End-Semester Report

Development Engineering Project (CP301)

Designing Energy Efficient Buildings

Submitted by:

1. Aryan Prajapati (2020MEB1270)
2. Himanshu Bansal (2020MEB1284)
3. Mahir Neema (2020MEB1293)
4. Pratyodhaya P (2020MEB1302)
5. Tejaswini Deshpande (2020MEB1322)

Submitted to:
Dr. Navaneeth K.M. and Dr. Ramjee Repaka

Date of Submission: 10th May, 2023

Contents

1. Introduction

The traditional methods of generating energy, particularly the burning of fossil fuels, are not sustainable in the long term due to their finite nature and significant negative impacts on the environment. The extraction, transportation, and use of fossil fuels contribute to air and water pollution, habitat destruction, and climate change, with profound ecological and social consequences. Thus, the transition towards sustainable energy sources is imperative for ensuring a resilient and sustainable future. Energy efficient buildings play an important role in promoting sustainable energy because buildings are one of the largest energy consumers globally. Buildings have a significant impact on the environment with energy consumption being one of the significant contributors. Buildings account for about 39% of global energy-related carbon dioxide (CO2) emissions, with most of these emissions coming from the energy used to power, heat, and cool buildings [1]. In the United States alone, buildings account for 68% of total electricity consumption, 12% of water consumption, and 38% of carbon dioxide emissions [2].

By improving the energy efficiency of buildings, we can reduce their energy consumption, which in turn reduces the demand for energy and the associated environmental impacts. Energy efficient buildings can also reduce energy costs for building owners and occupants, improve indoor comfort and air quality, and increase the resilience of buildings to climate change. green building practices, such as using energy-efficient technologies and renewable energy sources, can significantly reduce the environmental impact of buildings. The U.S. Green Building Council estimates that LEED-certified buildings use 25% less energy and 11% less water than non-certified buildings [3].

It becomes the need of the hour to study about green building practices and apply them on real buildings to drive our future towards sustainability.

2. Objectives

- Understanding the principles of nature-inspired cooling and heating technologies and evaluating the feasibility of implementing nature-inspired cooling and heating technologies in real-life applications.
- Identifying the factors that influence the cost of implementing the feasible options for cooling and heating technologies through conducting energy simulations and analyze the overall cost for all the proposed options.
- Choosing optimal value of factors to find a balance between the performance and cost for all the proposed options.

3. Problem description

The research work in the area of energy-efficient buildings has gained significant attention in recent years due to the increasing demand for sustainable development. However, most of the studies have been confined to limited regions, leading to a limited understanding of their application in the regions that are left. There is a considerable research gap when it comes to the study of energy-efficient buildings in Indian regions, specifically in Punjab.

This research will address this gap by exploring approaches to create energy-efficient buildings with a focus on regions of Punjab. The study will analyse the energy consumption patterns, climatic conditions, and building design parameters in the region to identify the best approach to creating energy-efficient buildings. The findings of this study will provide significant insights into the design of energy-efficient buildings in Punjab, which can help policymakers, architects, and builders in the region to make informed decisions regarding the construction of energy-efficient buildings.

4. Overview

Study will be initiated through investigating several nature-inspired cooling and heating technologies and evaluate the possibility of studied approaches in real-life applications. Then the study will involve conducting energy simulations for performing the cost analysis for cooling and heating of a structure. Initially, the simulation will be conducted on a building envelope that is constructed according to the ASHRAE Standard 140 test case 600 for weather data of Singapore. Then, the similar simulation will be conducted for weather data of Porto Allegre. This simulation will test the performances of various approaches to cooling and heating, and the results will be compared for different locations. Finally, the simulations will be conducted for cities of Chandigarh and Amritsar in Punjab and considering geometry variations like, position of windows and considering all the approaches. A feasible approach for heating and cooling will be determined based on the results of the simulations. Study aims to provide insights into the efficiency of nature-inspired cooling and heating approaches and their suitability for different regions in Punjab.

5. Existing Studies

Various bio- inspired technologies that can be adapted for constructing energy efficient buildings are discussed briefly in the following section.

This section aims to provide different heating and cooling strategies found in the nature and how they can find application in buildings. The strategies concerned are just not limited to replicate the shape of plants and animals, but also involves identifying the design strategies, logic, and methods that mimic nature’s processes. The study approach is to classify them according to different heat transfer mechanisms: conduction, convection, evaporation/phase change and radiation.

5.1: Design modifications based on conduction

This section will focus on approaches where the dominating mechanism for heat transfer is conduction.

5.1.1: Insulation inspired from polar bears

Polar bears have naturally adapted to cold extreme conditions and the main contribution to survive such extremes is due to their 3-layer fur and skin protection. The polar bear has a remarkable ability to withstand harsh and frigid climates, thanks to its three-layered fur and skin protection system. The outermost layer comprises guard hair and a dense underfur that insulates against the cold. The second layer is the bear's black skin, which absorbs heat from the sun. The innermost layer is made up of blubber, which acts as an insulator to maintain body temperature.

To replicate this system using sustainable and biodegradable materials, one could create an outer layer from white fur made of recyclable polyamide, which would be both insulating and translucent. The second layer could be a honeycomb structure made from materials such as biobased PLA, providing both panel stiffness and some absorption of radiation. Finally, an inner layer made of black, hollow material with heat-absorbing properties could serve as a heat buffer, mimicking the function of the bear's blubber. Following attached figure overviews how carbon tube aerogels are created inspired by polar bears' three-layer fur and skin protection for building materials [4]:

