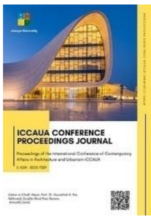

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Towards Breathable Building Envelopes for a Synergy between Thermal Comfort and Energy Efficiency

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Abstract

Over the past few decades, architectural practice has taken a new direction, giving rise to a remarkable trend in the design of modern building envelopes. These envelopes, often adaptive and inspired by nature, have emerged through innovative manufacturing techniques based on advanced technologies and novel materials. They represent a new generation of building envelopes capable of breathing, adapting, and reacting to external factors in real time, symbolizing a shift from static architecture to kinetic architecture.
With this in mind, this paper outlines the various aspects of breathable envelopes designed using a biomimicry approach. It highlights the transformation of knowledge derived from nature into architectural solutions that introduce innovative techniques in the construction field through the use of smart materials. These breathable envelopes aim to achieve indoor thermal comfort while reducing energy consumption to enhance overall energy efficiency.
Keywords: Breathable envelopes, Biomimicry, Smart materials, Thermal comfort, Energy efficiency.

1. Introduction

Global warming, caused primarily by greenhouse gas emissions, is leading to a rise in global temperatures, resulting in excessive use of air-conditioning systems in buildings and, consequently, an increase in energy consumption. Paradoxically, the COVID-19 pandemic has highlighted the vital need to ensure indoor thermal comfort without the spread of airborne pollutants by relying on natural ventilation rather than mechanical air conditioning, particularly in shared spaces frequented by the public.
To this end, comfort requirements in buildings are constantly increasing and have become a key challenge in architectural design, particularly for buildings intended to accommodate large numbers of people, especially in regions characterized by a hot, arid climate, where there is a considerable reliance on electricity to power air-conditioning systems. This consumption is closely linked to the building envelope, as it is often ill-suited to local climatic and environmental conditions, leading to increased energy use and discomfort for occupants.
To meet this challenge, architects are turning to the genius of nature, which has evolved over 3.8 billion years and offers exemplary models of adaptation, innovation, and efficient resource management (Nasir & Arif Kamal, 2022), to mimic biological strategies to design non-biological systems that can solve technical problems already solved in the natural world (Fiorito et al., 2016).
This inspiration is based on a biomimetic approach, which draws on biological processes to create innovative and sustainable architectural solutions (Kuru, 2020), offering the potential to address the environmental, cultural, social, economic, and energy challenges facing future generations while helping to optimize the building's performance and meet users' comfort requirements, as well as harmonizing the building with its surroundings.
Consequently, a new generation of building envelopes has emerged, thanks to the integration of advanced technologies, incorporating smart materials that respond to changes in climatic conditions to improve the building's performance in terms of heating, natural ventilation (Badarnah et al., 2010), a reduction in energy consumption for cooling (ElDin et al., 2016), a reduction in indoor air pollution, and improved energy efficiency. This helps to create healthy indoor environments while optimizing the well-being of occupants.
In this regard, breathable walls represent an innovative technique designed to provide solutions for the structural design of buildings, drawing inspiration from the principles of biomimicry. These walls, which operate on the same principle as

the respiration of living organisms, enable the building to interact with its environment by facilitating gas exchange adapted to climatic variations, promoting passive cooling through natural ventilation, improving indoor air quality, and ensuring greater energy efficiency in buildings, particularly since the COVID-19 pandemic.
With this in mind, this study focuses on presenting breathable walls from various angles and through various examples, highlighting their mechanism, their role in thermal regulation, their contribution to energy efficiency, and their potential to promote more sustainable buildings that are resilient to environmental fluctuations.

2. Definition of the breathable wall

The idea behind a breathable wall is based on a biomimetic approach, coming from looking at how living things work and using that information to cool down indoor spaces, make traditional facades work better thermally, and make buildings that can interact with their surroundings (Gheznawy et al., 2020). To comprehend the concept of a breathable wall, one must consider it from both biological and architectural perspectives.

2.1. From a biological perspective

Respiration in living beings is a complex and involuntary process (Dezube, 2023) that involves physical, chemical, and biological processes. It is necessary for gas exchange and energy production, both of which are necessary for their survival (May, 2005).
The respiration process is the transition and interchange between the organism and air in its environment.These exchanges rely on a series of actions, notably the movements that allow oxygen (O_2) from the surrounding environment to be drawn into the body (inhalation) and carbon dioxide-rich air (CO_2) to be expelled (exhalation). During this process, air moves naturally from areas of high pressure to areas of low pressure, allowing it to enter the body, thereby supporting essential metabolic activities and helping to maintain the body temperature of living organisms (RespirFil, 2023; Rezek, 2015).

2.2. From an architectural perspective

The wall, as an architectural element, plays a crucial role in managing temperature differences between the interior and exterior. On this basis, the concept of 'breathing walls' was first introduced in Germany in 1969 by Professor Anton Schneider (IBEF, 2022) in the field of 'Baubiologie' (Elghawaby, 2013). These walls were subsequently developed using a biological approach based on imitating the respiratory mechanism of certain natural organisms, such as the human lungs (Rezek, 2015). They allow air to move from the outside to the inside of the building, promoting indoor air renewal via natural ventilation thanks to a pressure difference between the inside and outside. They thus serve to respond to climate change and improve the thermal performance of existing façades (Elghawaby, 2012), meeting the needs of occupants while reducing their dependence on mechanical systems, which leads to savings in energy and electricity consumption (Gheznawy et al., 2020).
In this context, in climates with high humidity, breathable walls have been valued for their thermal performance when they are able to control humidity while providing insulation (Elghawaby, 2013). In hot climates, the walls have been recognized as being used for ventilation to cool internal spaces. They help to reduce the air temperature, as well as surface temperatures, and control air movement in their spaces (Elghawaby, 2013; Gheznawy et al., 2020).

