Approaches to Passive Cooling Systems for Sustainable Building Designs in Various Climates

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Abstract

Passive cooling utilizes heat gain management and dispersion naturally. This research paper explores passive cooling strategies for buildings, focusing on climate change and sustainability. Buildings account for over 40% of global power demand and CO_2 emissions. These strategies can reduce cooling energy by 23.6% annually, increasing resilience to changes in the environment and reducing the need for mechanical cooling.

In this context, this research investigates four actions of passive cooling: storing, avoidance, slowing, and removal, and clarifies the attributes of various climates and their impact on the efficacy of passive design solution methods. It examines the feasibility of a solar chimney-powered system, aiming to provide fresh air, indoor comfort, and reduce room cooling loads. The study also explores passive design measures for energy efficiency in residential buildings using building simulation.

It concludes that passive cooling systems can improve building performance, energy conservation, and resilience in extreme weather by incorporating sustainable energy sources, protecting buildings from solar radiation, reducing mechanical cooling, diminishing carbon footprints, and advancing environmental sustainability.

Keywords: Passive Cooling Strategies, Various Climates, Indoor Comfort, Energy Conservation, Environmental Sustainability.

Introduction

Concerns about climate change, energy use, and sustainable development have changed architecture and building design. Passive cooling systems are a cornerstone of building sustainability, among the many environmental mitigation measures. These systems use natural processes to lower indoor temperatures without energy, making them essential for sustainable building design. Passive cooling systems offer solutions for varied environmental contexts across regions and climates. This paper discusses passive cooling systems' numerous uses and how they promote sustainable building design in different climates (Freewan, 2019).

Passive cooling systems were inspired by traditional buildings that used natural airflow, thermal mass, and shade to ensure thermal comfort. Passive cooling solutions lower energy use and carbon footprints compared to mechanical active cooling systems. These include 40% of worldwide energy consumption, 30% of raw materials, 25% of timber harvesting, 41% of global CO_2 emissions, and 40% of municipal solid waste ends up in landfills. Global warming, urban heat islands, and rising energy demands make passive cooling even more urgent (Williams, 2012;Mostafa, 2014;Punia, 2022).

Climate variables have an impact on the building's design and energy use, as shown in the Fig. 1. The variables encompass the following:

1- Temperature: daily (maximum and lowest) in degrees Celsius (°C).
2- Humidity: expressed as a percentage, this refers to the relative humidity.
3- Solar radiation is measured in megajoules per square meter (MJ/m2) or watts per square meter (W/m2).
4- Sunshine (%)
5- Amount of cloud cover.
6- Wind: Provides information about the velocity (in meters per second or miles per hour) and direction of the wind.
7- Precipitation: cumulative monthly amount (in millimeters or inches).

The architect may endeavor to ascertain the microclimate by gathering on-site data. ASHRAE and other design handbooks and standards offer comprehensive climatic data for building design and manual load estimates. Alternatively, climate graphs and charts can be generated from annual data by utilizing climate analysis tools like Climate Consultant and the Weather Tool component of Ecotec.

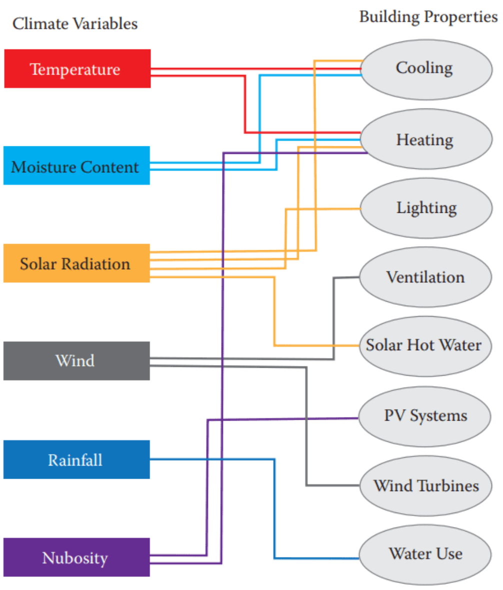

Fig. 1: The impact of climate variables on building design.
Source: Roche, 2024

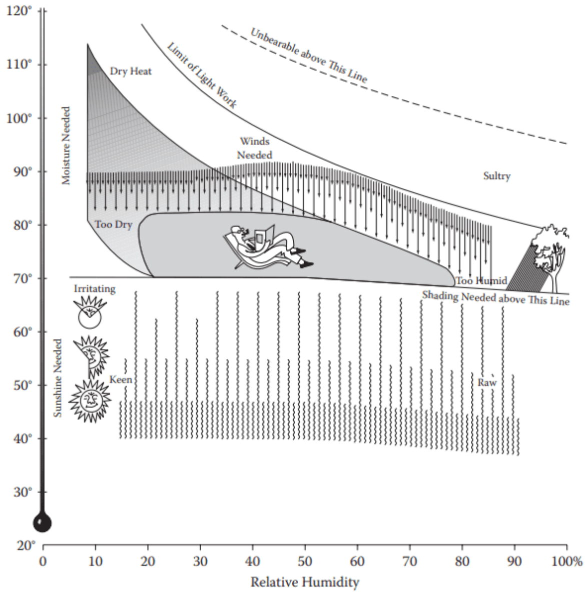

Fig. 2: Olgyay's bioclimatic chart for building design was released in 1963.
Source: Roche, 2012

Therefore, this research examines passive cooling systems as a sustainable building design method. It examines the mechanics, efficacy, and applicability of passive cooling techniques in diverse climates. The paper uses example and actual data to bridge passive cooling theory and practice. So, the paper's objectives are:

- To investigate the fundamental principles and mechanisms of passive cooling systems, to provide a theoretical foundation for understanding their operation and effectiveness.
- To study passive cooling strategies in dry, tropical, temperate, and cold regions. These systems' adaptability to local environmental and cultural factors is examined.
- To provide standards for designing passive cooling systems in sustainable building designs, in order to enhance energy efficiency, thermal comfort, and environmental sustainability.