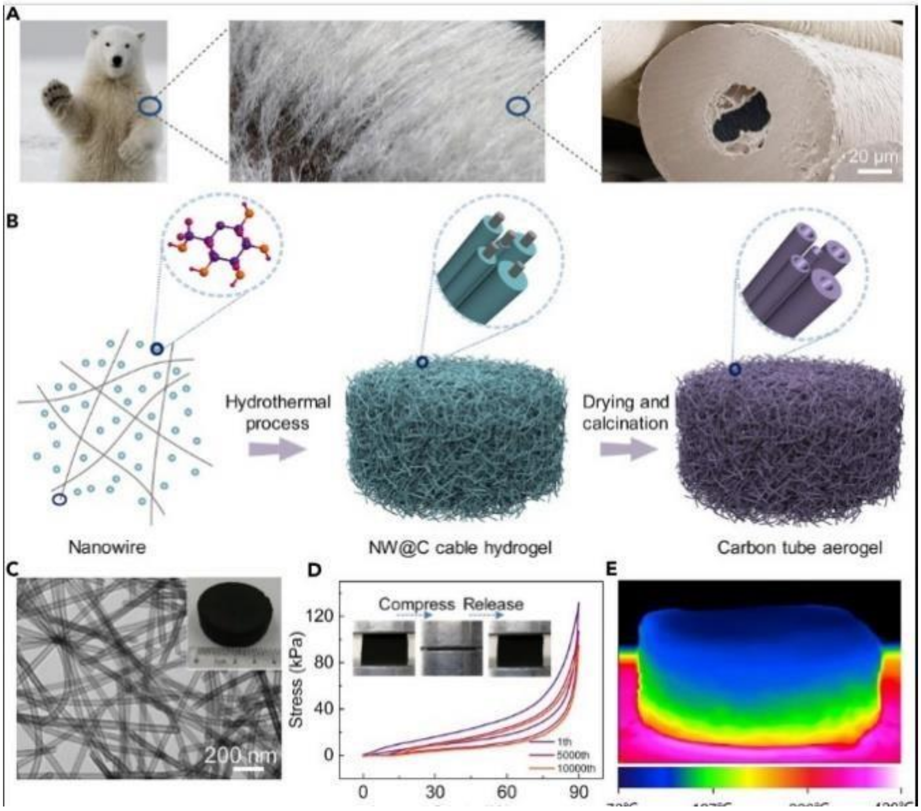


Fig 1. Generation of Carbon Tube Aerogels (CTA) (Source: H. J. Zhan et al. [4])

5.1.2: Penguins' pelts

Adelie penguins have a highly advantageous surface area to volume ratio that allows them to conserve heat effectively, enabling them to survive in extreme weather conditions. The penguins' pelts consist of four layers: the main supporting system called the Ranchis, branches of the stem known as Ramus, Barb, and Barbules, and little hooks called cilia, with a softer part called the afterfeather. These layers are aligned in a way that maximizes trapped air and increases conduction insulation.

Scientists have used morphological measurements of penguin feathers to develop a thermal model that simulates heat transfer through the coat. This model assumes a uniform distribution of feathers and their associated afterfeathers, allowing researchers to apply standard theory to predict heat transfer through the penguin's coat. According to the model, convection does not occur within the coat of the penguin, and radiative heat loss is kept to a minimum. The predicted thermal conductivity of the coat is 2.38

W m−2K−1, which matches well with an empirically measured value of 1.93 W m−2K−1

This knowledge has been applied to design biomimetic facades that emulate the pelt's efficient design on building facades. These facades have a lower U-value than traditional double wall systems, indicating better insulation and improved energy efficiency[5]

5.1.3: Temperature regulation in beehives

Beehives and wasp nests maintain consistent internal temperatures using numerous stationery and millimeter-scale air pockets that create highly effective insulation against thermal conduction. This allows the hives to remain relatively unaffected by outside conditions. Additionally, the breeding chambers have adjustable valves that can be manipulated by altering the materials and thickness used.

The planar hexagonal comb structure of these hives and nests not only provides excellent insulation, but also minimizes the amount of material required for construction. This makes it an ideal structure for use in building walls, as it offers improved structural integrity while maximizing energy efficiency. For utilizing this beehive structure has to be studies and for this standard Langstroth beehive is used[6]

Fig 2. Standard Langstroth beehive (Source - http://galenafarms.com/blogs/articles/parts-ola-beehive)

5.2: Design modifications based on convection

This section will focus on approaches where the dominating mechanism for heat transfer is convection.

5.2.1: Termite Mounds

There exist two types of termite mounds – capped and open. In capped mounds, heat generated pushes air upwards, and exchange of air takes place through pores thereby creating a circular flow. In case of open mounds, large vent exposed at top, while induced flow takes place with help of small openings on ground. Both natural and forces convection is involved in this process. Flow is unidirectional. Constant humidity and temperature maintained irrespective of outside environment conditions. This design has been successfully implemented at various locations and one such example is Eastgate Centre, Harare [7]. Voluminous air spaces are designed for air to permeate. Here flow is induced by the heat produced by occupants and the thermal mass of the building.

5.2.2: Elephant ear and gular fluttering

Elephant air has an extensive vascular network of vessels for thermal regulation. It can be used to dissipate, conserve, or deliberately lose heat. Motion of the pinnae increases heat loss from the ear [8]. Radiation is enhanced as both surfaces are exposed. Convective heat loss is amplified by increased air movement. Gular fluttering is used by several bird groups to help dissipate excess heat through enhanced evaporative heat loss. This is due to increased airflow across moist surfaces. Studies have shown that gular fluttering rate increases with increase in temperature [9]. Real life application of this process is flags. The local heat transfer in a flag-channel system is 3 times that of a bare channel [10]. Disruption of boundary layer due to turbulence enhances thermal performance. The turbulence causes increase in Reynold's number and subsequently the heat transfer coefficient. This eliminates need for external power and is readily scalable.

5.2.3: Fractal heat sinks

Assuming constant Nusselt number at each branch and uniform flux throughout, the heat transfer coefficient increases with each higher-level branching as diameter decreases [11]. Convective heat transfer coefficient of each branch various as follows

$$\frac{h_{k+1}}{h_k} = \frac{d_k}{d_{k+1}}$$

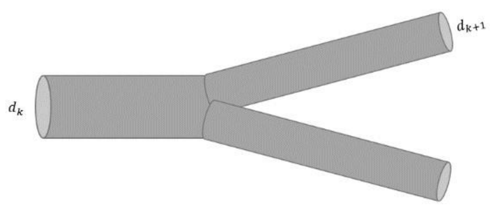


Fig 3. Branching of microchannels

This is advantageous over straight microchannels where heat transfer coefficient decreases from inlet to outlet.

5.3: Design modifications based on Evaporation

5.3.1: Fractal heat exchanger devices

Fractal heat exchanger devices use evaporation and fractal patterns for heat transfer. They consist of interconnected channels designed to maximize surface area for evaporation to transfer heat from one fluid to another [12]. Fractal heat exchanger devices using evaporation are efficient and sustainable cooling or heating solutions with potential applications in refrigeration, energy recovery, residential and commercial buildings, vehicles, and industrial processes. They can also be used in cooling systems for electronic devices to improve performance and reliability. The devices work by transferring heat from one fluid to another through the process of evaporation, helping to reduce the use of refrigerants that contribute to greenhouse gas emissions. Fractal Heat Sinks Provide Performance Benefits like Larger Heat Transfer Capacity, Lower Pressure Drop, a larger total number of branching levels result in a stronger heat transfer capability and require less pumping power. Fractal Heat devices can be integrated into HVAC (Heating, Ventilation, and Air Conditioning) systems to improve energy efficiency and reduce the use of refrigerants that contribute to greenhouse gas emissions. The compact design of fractal heat exchangers also saves space and makes them a suitable solution for residential and commercial buildings where space is a concern. In addition, their efficient heat exchange capabilities can result in lower energy bills and increased comfort for building occupants.

5.3.2: Inspired by Water capture by a desert beetle

The beetles found in the Namib Desert have a unique ability to collect drinking water from the moisture in fog by using their bumpy backs [13]. The surface of these insects is composed of hydrophobic regions coated with wax and hydrophilic regions without wax, which results in the formation of large droplets of water. This design can be replicated easily and inexpensively, and it could be utilized in products such as water trapping tents, building covers, water condensers, and engines.