3. Various examples of breathable walls

Over the past few decades, technological advances marked by the emergence of new techniques and innovative materials with distinctive characteristics have given rise to a new generation of different forms of breathable walls (envelopes) to create buildings capable of breathing like living beings and adapting to environmental changes.
The next section presents a literature review, describing different types of breathable walls. It highlights how insights drawn from nature have been transformed into architectural and technical solutions. These solutions aim to improve indoor thermal comfort by reducing air temperature while minimizing energy consumption, with a view to achieving optimal energy efficiency. This analysis is structured as follows:

3.1.1. Advanced technology

This advanced technology is characterised by the use of smart materials such as the following:

3.1.1.1. Thermobimetal

Doris Kim Sung is an architect and biologist, a professor of architecture at the University of Southern California (USC), and the director of the DO|SU architecture studio. She is interested in the convergence of architecture and biology through a biomimetic approach. Her work explores how architecture can mimic the mechanisms of nature in general and the human body in particular. Her main objective is to make prototypes that can self-ventilate, self-shade and self-structure in response to temperature changes. She wants to create sustainable and adaptable architectural solutions without using any energy, using a smart material called thermobimetal (Sung, 2021).
This material consists of two metals in the form of strips made from metals with different coefficients of thermal expansion, which allows them to simply deform when heated or cooled. When the surface becomes hot, the thin panels curl up to allow air to pass through to the space below, and when they cool, they close again (Sung, 2011)(Figure 1.).

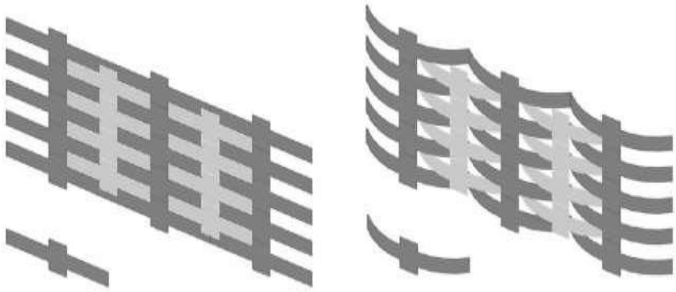


Figure 1. Operating mechanism of thermobimetal strips.
Source: Sung (2011).

•In March 2010, the architectural studio DO|SU, led by Sung, created a work entitled "Armoured Corset" (Figure 2.), designed as a self-ventilating skin utilizing thermobimetal. Its mechanism relies on the curvature of each metal component (a foldable cross), causing the skin to open when triggered by rising external or internal temperatures, allowing the building to ventilate automatically and hot air to escape to the outside.

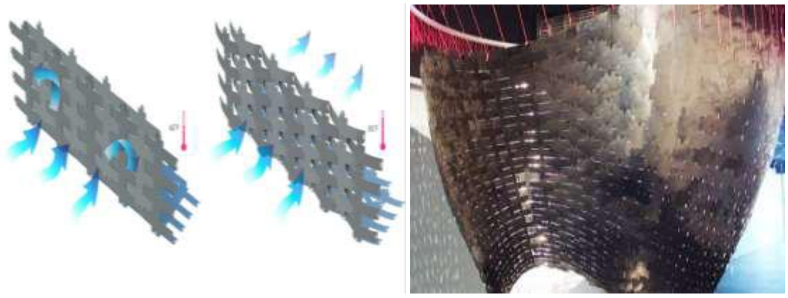


Figure 2. Armoured Corset.
Source: Sung (2010).

•In August 2012, Doris Kim Sung presented a work entitled "Tracheolis", created as a thermobimetal block, inspired by the respiratory system of grasshoppers, which is based on a complex tracheal network comprising small holes positioned at strategic points, functioning as control valves and operating on Bernoulli's principle. These valves open when the temperature rises (Figure 3.); when the temperature drops, they close, trapping the air and thus improving thermal insulation (Sung, 2012)(Figure 4.). Furthermore, this group has also produced other works, such as the Oculus in 2016 (Figure 5.).

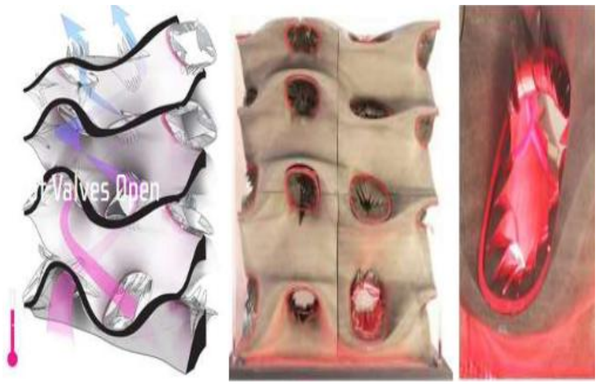


Figure 3. Tracheole with open spiracles.
Source: Sung (2012).

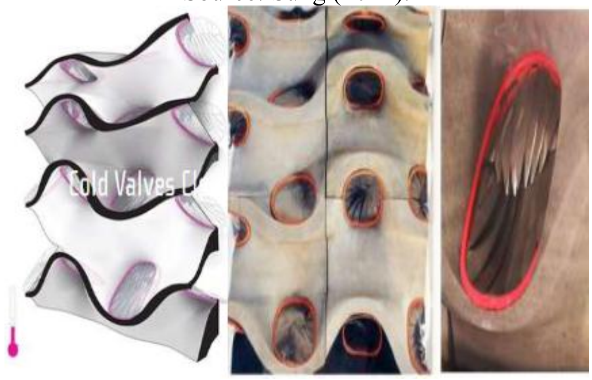


Figure 4. Tracheole with closed spiracles.
Source: Sung (2012).