This paper aims to add to the growing conversation on sustainable architecture by providing insights and practical solutions for architects, designers, and stakeholders working to promote sustainable development and resilience in the built environment.

Theoretical Framework

The theoretical framework revolves around three key principles: environmental sustainability, passive cooling systems, and the impact of climate on building design.

Environmental Sustainability in Architecture

Environmental sustainability in the context of building design emphasizes the necessity of creating structures that minimize ecological disruption while promoting energy efficiency and resource conservation. The Brundtland Commission's definition of sustainable development (World Commission on Environment and Development, 1987) serves as a foundational principle. In applying this to building design, theorists like Kibert (2022) argue for the "Whole Building Design" approach, which integrates sustainability from the planning phase through construction and operation, ensuring that buildings contribute positively to their environments.

Theoretical Underpinnings of Passive Cooling Systems

Passive cooling systems use natural components like wind, thermal mass, solar radiation, and evapotranspiration to control indoor temperatures without or with limited use of mechanical devices. Givoni (1969) emphasizes the significance of comprehending local climates and utilizing architectural components like orientation, insulation, and thermal mass to improve natural cooling in architectural design based on bioclimatic principles. Du (2019) and other scholars discuss solutions such as natural ventilation, shading devices, and cool roofing materials, showing how they can be tailored for various climatic regions to enhance thermal comfort.

Climate Influence on Architectural Design

The influence of climate on passive cooling systems is a crucial topic of academic discussion. The effectiveness of passive cooling strategies is greatly impacted by climatic circumstances, making it crucial to tailor these systems to specific local climates. Dear and Brager's (2002) adaptive model of thermal comfort proposes a framework that modifies expectations for indoor thermal conditions according to the outdoor climate, emphasizing the need for passive design strategies to adapt to the unique thermal and environmental conditions they are situated in. This is corroborated by a study conducted by Bodach et al. (2014), which underscores the importance of climate-responsive building design in enhancing occupant comfort while simultaneously decreasing energy usage and greenhouse gas emissions.

Synthesis

By combining the theories of environmental sustainability, passive cooling systems, and climatic effects, a thorough theoretical foundation for sustainable building design is created. This method promotes a comprehensive awareness of the relationships between building design, its environmental effects, and the climatic conditions it aims to address. The study aligns itself with an academic discourse that emphasizes rigor, sustainability, and innovation in developing ecologically responsible and climatically adaptive architecture designs by incorporating theoretical contributions from scholars in various areas.

This theoretical framework offers a fruitful foundation for studying passive cooling systems in sustainable building design in different regions. An interdisciplinary approach is essential, combining architectural design with environmental sustainability principles and climate-specific solutions. Future studies should further investigate this connection, emphasizing the verification of theoretical models through empirical evidence and the creation of new design methods that can adjust to the changing requirements of climate change and sustainability.

Review of Literature

Environmental sustainability in architecture is founded upon the concept articulated by the Brundtland Commission (1987), which defines it as the pursuit of development that fulfills the requirements of the current generation while safeguarding the capacity of future generations to fulfill their own demands. Thus, McDonough and Braungart (2002) further develop this concept by applying it to the constructed environment and advocating for design principles that are environmentally sustainable. This viewpoint elucidates passive cooling systems as an integral component of a sustainable design framework that aims to achieve synergy with the natural environment rather than solely focusing on energy conservation strategies. Moreover, Jones & Petrescu (2015) highlights the importance of constructing buildings that are both resilient and sustainable, capable of adjusting to evolving environmental conditions. The authors of F. Brandão et al. (2020) also mention progress in sustainability that goes beyond energy efficiency, encompassing environmental, social, and economic aspects. Thomson & Newman (2008) argue in favor of designs that promote urban ecosystems by treating cities and buildings as ecological systems.

In this regard, passive cooling systems employ natural mechanisms to reduce indoor temperatures without the use of mechanical cooling. Passive cooling relies on the principles of thermodynamics and the science of building construction. Thus, Givoni (1969) presents a conceptual structure for comprehending the relationship between building design and climatic factors, with a particular emphasis on utilizing passive methods to achieve thermal comfort. Olgyay's (1963) bioclimatic design incorporates a comprehensive strategy that integrates architectural and climatic design. Omrani, et al. (2017) also provide a comprehensive analysis of natural ventilation, an essential passive cooling technique, covering its mechanics and efficacy in various climatic conditions. Hong et al. (2021) prioritize the examination of microclimate in the design of passive cooling systems through the utilization of computational techniques. Similarly, Du (2019) offers a comprehensive study that investigates the advantages and disadvantages of passive cooling systems under different climatic conditions.