By imitating the beetle's water-harvesting abilities, we can create building materials and technologies that can collect and store water in arid and dry climates. This can reduce the amount of water needed for building maintenance and cooling systems, thus reducing energy usage and costs. Additionally, capturing and storing water can help mitigate the urban heat island effect, which occurs when the temperature in urban areas is higher than in rural areas due to increased heat absorption by buildings and pavements. By reducing water usage, energy-efficient buildings can help to reduce the demand for energy-intensive water treatment and distribution systems, making them more sustainable and environmentally friendly.

5.3.3: Hydrogel

Hydrogel's properties change based on temperature changes due to its temperature sensitivity. It is a polymer-based material containing a lot of water and can absorb and retain water. Temperature changes cause the hydrogel to undergo phase transitions, resulting in changes in physical and mechanical properties like size, shape, and stiffness. For instance, when temperature increases, the hydrogel swells and becomes more flexible; when temperature decreases, it shrinks and becomes stiffer. This temperature-sensitive property of hydrogel makes it suitable for use in temperature-sensitive cooling technology and other applications [14]. Hydrogel can help make energy-efficient buildings by incorporating it into building materials and systems that regulate temperature and humidity. Hydrogel can also be used in windows and other building components to reduce heat transfer and improve thermal insulation. Using hydrogel in building materials can make buildings more energy-efficient, reducing their reliance on heating and cooling systems and lowering energy consumption [15].

5.4: Design modifications based on phase change

5.4.1: Using Phase Change Materials (PCM)

This section will focus on the applications of phase change materials (PCM). PCMs are those substances which absorb or release large amounts of latent heat when they go through a change in their physical state. The idea behind the use of PCMs is to decrease the heat loss through the building envelops in winters or at night while at the same time to store the excessive heat in hot summer or daytime. The excessive heat will be compensated for the heating energy requirements in winter or at night. Humans and many northern mammals possess this thermal ability. While fatty tissues in normal mammals serve as thermal insulators, researchers have also found that blubber in the outer layer of northern mammals can store or release heat due to its phase change properties. Specifically, the deep blubber of Atlantic bottlenose dolphins has been observed to have significantly higher heat flux than their superficial surface, likely due to the composition of fatty acids in their blubber, which allows it to function as a phase change material for absorbing heat [16].

The use of phase change materials (PCMs) for cooling or storing heat in buildings is currently a popular and promising method. PCMs can effectively absorb thermal energy from the surrounding environment and store it through a process of phase transformation. They can also release the stored thermal energy through a similar process, which helps to maintain a relatively constant temperature range.

There are some successful applications of using PCM in buildings. Integration of microencapsulated PCMs into plaster resulted in room to be 4oC cooler when the indoor temperature was over the melting range [17]. Another successful application is when building wallboards are integrated with PCMs, the energy cost of HVAC system is decreased. At temperatures higher than 18.49°C, the PCM contained in wallboards begins to melt, absorbing heat at a rate of 39.12 kJ/kg until the temperature reaches 24.26°C. This process provides a form of cooling storage for the building and reduces electricity costs associated with air conditioning. When the indoor temperature drops below 18.59°C, the latent heat stored in the PCM is released, significantly reducing heating energy costs [18].

The use of PCMs in building elements is currently widespread, but there are concerns regarding their safety. Traditional PCMs are often flammable, which limits their application in building materials. However, bio-based PCMs are less flammable and considered safer for use [19]. PCMs derived from fatty acids have a higher heat capacity and can achieve desirable phase change temperatures [20], [21]. This makes them a promising area of development for future PCMs, particularly in the context of high thermal energy storage in buildings.

5.5: Design modifications based on radiation

This section will focus on approaches where the dominating mechanism for heat transfer is radiation.

5.5.1: Poplar leaf hair

The hollow fibers in the hair layer act as an energy-efficient "cool roof" to shield the poplar leaf from being scorched by direct sunlight. In order to create an effective and eco-friendly "cool roof," coaxial electrospinning technology is employed to produce a highly reflective and superhydrophobic white covering. The film reflects light at high levels in the visible and infrared spectrums. The synthetic leaf hairs are hollow and superhydrophobic, which can act as an insulating layer to fend off erosion and water damage. The form and function of the hair on a poplar leaf serve as inspiration for a variety of highly reflective white coatings. White coatings with a fiber width of about 14 mm and a film thickness of about 200 mm have a reflectance of around 60% [22]. The films may be produced using a variety of popular polymers, including PSt, PVDF, and PVP. These highly reflecting coatings are also extremely hydrophobic and lightweight because to their hollow fiber nature. By reflecting more sunlight back into space, they claim that "cool roofs" will be efficient and environmentally benign ways to reduce global warming and offset CO_2 emissions.

5.5.2: Tree barks

Barks exhibit a strong reflection between 0.7 and 2 μm (700–2000nm). High levels of tannins, which have a variety of beneficial characteristics, are present in bark. They defend against insect, bacterial, and fungal assaults [23]. Moreover, it exhibits considerable absorption behavior in the 6–10 μm spectral band. Furthermore, tannin (polyphenol) absorption via OH vibrations is seen between 1450 and 1900 nm. This indicates that long-wavelength radiation about 10 μm can no longer travel through bark or cellulose sheets that are many tenths of a millimeter thin. Moreover, this implies that cellulose, a substance found in bark and leaf tissue, absorbs, and then emits light at a wavelength of around 10 μm. A structural material with a mechanical strength of 404.3 MPa—more than eight times that of natural wood—is created by a process of total delignification and densification of wood [24]. Cellulose nanofibers that are partially aligned in the direction of the tree's growth make up the cooling wood. In the visible spectrum, these fibers are non-absorbing. For a strong, wide reflection at all visible wavelengths, the multiscale fibers and channels serve as randomized and disordered scattering components. Meanwhile, cooling wood allows for high infrared emission due to the cellulose's molecular stretching and vibration. Passive sub ambient radiative cooling occurs both during the day and at night because the heat flux released by cooling wood is greater than the amount of solar radiation received.

5.5.3: Saharan silver ants

On the top and sides of their bodies, Saharan silver ants have a thick covering of triangular hairs. These silvery hairs shield the ants from overheating in at least three different ways. The hairs increase reflectivity in the visible and near-infrared regions, where solar radiation is most intense, as a result of Mie scattering and total internal reflection. The hairs serving as an antireflection layer in the MIR, where sun light is minimal for wavelengths over 2.5 mm, boost emissivity and consequently the ants' capacity to dissipate excess heat through blackbody radiation. The ants' naked bottom surface reflects the hot desert floor's MIR radiation more effectively than if it were coated with hair [25]. Flexible hair-like photonic structures with either the triangular air gap (TAG) or the bridge-like air gap (BAG) was created on polydimethylsiloxane (PDMS) as an example of this bio-inspired method [26]. Both the marginally improved mid-infrared emission and the much-improved optical reflection were seen when they were attached to glass bottles. Due to these characteristics, the glass bottles' temperature was lowered by around 5.6C over the sweltering day. Investigations on the thermal characteristics of TAG at night revealed a little temperature drop of 0.71 C on the top surface.