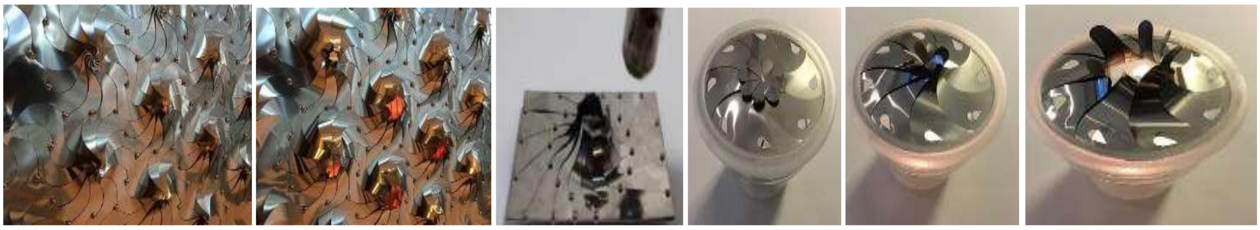


Figure 5. Oculus.
Source: Sung (2016).

3.1.1.2. Shape-memory alloys

In 2007, as part of a project to create breathable building envelopes, the LIFT Architects group, founded by Andrew Payne, developed a work entitled 'THE AIR FLOW (ER)' (Figure 6.). The aim of this installation is to promote natural ventilation, regulate air flow and maintain comfortable indoor temperatures in buildings, without the use of electricity.

Figure 6. Air Flow(er).
Source: Payne (2007).

This work is inspired by the phenomenon of thermonasty observed in yellow crocus flowers (Figure 7.); it replicates the behavior of their petals, which are composed of two layers of cells: an inner layer and an outer layer. In response to temperature fluctuations, this natural mechanism produces a kinetic reaction that is reflected in the structure's design. The petals fold inwards when temperatures are low, as the outer layer of cells expands more rapidly than the inner layer, causing the flower to close. Conversely, the flower opens and its petals unroll as the temperature rises.
LIFT Architects has used this natural concept through the use of a smart material, shape-memory alloy (SMA). In the form of wires, they work like sensors and actuators on their own since they are superelastic and can vary with temperature. Their microstructures change from martensite at low temperatures to austenite at high temperatures, enabling them to adapt to temperature changes.

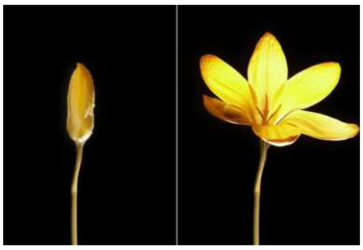


Figure 7. Yellow crocus flower.
Source: Payne (2007).

The prototype illustrating this concept is a square wooden box with a square hole in its top face. It has four adjustable rigid flaps that can open and close on their own. A shape memory alloy (SMA) wire joins each pair of panels that are opposite each other. This makes sure that the system can open and close (Al-Masrani et al., 2018). When the SMA wires get too hot, around 26.66°C, they shrink, which opens the panels and lets air flow through the box. On the other hand, if the temperature dips below the lower limit around 15.55°C. The wires expand, so the panels close to keep the inside temperature bearable. Because they are superelastic, the SMA wires can shrink by up to 8% due to their superelasticity, ensuring reliable and repeatable operation of the system (Figure 8.).

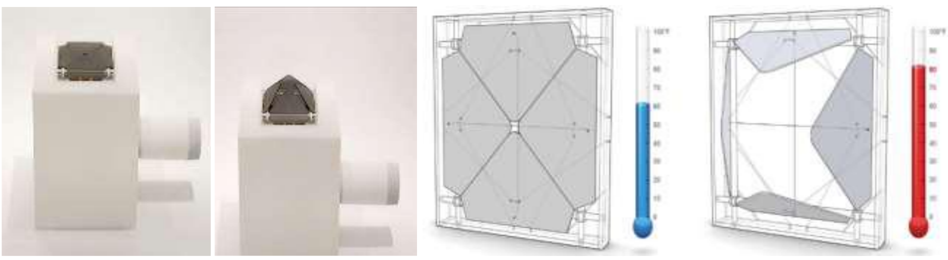


Figure 8. Mechanism of air flow (er).
Source: Payne (2007).

This design was developed into three further physical prototypes (Figure 9.), which were tested for various applications in the construction sector. The results demonstrated that these openings allow for natural ventilation in buildings without the need for active energy. This not only leads to a reduction in maintenance and operating expenses but also to a significant reduction in the energy requirements associated with mechanical ventilation systems.

Figure 9. Air Flow(er) prototypes.
Source: Payne (2007).

With the aim of designing a building envelope capable of "breathing" by drawing inspiration from the principles of biological respiratory adaptation, Scott Crawford developed an adaptive building skin in 2010. This concept presents itself as an innovative and alternative solution to traditional fans for air distribution and natural ventilation, drawing inspiration from the movement of air towards the lungs, which involves thoracic variation through the expansion and contraction of the diaphragm (Figure 10.).

This device replicates the principle of opening and closing using a flexible structure. The shape memory alloy (SMA) as an actuator is used as an actuator to regulate the opening and closing, such as a diaphragm. In addition, two other types of material are incorporated, which function as living hinges, providing flexibility and adaptability to the system. Pneumatic actuators are integrated into this design and attached to an external hub of the space frame structure and to the center of the diaphragm.

