

BIOMIMETIC ARCHITECTURE AS A NEW APPROACH FOR ENERGY EFFICIENT BUILDINGS THROUGH SMART BUILDING MATERIALS

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INTRODUCTION

As skin wraps our body, building envelopes wraps buildings and therefore acts and performs the functions that the skin performs, especially in thermoregulating the building which results in decreasing the energy consumed. The objective of this paper is to establish a building envelope as a living envelope able to control the heat in buildings the same way that nature does with our skin, without the use of electricity or mechanical elements, and hence decrease energy consumption and its devastating effect on the environment. This objective can be reached by using suitable smart building material and integrating it into the architectural design of the building.

The methodology and objectives of this paper are as follows:

1. Review the global warming problem, its consequences, and the role of the building sector in this problem.
2. Study Biomimicry in architecture and its potential to decrease the share of the building sector's role in global warming.
3. Select a smart building material that would allow the building envelope to perform the same as human skin and review the reasons for its selection.
4. Application of the selected building material in a case study and perform a thermal analysis simulation.

KEYWORDS

global warming, greenhouse gases, biomimicry, biomimetic, smart building materials, shape memory polymers

1. GLOBAL WARMING

1.1 What is Global Warming and Climate Change?

Global warming and climate change refer to an increase in average global temperatures. Natural events and human activities are believed to be contributing to an increase in average

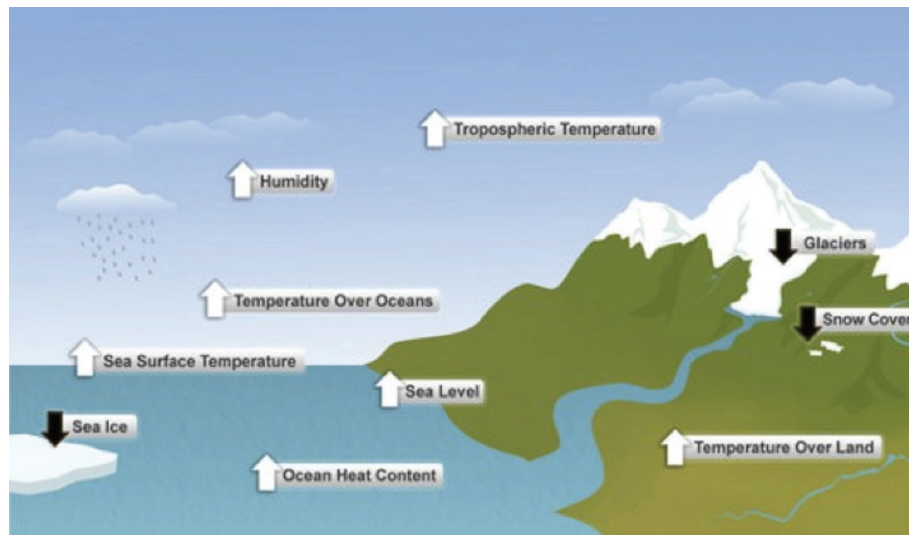
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global temperatures. This is caused primarily by increases in “greenhouse” gases such as carbon dioxide (CO_2). A warming planet leads to a change in climate that can affect weather in various ways, as discussed below.

1.2 What Are the Main Indicators of Climate Change?

As explained by the National Oceanic and Atmospheric Administration (NOAA), there are 7 indicators that would be expected to increase in a warming world (see upward arrows in Figure 1) and 3 indicators would be expected to decrease (see downward arrows in Figure 1):

FIGURE 1. Ten indicators for a warming world. According to scientists in 48 Countries, this past decade was the warmest on record, NOAA, July 28, 2010.



1.3 What is the Greenhouse Effect?

The term greenhouse is used in conjunction with the phenomenon known as the greenhouse effect (Fig 2).

- Energy from the sun drives the earth's weather and climate and heats the earth's surface;
- In turn, the earth radiates energy back into space;
- Some atmospheric gases (water vapor, carbon dioxide, and other gases) trap some of the outgoing energy, retaining heat somewhat like the glass panels of a greenhouse;
- These gases are therefore known as greenhouse gases;
- The greenhouse effect is the rise in temperature on earth as certain gases in the atmosphere trap energy.