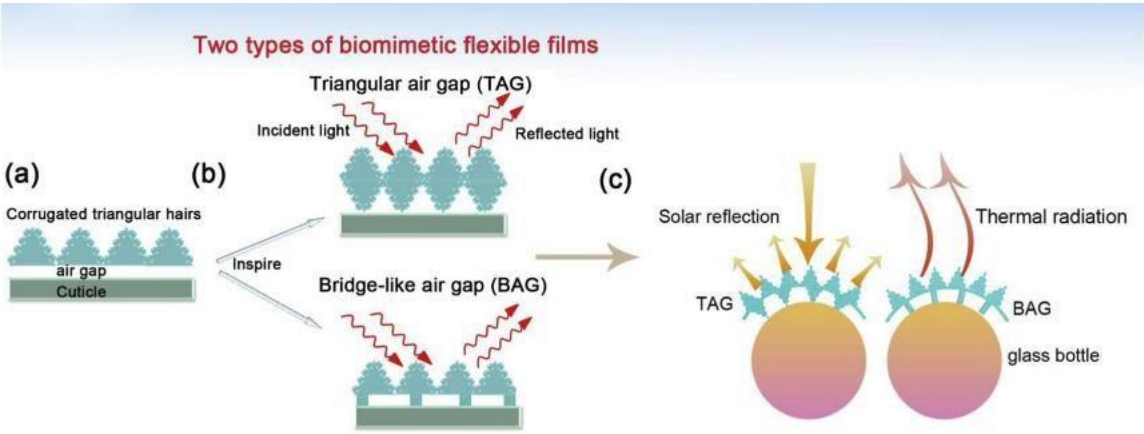


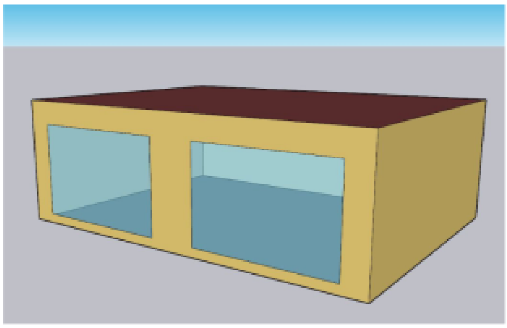
Fig 4. Illustration in concept of the Desert silver ant imitation for experiment (Source: W. Wu et al [26].)

5.5.4: Moth-eye antireflection surfaces

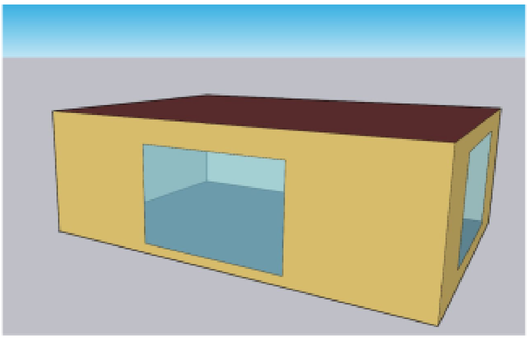
High-performance thermochromic smart windows that can transmit sunlight while blocking solar heat are made using biomimicry. To improve the thermochromic characteristics like periodicity (d) and accomplish antireflection (AR), vanadium dioxide (VO_2) films containing moth-eye nanostructures have been created. When d decreases, VO_2's average luminous transmission and infrared transmission rise [27]. The patterned VO_2 might be given a hydrophobic coating to create a contact angle of about 120 degrees. In study, this biomimicry is used, and some of the findings have been presented. The bio-inspired nano-patterned antireflection surfaces demonstrated a 10% gain in luminous transmission and a 24.5% increase in solar modulation ability when compared to the planar VO_2 film. Without any extra treatment, the super hydrophobicity caused by the aspect ratio of the moth-eye surface structures and the inherent hydrophobicity of VO_2 may provide the smart window with an additional self-cleaning mechanism [28].

6. Methodology

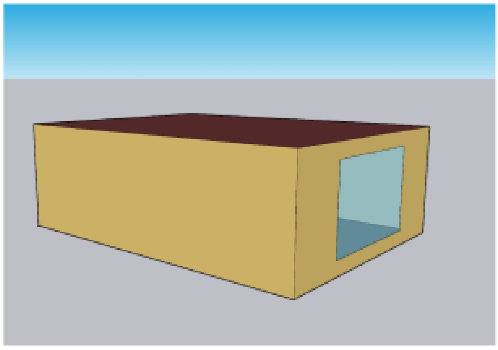
Simulations were conducted with the help of Energy Plus software on a building envelope constructed according to ASHRAE Standard 140 Test case 600 [29]. The material used and properties are listed below. The following image shows the building envelope being used in the simulation.



Standard test case 600



South West facing windows



East West facing windows

Fig 5. Sketches of building envelops used in simulations

Table 1: Interior and exterior material properties

Element	K (W/mK)	Thickness (m)	U (W/m^2K)	R (m^2K/W)	Density (kg/m^3)	Cp (J/kgK)
Wall						
Plasterboard	0.160	0.012	13.333	0.075	950.00	840.000
Fibreglass Quilt	0.040	0.066	0.606	1.650	12.000	840.000
Wood Siding	0.140	0.009	15.556	0.064	530.00	900.000
Floor						
Timber Flooring	0.140	0.025	5.600	0.179	650.00	1200.000
Insulation	0.040	1.003	0.040	25.075	0	0
Roof						
Plasterboard	0.160	0.010	16.000	0.063	950.00	840.000
Fibreglass Quilt	0.040	0.1118	0.357	2.800	12.000	840.000
Roof Deck	0.140	0.019	7.368	0.136	530.00	900.000

Table 2: Double pane window properties

Window	
Property	**Value**
Pane thickness	3.048 mm
Thickness of space between panes	12.00 mm
Fill gas	Air
Thermal conductivity of glass	1.00 W/(m.K)
Density of glass	2470 kg/m3
Specific heat of glass	750 J/(kg.K)
Direct beam transmittance through each pane	0.834 at normal incidence

Direct beam reflectance for each pane	0.075 at normal incidence
Air Properties	
Conductivity	0.024069 W/(m.K)
Specific heat	1006.103271 J/(kg.K)
Density	1.292498 kg/m3
Viscosity	0.000017 kg/(m.s)
Prandtl Number	0.7197
Molecular weight	28.970 g/mol

In the first case, fiberglass quilt in the walls was replaced with nanogel of same thickness. Thermal conductivity of the material can attain thermal conductivity values as low as 0.023 W/mK [30] hence resulting in reduction of overall heat transfer coefficient of the walls. For thermochromic windows, glazing of vanadium oxide (VO_2) was used as the thermochromic material [31] over the existing double pane window. In the next simulation, a product BioPCM™ Q25 by Phase Energy - Solutions was used in the place of fiberglass quilt in the walls. The material melts around 25°C according to the enthalpy curve provided by the manufacturer (Fig. 6). In the next simulation, a reflective coating was applied on the roof with reflectivity as high as 0.65[32] to reduce heat transfer through the roof.