Based on that, studying the correlation between climate and architecture is crucial. Koenigsberger et al. (1975) highlight the importance of climate-responsive architecture in locations experiencing substantial climatic fluctuations. This study highlights the necessity of adapting passive cooling systems to arid, tropical, and moderate environments. Similarly, Banham (1969) elucidates the historical transition from passive to active cooling systems and the present return of passive techniques in architectural responses to climate. Further, Looman (2017) presents a framework for climate-responsive design that highlights the importance of adapting urban planning. DeKay & Brown (2014) focus on the importance of integrating sun, wind, and light into architectural design to achieve passive cooling and sustainability. Kaiyu et al. (2021) demonstrate the process of enhancing passive cooling strategies tailored to various climates, providing valuable insights for sustainable design.

This review offers an insight into the various studies that have examined passive cooling systems in sustainable building design in different regions. However, an interdisciplinary approach is essential, combining architectural design with environmental sustainability principles and climate-specific solutions. Future studies should further investigate this connection, emphasizing the verification of theoretical models through empirical evidence and the creation of new design methods that can adjust to the changing requirements of climate change and sustainability.

Research Methodology

This research employs a comprehensive literature investigation and a detailed case study analysis to evaluate passive cooling systems in sustainable building design across diverse climates. A survey compiled and synthesized passive cooling system research for sustainable building design. The research extensively examined papers from 2010 to 2024. A thorough analysis of passive cooling approaches, design implementations, climate adjustments, and performance outcomes identified patterns and topics for additional study. The case studies were selected for their exemplary use of passive cooling strategies within specific climatic contexts, based on innovative design, documented performance, and the availability of detailed operational data. Data on indoor environmental quality (temperature, humidity) and energy usage were collected before and after the implementation of passive cooling strategies.

The literature survey and case studies were used to assess passive cooling systems across climates for temperature decrease, energy savings, and occupant comfort. The paper summarizes passive cooling systems by climate, physiological impacts, and prominent building features.

Constructing a Bioclimatic Chart to Represent Diverse Climates

It is employed to develop architectural design strategies that utilize natural energy resources in order to get optimal thermal comfort. The chart in Fig. 2 displays the comfort zone, which has a lower limit of approximately 21°C and an upper limit of around 27°C. The higher limit steadily decreases until it intersects with the lower limit of the comfort zone at a relative humidity of 90% (Roche, 2012). Every temperature zone has distinct features that determine precise design approaches for maximizing passive cooling.

Vernacular Architectural Design Principles in Various Climates

Vernacular Architecture in Warm and Humid Climates

In a warm and humid climate, overheating is not a major concern, but the presence of excessive humidity restricts the effectiveness of evaporative cooling. In this environment, a typical building is designed to be lightweight, allowing for easy airflow to facilitate evaporative cooling. Additionally, it features a spacious roof that extends beyond the walls to shield the inside from sun radiation, as depicted in Fig. 3-1.

Occasionally, there is an inclination to increase the vertical dimension of the conical roof, resulting in an elongated shape with rounded extremities. The lower wall possesses sufficient thermal mass that effectively regulates temperature, while the higher roof offers shade and retains humidity from the surrounding air, reducing the air temperature through evaporation. Occasionally, there is an aperture in the roof that allows sunshine to enter and facilitates the removal of hot air; refer to Fig. 3-2.

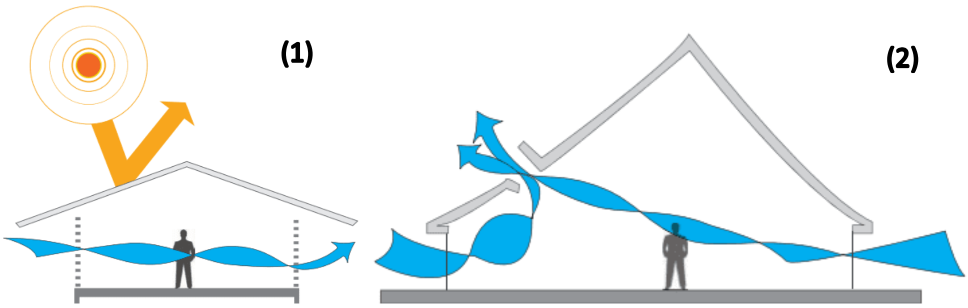

Fig. 3: Climate Archetype: Warm and Humid.
Source: Roche, 2024

Vernacular Architecture in Warm and Dry Climates

The primary issue is excessive heat, yet because of the arid conditions, evaporative cooling can occur. These climates are characterized by elevated temperatures and high levels of radiation. A building typically refers to a sturdy construction that regulates exterior temperatures. It achieves this by incorporating small windows to minimize the entry of solar heat into the interior space while still allowing for some airflow during nighttime cooling. This design is seen in the Fig. 4. Moreover, buildings are equipped with effective insulation, shading elements and measures to minimize air leakage.

The typical exterior colors are predominantly white, which effectively reflect swings. The presence of fountains and other water bodies in the courtyard offers further possibilities for evaporative cooling.