The six main greenhouse gases are carbon dioxide (CO_2), methane (CH_4) (which is 20 times as potent a greenhouse gas as carbon dioxide) and nitrous oxide (N_2O), plus three fluorinated industrial gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Water vapor is also considered a greenhouse gas.¹

¹<http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/>

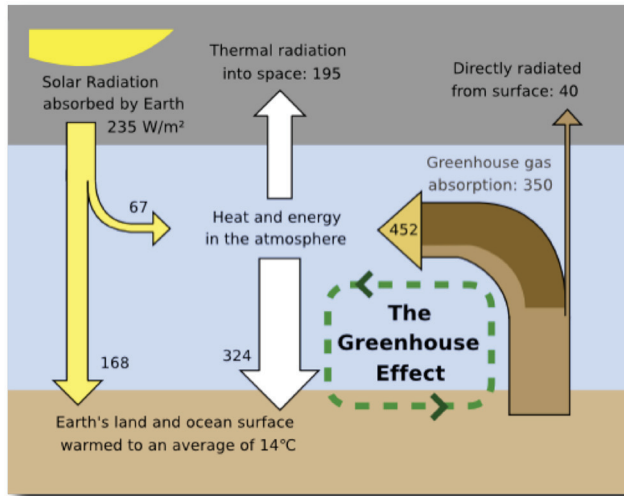


FIGURE 2. Greenhouse effect.

After reviewing the greenhouse gases, their rates of increase, and their impact on raising the temperature of the Earth, let's examine electrical consumption in Egypt according to the Ministry of Electricity and Energy (Table 1).

The importance of analyzing electrical consumption and energy resources is that nonrenewable energies derived from fossil fuel emit tons of CO_2 , which is the main greenhouse gas contributing to increasing temperatures.

From the table on the following page we deduce that the thermal source of energy is the greatest source, and consequently this source is responsible for emitting the largest quantities of CO_2 .

By reducing the electrical consumption of Egyptian buildings, then, CO_2 emissions can be reduced and this could be achieved through biomimetic architecture.

2. BIOMIMETIC ARCHITECTURE

2.1 What do we mean by Biomimicry?

The term "biomimicry" first appeared in scientific literature in 1962, and grew in usage particularly amongst materials scientists in the 1980s. Some scientists preferred the term "biomimetics" or, less frequently, "bionics." There has been an enormous surge of interest during the last ten years, brought about to a large extent by biologists, like Janine Benyus, Steven Vogel, and Julian Vincent, all of whom have written extensively in this subject area. Julian Vincent defines it as "the abstraction of good design from nature" while for Janine Benyus it is "the conscious emulation of nature's genius."

There are two other terms that are worth clarifying. Firstly, "bio-utilisation" and secondly "biophilia." Bio-utilisation refers to the direct use of nature for beneficial purposes, such as incorporating planting in and around buildings to produce evaporative cooling. Biophilia was a term made popular by the biologist E.O Wilson, and refers to a hypothesis that there is an instinctive bond between human beings and other living organisms.

From an architectural perspective there is an important distinction to be made between "biomimicry" and "biomorphism." Modern architects have frequently used nature as a source

TABLE 1. Showing different sources of energy in Egypt.²

Description		2010/2011	2011/2012	Variance%
Peak load	MW	23470	25705	9.5
Total energy generated	GWh	146796	157406	7.2
Hydro	GWh	13046	12934	(0.9)
Thermal	GWh	118500	129361	9.2
Renewable	GWh	1704.4	2004	17.6
Energy Purchased from IPP's	GWh	27.3	29	6.2
Private Sector (BOOTs)	GWh	13309	12855	(3.4)
Isolated Plants	GWh	209	223	6.7

for unconventional forms and for symbolic association. There are some examples of how this has produced majestic works of architecture, such as Eero Saarine's TWA terminal (Fig. 3).

To date, biomimicry has only been applied to building design to a fairly limited extent, often relying on frequently cited examples such as termite mounds and spider webs. In recent years, biomimicry has developed very rapidly in other fields such as industrial design and medicine.³

2.2 Principles of Biomimetic Architecture

The Biomimetic architecture approach is implemented through the following principles:

1. Efficient structures
2. Materials manufacture
3. Waste management systems
4. Water management

FIGURE 3. Eero Saarine's TWA terminal.



² http://www.moec.gov.eg/english_new/EEHC_Rep/2011-2012.pdf

³ Pawlyn, 2011, pp

5. Thermal environment control
6. Energy Production

In this paper the focus is on Materials manufacture.