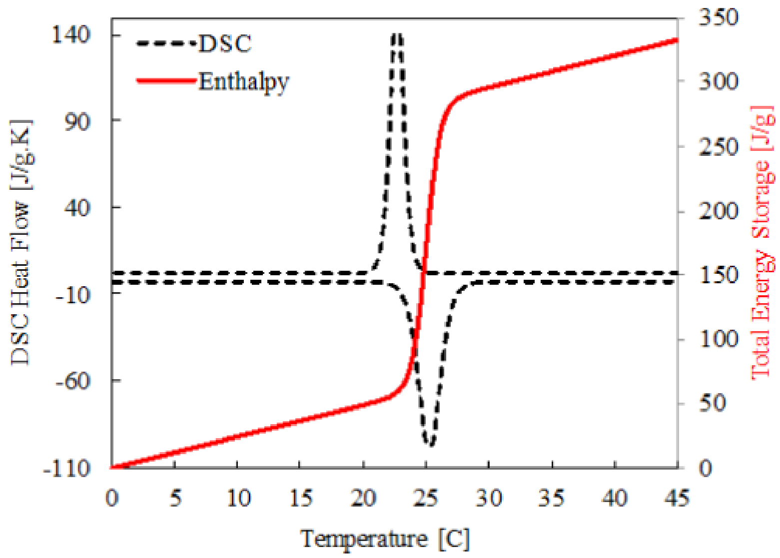


Fig 6. Enthalpy curve of phase BioPCM™ Q25 material

Table 3: Nanogel properties

Element	K (W/mK)	Thickness (m)	U (W/m^2K)	R (m^2K/W)	Density (kg/m^3)
Wall					
Nanogel	0.023	0.066	0.3484	2.870	8

Table 4: Thermochromic window: Standard case-properties

Element	Thickness (m)	Solar Transmittance	Visible Transmittance	Front Solar Reflectance	Back Solar reflectance
Glazing					
Glazing Material	0.003048	0.44	0.435	2.870	8

Table 5: Phase change material: Standard case properties

Element	K (W/mK)	Thickness (m)	Density (kg/m^3)	Cp (J/kgK)
Wall				
PCM	0.202	0.066	900	2500

Table 6: Reflective roof properties

Element	Roughness	Thermal resistance	Thermal absorptance	Solar absorption	Visible absorptance
Roof					
Reflective Roof	Medium smooth	2.2	0.35	0.35	0.35

The air infiltration rate is 0.5 ach throughout the year independent of external conditions. Dead-band thermostat is used to sense air temperature where cooling starts at 27°C and heating at 20°C. Continuous internal load of 200W is used. Cooling load was calculated for weather conditions of Amritsar and Chandigarh.

The algorithms used are:

- Sky Diffuse Modelling Algorithm- Simple sky diffusion model
- SurfaceConvectionAlgorithm:Inside -TARP,
- SurfaceConvectionAlgorithm:Outside- DOE2, and
- Heat Balance Algorithm -Conduction transfer

{Where TARP is used for variable natural convection problems based on temperature difference and DOE2 is used for rough surface problems specifically. And the heat balance algorithm and sky diffuse modelling algorithm are determined as defined in ASHRAE standard test case 600.}

While using EnergyPlus to calculate cooling and heating load in any building it is important to know what are the specific parameters that affect the simulation as well as how exactly EnergyPlus interpret and use our input to finalize the outcome. A few of these parameters and respective equations and algorithm used by EnergyPlus are mentioned below [33]:

- Shading and sunlight area calculation: The fractional year is calculated, in radians:

$$\gamma = \frac{2\pi}{366}\,(day\ of\ year)$$

From this fractional year, the equation of time and solar declination angle are calculated. For each time step (time value = fractional hour), the hour angle is calculated from:

$$Hour\ angle = 15g12 - TimeValue + EquationOfTime + TimeZoneMeridian - Longitude$$

TimeZoneMeridian is the standard meridian for the location's time zone {GMT +/-}. Solar HourAngle (*H*) gives the apparent solar time for the current time period (degrees) by given relation: 1 radian= 3.819719 hours.

- Overlapping of shadows- If two shadows overlap the receiving surface, they may also overlap each other. The vertices of this overlap can be computed. The areas of all overlaps can be computed. The total sunlit area can be expressed as the sum of all polygon areas given a proper sign on each of the areas.
  Two methods for polygon clipping (treating of overlapping shadows) are currently in use in Energy Plus:
  - Convex Weiler–Atherton: - developed to be sufficiently general to clip concave polygons with holes.
  - Sutherland–Hodgman: - is well-suited to clipping convex polygons.

- Solar gain-The total solar gain on any exterior surface is a combination of the absorption of direct and diffuse solar radiation given by

$$Q_s = \alpha g(I_b g cos\theta \frac{S_S}{S} + I_s g F_{ss} + I_g g F_{ss)}$$

where,
a =solar absorptance of the surface
A =angle of incidence of the sun's rays

S =area of the surface
S_s = sunlit area
I_b =intensity of beam (direct) radiation
I_s =intensity of sky diffuse radiation
I_g =intensity of ground reflected diffuse radiation

F_{ss} = angle factor between the surface and the sky
F_{sg} = angle factor between the surface and the ground

For the surface of a building located on a featureless plain

$$F_{ss} = \frac{1 + cos\phi}{2} \; and \; F_{sg} = \frac{1 - cos\phi}{2}$$

- Solar Distribution- It is determined by five choices:
  - Minimal shadowing
  - Full Exterior
  - Full Interior and exterior
  - Full exterior with reflection
  - Full interior and exterior with reflections
- The short-wave radiation absorbed on the inside face of an opaque surface (floor, wall or ceiling) is given by

$$QRadSWInAbs(x) = QS(y) \cdot AbsIntSurf(x) + AISurf(x) \cdot BeamSolarRad \left[\frac{W}{m^2}\right]$$

where, x = surface number,
y = Zone number that surface belongs to,
QS(y) = short-wave diffuse irradiance in the zone [W/m2],
AbsIntSurf(x) = inside solar absorptance of the surface,
AISurf(x) = inside beam solar irradiance factor for the surface [-],
BeamSolarRad = outside beam normal solar irradiance [W/m2].

These above mentioned all values are determined by weather data and geometry of simulation.

7. Validation

Simulations were carried out for Denver the standard weather data provided by ASHRAE for energy simulations. In Fig.7 Values of peak heating, peak cooling, annual cooling and annual heating were compared with the data provided by EnergyPlus [34] The errors were minimal hence validating our results. For a standard 140 test case 600 building envelope a cooling load of 3446.15 kWh was stated by A.P Melo et.al[35] for weather conditions of Porto Allegre, and we attained a cooling load of 3411.94 kWh. The following plot shows how closer the values are with the research paper results.