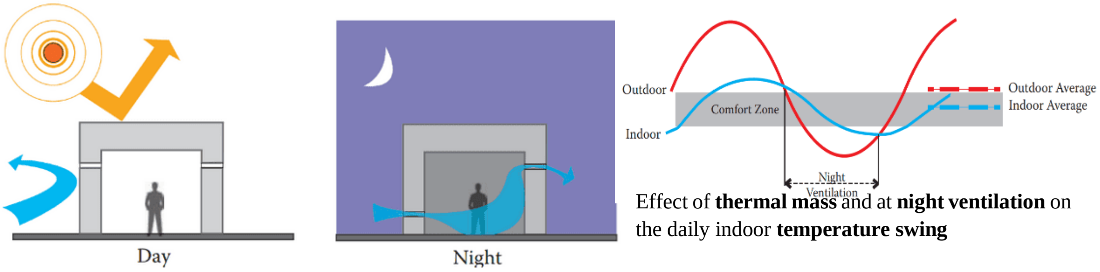

Fig. 4: Climate Archetype: warm and dry.
Source: Roche, 2024

Vernacular Architecture in Temperate Climates

These buildings optimize thermal comfort by strategically positioning and insulating the building to accommodate both winter heating and summer cooling requirements. The buildings effectively keep heat during winter, shielding it from frigid winds while allowing ample natural light to enter. In the summer, the building effectively insulates against heat while also offering shade and ventilation through expansive windows. Given such conditions, an ideal archetype would be one that is small, has excellent insulation, and is airtight. While offering a certain passive solar heating throughout the winter, as illustrated in Fig. 5. designs incorporate a significant utilization of verandas and courtyards and has the option to incorporate either Venetian blinds or wooden louvers.

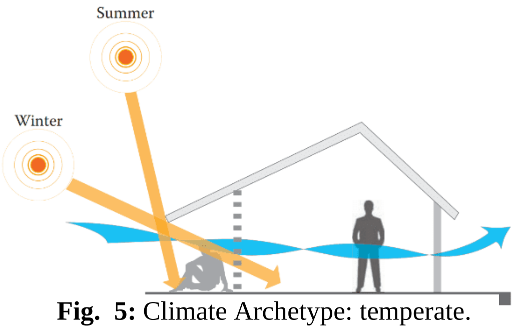

Fig. 5: Climate Archetype: temperate.
Source: Roche, 2024

Fig. 6: Climate Archetype: cold.
Source: Roche, 2024

Vernacular Architecture in Cold Climates

These optimally utilize solar heat gain and reduction of heat loss in the presence of low temperatures and high heating demand. The primary issue is the absence of thermal energy. A climate-responsive building is characterized by an envelope that efficiently covers a significant internal space with minimal external surface area. Buildings in cold climates sometimes feature architectural elements such as domes, cylinders, or cubes to accommodate the specific weather conditions. The insulation of walls is typically achieved through their thickness, which is commonly constructed utilizing indigenous materials like stone (DCLG., 2023).

Windows minimize heat loss, which results in a reduction of incoming radiation and light entering the structure. Typically, these structures are equipped with an internal heat source, such as a fireplace, as outlined in the Fig. 6 (Marnich, 2019).

Passive Systems

Not all passive cooling or heating solutions are universally appropriate; however, it is crucial to comprehend the most favorable climatic circumstances. Thus, using Givoni's psychrometric chart with passive techniques on top of it is the best way to figure out when and where to use a certain strategy. To obtain additional information, refer to Fig. 7 (Marnich, 2019).

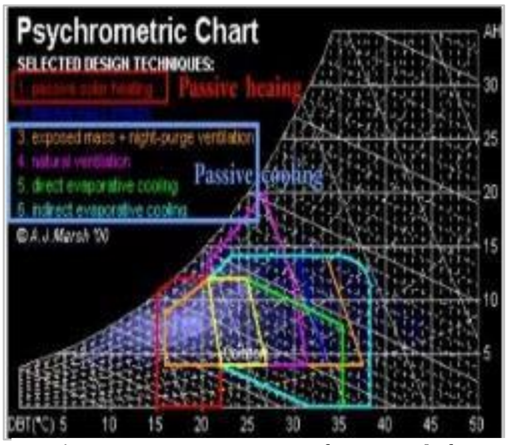

Fig. 7: Primary strategic framework for implementing PASSIVE design.
Source:*(http://www.architecture.uwaterloo.ca/faculty_projects/terri/green.html, n.d.)*

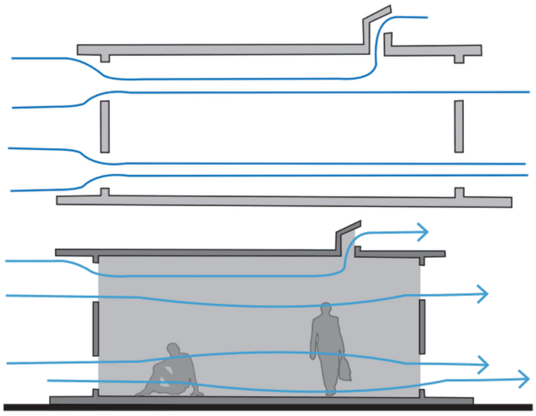

Fig. 8: Windows facilitate air circulation at various positions throughout the area.
Source: Roche, 2012

Passive Cooling Systems

Principles of passive cooling:

1. Ventilative Cooling. 2. Utilizing Evaporative Cooling. 3. Radiative cooling.
4. Removal of moisture from the air. 5. Cooling of Mass Effect.

Ventilation for Comfort

Natural ventilation, or mechanical means can induce pressure differences at the inlets and outlets. An efficacious approach would involve the integration of ceiling fans to facilitate air circulation and natural ventilation, which would serve to chill occupants while facilitating air exchange within the building refer to the Fig. 8 (Ghiabaklou, 2021).

