The Green Side of Passive Cooling: Building Facades Inspired by Evapotranspiration in Trees

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Abstract

Buildings suffer from uncontrolled heat gain through their skin, which creates an urgent need for thermal comfort. In hot climates such as India, a growing economy with a rising per capita income is leading to an expected rise in cooling demand—by 11 times in the next two decades. The use of passive cooling strategies to reduce direct heat gain through building envelopes is an integral step in reducing the energy demand for cooling.
The system works as a shading device similar to adjustable louvres, moreover, the terracotta's porosity mimics cooling evapotranspiration. It adapts to sun angle, building orientation, and design. It combines terracotta and water to effectively cool, especially in multi-story buildings. The efficiency of the proposed passive cooling system was tested in the composite climatic regions of Raipur and Hyderabad, the nature-inspired passive cooling system reduced cooling energy needs by 30% and 47% respectively. The future of space cooling in buildings can benefit by using efficient passive cooling envelopes that can reduce the heat gain in the buildings. Climatically adaptive designs hold the potential to influence the shape of future buildings, landscapes, and cities, perhaps with earthy tones.

Keywords - Envelope Cooling, Passive Cooling, Building Façade, Climate Responsive, Biomimicry

1. Introduction

In India, a country experiencing hot climates, a growing economy with a rising per capita income is leading to an increased demand for cooling. Most of this demand is attributed to the construction industry as space cooling in buildings. According to the India Cooling Action Plan (ICAP), the cooling demand in the building sector is expected to rise by 11 times in the next two decades [9].
Using RACs for cooling our indoors is effectively heating up our outdoors. This leads to a further increase in demand for indoor cooling, what we can call the 'cooling paradox.' Navigating this demand effectively necessitates a well-balanced approach, involving adoption of energy-efficient cooling systems and integrating sustainable design practices that utilize passive cooling techniques for buildings.

Building Envelopes, made of roofs and facades, face high heat and solar radiation. This causes thermal transmission that affects indoor spaces negatively in tropical regions where temperatures are already too hot [8] (pp. 104-113). In Indian homes, ACs account for 20-40% of the electricity consumption [7]. Hence, it is important to lower the cooling energy consumption in buildings while maintaining thermal comfort.

1.1 Towards Alternative Cooling Techniques: Inspired by Nature, Guided by Tradition

Traditionally in India, buildings were designed in consideration of the environmental context, using passive strategies that channel air and sun into the building interiors in a way that reduced heat gain and increased thermal comfort [13] (p. (pp. 1901-1911). According to ICAP, using building envelopes that suit the climate can reduce the cooling energy demand by 20% by 2037-38 [9].
The temperature under a tree is often 10-12° C lower than the surroundings [1] (pp. 139-148). This difference in temperature is the combined result of the phenomenon of ventilation, shading, and evapotranspiration. Passive cooling systems based on the principle of evapotranspiration can be very effective for providing thermal comfort in building interiors, especially in hot-and-dry climatic regions such as India. Such cooling systems can be realized as an additional 'second skin' that can also be attached to the existing building facade to provide thermal comfort through passive means.

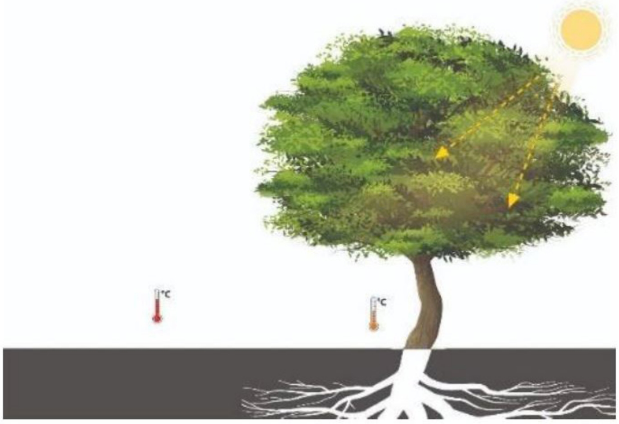

Figure 1: Lower Temperatures Below the Tree (source: Author)

1.2 Research Questions

1. Can building envelopes be inspired from the natural process of trees? What if buildings had a second skin that acts like the foliage of the tree?

2. What is the impact of such building envelopes on the Cooling Load of buildings?

3. What is the impact of such building envelopes on the Thermal Comfort of the occupants?

4. How can passive design strategies effectively reduce the energy demand for cooling in buildings in hot and dry regions like India?