According to preliminary calculations, the use of this smart material minimizes the energy required for operation. Furthermore, this system is two to four times more energy-efficient than large industrial fans when moving an equivalent volume of air.

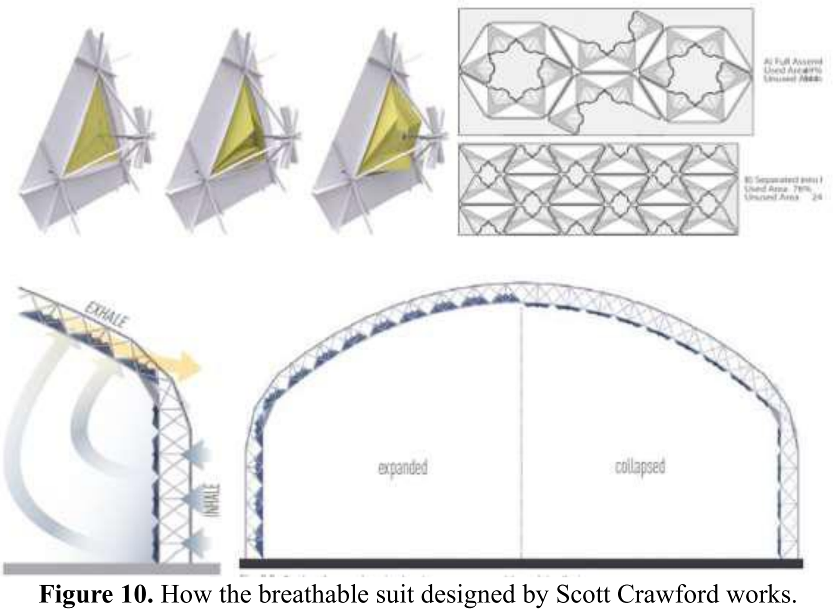


Figure 10. How the breathable suit designed by Scott Crawford works.
Source: Crawford (2010).

3.1.1.3. Pneumatic system

In 2017, Tobias Becker created an exhibition space in Germany entitled "Breathing Skins". This project covers an area of 8, 00 m² and is based on an innovative concept of a breathable façade, which functions as a living system (Figure 11.). This façade combines two layers of transparent, perforated polycarbonate with 140 pneumatic muscles (Becker, 2017), which are mechanical components positioned between the polycarbonate layers. Thanks to these pneumatic muscles, it is possible to control external conditions such as air temperature and humidity levels, whilst also regulating internal conditions. Air regulation is achieved using balloon-shaped air pockets, positioned at each end of the façade, via openings (inlet and outlet) on both wall surfaces (Felkner et al., 2021).

The mechanism works by allowing pressurized air to enter the facade through small tubular openings. These perforations open to outside air, causing the pneumatic muscles and air pockets to expand or contract. The facade reconfigures itself as a result of this interaction, adapting by opening or closing its pores according to the thermal and ventilation requirements of the interior space.

This system creates a breathing effect, whereby the facade constantly adapts to changes in the weather. Its function is to control the amount of outside air entering the building, the speed of air circulation, and the distribution of heat and humidity. This facade establishes a dynamic harmony between the external environment and the interior spaces by optimizing indoor temperature and air quality without the need for mechanical air-conditioning systems (Baron, 2016; Felkner et al., 2021).

Figure 11. Breathing Skins designed by Tobias Becker.
Source: Becker (2017).

Another adaptive pneumatic skin has been developed by students at the Institute of Advanced Architecture of Catalonia. Inspired by the respiratory system, it is based on an innovative wall that actively uses air to respond to changes in light and temperature via a light sensor. When the sensor detects high levels of solar radiation, an air valve is activated, causing air to be released into balloons connected by tubes. The balloons' inflation and deflation are like breathing in and out mimic inhalation and exhalation, respectively (Felkner et al., 2021).

This adaptive facade allows for the control of light transmission and limits the rise in internal temperature, thereby helping to stabilize indoor conditions in response to the external environment. The balloons play a key role in terms of color and transparency, as they affect visual transmission and serve as dynamic sun protection. This project goes beyond the concept of a breathable skin by introducing a mechanical feedback system able to actively interact with the environment to improve thermal and visual comfort inside (Figure 12.) (Felkner et al., 2021).

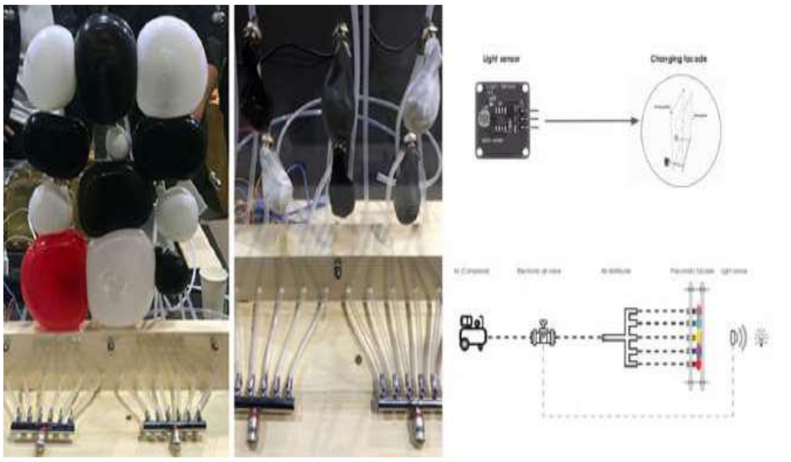


Figure 12. Breathable envelope designed by students at the Institute for Advanced Architecture of Catalonia.
Source: IAAC (2019).

