and exterior. Insulation also controls the interior mean radiant temperature (MRT) by isolating the interior surfaces from the influence of the exterior conditions, and also reduces draughts produced by temperature differences between walls and air. Insulation is of great value when a building requires mechanical heating or cooling and helps reduce the space-conditioning loads. Location of insulation and its optimum thickness are very important. In hot climates, insulation is placed on the outer face (facing exterior) of the wall or roof so that thermal mass of the wall is weakly coupled with the external source and strongly coupled with the interior. Use of 40 mm thick expanded polystyrene insulation on walls and vermiculite concrete insulation on the roof has brought down space-conditioning loads of the RETREAT building in Gurgaon by about 15% Majumdar [17]. Air cavities within walls or an attic space in the roof ceiling combination reduce the solar heat gain factor, thereby reducing space-conditioning loads. The performance improves if the void is ventilated. Heat is transmitted through the air cavity by convection and radiation.

### 4.3 Induced ventilation

Where natural ventilation is desirable but, lacking wind, not possible, a building can be designed to induce its own ventilation by duplicating the temperature stratifications that are the source of wind itself.As air warms, it rises, seeking its way upward (and out of an enclosed space) and drawing cooler replacement from below. By using sunlight to heat an isolated pocket of interior air to greater than ambient temperatures and controlling its escape, a building can generate air circulation and maximize the influx of cooler air.

The most effective application of this natural law is a "thermal chimney," a solar-exposed enclosure tall enough to generate maximum air flow and massive enough to retain heat and power the system into the evening hours. Other solar design elements usually associated with passive heating—thermo-siphon systems, indirect gain greenhouses, and trombe walls—can be used to the same cooling effect. The optimal system draws its replacement air from the coolest possible location, a planted, shaded area to the north or an underground air pipe or storage chamber.

The induced ventilation can be obtained through the following methods:

#### 4.3.1 Air vents

Curved roofs and air vents are used in combination for passive cooling of air in hot and dry climates, where dusty winds make wind towers impracticable. Suited for single units, they work well in hot and dry and warm and humid climates. A hole in the apex of the domed or cylindrical roof with the protective cap over the vent directs the wind across it. The opening at the top provides ventilation and provides an escape path for hot air collected at top. Arrangements may be made to draw air from the coolest part of the structure as replacement, to set up a continuous circulation and cool the living spaces. The system works on the principle of cooling by induced ventilation, caused by pressure differences.

#### 4.3.2 Solar chimney

A solar chimney is a modern device that induces natural ventilation by the thermal-buoyancy effect. The structure of the chimney absorbs solar energy during the day, thereby heating the enclosed air within and causing it to rise. Thus air is drawn from the building into an open near the bottom of the chimney. The air exhausted from the house, through the chimney, is replaced by ambient air. However, if the latter is warmer than the air inside the house, as it usually is during the day in hot climates, the continued use of the solar chimney will then begin to heat the structure of the building previously cooled overnight Barbera, Gammarata, Margni & Mariette[4]. The solar chimney is used to exhaust hot air from the building at a quick rate, thus improving the cooling potential of incoming air from other openings. Thus solar chimneys having a relatively low construction cost, can move air without the need for the expenditure of conventional forms of energy, and can help achieve comfort by cooling the building structure at night. They can also improve the comfort of the inhabitants during the day if they are combined with an evaporative-cooling device.

#### 4.3.3 Wind tower

In a wind tower, the hot ambient air enters the tower through the openings in the tower, gets cooled, and thus becomes heavier and sinks down. The inlet and outlet of rooms induce cool air movement. When an inlet is provided to the rooms with an outlet on the other side, there is a draft of cool air. It resembles a chimney, with one end in the basement or lower floor and the other on the roof. The top part is divided into several vertical air spaces ending in the openings in the sides of the tower. In the presence of wind, air is cooled more effectively and flows faster down the tower and into the living area. The system works effectively in hot and dry climates where diurnal variations are high. Figure 8 shows the section and detail of a wind tower.

### 4.4 Radiative cooling

The roof of a building can be used both as a nocturnal radiator and also as a cold store. It is often a cost-effective solution. During the night the roof is exposed to the night sky, losing heat by long-wave radiation and also by convection. During the day, the roof is externally insulated in order to minimize the heat gains from solar radiation and the ambient air. The roof then absorbs the heat from the room below.

All objects constantly emit and absorb radiant energy. An object will cool by radiation if the net flow is outward, which is the case during the night. At night, the long-wave radiation from the clear sky is less than the long-wave infrared radiation emitted from a building, thus there is a net flow to the sky. Since the roof provides the greatest surface visible to the night sky, designing the roof to act as a radiator is an effective strategy. There are two types of radiative cooling strategies that utilize the roof surface: direct and indirect Lechner & Norbert [14].