3. SMART BUILDING MATERIALS

3.1 Definition

NASA defines smart materials as ‘materials that “remember” configurations and can conform to them when given a specific stimulus. A more sweeping definition comes from the Encyclopedia of Chemical Technology: ‘smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment’.

Does ‘smartness,’ then, require special materials and advanced technologies? Most probably no, as there is nothing a smart material can do that a conventional system can’t. A photochromic window that changes its transparency in relation to the amount of incident solar radiation could be replaced by a globe thermometer in a feedback control loop sending signals to a motor that through mechanical linkages repositions louvers on the surface of the glazing, thus changing the net transparency. Perhaps unwieldy but nevertheless achievable with commonly used technology and materials. (Indeed, many buildings currently use such a system.) So, perhaps the most unique aspects of these materials and technologies are the underlying concepts that can be gleaned from their behavior. Whether a molecule, a material, a composite, an assembly, or a system, ‘smart materials and technologies’ will exhibit the following characteristics:

- Immediacy – they respond in real-time.
- Transiency – they respond to more than one environmental state.
- Self-actuation – intelligence is internal to rather than external to the ‘material’.
- Selectivity – their response is discrete and predictable.
- Directness – the response is local to the ‘activating’ event.

3.2 Type characterizations

Smart materials are classified into two types: Type 1 and Type 2

- Type 1 – a material that changes one of its properties (chemical, mechanical, optical, electrical, magnetic or thermal) in response to a change in the conditions of its environment and does so without the need of external control.
- Type 2 – a material or device that transforms energy from one form to another to affect a desired final state.⁴

3.2.1. Type 1: Property changing materials

3.2.1.1 Phase Change Materials

Many materials can exist in several different physical states – gas, liquid or solid – that are known as phases. A change in the temperature or pressure on a material can cause it to change

⁴Addington and Schodek, 2005, pp

from one state to another, thereby undergoing what is termed a 'phase change'. Phase change processes invariably involve the absorbing, storing or releasing of large amounts of energy in the form of latent heat. A phase change from a solid to a liquid, or liquid to a gas, and vice versa, occurs at precise temperatures. Thus, where energy is absorbed or released can be predicted based on the composition of the material. Phase changing materials deliberately seek to take advantage of these absorption/release actions.

While most materials undergo phase changes, there are several particular compositions, such as inorganic hydrated salts, that absorb and release large amounts of heat energy. As the material changes from a solid to a liquid state, and then subsequently to a gaseous state, large amounts of energy must be absorbed. When the material reverts from a gaseous to a liquid state, and then to a solid state, large amounts of energy will be released. These processes are reversible and phase-changing materials can undergo an unlimited number of cycles without degradation.⁵

3.2.1.2 Hydrogel

A hydrogel is a network of polymer chains that are hydrophilic, sometimes found as a colloidal gel in which water is the dispersion medium. Hydrogels are highly absorbent (they can contain over 90% water) natural or synthetic polymeric networks. Hydrogels also possess a degree of flexibility very similar to natural tissue, due to their significant water content. The first appearance of the term 'hydrogel' in the literature was in 1894.⁶

Hydrogel consists mainly of water, a water-soluble polymer with hydrophobic groups, an amphipathic molecule and sodium chloride. The hydrogel was developed after conducting fundamental studies on hydrophobic bonding. The amphipathic molecule enables autonomously reversible light adjustment while retaining its homogeneity.

FIGURE 4. Pellets contain encapsulated phase-changing materials. They are used in radiant heating floor systems.



3.2.2 Energy exchanging materials

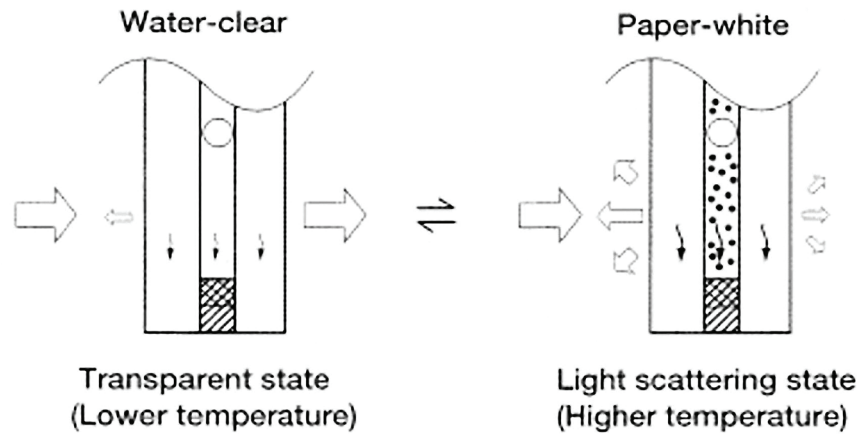
3.2.2.1 Thermo Bimetals

Thermobimetals (TB) are laminated composite materials and consist of at least two components, usually bands or strips, made from metals with different thermal expansion coefficients, which are permanently bonded to one another, for example by plating. The component with

