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A study of Climate-adaptive façade design for hot climates

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Abstract : The modern building envelope design focuses on building interior comfort optimization rather than just aesthetics. Modern building facades play major roles in regulating natural heat generated through solar radiation, thereby moderating the extents of thermal transfer into building. This function primarily promotes energy conservation, therefore making effective building façade designs an energy efficient option in sustainable building designs. This paper presents the option of a Double-skin climate-adaptive (DSCAF) façade (wall) design that will function like a barrier used to trap excessive heat radiated through the building walls in hot climates and utilizes the double layer to preserve the indoor cool conditions. A review of the evolution of modern active and intelligent building façades employed by designers over the years revealed the climate responsive concepts associated with these designs. Finally, the study presented an active design tectonics for a climate adaptive double skin façade (DSF) design. In order to identify the thermal control properties of this façade design, a simulation was conducted on the model using Phoenix-VR application. This revealed that the design reduced the thermal impact on the building façade by a significant margin as identified in the interior air temperature and internal façade values.

Keywords - **Double skin façade, climate-adaptive façade, climate-active design, energy saving, building skin, building envelope, building façade design.**

1. INTRODUCTION

1.1 Background of the Study

The climate of an enclosed space can be said to be a logical factor of the enclosure itself. The building fabric ranging from the floors, walls, roof covering and the other interior elements are put in building designs with the primary objective of altering the interior climate for the comfort of the human occupants. The building façade serves to separate the interior and the exterior environments and plays an important role in solar heat/gain management, thermal load control, air infiltration and ex-filtration, ventilation, noise control, design quality and aesthetic definition [1]. Traditionally, building envelope designers regarded the external skin as a barrier between the variable outdoor climate and the highly controlled interior environment, and the efficiency of the façade was measured by its ability to shield from the outdoor environment so that the indoor air system could be controlled or contained as efficiently as possible. However in recent times owing to technological development, newer concepts of facade design look at the building facade as a system (filter) which moderates between the external and internal environment [2].

The fundamental concept of façade design should be such that it achieves the goals that are critical and important to the particular context in which it is built in. For instance, the facades of buildings in hot climates would be different in their design, performance and appearance from the facades in the colder and temperate climates. Likewise, their design goals and needs would differ because of the extreme difference in the external climatic conditions and their appearance would vary because of the difference in the materials and construction technologies that are so different from country to country.

As the case maybe, contemporary building and façade designs in most developing countries are based on 'western' concepts of design, which in most cases completely ignore the climatic conditions of the vastly different zones that exists within the countries. There is very little concern shown for designing according to the climate, with indigenous materials, using passive design strategies to reduce energy consumption in buildings. The result is that the energy required for cooling in these buildings is phenomenal, leading to pressure on the overall energy resource.

Presently, there exist a number of strategies developed to use the potential of the façade as a major energy saving component in building design [3]. As the case maybe, fundamental goals of a façade in a hot or cold region is be to reduce solar heat gain or enhance passive solar gain and provide day lighting. There are now a number of strategies like using (changeable) external/internal shading devices, advanced glazing technology, passive/active ventilation systems, and double skin façade systems, by which these goals can be achieved.

Although double envelopes with cavities and other passive solar design ideas like the “Trombe” wall have been around for a number of years, the concept of double skin design has become analogous with explorations in transparent and glass architecture. It is becoming acclaimed as an environmentally responsible design strategy with major predicted savings in energy and life cycle costs. The double-skin façade principally refers to a pair of glass skins separated by an air-corridor. The air space between the two skins acts as insulation against temperature extremes, wind and sound and may also have shading devices, which may be controlled [4]. This design is said to incorporate the passive strategies of natural ventilation, day lighting and solar heat gain into the fabric of a building which form the key components with respect to energy efficiency and comfort.