5. How do these strategies and their performance differ as per different building typologies and project briefs?

2. Methods

2.1 Nature-Inspired Second Skin as Passive Cooling Systems

The proposed solution is realized as a second skin facade, called the 'Aerofoils' made with an assembly of porous material modules.Water is circulated through this system which cools the passing air through the principle of evaporative cooling.

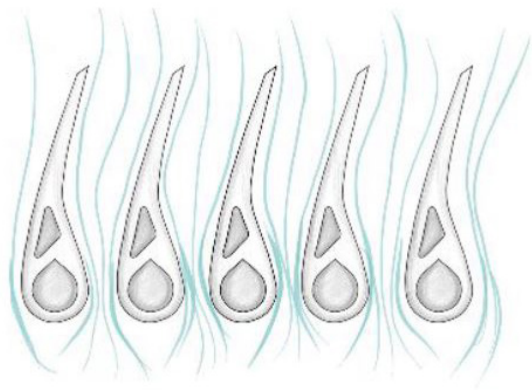

Figure 2: Part plan of the system (source: Author)

Each module in the system is designed in the shape of an aerofoil made of terracotta to imitate evapotranspiration of trees. It stores water which gradually evaporates through its surface to facilitate evaporative cooling as air flows between two modules. The aerofoil shape is assembled to create a nozzle effect that creates a pressure difference to allow better airflow.

For a comprehensive evaluation of the passive design strategies, we have considered different cases, pertaining to different building typologies and project briefs. Two of those cases are described in this paper: the first is a residential project in Hyderabad, and the second is a commercial complex at Raipur, both in composite climate. The selection of these cases is based on the fact that they belong to a similar climatic classification, but have differences in the project requirements and briefs, making them comparable. For Case 1 (Residence), the overall building envelope (facades) was adapted to the climatic context using shading devices, and optimising material specifications. In the second case, variations were introduced in the passive cooling facade as there was a lack of flexibility in specialising other envelope materials.

The evaluation parameters for both the cases considered overall temperature difference, energy consumption, and cost savings. Parameters specific to certain aspects of both cases were also evaluated: in the context of the Commercial Complex, performance in different scenarios- with ventilation, with evaporative cooling, with the shading only, etc. were considered to evaluate the monthly energy consumption and savings, carbon footprint and Energy Performance Index (EPI). Whereas, for the residential project, the paramount goal was to realise thermal comfort of the spaces throughout the year.

2.2. Evaluation

The studies are both located in regions where buildings predominantly receive maximum sun-exposure from the south and west facade; therefore the second skin is considered in these cardinal directions.

2.1.1. Case 1 | Residence in Hyderabad

Project Type: Residential
Location: Hyderabad,
Telangana Climate: Composite [10]
Built up Area: 2000 sqft.
Facade orientation: Aerofoils proposed on West and South Facades

Figure 3: Rendered View of the Hyderabad Residence

Plotting the average diurnal variations against wet bulb depression in the region gives us the potential of evaporative cooling in the region.

Upon close investigation, feasibility of evaporative cooling, as described in the image above, 33% of time of the year (approx. 2931 hours) passive cooling strategies such as Aerofoil facade have the potential to reduce the outdoor air by more than 5°C. The analysis is primarily to evaluate the potential of façade based evaporative cooling for providing comfort in Naturally ventilated or Hybrid Air-conditioned modes of operation. Three scenarios are evaluated:

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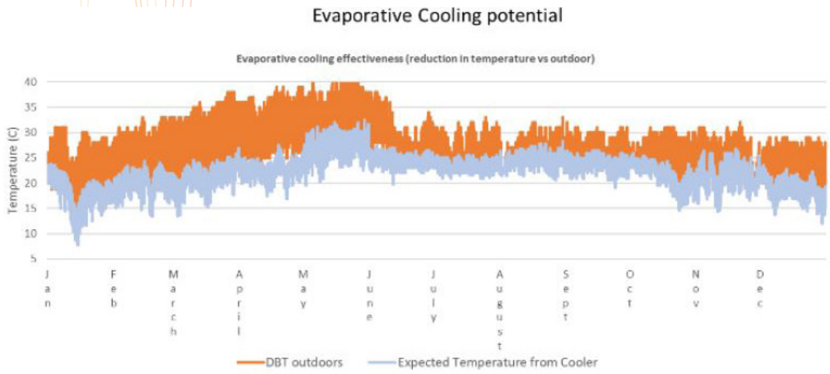

Feasible hours showing more than 5C reduction in temperature

Feasible Hours

	Jan	Feb	March	April	May	June	July	August	September	October	November	December
Daytime	260	249	346	342	271	153	83	1	14	178	85	207
Nightime	48	39	187	242	105	85	3	0	0	29	0	4

Figure 4: Evaporative Cooling Potential

1. AC mode to assess peak cooling load performance.

2. Naturally ventilated with Evaporative cooling,

3. Evaporative Cooling. To model the evaporative effect of the fins the model is to mimic through an Indirect Evaporative Cooler. Secondary air stream was kept the same as Primary air stream. Primary Air flow rate was calculated through Heat Load assessment assuming an AC building running on 24°C setpoint. Heat load calculations made using simulations- ASHRAE Heat balance method.