⁵*Ibid*, pp 88

⁶<https://en.wikipedia.org/wiki/Gel>

FIGURE 5. Shows the sectional structure of an intelligent window that consists of hydrogel of two states with homogeneous reversibility between water-clear and paper-white according to temperature.⁷



the lower coefficient of thermal expansion is called passive, while the one with the higher coefficient active. Depending on the way the temperature changes over time, the components used and their geometries, the composite takes up a curved shape and can be used for various applications and purposes. The terms used in Europe to describe TBs refer to the composition of the active component alloy, whilst the United States refers to that of the passive component.

TBs are relatively old smart materials and have been around since the beginning of the industrial revolution. Today they are mainly used in measurement and control systems, e.g. as thermostats, and with electrical control as components in mechatronic systems.

TBs can be made corrosion-resistant by plating with chrome and copper, and their electrical conductivity improved for active heat gain by incorporating a layer of copper between the two components.

Components for the manufacture of TBs should possess good platability, hot and cold ductility, a high melting point, a high modulus of elasticity (Young's modulus), high strength and predictable behaviour. Furthermore, a certain range of divergent behaviour regarding the melting point, modulus of elasticity and strength of components should not be exceeded. Specific dimensional relationships are to be maintained.⁸

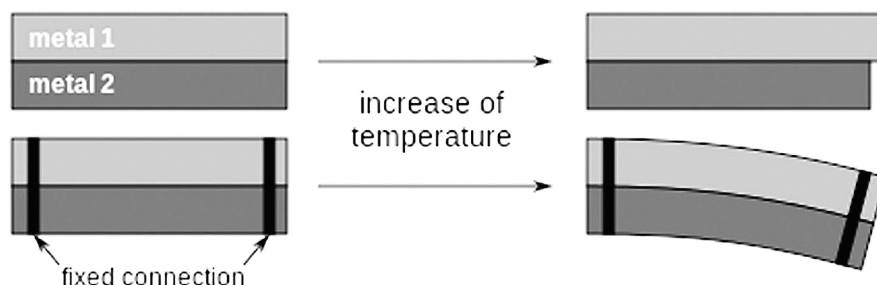
A bimetallic strip is used to convert a temperature change into mechanical displacement. The strip consists of two strips of different metals which expand at different rates as they are heated, usually steel and copper, or in some cases steel and brass. The strips are joined together throughout their length by riveting, brazing or welding. The different expansions force the flat strip to bend one way if heated, and in the opposite direction if cooled below its initial temperature. The metal with the higher coefficient of thermal expansion is on the outer side of the curve when the strip is heated and on the inner side when cooled

⁷ Watanabe, 1998, pp. 205

⁸ Ritter, 2007, pp. 52

The sideways displacement of the strip is much larger than the small lengthways expansion in either of the two metals. This effect is used in a range of mechanical and electrical devices. In some applications the bimetal strip is used in the flat form. In others, it is wrapped into a coil for compactness. The greater length of the coiled version gives improved sensitivity.⁹

FIGURE 6. A bimetallic strip showing how the difference in thermal expansion in the two metals leads to a much larger sideways displacement of the strip.



3.2.2.2 Shape Memory Polymers

Often polymers are classified by how they behave when heated. If they soften when warmed, they are called thermoplastic polymers. However, if they never become soft but only char after intensive heating, they are known as thermosets.

Shape-memory polymers are dual-shape materials belonging to the group of ‘actively moving’ polymers. They can actively change from a shape A to a shape B. Shape A is a temporary shape that is obtained by mechanical deformation and subsequent fixation of that deformation.

This process also determines the change of shape shift, resulting in shape B, which is the permanent shape. In shape-memory polymers reported so far, heat or light has been used as the stimulus.