Direct radiant cooling - In a building designed to optimize direct radiation cooling, the building roof acts as a heat sink to absorb the daily internal loads. The roof acts as the best heat sink because it is the greatest surface exposed to the night sky. Radiate heat transfer with the night sky will remove heat from the building roof, thus cooling the building structure. Roof ponds are an example of this strategy. The roof pond design became popular with the development of the Sky thermal system designed by Harold Hay in 1977. There are various designs and configurations for the roof pond system but the concept is the same for all designs. The roof uses water, either plastic bags filled with water or an open pond, as the heat sink while a system of movable insulation panels regulate the mode of heating or cooling. During daytime in the summer, the water on the roof is protected from the solar radiation and ambient air temperature by movable insulation, which allows it to serve as a heat sink and absorb, though the ceiling, the heat generated inside. At night, the panels are retracted to allow nocturnal radiation between the roof pond and the night sky, thus removing the stored heat from the day's internal loads. In winter, the process is reversed so that the roof pond is allowed to absorb solar radiation during the day and release it during the night into the space below Sharifi, Ayyoob; Yamagata, & Yoshiki [22].

Indirect radiant cooling - A heat transfer fluid removes heat from the building structure through radiate heat transfer with the night sky. A common design for this strategy involves a plenum between the building roof and the radiator surface. Air is drawn into the building through the plenum, cooled from the radiator, and cools the mass of the building structure. During the day, the building mass acts as a heat sink.

### 4.5 Evaporative cooling

Swamp coolers, fountain courts, and atrium pools are all applications of evaporative cooling, a particularly powerful technique in climates of low relative humidity. When a body of water is placed in a hot and relatively dry space, the water evaporates into the air and increases humidity. In the process it turns sensible heat into latent heat, literally lowering the temperature of the air at a rate equivalent to 1,000 BTUs lost for every pound of water added to the air.

Evaporative cooling is a passive cooling system in which outdoor air is cooled by evaporating water before it is introduced in the building. Its physical principle lies in the fact that the heat of air is used to evaporate water, thus cooling the air, which in turn cools the living space in the building. However passive evaporative cooling can also be indirect. The roof can be cooled with a pond, wetted pads or spray, and the ceiling transformed into a cooling element that cools the space below by convection and radiation without raising the indoor humidity.

The design relies on the evaporative process of water to cool the incoming air while simultaneously increasing the relative humidity. A saturated filter is placed at the supply inlet so the natural process of evaporation can cool the supply air. Apart from the energy to drive the fans, water is the only other resource required to provide conditioning to indoor spaces. The effectiveness of evaporative cooling is largely dependent on the humidity of the outside air; dryer air produces more cooling. A study of field performance results in Kuwait revealed that power requirements for an evaporative cooler are approximately 75% less than the power requirements for a conventional packaged unit air-conditioner Maheshwari, Al-Rgom [16]. As for interior comfort, a study found that evaporative cooling reduced inside air temperature by 9.6 °C compared to outdoor temperature Amer [2].

#### 4.5.1 Passive downdraft evaporative cooling (PDEC)

Passive downdraft evaporative cooling systems consist of a downdraft tower with wetted cellulose pads at the top of the tower. Water is distributed on the top of the pads, collected at the bottom into a sump and re-circulated by a pump. Certain designs exclude the re-circulation pump and use the pressure in the supply water line to periodically surge water over the pads, eliminating the requirement for any electrical energy input. In some designs, water is sprayed using micronisers or nozzles in place of pads, in others, water is made to drip. Thus, the towers are equipped with evaporative cooling devices at the top to provide cool air by gravity flow. These towers are often described as reverse chimneys. While the column of warm air rises in a chimney, in this case the column of cool air falls. The air flow rate depends on the efficiency of the evaporative cooling device, tower height and cross section, as well as the resistance to air flow in the cooling device, tower and structure (if any) into which it discharges Thompson, Chalfound and Yokhe [23]. Passive downdraft evaporative cooling tower has been used successfully at the Torrent Research Centre in Ahmedabad (Fig. 9). The inside temperatures of 29 –30 °C were recorded when the outside temperatures were 43 – 44 °C. Six to nine air changes per hour were achieved on different floors.

#### 4.5.2 Roof surface evaporative cooling (RSEC)

In tropical countries, the solar radiation incident on roofs is very high in summer, leading to overheating of rooms below them. Roof surfaces can be effectively and inexpensively cooled by spraying water over suitable water-retentive materials (e.g., gunny bags) spread over the roof surface. Wetted roof surface provides the evaporation from the roof due to unsaturated ambient air. As the water evaporates, it draws most of the required latent heat from the surface, thus lowering its temperature of the roof and hence reduces heat gain. Therefore, the are much lower than the ambient air about 55°C. However, the water requirement for such arrangement is very high and it is a main constrain in the arid region to adopt this technique Jain [10]. Wetted roof temperatures 40°C

### 4.6 Earth coupling

Earth coupling uses the moderate and consistent temperature of the soil to act as a heat sink to cool a building through conduction. This passive cooling system is most effective when earth temperatures are cooler than ambient air temperature, such as hot climates.