2.1.2. Case 2 | Commercial Complex in Raipur

Project Type: Commercial
Location: Raipur, Chhattisgarh
Climate : Composite [10]
Building Floor Area: 2145 sq m
Facade orientation: Aerofoils proposed on West and South Facades

Figure 5: Rendered view of Commercial Complex in Raipur

The performance of the aerofoil cooling facade system is assessed based on the following parameters:

1. Temperature Variation- between Indoors and Outdoors.

2. Cooling Load and Capital Cost savings- A lower temperature achieved through passive means translates to a reduced cooling demand. This reduces capital costs- an important factor considering the affordability of the system.

3. Building Energy Consumption- Reduced Cooling Load on buildings leads to a reduction in overall energy consumption in the building.

4. Energy Performance Index and Operational Savings.

5. Carbon Footprint- as annual and incremental savings in kgCO2e/kg

6. Water Consumption

2.3. Simulation

For both the cases, assessment of the applied strategies was carried out by simplifying the building design in Rhino 3D and analysed with the use of Energyplus on Openstudio and Honeybee (Ladybug tools).

3. Results

3.1 Case 1 | Residence in Hyderabad

The first set of assessments evaluated the impact of shading to reduce the Radiant and surface temperatures. "Fins Shading" indicates the effect using Aerofoil Cooling Facade. 3.1

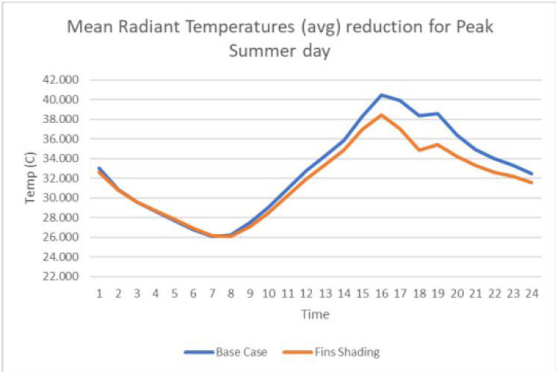

Figure 6: Average Reduction of Mean Radiant Temperatures for Peak Summer Day

The next set of iterations was performed to improve the envelope specification further to reduce the Peak Cooling loads and Average Mean Radiant Temperature. The iterations are summarized as follows:

Table 1: Reduction in Peak Cooling Loads by optimising various Building Materials

Case	Baseline	With Passive Cooling Building Façade (Shading Only)	With Glass specs (U value 3.8 W/m2k, SHGC 0.29)	With Roof Insulation (50mm XPS insulation- U value of 0.55 W/m2K)	With Wall insulation (AAC blocks 200mm- U value 0.8 W/m2K)
Peak Cooling Load (Building Level) kW	61.21	55.5085	50.99	44.69	40.59
% Reduction	0%	9.31%	16.70%	26.99%	33.69%

https://doi.org/10.62744/CATE.45273.1160-131-139

3.1.1. Thermal Comfort Analysis: Natural Ventilation, Passive Cooling Building Façade, and Optimized Fan Speed

A further reduction in temperatures were assessed by ceiling fan operation at 1.2 m/s fan speed. The Elevated Air speed method of ASHRAE 55 2016 [2] was used to calculate the Operative temperature. Upon Fan speed adjustment the hot hours diminished with the use of Ceiling fans at 0.9-1.2m/s. Adding and optimising operative schedules of ceiling and exhaust fans, along with Aerofoil Cooling facade and optimized construction materials, the comfort is achieved for 40.2% hours of the year. About 32.1% of the year is 'humid', 7.6% is dry, 15.4 % is 'cold', while 4.6 % of it is 'hot'.