The shape-memory effect is not an intrinsic property, meaning that polymers do not display this effect by themselves. Shape memory results from a combination of polymer morphology and specific processing and can be understood as a polymer functionalization.

By conventional processing, e.g. extruding or injection molding, the polymer is formed into its initial, permanent shape B. Afterwards, in a process called programming, the polymer sample is deformed and fixed into the temporary shape A. Upon application of an external stimulus, the polymer recovers its initial permanent shape B. This cycle of programming and recovery can be repeated several times with different temporary shapes in subsequent cycles. Shape-memory polymers are elastic polymer networks that are equipped with suitable stimuli-sensitive switches. The polymer network consists of molecular switches and netpoints (Fig. 7). The netpoints determine the permanent shape of the polymer network and can be of a chemical (covalent bonds) or physical (intermolecular interactions) nature.

⁹https://en.wikipedia.org/wiki/Bimetallic_strip

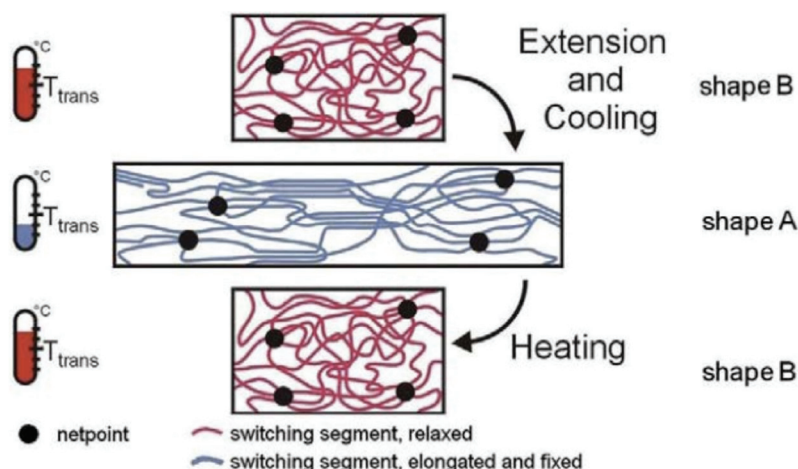


FIGURE 7. Molecular mechanism of the thermally induced shape-memory effect. T_{trans} = thermal transition temperature related to the switching phase.

Shape-memory polymers are an emerging class of polymers with applications spanning various areas of everyday life. Such applications can be found in smart fabrics, heat shrinkable tubes for electronics or films for packaging, self-deployable sun sails in spacecraft, self-disassembling mobile phones, intelligent medical devices, or implants for minimally invasive surgery. These examples cover only a small number of the possible applications of shape-memory technology, which shows potential in numerous other applications.¹⁰

In this paper, shape memory polymers will be applied in architecture through the building envelope, especially in the openings.

4. APPLICATION

Out of all the smart building materials that were discussed previously, the Shape Memory Polymers were chosen as the focus of this paper for the following reasons:

1. It reacts to low temperatures that range from 25 to 40 degrees Celsius.
2. Has various applications within architecture design
3. Less expensive
4. Transparent

The paper author worked on Shape Memory Polymer (SMP) sheets that functioned as an internal window within internal walls to enhance air flow because the internal walls block cross ventilation and hence block the air flow that affects the indoor thermal comfort.

The application of the SMP sheets could be variable in architecture such as:

- Windows in internal and external walls
- Solar chimneys
- Openings in domes
- Skylights

¹⁰Behl and Lendlein, 2007, pp. 20-21

4.1 Process of the experiment:

A sample of Shape Memory Polymer with the following specifications was chosen for the experiment:

- 2mm thick Shape Memory Polymer sheet
- Temperature of Glass transition: 35-40 degrees Celsius
- The sheet is programmed to be bended, and when warmed, it becomes more elastic. It was flattened and then exposed to air flow heated up to 35 degrees Celsius.

After flattening the sheet in warm water, the sheet was then placed in cold water to maintain its new flat shape, then exposed to warm air that was heated up to 35-40 degrees Celsius. When the flattened sheet is exposed to the hot air coming out of the blower, it regains its original bended shape.

This 2mm thick Shape Memory Polymer sheet achieved the target of the experiment because the sheet was stable when facing wind pressure, and it was bended gradually when exposed to the hot air heated to 40 degrees Celsius that allowed the air to flow. This sample sheet was placed into a simple model and the internal temperature and air flow was monitored. (Figure 8)

The air flow through the three positions of the SMP Figure: 9) 180 degrees, 10) 45 degrees, and 11) 90 degrees was monitored and calculated by ANSYS simulation.