Ventilative Cooling at Night

A high-mass building with insulation is ventilated with cool night exterior air, as indicated in Fig. 9, Through properly opened and closed windows, this ventilation system can be fan-forced or natural. Air humidity affects the practicality of ventilation strategies.

Night ventilation is used in places with diurnal temperature variations above 15°C, daytime temperatures between 31°C and 38°C, and nighttime temperatures below 20°C Fig. 10. Hot, dry temperatures are ideal for this method, whereas warm, humid climates are not.

Computer programs like Home Energy Efficient Design (HEED) help architects assess the impact of mass, ventilation rates, and insulation on indoor air temperature, air conditioning needs, and night ventilation efficiency (Milne, 2022).

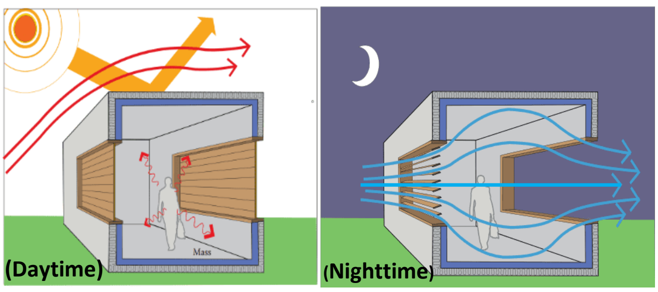

Fig. 9: Cooling during night.
Source: Roche, 2024

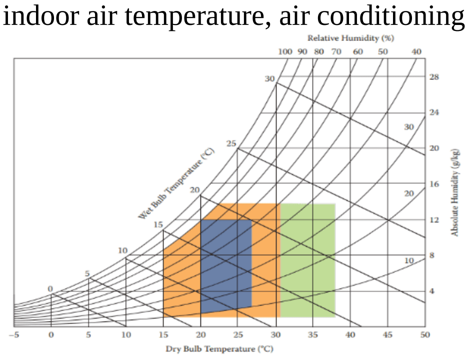

Fig. 10: Night ventilation with thermal mass (**green**) or separately (**orange**) is applicable.
Source: Roche, 20*12*

Ambient Air Acts as a Heat Skin

Evaporative with Direct Cooling

In a direct evaporative cooling system, the air is cooled through the process of water evaporation. The resulting humidified and cooled air is then delivered into the building to lower the temperature of the space. According to Roche (2024), direct and indirect evaporative cooling can be used when the wet-bulb temperature (WBT) is approximately 22°C and 24°C, respectively (Harvey, 2022;Aukhadiyeva,2023).

Cooling towers typically incorporate wetted pads or "showers" at the top to sustain humidity, as depicted in the Fig. 11. This system successfully attained exit temperatures of 23.9°C while the outdoor temperatures reached 40.6°C, showcasing the effectiveness of cool towers in hot and arid areas. The following equation is utilized to compute the temperature of the air as it exits the tower:

The equation for Texit is given by Texit = DBT - 0.87 x (DBT - WBT). A cooling tower has been designed utilizing a shower system instead of wetted pads, as depicted in Fig. 12. Water is cooled through the process of water droplets evaporating (Guy S., 2021).

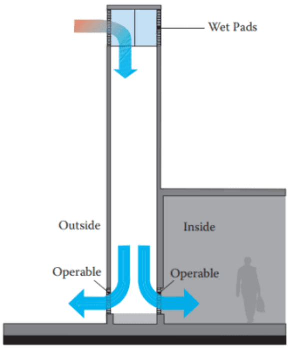

Fig. 11: Use a cold showerhead with a damp pad.
Source: Roche, 20*12*

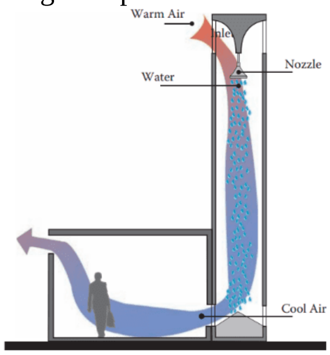

Fig. 12: Evaporative cooling in a direct shower setting.
Source: Roche, 20*12*

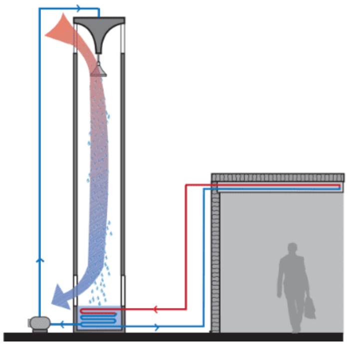

Fig. 13: Utilizing a shower for indirect evaporative cooling.
Source: Roche, 20*12*

Evaporative with Indirect Cooling

It functions as a thermal sink for the building, absorbing the internal heat. The heat is transferred from the water to a shower, where it is cooled through the process of evaporation. An advantage of this system is that it cools the interior area without increasing the humidity, hence ensuring thermal comfort in regions with high humidity, as shown in the Fig. 13. Additional instances of such systems encompass the roof pond system, wherein the roof is capable of being cooled through radiation while the indoor area is cooled via the transfer of heat from the interior to the cooler exterior. During daylight hours, the roof pond is shielded and shaded to prevent solar radiation and minimize heat transfer from the outside. Meanwhile, it collects energy from the interior of the structure, as depicted in the Fig. 14. Water is a highly effective thermal reservoir capable of absorbing 1,157 watt-hours of heat per cubic meter.