3.1.1.4. Piezoelectric materials

In 2007, Lidia Badarnah and Ulrich Knaack developed a facade inspired by the respiratory system of living beings, particularly the lungs, to create natural ventilation integrated into the building envelope. This system works by regulating air pressure, replicating the processes of inhalation and exhalation according to users' requirements regarding the quality and quantity of air entering and leaving the building. The rate at which the facade elements deform and the increase in the exchange surface area are the factors that influence the air exchange rate, thereby optimizing ventilation. The system is organized into three hierarchical sections: open, semi-open, and closed chambers, which create the necessary air pressure differential for the inflow and outflow of air. The inner and outer surfaces of the envelope expand and stretch when tension is applied. The excess pressure then forces the air out of the lung chamber through the other side via contraction (Figure 13.).

This mechanism relies on piezoelectric sensors implanted under the skin, which convert mechanical energy into electrical energy and vice versa, thereby ensuring precise control of the system. These sensors respond differently for each area of the skin, and the elastic membrane materials change shape in response to the signals, allowing the facade's geometry to be adjusted to respond to changes in the environment.

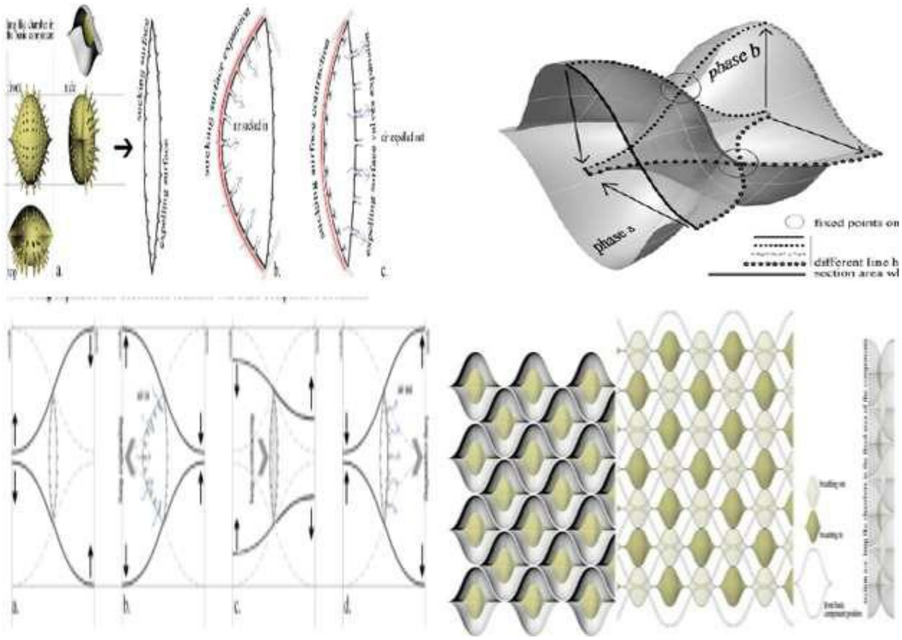


Figure 13. Composition of the breathable membrane.
Source: Badarnah and Knaack (2007).

3.1.2. Processes

Lidia Badarnah et al. (2010) developed a system known as 'Stoma Brick'. The main aim of this project is to develop an evaporative cooling system for building envelopes in regions with arid and dry climates. This work draws on various sources of inspiration, as listed below:

- The hair around the eyes protects them from small particles, which has inspired the creation of a system that prevents dust from entering the building.
- The functioning of stoma, which controls the openings for evaporation in response to changes in osmotic pressure, serves as a model for managing heat and moisture exchange.
- Pine cones have the ability to change shape in response to fluctuations in relative humidity, resulting in an adaptive mechanism that regulates the system's opening according to climatic conditions.
- Human skin can lose latent heat, ensuring evaporative cooling.

The natural sources of inspiration for this project are interpreted architecturally through a framework structure that combines various functional elements suited to hot, dry climates. This system consists of different layers (Figure 14.):

- The Stoma brick is made of a porous material that regulates temperature; it features an outer layer with a hair-like structure that filters incoming air by trapping particles, and a veneer flap that opens and closes in response to humidity levels, thereby enabling dynamic control of air and humidity. The spongy inner layer serves to retain moisture and promote water evaporation, thereby ensuring evaporative cooling when the system is in operation.
- The single brick is essential for ensuring an irrigation cycle. It is connected to the holes in the Stoma brick, which maintains the continuous irrigation system, thereby ensuring humidification and air regulation.
- The cooling system is stable because of the steel support construction.
- The inner layer, consisting of a HEPA filter, serves to purify the air.
- During irrigation cycles, water droplets flow over the cladding panel. The deformation of the veneer under the effect of humidity allows air to penetrate and pass through the spongy structure. This process humidifies the air, making it more comfortable when it reaches the interior space. This system, on the other hand, functions as an insulating layer during cold and dry times, which keeps heat from escaping.