FIGURE 8. Shows the progress of the 2mm SMP sheet placed in the internal window within the model and exposed to hot air heated to 37 degrees Celsius, and it shows the movement of the sheet from 180 degrees to 45 degrees to 90 degrees, allowing the air to flow in the model.



FIGURE 9. 180 degrees

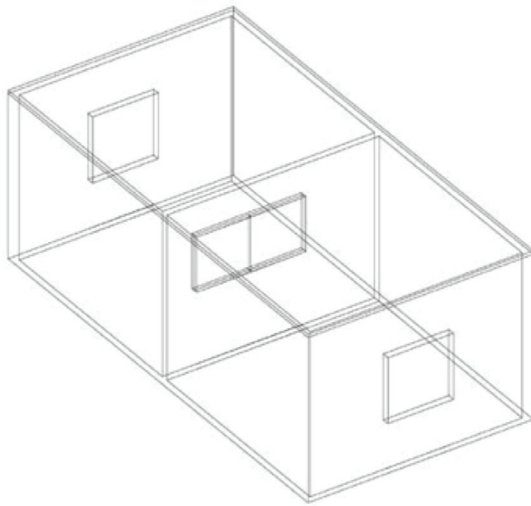


FIGURE 10. 45 degrees

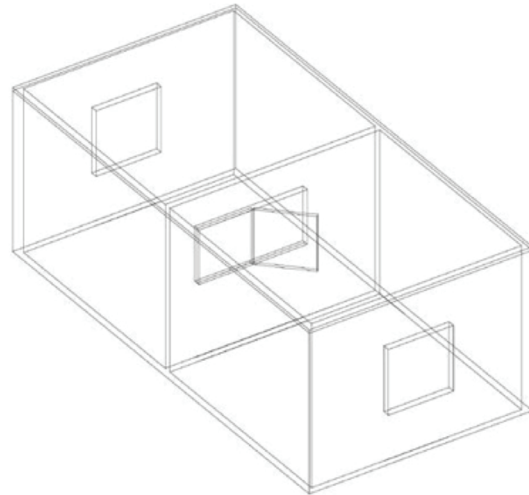
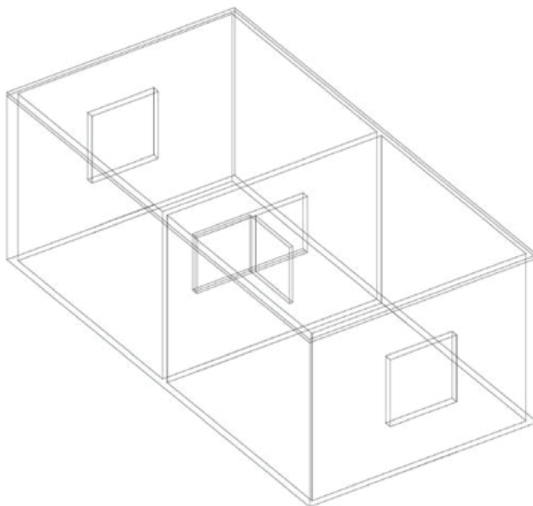


FIGURE 11. 90 degrees



4.2 RESULTS:

1. With the Shape Memory Polymer sheet at 180 degrees, i.e. the window was closed, there was no air flow.
2. ANSYS analysis showing the air flow and speed in the model with the second position: SMP sheet opens 45 degrees.
3. ANSYS analysis showing the air flow and speed in the model with the third position: SMP sheet open 90 degrees.

When the sample was heated and opened to 45 degrees, air flow started moving through the internal space. When opened to 90 degrees, which was the maximum opening, allowed greater air flow in internal space. By opening the shape memory sheet in the model, it allowed the flow of air in the internal space and thus reduced the internal temperature which will lead to reduced cooling loads.

FIGURE 12. Shows wind speed.