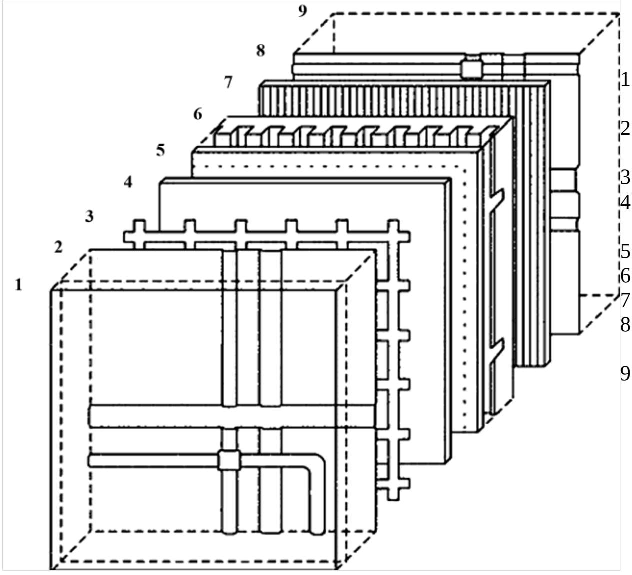
It’s a logical idea that the closer one is to a building surface, the more effect the surface temperature of that surface has on the individual. Also as one moves around a room space, so do the value of radiated temperature through the walls change with the new location. Fundamental reaction also expects that the closer one is to a warm or cold surface, the more effect that surface has on the individual. In theory, the value or extent of the coolness or the radiated heat that one experiences in an indoor environment is dependent on the quality of the building envelope [5]. Thus as long as the indoor air temperature and the inner (wall) surface temperatures stay within controlled limits by regulating the radiation through the external building façades, the related humidity value and the indoor airflow are parameters with secondary influence on the general indoor thermal comfort.

The significance of this study is geared towards achieving considerable relieve in terms of thermal sensation in residential buildings while at same time realizing energy saving objectives. It further discusses design ideas towards the development of an effective façade design that will tend to moderate the climate extremes thus improving the thermal quality at the indoor level for occupants.

1.2 Evolution and concepts of façade designs

The concept of innovative façade systems kicked off from the era of the Double Skin Façade (DSF), which evolved via efforts to upgrade the performance factor of Building skins/envelope. The Building envelope, here defined as the interface between the interior of the building and the outdoor environment [6], which in most cases acts as the determinant of the amount of energy used to heat, cool and or ventilate the spaces within. It is common idea that a more Energy-efficient envelope means lower energy used in the building-unit and its performance value must be adjusted as to ensure the desired conditions of its occupiers, in other words, the conditions of thermal and air quality. This could be listed as the basis on which to design room spaces and also of evaluating their performance [7]. The key fundamental challenge to most building façade designs relative to indoor comfort conditions is the climate of its environment. Also the performance of all Building envelopes is chiefly associated to this factor too, where the concept of building envelope in this case extends through the external building façade, its interior and exterior surfaces that can be used to store, release, control and distribute energy and by this further improving the overall efficiency of the building.

A typical double skin facade structurally consists of an external façade, an intermediate air space and an inner façade [8]. The outer layer provides protection against weather and acoustic insulation. The façade allows ventilation of intermediate space and also provides thermal insulation [9]. Overtime this gave rise to the development of intelligent building skins. The first expression of the principle of intelligence being applied to building skins was first proposed by Mike Davies of Chrysalis architects and Richard Rogers Partners in the design of the ‘polyvalent wall’, as shown in figure 1.



1. Silica weather skin and deposition substrate.
2. Sensor and control logic layer, external.
3. Photoelectric grid.
4. Thermal sheet radiator / selective absorber.
5. Electro-reflective deposition.
6. Micro-pore gas-flow layer.
7. Electro-reflective deposition.
8. Sensor and control logic layer, internal.
9. Silica depositions substrate and inner skin.

Figure. 1 Polyvalent Wall designed by Mike Davies [10]

The history of Double Skin Facades can be found in several books, reports and articles. In 1849, Jean-Baptiste Jobard, at that time director of the industrial Museum in Brussels, described an early version of a mechanically ventilated multiple skin façade. He mentions how in winter hot air should be circulated between two glazed panels, while in summer it should be cold air [11]. Below are two distinctive types, showcasing the trend of double skin façade concepts and application in building construction:

i. The double-skin façade can be identified earliest in the vernacular concepts of “Box windows”, one of the oldest forms of a two-layered façade. This consists of a frame with inward-opening casements. With single-glazed external skin opened to allow the access of fresh air and the outlet of exhaust air, thus serving to ventilate both the intermediate space and internal rooms [9]. The cavity in this case is divided vertically or horizontally to avoid transmission of sounds and smells from bay to bay and room to room, by this dividing the façade into smaller and independent boxes. It was used commonly in situations where there are high external noise levels and where special requirements are made in respect of the sound insulation between adjoining rooms. Each box window element required its own air intake and extract openings [9].