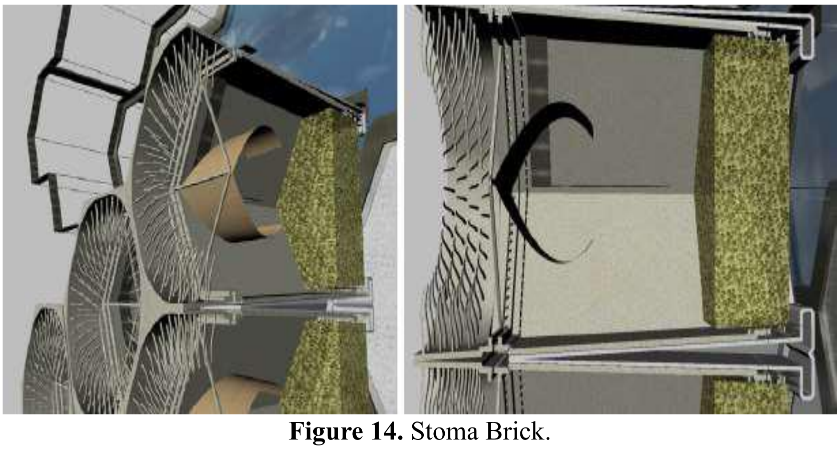


Figure 14. Stoma Brick.
Source: Badarnah et al. (2010).

Given the desert climate of the Sinai Peninsula (Egypt), Mahmoud Elghawaby (2013) proposed the creation of a breathable wall inspired by the layers of natural skin, designed to regulate natural ventilation, prevent heat gain, dissipate internal heat build-up, and provide effective insulation. To achieve these objectives, Elghawaby developed this process into three layers (Figure 15.):

• **The outer layer** is designed to mimic the insulating properties found in desert animals and plants, such as furry skins and thick waxy layers. It is made from materials capable of absorbing moisture, for example, natural textiles, clay, and wood or reeds, featuring openings that limit direct light and control the intensity of sunlight according to users' needs while allowing air to circulate.

• **The intermediate layer** consists of a network of air ducts comprising controlled air inlets, a water spray system, and a network of ventilation ducts designed to provide cooling through evaporation and conduction by allowing the flow of air from the ground (geocooling). This strategy aims to provide thermal insulation from the outside, evaporative cooling and control over oro air movement via a network of ducts. This is achieved either through direct ventilation via direct connections between the outside and the inside, or insider indirectly when the airflow passes through the subsoil in contact with the earth.

• **The inner layer** has air outlets that are controlled by features on the wall or grouped together in a ventilation grille. This helps you manage the flow of air into the room.

As a prototype, this idea was put into practice in the field. It measured (1.00 x 1.00 x 1.00) m, and each square meter of the facade had 28 air vents for direct ventilation and 21 air vents for indirect ventilation. The findings indicated that the temperature disparity between the actual and the simulated scenarios peaked at 5.6 °C. This technology helps make cooling and ventilation systems better so that buildings in hot places like the Sinai can be comfortable.

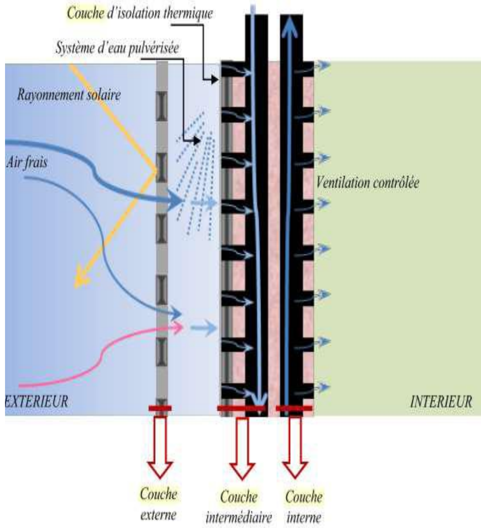


Figure 15. Breathable wall designed by Elghawaby.
Source: Elghawaby (2013).

Figure 16 shows the several parts of the breathable wall that Craig and Grinham (2017) designed. It also gives a short description of each layer:

• **The outer layer** is a perforated exterior rain screen that protects the insulating layer from physical interactions and outside factors like severe weather and wind (Gheznawy et al., 2020).

• **Intermediate layer (breathable wall)** is an important part of how a breathable wall works. It is composed of porous materials, such as wood, concrete, rock wool or glass, that are characterized by the presence of air channels measuring just a few millimeters in size. This layer may also incorporate dynamic insulation support, thereby optimizing its effectiveness. This setup lets air flow freely across the whole surface in a controlled way while also making a good barrier against heat loss and gain (Gheznawy et al., 2020).

It also lets water flow about as vapor while stopping it from moving around as liquid, which keeps the relative humidity at the right level. This helps keep mold from growing, makes the air within the building better, and makes the building more energy efficient (Gheznawy et al., 2020; Larsen et al., 2014).

This configuration offers considerable advantages over traditional walls under comparable temperature and pressure conditions. It combines the functions of the building envelope with those of a ventilation system. Indeed, fresh air is drawn into a warm space due to pressure differences (Gheznawy et al., 2020). Hassan Fathy discussed the benefits of these walls, which are made of natural organic materials like leaves, animal skins, wood, reeds, and clay that let air flow through them. These materials can take in moisture and chill the inside by letting it evaporate, which makes the air temperature decrease considerably (Elghawaby, 2013).

• **Inner layer** is the inside of the wall, which is usually made up of a cladding panel. It has a visible, porous, and air-permeable inner substance that also acts as a dynamic insulator, like concrete. This material has a high thermal conductivity and a high thermal mass, which means it can store and recover heat. This makes the building envelope work better thermally (Larsen et al., 2014). In this layer, it is recommended to avoid the use of epoxy or rubber paints, as they can block the pores of the wall, thereby hindering the three modes of moisture transmission (Gheznawy et al., 2020).