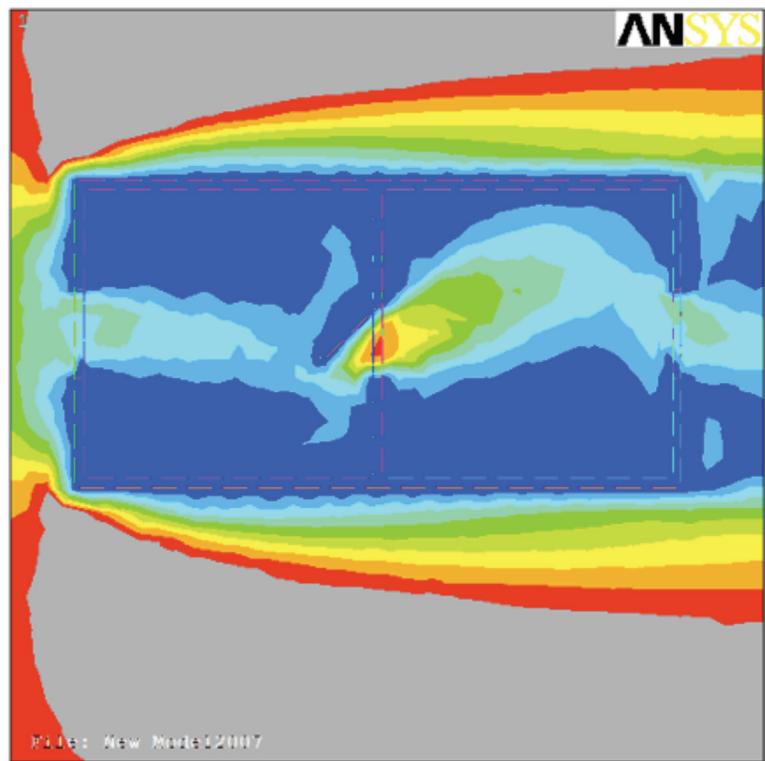
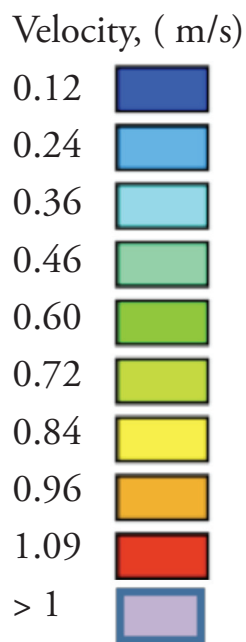
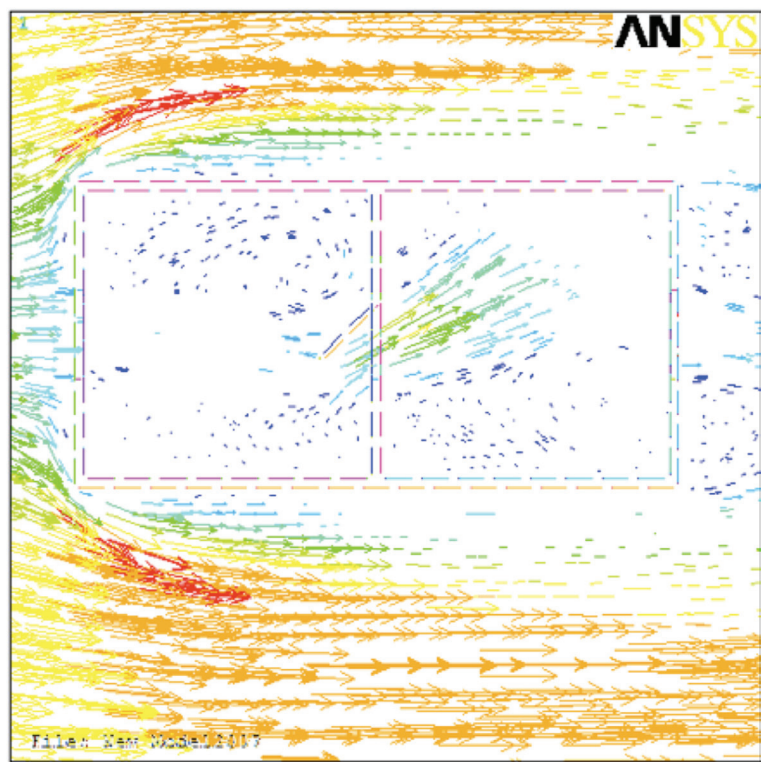


FIGURE 13. Shows wind speed and flow direction and turbulences.