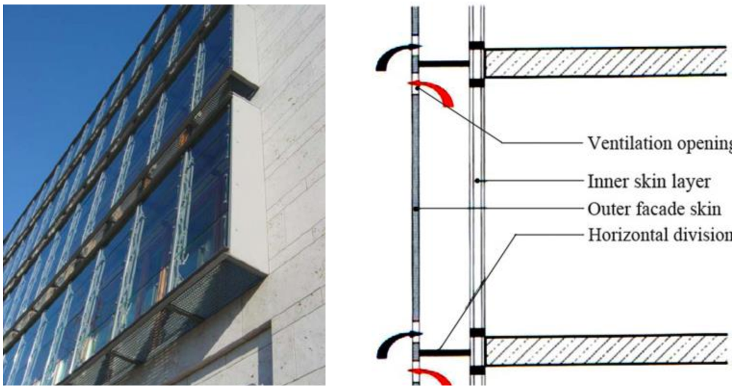


Figure 2. Image and detail of a Box window façade

ii. Another modern case of double skin façade application was the Occidental Chemical center built in 1978. Cannon design in association with HOK designed the Occidental Chemical Centre, also called the Hooker Office building. It can be regarded as the first modern instance of a glazed double skin façade incorporating the Le Corbusier's ideas in ventilation. Its 20cm cavity houses a system of louvers, grouped in banks. On each bank, a louver has a solar cell that registers when the sun hits it and reacts by tilting the whole bank out of the sun. Apparently, the louver system was designed to automatically rotate to control daylight entering the building, while the louvers collect radiation energy as the bank bounces the sunlight back. This results in a stack effect where warm air rises to the top where it is collected in cold weather and discarded on warm weather. The louver itself picks up the solar heat gain, which could be exhausted by the stack effect of the cavity if desired (in summer conditions). For insulation purposes the louvers would rotate to a closed position and provide additional R-value at night. The skin system used by Occidental is termed dynamic owing to its ability to change as a function of the time of year and time of day.

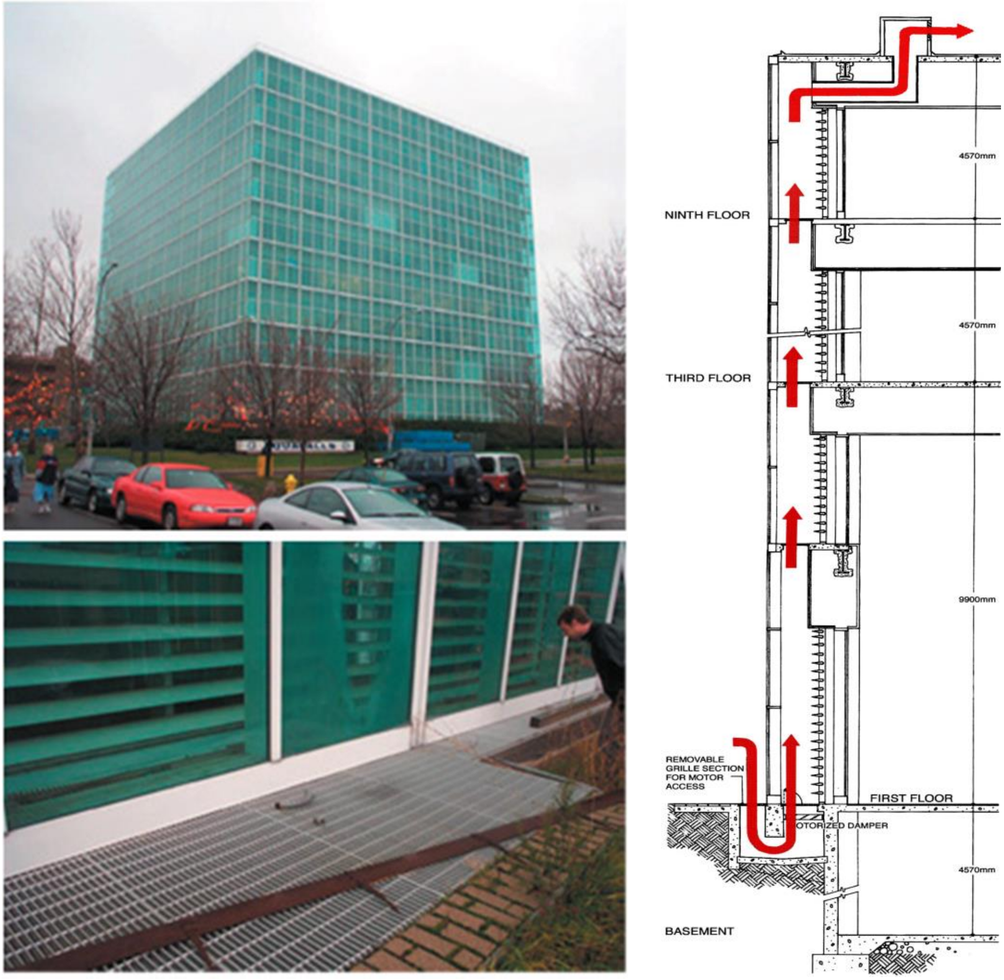


Figure 3. Detail of the Occidental Building [11]