Direct coupling - Direct coupling, or earth sheltering, occurs when a building uses earth as a buffer for the walls. The earth is an endless heat sink and can effectively mitigate temperature extremes. Earth sheltering improves the performance of building envelope assemblies by reducing the magnitude of conductive and convective heat loss and gains by reducing infiltration Kwok, Alison; Grondzik, Walter [12].

Indirect coupling. A building can be indirectly coupled with the earth by means of earth ducts. An earth duct is a buried tube that acts as avenue for supply air to travel through before entering the building. Supply air is cooled by way of conductive heat transfer between the concrete tubes and soil. Therefore, earth ducts will not perform well as a source of cooling unless the soil temperature is lower than the desired room air temperatureKwok, Alison; Grondzik, Walter [12]. Earth ducts typically require long tubes to cool the supply air to an appropriate temperature before entering the building. A fan is required to draw the cool air from the earth duct into the building. Some of the factors that affect the performance of an earth duct are: duct length, number of bends, thickness of duct, depth of duct, diameter of the duct, and air velocity.

### 4.7 Desiccant cooling

Desiccant cooling system is effective in warm and humid climates. Natural cooling of human body through sweating does not occur in highly humid conditions. Therefore, a person’s tolerance to high temperature is reduced and it becomes desirable to decrease the humidity level. In the desiccant cooling system, desiccant salts or mechanical dehumidifiers are used to reduce humidity in the atmosphere. Materials having high affinity for water are used for dehumidification. They can be solid like silica gel, alumina gel and activated alumina, or liquids like triethylene glycol. Air from the outside enters the unit containing desiccants and is dried adiabatically before entering the living space. The desiccants are regenerated by solar energy. Sometimes, desiccant cooling is employed in conjunction with evaporative cooling, which adjusts the temperature of air to the required comfort level Nayak, Prajapati [18].

In regions of high humidity, where moisture in the air actually prevents the body from cooling itself evaporative, desiccant cooling is a valued traditional strategy. Dehumidifiers have replaced the salt barrels that were once ubiquitous in the Southeast, but before energy was harnessed and plentiful, desiccant salts were effective coolers to which the only drawback was the need to throw them out once they were saturated.

Passive cooling in regions of high humidity remains a problem today, and desiccant solutions remain the focus of research and current design experimentation. One new hybrid system in use rotates two desiccant salt plates, one of which is inside the living space absorbing moisture from the air while the other, already saturated, is outside in the sunlight losing its moisture through evaporation and being readied for reuse. Another system combines induced ventilation to bring air from underground over an activated charcoal desiccant and cool the interior with dry air. As the air warms and exits high on the south wall, it passes over the saturated desiccant plate, spurring the evaporative process.

The selection of activated charcoal over desiccant salts in the latter system is the product of research, which is rampant in this particular area; one chemical researcher reports that coconut husk charcoal may be the most effective natural desiccant available. The real frontier in desiccant research, however, as in other areas of passive design, is to develop a system capable of cooling buildings larger than residential scale.

## V. CONCLUSION

Several passive cooling systems in this paper were reviewed and discussed with regards to their design implications and architectural interventions. The continuing increase of energy consumption of air conditioning systems suggests a more profound examination of the urban environment and the impact on buildings as well as to an extended application of passive cooling systems. Appropriate research should aim at better understanding micro-climates around buildings, and to understand and describe comfort requirements under transient conditions during the summer period. Also of importance are improving quality aspects, developing advanced passive cooling systems, and finally, developing advanced materials for the building envelope Santamouris [20].

Theoretical studies have shown that the application of all the above techniques in buildings may decrease their cooling load up to 50% - 70%. Generally, concern for energy consumption is only marginal in the majority of architectural-design practices, even in the developed countries. Passive solar energy-efficient building design should be the first aim of any building designer, because, in most cases, it is a relatively low-cost exercise that will lead to savings in the capital and operating costs of the air-conditioning plant.

In today's architecture, it is now essential for architects and building engineers to incorporate passive cooling systems in buildings as an inherent part of design and architectural expression and they should be included conceptually from the outset. Incorporation of these passive cooling systems would certainly reduce our dependency on artificial means for thermal comfort and minimize the environmental problems due to excessive consumption of energy and other natural resources and hence will evolve a built form, which will be more climates responsive, more sustainable and more environmental friendly of tomorrow.

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