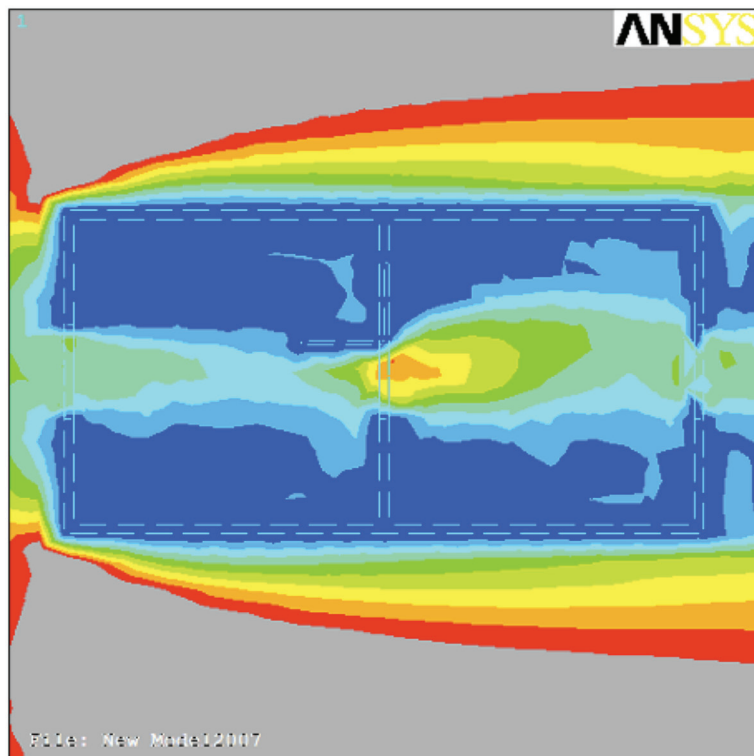


FIGURE 14. Shows wind speed.

Velocity, (m/s)

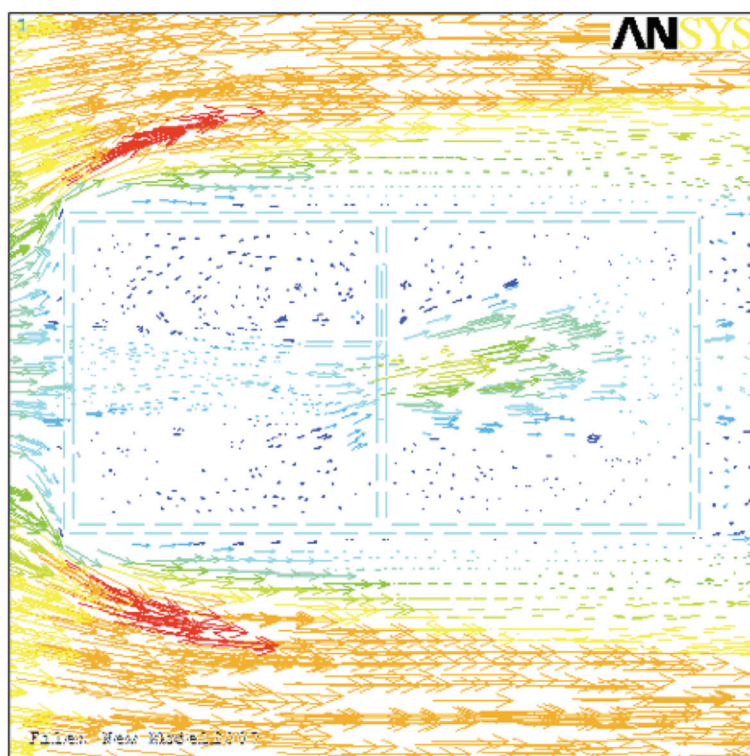


FIGURE 15. Shows wind speed and flow direction and turbulences.

CONCLUSION AND RECOMMENDATION

Building envelopes and the internal walls have a great effect on the internal temperature of a building and the use of conventional materials that don't respond to the surrounding stimulus (e.g., temperature, light, or humidity) is not the best way to effectively manage and reduce energy demand and prevent the negative effect of climate change. Using smart materials that are responsive to surrounding stimulus, like Shape Memory Polymers, can contribute much more to energy efficient design. Smart materials integrated into the design and construction of a building can perform the same thermoregulating function that skin performs for the body. A decrease in electrical consumption is achieved with the application of Shape Memory Polymers because natural ventilation will increase and therefore the reliance on air conditioning to maximize occupant comfort in buildings is minimized. The two way shape memory polymer sheets that act as a temperature actuator in the building envelope is an ideal smart material that is capable of reacting to temperature on its own.

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