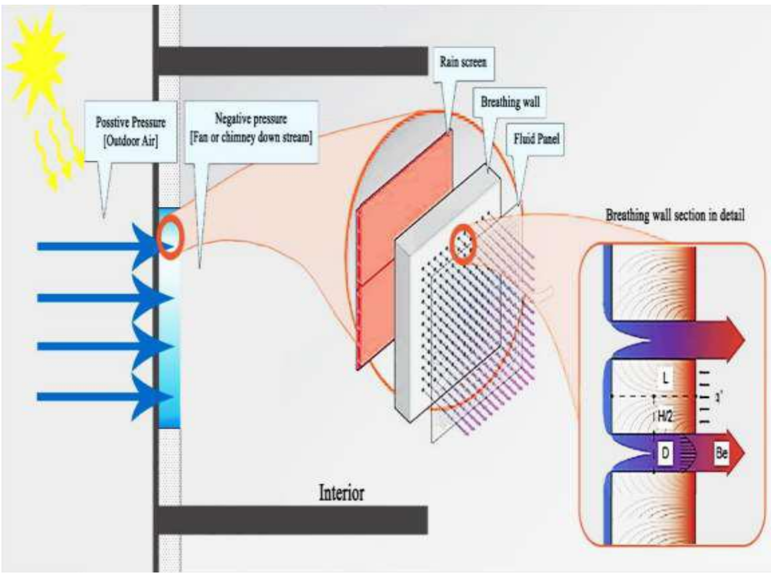


Figure 16. The different layers that make up a breathable wall.
Source: Craig and Grinham (2017).

Askel and Eric et al. (2019) made Phalanx, a complicated cladding system made up of many layers that are stacked on top of each other. The architecture of this system is based on how nature works, and it has three separate layers, each based on a different natural source. It is meant to be put on the outside walls of structures that are already there in coastal cities in Southern California (Figure 17.). The goal of this system is to:

- Reduce indoor temperatures passively without using electricity;
- Dissipate heat;
- Optimise passive cooling;
- Reduce reliance on air conditioning;
- Improve the energy efficiency of buildings;
- Achieve financial savings;
- Reduce the building's carbon footprint.

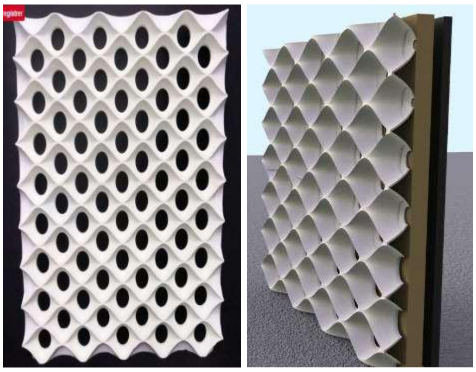


Figure 17. The Phalanx.
Source: Askeland et al. (2019).

Table 1: outlines the origins of the idea behind the creation of the Phalanx, inspired by various natural sources.

In 2014, Abu Khadra and Chalfoun sought to improve thermal performance, reduce energy consumption and create an efficient working environment by drawing on the human body's thermoregulatory mechanism. Their study was conducted on the south-facing façade of a 152.40 m² office space in Tucson, Arizona (hot climate), equipped with a single zone HVAC system, as Tucson's office buildings are usually cooled by mechanical systems and don't have access to natural airflow.
With this in mind, the proposed façade combines various techniques: natural ventilation, a double-skin façade, and a grid structure to support the outer skin and hold the shading devices in place. In addition, an evaporative cooling system is integrated in the form of pads positioned at the top of the system. A small electric pump supplies water to these pads, generating downward airflow that draws cool air into the interior space via the automated windows of the inner skin (Figure 18.).

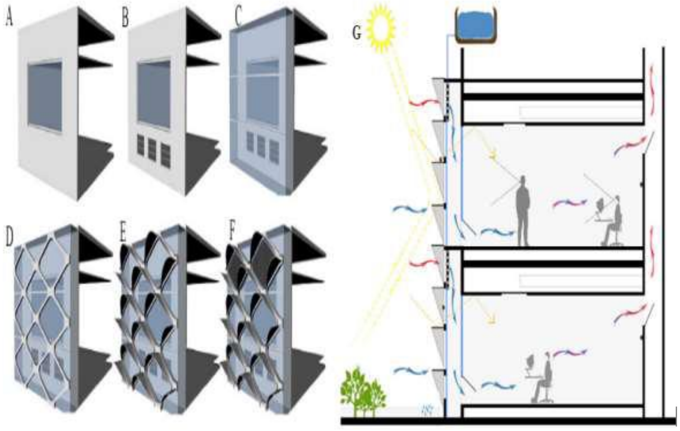
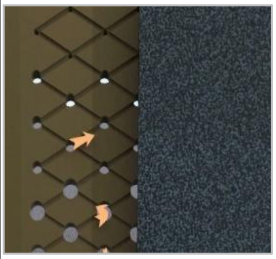
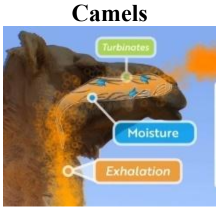
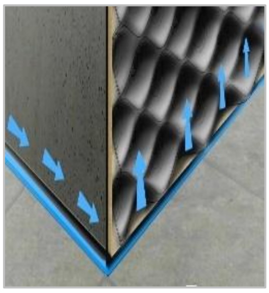


Figure 18. Design process: (A): actual case; (B): implementation of the natural ventilation system; (C): creation of the double skin; (D): installation of the support mesh; (E): creation of the sunshade; (F): implementation of the evaporative cooling system; (G): final building envelope.
Source: Abu Khadra and Chalfoun (2014).

The proposed facade has been shown to work by using passive cooling techniques in office buildings in hot, dry areas. These strategies aim to reduce energy consumption while promoting thermal and visual comfort. As a result, the cooling demand has been cut by about 70% over the course of the year, but the heating load has gone up slightly in the winter.