Earth Functions as A Heat Sink

This can be achieved through direct contact of an important part of the building envelope with the ground or through injecting air that has been circulated underground into the building using earth-to-air heat exchangers. Temperature of the Earth below a depth of two meters will be lower than ambient air, and heat will transfer from the building to the ground. If this ground temperature at a depth of 2-3 m is around or below 22°C, the soil acts as a heat sink for buildings (Roche, 2024).

Building Cooling Through Direct Contact with the Ground

To enhance the conductive heat transfer between the building and the ground, it is beneficial to maximize the surface area of the building that is in direct touch with the ground. For a visual representation, please refer to the Fig. 15 (Marnich, 2019)

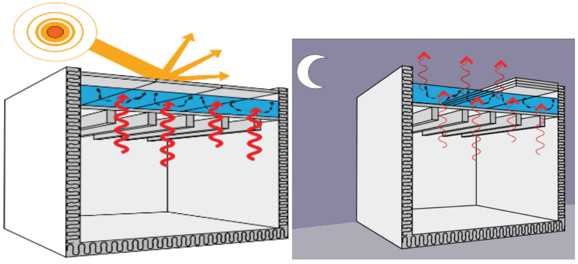

Fig. 14: Roof Pond performance.
Source: Roche, 2024

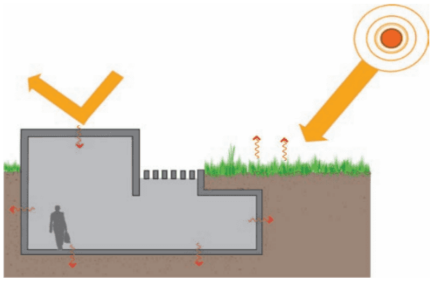

Fig. 15: Utilizing direct ground contact for building cooling.
Source: Roche, 2024

Earth-To-Air Heat Exchanger Underground Building Cooling

If the building lacks sufficient ground contact surfaces, cooling can be enhanced by employing earth-to-air heat exchangers, therefore indirectly augmenting the building's contact with the soil. These exchangers are subterranean tubes that are buried horizontally at a depth of approximately 2 meters. In order to facilitate heat transfer between the pipe and the earth, it is crucial to use a material that is conductive, such as plastic, concrete, or metallic pipes. Earth tube systems are typically categorized as open-loop, as seen in Fig. 16, and closed-loop, as demonstrated in the Fig. 17. As the air is being expelled from the structure, it is possible that it retains a lower temperature and lower humidity compared to the air outside. An enclosed feedback system can exhibit higher efficiency compared to an unenclosed feedback system. ground tubes are commonly believed to be capable of providing enough cooling using pipes that have an average ground temperature of 27°C, a soil temperature of 26.6°C, and an air temperature of 40.8°C (Roche, 2024).

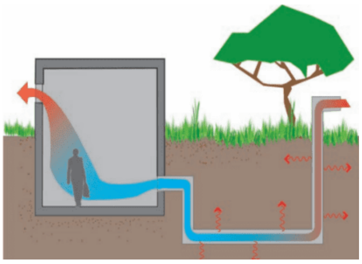

Fig. 16: Utilizing closed-loop air exchangers to achieve building cooling.
Source: Roche, 2012

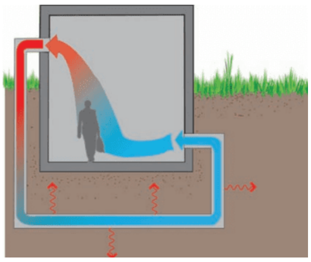

Fig. 17 : Utilizing closed-loop air exchangers to achieve building cooling.
Source: Roche, 20*12*

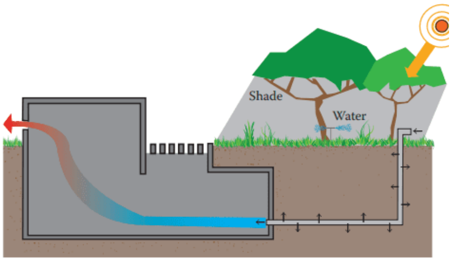

Fig. 18: Cooling the ground surrounding a building.
Source: Roche, 20*12*

Cooling the Earth

To cool a surface and avoid soil heating, shade is the easiest method. This easily drops the surface temperature by 8°C to 10°C. Other methods include mulching the soil with wood or gravel at least 10 cm thick and irrigating at specified times. The top 3 cm or 5 cm of the layer absorbs and intercepts solar energy, and heat conduction down the pebble layers is low. However, irrigation fluid evaporates, lowering soil temperature, as shown in the Fig. 18 (IEA., 2019).

Case Studies

Case Study 1: The Givoni–La Roche Roof Pond Is Located At UCLA.

At UCLA's Energy Laboratory, La Roche and Givoni (2000) has evaluated a roof pond. An insulated, night-cooled water tank and a test cell with cooled water circulating in pipes in its concrete roof make up the system as in Fig. 19. With 190 concrete blocks as thermal mass, the test cell is 1.25 m wide, 1.40 m high, and 2.55 m long. Two independent water systems and four metal frames connected with screws and L connectors form the pond. The first system pumps pond water to the roof, while the second cools it by pushing tank water over insulation. For sun protection, water circulates through tubes lined with insulation and aluminum foil.