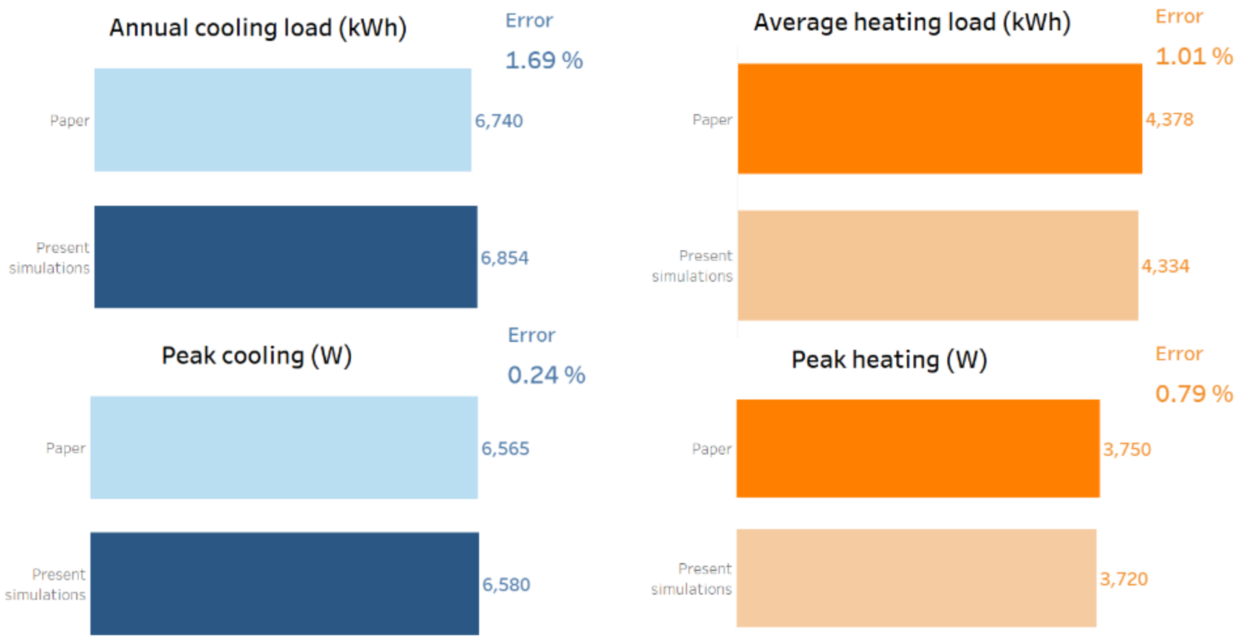


Fig 7. Comparison of heating and cooling loads

8. Results

Simulations were carried out on Energy Plus for standard test case 600 as prescribed by ASHRAE. Annual cooling load of 8897.72 kWh was obtained. The results were compared with the values reported by S.C. Fu, X.L. Zhong et al [36]. The monthly cooling loads obtained were similar and depicted in the below graph.

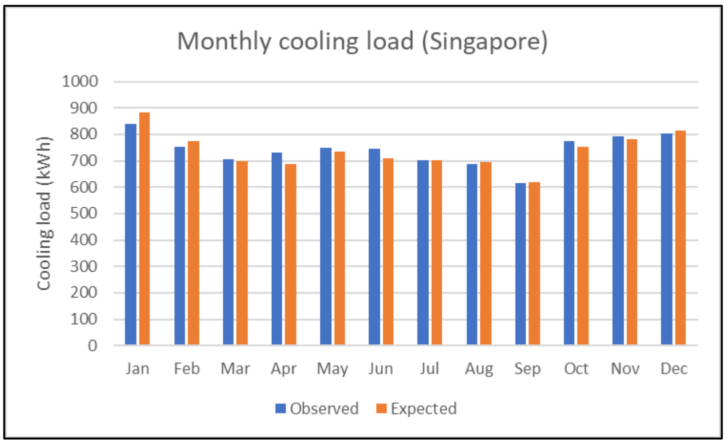


Fig 9: Comparison of monthly cooling loads

The following modifications are implemented in simulations: a) Thermochromic Windows, b) Nanogel, c) PCM, and d) Reflective roof. The cooling load is compared by taking south facing windows as a reference. The results for both Chandigarh and Amritsar, are presented in the following plots.

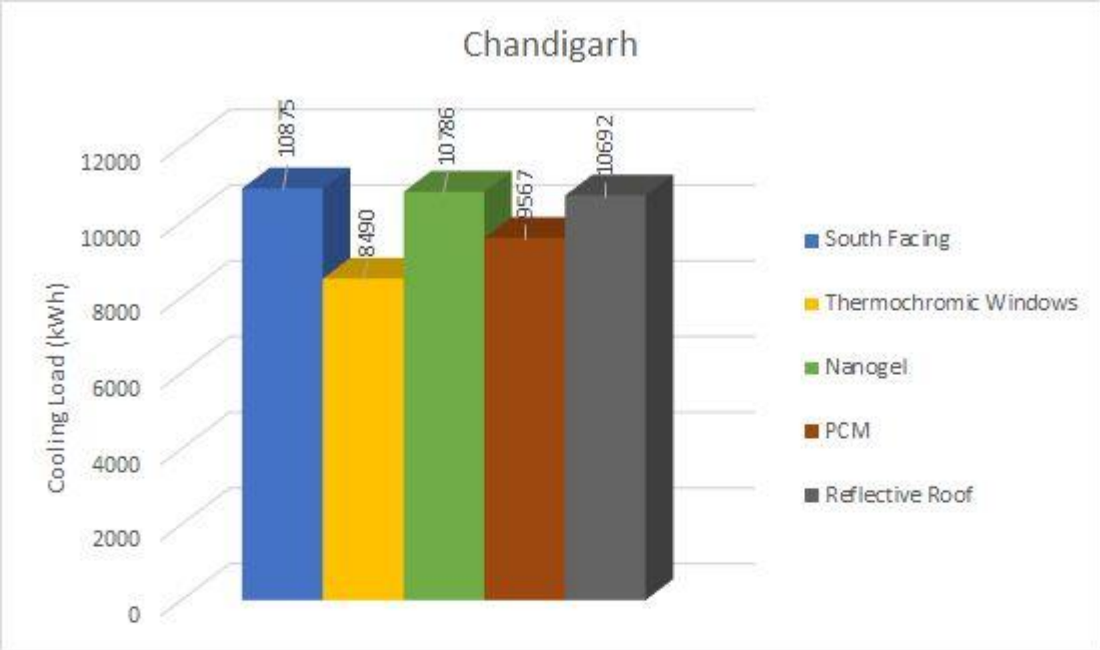


Fig 10. Cooling loads after implementing modifications for Chandigarh weather conditions