Table 1: Genesis of the idea of creating the Phalanx. Source: compiled by the author from the data presented by Askeland et al. (2019).

<table>
<tr><th>Layer</th><th>Source of inspiration</th><th>Level of inspiration</th><th>Mechanism</th><th>Architectural interpretation</th><th>Figure</th></tr>
<tr><td rowspan="2">External</td><td>Echinofossulocactus
</td><td>Morphological: The undulating ribs of Echinofossulocactus.</td><td>Its ability to scatter and reflect sunlight.</td><td>Undulating outer surface.</td><td rowspan="2"></td></tr>
<tr><td>Silver ant
</td><td>Morphological: The hairs of the silver desert ant.</td><td>These ants have a unique type of hair that reflects light 10 times better than ordinary ants.</td><td>The outer layer is white, reflecting the sun's rays.</td></tr>
<tr><td>Intermediate</td><td>Termite mounds
</td><td>Morphological: The presence of holes and tunnels in the termite mound of cathedral termites.</td><td>The tunnels and passages in the mound of the cathedral termites let hot air out through the top and cool air in through the bottom. This lets the colony provide natural ventilation, keeping the pressure and temperature inside and outside the mound in balance.</td><td>When hot air enters the inlet hole pattern in the first layers, it cools down due to the Venturi effect, which directs the hot air upwards and out of the system.</td><td></td></tr>
<tr><td rowspan="2">Internal</td><td>Camels

</td><td>Physiology: Nasal breathing.</td><td>The moist mucous membranes of the nasal passages humidify the warm air we breathe in. Before the air reaches the lungs, this process helps to lower the temperature of the blood flowing through the surrounding capillaries through efficient heat exchange.</td><td rowspan="2">Evaporative cooling is achieved using a wet capillary mat, the underside of which collects dew and also draws in greywater from the building's drainage system; the water then rises through the mat by capillary action and osmosis.</td><td rowspan="2"></td></tr>
<tr><td>Wheat
</td><td>Physiology: The mechanism of capillary action via the osmosis system in wheat plants.</td><td>Wheat leaves use capillary action to draw water into themselves; when they heat up, the leaves release the water to cool down.</td></tr>
</table>

3. Results and Discussion

Breathable walls have several key benefits, as outlined below:

3.1. Thermal insulation

Using thermal insulation, breathable walls help keep the temperature inside where you want it by letting in fresh, filtered air. This lowers the amount of heating and cooling needed, which makes the building more energy efficient overall (Gheznawy et al., 2020; Larsen et al., 2014).

3.2. Natural ventilation

Breathable walls have materials that are porous, which lets air flow naturally. This makes natural ventilation work better and helps make the inside spaces more comfortable and dynamic in terms of temperature. It also means that mechanical ventilation and air-conditioning systems don't have to work as hard (Elghawaby, 2013; Gheznawy et al., 2020; Rezek, 2015).

3.3. Moisture Management and Control

Moisture in breathable walls is managed due to a passage of water vapor through the wall while preventing liquid from entering into the wall. In this way, it prevents the formation of excessive humid conditions within an internal space, resulting in less likelihood of mold and/or condensation forming. As such, breathable walls assist in providing improved indoor air quality (Elghawaby, 2013; Gheznawy et al., 2020).

3.4. Air quality

The wall has an open structure that is conducive for natural ventilation (Gheznawy et al., 2020; Imbabi & Peacock, 2004; Stavridou, 2015), which helps to purify the interior atmosphere through the continuous renewal of air and reduction of pollution, thus contributing to a better and safer indoor living space and also limiting the presence of smells and harmful substances.

3.5. Improved thermal performance

The pores in the breathable walls regulate the temperature inside by controlling the amount of heat exchanged with the outside. The breathable walls can help control the temperature inside by controlling how much of that is exchanged with the outside because of the pores. That helps create a layer between temperatures so it can also improve indoor thermal comfort without using conventional insulating materials (Elghawaby, 2012; Gheznawy et al., 2020).

3.6. Thermal comfort

The fundamental goal of permeable walls is to keep the temperature comfortable. They achieve this goal by being able to keep a consistent temperature and control humidity, which makes the air inside better and makes the space healthier for the people who live there (Fauzi et al., 2024; Gheznawy et al., 2020).

3.7. Reducing energy costs

The walls that breathe can aid in regulating temperature and humidity, which will result in reduced cost for heating and cooling and improved performance on the energy of the entire building (Imbabi & Peacock, 2004).

3.8. Sustainability

Breathable walls are also environmentally friendly due to their use of natural and eco-friendly products and therefore assist in maintaining the structural integrity of a building while decreasing the environmental impact through reduction in carbon emissions (Gheznawy et al., 2020).

4. Conclusions

The paper reviewed systematically the literature for the topic "breathable wall," which was defined as a biomimetic technique that allows gas exchange similar to how it occurs in living things. Such walls have transcended the conventional method of designing walls by supplying fresh air and ensuring sufficient oxygen levels while dissipating excess heat and improving air quality indoors.

This is achieved through various configurations of breathable walls or breathable building envelopes, implemented using a range of techniques, including the use of new technologies such as smart materials, including thermobimetal, shape-memory alloys, pneumatic systems and piezoelectric materials, or in the form of processes allowing air to pass through a circuit subjected to a cooling mechanism before entering the building, with the aim of improving temperature, humidity and air quality by controlling gas exchange between the interior and exterior of the building.

All of this has enabled us to draw up guidelines for designers and architects to help them adopt these new techniques in building design while ensuring the well-being of occupants, maintaining a comfortable indoor climate, achieving thermal safety and energy efficiency, and reducing air pollution and the urban heat island effect in urban areas.

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