Indoor dry-bulb temperature is best correlated with wet-bulb temperature, and the maximum dry-bulb temperature in the test chamber is defined by Tmx = WBTavg + Δt .The first step is pumping water from the pond to the experimental room ceiling, either continuously or intermittently (Roche, 2024).
Tmx. = expected maximum dry-bulb temperature within the chamber on a specific day
Δt = average interior maximum elevation above outdoor average
WBTavg = daily average wet-bulb temperature

Pumping water from the tank and spraying it on the insulation cools the pond at night. Insulation and aluminum foil prevent sun warming in a 10 m tube from the experimental chamber to the pond 6 m away. Water flows via this tube into the cell's concrete roof, cooling it during the day. Fig. 20 shows a data recorder with multiple temperature sensors.

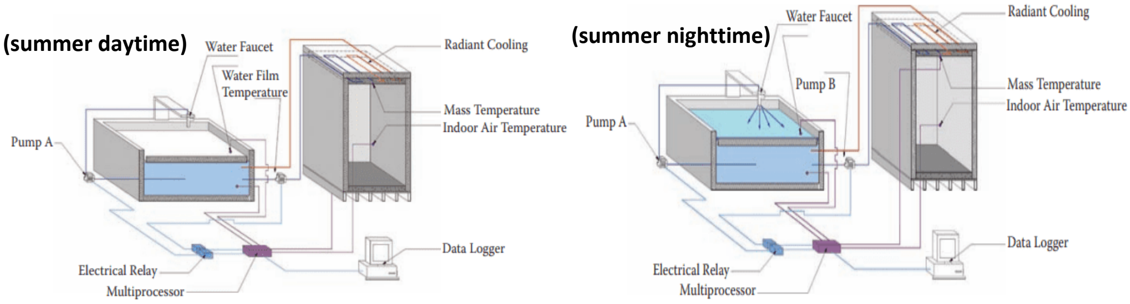

Fig. 19: UCLA rooftop pond with floating insulation and smart controller.
Source: Roche, 2024

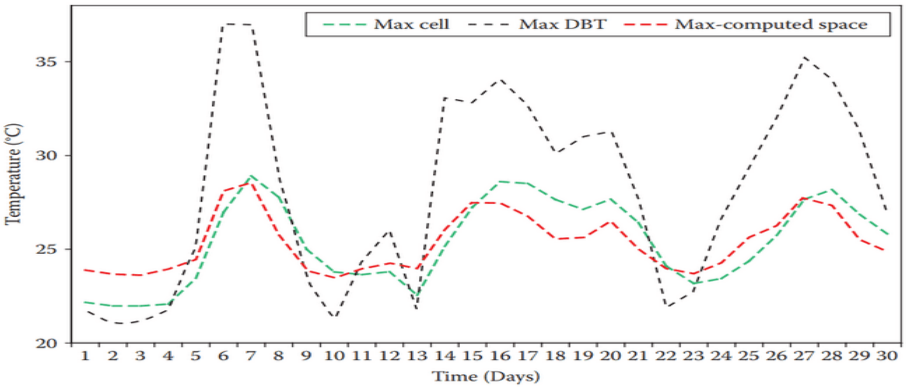

Fig. 20: An assessment was conducted on the UCLA roof pond during a period of 30 days.
Source: Roche, 2024

Case Study 2: Utilizing Roof Ponds in a Hot and Humid Climate

A smart-controlled roof pond with floating insulation has been designed and tested at Cal Poly Pomona's Lyle Center for Regenerative Studies, as depicted in the Fig. 22. First, a timer controlled the pumps, but in summer 2006, a smart controller controlled a roof pond pump. Lightweight, non-thermal test cells have been constructed. Comparing the ambient temperature to a metal-coated black surface facing the sky was one of several guidelines tried. At night, the pump would activate if the temperature was lower than the air temperature and turn off otherwise.

Compare the external metal plate temperature to the outdoor dry-bulb temperature and the test cell water temperature to the roof pond to test a more complex rule as in Fig. 21. The roof pond cell was always 8°C cooler than the control cell. This shows that the approach works and that lightweight buildings can have substantially lower indoor midday temperatures than outdoor ones (Marnich, 2019).