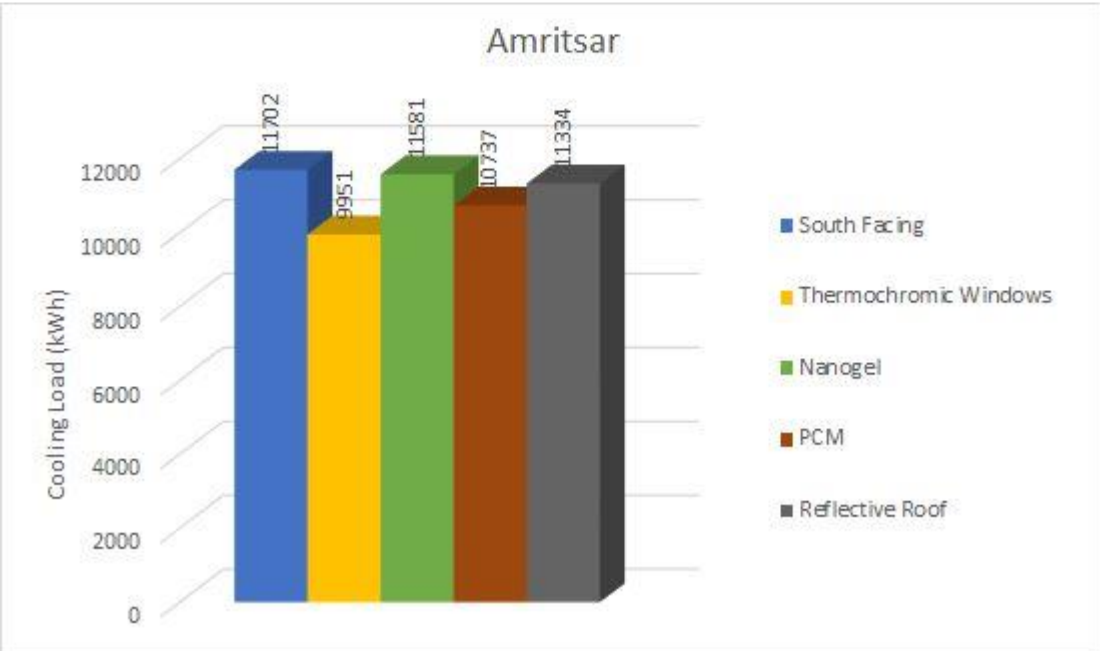


Fig 11. Cooling loads after implementing modifications for Amritsar weather conditions

9. Conclusion

The study utilized several techniques to investigate the reduction of cooling load in Punjab. Geometric modifications were made by placing windows with east-west and east-south spacing, resulting in a reduction of cooling load ranging from **7%** to **16%**. The combination of this geometric approach with changes in building materials showed a reduction of less than **1%** and **8-20%** using nanogel and phase change materials, respectively. Additionally, reflective roofs demonstrated a reduction of approximately **3%** in cooling load. However, the most promising results were achieved using thermochromic windows, which showed a significant reduction of **14-34%** in cooling load. Overall, the study demonstrated that the implementation of various techniques, such as geometric modifications, changes in building materials, and the use of reflective roofs and thermochromic windows, can effectively reduce the cooling load in Punjab.

10. Future Scope

The primary objective of this project was to find an effective cooling method that can serve as a substitute for traditional cooling methods in the Punjab region. Although various bio-inspired technologies and geometric designs were reviewed during the project, there is still room for further exploration to identify a more practical and appropriate technique. Additionally, the project can be extended to evaluate these methods in different locations to determine the best method for each region.

Based on the simulation outcomes, the project can also be extended to optimize the parameters for the identified cooling methods. By optimizing the parameters, we can improve the performance and cost-effectiveness of the design of energy-efficient buildings.

In conclusion, the scope of the project can be expanded to explore additional bio-inspired cooling and heating technologies and geometric designs, test them in different settings, and adjust their parameters based on simulation results. This will enable us to create energy-efficient structures that are both cost-effective and efficient in their use of energy.

11. Acknowledgement

We would like to express our deep appreciation to Dr. Navaneeth and Dr. Ramjee for their invaluable assistance and unwavering support throughout the project. Their extensive knowledge and guidance were instrumental in shaping the direction and success of our study. We are grateful for their commitment to our project and their willingness to share their expertise and insights with us.

We would also like to extend our gratitude to the Energy Plus software development team and the United States Department of Energy (DOE) for providing us with such a powerful tool for energy modeling. With the help of this software, we were able to conduct realistic and extensive simulations of various bio-inspired cooling and heating systems and their impact on different building designs.

We recognize that our project would not have been possible without their contributions. Their support was pivotal in achieving our objectives and enhancing our knowledge of energy-efficient building design. We would like to express our sincere appreciation to everyone who played a part in bringing this project to fruition.

12. References

[1] International Energy Agency. and Global Alliance for Buildings and Construction., *2019 global status report for buildings and construction*. International Energy Agency, 2019.

[2] “Buildings and their Impact on the Environment: A Statistical Summary.” [Online]. Available: http://www.eia.doe.gov/emeu/recs/recs97/decade.html#totcons4

[3] “https://www.usgbc.org/press/benefits-of-green-building.”

[4] H. J. Zhan *et al.*, “Biomimetic Carbon Tube Aerogel Enables Super-Elasticity and Thermal Insulation,” *Chem*, vol. 5, no. 7, pp. 1871–1882, Jul. 2019, doi: 10.1016/j.chempr.2019.04.025.

[5] C. Dawson, J. F. V Vincent, G. Jeronimidis, G. Rice, and P. Forshawa, “Heat Transfer through Penguin Feathers,” 1999. [Online]. Available: http://www.idealibrary.comon

[6] J. C. Jones and B. P. Oldroyd, “Nest Thermoregulation in Social Insects,” *Advances in Insect Physiology*, vol. 33. pp. 153–191, 2006. doi: 10.1016/S0065-2806(06)33003-2.

[7] I. Wallis, L. Bilan, M. Smith, and A. S. Kazi, “Integrating affordable housing and sustainable housing: bridging two merit goods in Australia Industrialised, Integrated, Intelligent Sustainable Construction I3CON Handbook,” 2013. [Online]. Available: http://hdl.handle.net/2440/84302

[8] P. Phillips and Ja~edwardh~~, “HEAT EXCHANGE BY THE PINNA OF THE AFRICAN ELEPHANT (LOXODONTA AFRICANA),” 1992.

[9] G. A. Bartholomew, R. C. Lasiewski, and E. C. Crawford, “PATTERNS OF PANTING AND GULAR FLUTTER IN CORMORANTS, PELICANS, OWLS, AND DOVES.”

[10] R. K. B. Gallegos and R. N. Sharma, “Flags as vortex generators for heat transfer enhancement: Gaps and challenges,” *Renewable and Sustainable Energy Reviews*, vol. 76. Elsevier Ltd, pp. 950–962, 2017. doi: 10.1016/j.rser.2017.03.115.