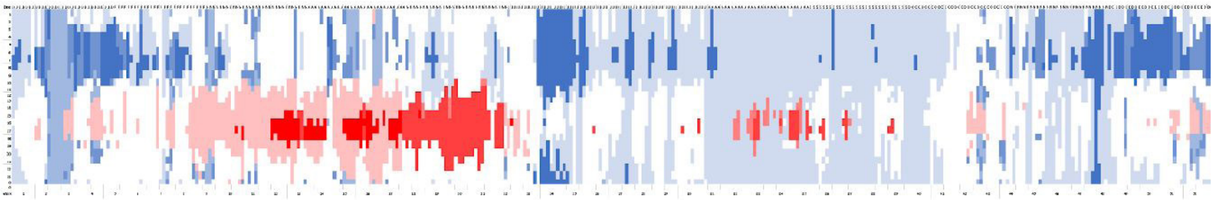

Figure 7: Final Comfort Conditions with Evaporative Cooling and Natural Ventilation

A comparison is also made on the Mixed mode band where all bedrooms are considered as Air conditioned. The perception of comfort in the evaporative cooled and natural ventilation is kept equating with the Naturally ventilated comfort band of IMAC.

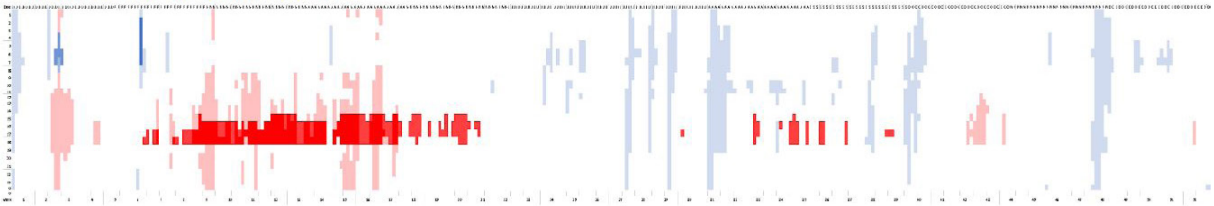

Figure 8: Comfort Analysis in the case of Mized Mode (Passive Cooling with AC)

The result of combining the mixed-mode operations (Passive Cooling with occasional use of Mechanical AirConditioning) was achieved of 85.5% of comfort hours.

Table 9: The Comfort, Energy and Cost assessment comparison for both the Air-Conditioned and Mixed Mode (AC+NV) and Evaporative Cooling with Natural ventilation mode.

		Evaporative Cooling + Fans + Natural Ventilation	Hybrid Mode (EVAP + AC + NV)	Air-Conditioned Mode
Comfort Assessment	Comfort Band	Natural Ventilation	Mixed Mode	Mixed Mode
	% reduction in comfort hours	29.51%	3.81%	0%
Capital Cost Assessment		Rs. 97, 472	Rs. 4,42,472	Rs. 4, 22, 472
Energy Consumption	EPI (kWh/m@)	52.61	86.79	98.44
	% of Reduction	46.55%	11.84%	
Water Consumption	Water (L)	93, 636	58,739	0
Operational Cost Assessment	Annual Running Cost* (at Rs 8 per unit energy and Rs 30 per Kl of water)	Rs. 82, 423.08	Rs. 1, 33, 096.07	Rs. 1, 48, 963. 84

3.2 Case 2 | Commercial Complex in Raipur

3.2.1 Average Monthly Temperature of the Interior

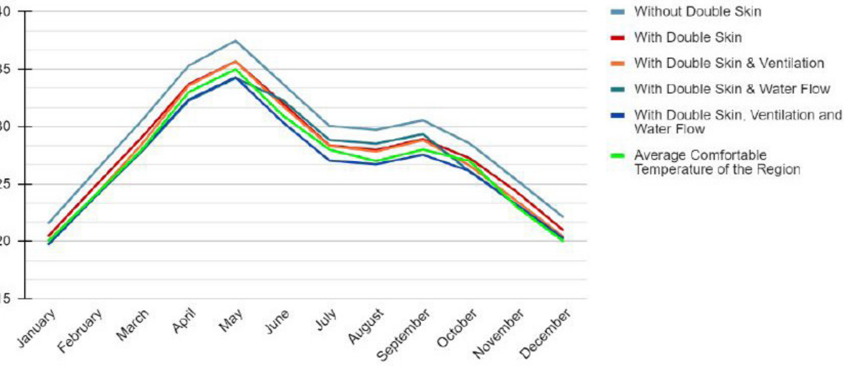

Figure 9: Average Monthly Temperature Variation

The temperatures throughout the year in the case of the building without any double skin is constantly 2-5°C higher. For the month of May the temperature rises to 37.5°C without double skin, in contrast to the building when treated with double skin, ventilation and waterflow experiences a temperature of 33°C.