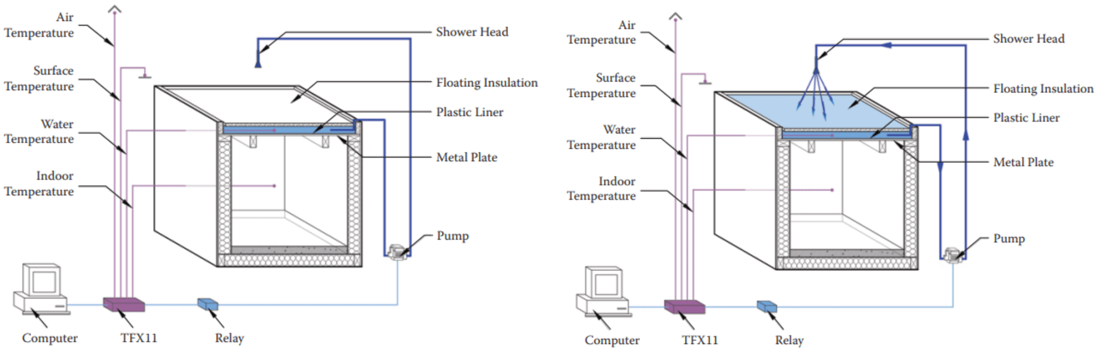

Fig. 22: Cal Poly Pomona's Smart Roof Pond.
Source: Roche, 2024

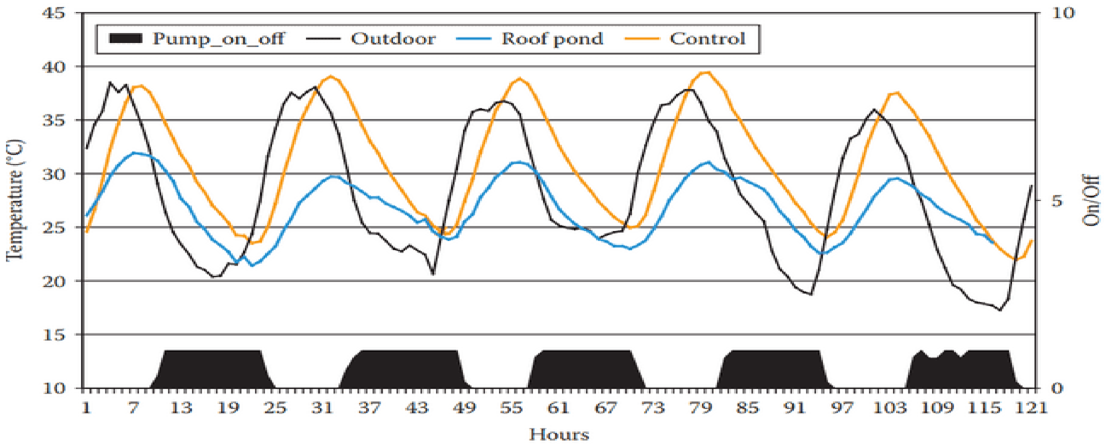

Fig. 21: The indoor temperatures of the control unit and the intelligent roof pond-cooled cell.
Source: Roche, 2024

Conclusion

These tactics encompass the use of natural airflow, the process of cooling through evaporation, and the application of materials that reflect light. So, this section concludes with essential insights into the fundamental principles of designing for cross-ventilation, employing shading devices, and selecting building materials that limit heat gain. The study also examines the role of landscaping and water features in enhancing passive cooling as in the Table 2.

Table 2: Summary of Passive cooling systems.
Source: Author

Passive System	Thermal Dissipator	Climate Range	Physiological Impact	Main Architectural Feature
Comfortable ventilation	Air	Max temp < 30°C RH <80% WBT <24°C	Enhances the process of perspiration evaporation from the skin. Thermal regulation and dissipation of heat through convection from the body.	Wide windows to facilitate airflow Minimizing mass to prevent heat retention
Nocturnal ventilation and cooling.	Air	Large diurnal range>12°K Min DBT < 20°C Max DBT< 38°C RH Absolute humidity < 14 g/kg	Reduces Mean Residence Time (MRT) of interior walls	Massive mass with an outer layer of insulation Windows should be functional to facilitate nocturnal air circulation while being closed during the day.
Cooling by radiation	Outer space or the Earth's	Nights with no clouds or obstructions. The significance of humidity and	Decreases Mean Residence Time (MRT) of interior walls	Roof area exposed to the sky.

	upper atmosphere	temperature is rather low.		
Direct and indirect evaporative cooling	Air. Utilizes water as both a thermal sink (indirect) and transport medium (direct).	WBT<21°C DBT < 42°C WBT< 24°C DBT < 44°C	Enhancing comfort can be achieved by increasing RH when it is low. In the presence of excessive RH, an indirect system is preferable.	Architectural structure for the topmost part of a building, typically designed as a roof or tower. These qualities could also exist in the surrounding landscape of a building.
Earth-related interaction	Earth	The average annual temperature for earth tubing utilized in direct coupling is less than 13°C. In temperate climates, the soil temperature at a depth of 2 meters is expected to be lower than the air temperature. Reducing the temperature of the surface above the earth can effectively lower the temperature below the surface when the external temperature is high.	Enhances thermal comfort by amplifying the cooling action of radiation, hence lowering air temperature.	Connection with the earth in any of three orientations: horizontally, vertically, or beneath.
Note: DBT: Dry Bulb Temperature: Min DBT: Minimum Dry Bulb Temperature; MaxDBT: Maximum Dry Bulb Temperature RH: Relative Humidity; WBT: Wet Bulb Temperature.				

The paper examines the effectiveness of passive cooling systems in enhancing building sustainability and occupant comfort across diverse climates. The research emphasizes the importance of integrating passive cooling strategies into the design process, considering local climate, building orientation, material selection, and socio-cultural context. This holistic approach optimizes thermal comfort and contributes to the building's overall aesthetic and environmental performance. The study also highlights the dynamic interplay between traditional passive cooling methods and modern technological innovations, highlighting the evolving nature of sustainable building design. Future research directions include exploring passive cooling's role in mitigating urban heat island effects, its economic viability across different market segments, and developing design tools that integrate climate data with passive cooling strategies. In conclusion, passive cooling systems are a critical component in sustainable building design, offering a path to reduce energy consumption, enhance occupant comfort, and mitigate environmental impacts.

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