[11] D. Pence, “Reduced pumping power and wall temperature in microchannel heat sinks with fractal-like branching channel networks,” *Microscale Thermophysical Engineering*, vol. 6, no. 4, pp. 319–330, Jan. 2003, doi: 10.1080/10893950290098359.

[12] Z. Huang, Y. Hwang, and R. Radermacher, “Review of nature-inspired heat exchanger technology,” *International Journal of Refrigeration*, vol. 78. Elsevier Ltd, pp. 1–17, Jun. 01, 2017. doi: 10.1016/j.ijrefrig.2017.03.006.

[13] A.R. Parker and C.R. Lawrence, “Water capture by a desert beetle, Nature 414 (2001) 33.”.

[14] S. Cui, Y. Hu, Z. Huang, C. Ma, L. Yu, and X. Hu, “Cooling performance of bio-mimic perspiration by temperature-sensitive hydrogel,” *International Journal of Thermal Sciences*, vol. 79, pp. 276–282, May 2014, doi: 10.1016/j.ijthermalsci.2014.01.015.

[15] S. Cui, C. Ahn, M. C. Wingert, D. Leung, S. Cai, and R. Chen, “Bio-inspired effective and regenerable building cooling using tough hydrogels,” *Appl Energy*, vol. 168, pp. 332–339, Apr. 2016, doi: 10.1016/j.apenergy.2016.01.058.

[16] R. C. Dunkin, W. A. McLellan, J. E. Blum, and D. A. Pabst, “The ontogenetic changes in the thermal properties of blubber from Atlantic bottlenose dolphin Tursiops truncatus,”

Journal of Experimental Biology, vol. 208, no. 8, pp. 1469–1480, Apr. 2005, doi: 10.1242/jeb.01559.

[17] P. Schossig, H. M. Henning, S. Gschwander, and T. Haussmann, “Micro-encapsulated phase-change materials integrated into construction materials,” in *Solar Energy Materials and Solar Cells*, Nov. 2005, pp. 297–306. doi: 10.1016/j.solmat.2005.01.017.

[18] L. Shilei, F. Guohui, Z. Neng, and D. Li, “Experimental study and evaluation of latent heat storage in phase change materials wallboards,” *Energy Build*, vol. 39, no. 10, pp. 1088–1091, Oct. 2007, doi: 10.1016/j.enbuild.2006.11.012.

[19] K. Muruganantham, P. Phelan, P. Horwath, D. Ludlam, and T. McDonald, “Experimental investigation of a bio-based phase-change material to improve building energy performance,” in *ASME 2010 4th International Conference on Energy Sustainability, ES 2010*, 2010, pp. 979–984. doi: 10.1115/ES2010-90035.

[20] M. C. Floros, K. L. C. Kaller, K. D. Poopalam, and S. S. Narine, “Lipid derived diamide phase change materials for high temperature thermal energy storage,” *Solar Energy*, vol. 139, pp. 23–28, Dec. 2016, doi: 10.1016/j.solener.2016.09.032.

[21] T. Lee *et al.*, “Bio-inspired phase change materials designed for high specific heat of solid phase,” *Thermochim Acta*, vol. 591, pp. 61–67, Sep. 2014, doi: 10.1016/j.tca.2014.06.009.

[22] C. Ye, M. Li, J. Hu, Q. Cheng, L. Jiang, and Y. Song, “Highly reflective superhydrophobic white coating inspired by poplar leaf hairs toward an effective ‘cool roof,’” *Energy Environ Sci*, vol. 4, no. 9, pp. 3364–3367, Sep. 2011, doi: 10.1039/c0ee00686f.

[23] W. Henrion and H. Tributsch, “Optical solar energy adaptations and radiative temperature control of green leaves and tree barks,” *Solar Energy Materials and Solar Cells*, vol. 93, no. 1, pp. 98–107, Jan. 2009, doi: 10.1016/j.solmat.2008.08.009.

[24] T. Li *et al.*, “A radiative cooling structural material.”

[25] J. P. Whiteman *et al.*, “Summer declines in activity and body temperature offer polar bears limited energy savings,” *Science (1979)*, vol. 349, no. 6245, pp. 295–298, Jul. 2015, doi: 10.1126/science.aaa8623.

[26] W. Wu *et al.*, “Flexible passive radiative cooling inspired by Saharan silver ants,” *Solar Energy Materials and Solar Cells*, vol. 210, Jun. 2020, doi: 10.1016/j.solmat.2020.110512.

[27] X. Qian, N. Wang, Y. Li, J. Zhang, Z. Xu, and Y. Long, “Bioinspired multifunctional vanadium dioxide: Improved thermochromism and hydrophobicity,” *Langmuir*, vol. 30, no. 35, pp. 10766–10771, Sep. 2014, doi: 10.1021/la502787q.

[28] A. Taylor, I. Parkin, N. Noor, C. Tummeltshammer, M. S. Brown, and I. Papakonstantinou, “A bioinspired solution for spectrally selective thermochromic VO_2 coated intelligent glazing,” *Opt Express*, vol. 21, no. S5, p. A750, Sep. 2013, doi: 10.1364/oe.21.00a750.

[29] “Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs,” 2020. [Online]. Available: www.ashrae.org

[30] C. Chen and L. Hu, “Super Elastic and Thermally Insulating Carbon Aerogel: Go Tubular Like Polar Bear Hair,” *Matter*, vol. 1, no. 1. Cell Press, pp. 36–38, Jul. 10, 2019. doi: 10.1016/j.matt.2019.06.012.

[31] H. Ye *et al.*, "The demonstration and simulation of the application performance of the vanadium dioxide single glazing," *Solar Energy Materials and Solar Cells*, vol. 117, pp. 168–173, 2013, doi: 10.1016/j.solmat.2013.05.061.

[32] H. Suehrcke, E. L. Peterson, and N. Selby, "Effect of roof solar reflectance on the building heat gain in a hot climate," *Energy Build*, vol. 40, no. 12, pp. 2224–2235, 2008, doi: 10.1016/j.enbuild.2008.06.015.

[33] "https://bigladdersoftware.com/epx/docs/8-0/engineering-reference/page-034.html#shading-module."

[34] R. H. Henninger and M. J. Witte, "EnergyPlus 8.3.0-b45b06b780 Testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard 140-2011." [Online]. Available: www.gard.com

[35] A. P. Melo, D. Cóstola, R. Lamberts, and J. L. M. Hensen, "Assessing the accuracy of a simplified building energy simulation model using BESTEST: The case study of Brazilian regulation," *Energy Build*, vol. 45, pp. 219–228, Feb. 2012, doi: 10.1016/j.enbuild.2011.11.007.

[36] S. C. Fu *et al.*, "Bio-inspired cooling technologies and the applications in buildings," *Energy and Buildings*, vol. 225. Elsevier Ltd, Oct. 15, 2020. doi: 10.1016/j.enbuild.2020.110313.