Table 2: Cooling Load, Cost Savings and Energy Savings for Case 2: Commercial Complex in Raipur

	Without Double Skin (Base Case)	With Double Skin	With Double Skin & Ventilation	With Double Skin & Water Flow	With Double Skin, Ventilation and Water Flow
Total AC Tonnage	34.5	30.8	28.1	28.8	26.8
Capital Cost Savings	-	11%	18%	16%	22%
Operational Savings	-	15%	20%	26%	30%

3.2.2 Energy Performance Index (EPI) & Carbon Footprint

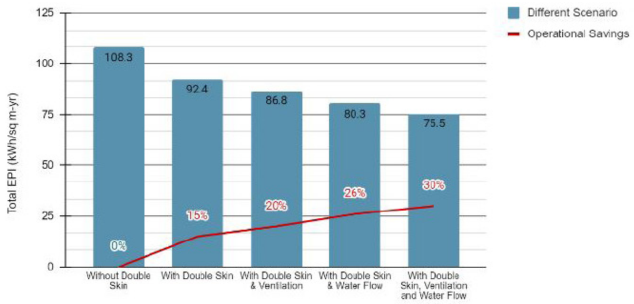

Figure 10: EPI in different Scenarios (source: author)

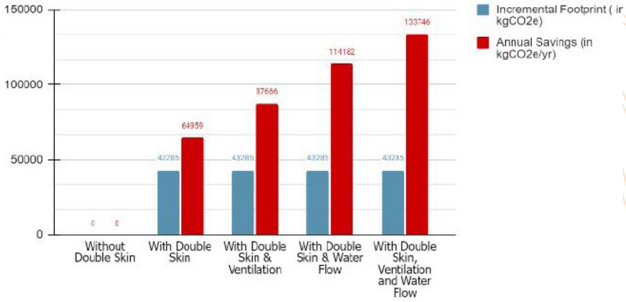

Figure 11: Annual Saving for Scenarios in kgCO2e/yr (source: Author)

The EPI further drops to 86.8 kWh/m²-yr and 80.3 kWh/m²-yr for facade with double skin with ventilation and double skin with waterflow, respectively. For scenario, with double skin, ventilation and water flow the EPI is the lowest at 75.5 kWh/m²-yr. Annual savings in carbon emissions observed is 133746 $kgCO_2e/yr$

4. Discussion

The resultant cooling system along with passive design strategies, has been shown to have a considerable effect on the building systems. For Case 1 (Residence in Hyderabad), it reduced the operational energy consumption by as much as 46.55% while delivering 80.49% comfortable hours. The Passive Cooling Skin is designed to also be effective as a shading device, thus being useful in humid conditions as well (making it better when compared to general evaporative cooling solutions which rely solely on hot and dry conditions). This feature also increases the adaptability of the system in areas with a shortage of water.

In Case 2 (Commercial Complex, Raipur) it resulted in an operational cost savings of up to 30% (table 3). The second skin also reduced the cooling load on the air conditioning system installed in the building by as much as 22% (table 3). It is notable that these results were obtained when the part of the south and west facades was not covered with the second skin, this was a deliberate decision on the part of the designers to leave some room for balancing the aesthetic needs of the project. The performance of the system is likely to enhance if the facades are fully covered.

4.3 Future Explorations

Further explorations for such strategies and passive cooling façade systems are being carried out, ranging from material specifics in terms of properties or possible additives, treatment of water and enhancement of its circulation system. Further explorations for terracotta products in specific, such as its symbiosis with moss and other organic growth and their subsequent impact on air quality are also being explored.

5. Conclusion

Building facades can be as much of a science as art. By integrating passive design strategies with thoughtful building practices, the research proves that it is possible to achieve comfortable living conditions without (or through minimal) use of mechanical cooling methods such as RACs. With conscious material choices with less embodied energy, proper orientation, and ventilation strategies, significant reduction in the building cooling loads, and the operational carbon footprint is observed.

Owing to practical constraints like site configuration, efficiency in utilization of space, design decisions etc., it might not be possible to always manage the best orientation in most of the buildings. With vertical fins, it is possible to design the best orientation at a micro level in building envelopes.

The future of space cooling in buildings will benefit by using efficient passive cooling envelopes that can reduce the heat gain into the buildings. Use of evaporative cooling integrated into building skins further enhances the performance of the buildings as seen in the results. Huge forest covers are lost in urbanization. Is it wishful thinking to imagine a future where buildings can perform the functions of a tree in a forest? Building Envelopes combined with biophilic solutions have tremendous potential to make up for these losses and creating sustainable and resilient habitats in our cities, focus on responsible and sustainable use of resources and energy. Such solutions can help mitigate climate change by reducing the dependency on energy intensive and refrigerant based cooling solutions.

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