2. TECTONICS OF BUILDING SKINS AND FAÇADE DESIGNS

In the light of energy and environmental problem currently besieging the modern built environment, the major objective of a building skin has altered from the fundamentals into that major goal of the reduction of energy consumption and energy expenses to a minimum, which involves moderating the environment around it. This requires a design of the building envelope as an element of a passive system with optimal performance in its control of heat, light and sounds [12]. Such a design of the building envelope will result in an increased performance of its passive system which in turn will reduce the load of the active systems. As a main determinant of the transmission of the physical factors, the major properties of the building envelope will depend on the following:

a. The surface properties of the skin elements (sound absorption coefficient, construction system, solar radiation absorption coefficient, etc.),
b. The cross-section properties of the skin elements (single or multiple layers, total mass, heat conduction coefficients of the materials, etc.)
c. The properties of the different components associated to the façade (door and window area, density, number of layers, total heat conduction coefficient of the component, etc.)

The optimal values of these parameters are the qualitative and quantitative framework for the building envelope design which will ensure the comfort conditions with respect to heat, light and sound control, as well as the highest performance of the façade system.

A typical concept is the Bio-tectonic principles in façade design for extreme climates. Using Nature as a Model, Animals and plants in their many life forms adapt to the conditions in the natural environment, in particular, to climate conditions. What is a matter of survival for them can be an important source of inspiration for architecture [13]. Today, numerous applications of the concepts of biology is being applied in architecture in the likes of; Bionics, Bio-tecture, Arcology etc. Looking from the perspective of an extreme climate zone; beneath their white, translucent fur, Polar bears have black skin. The hair of the fur guides the solar rays to the black skin, which is warmed by them. But the fur does not only transport sun to the body, it also acts as an insulating layer [14].

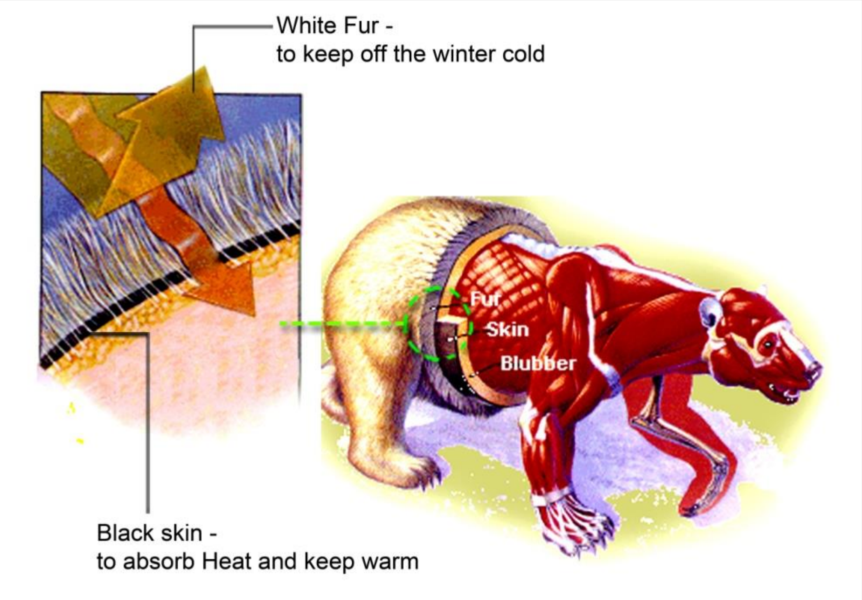


Figure 4. The Polar Bear skin structure.

The concept of the natural adaptive skin of some animals like the polar bear sheds some light into the principles of adaptive skin design. On the other hand, shell cased animals like the Tortoise and Snails (as seen in figure 5) that use their natural shell system as shield from dangers of all sorts, also conveys the idea of adaptability and changeability of façade. The changeable façade concept can be considered an effective idea in checking the diverse climate effects in HSCW buildings. This is mostly applicable in structures that have predominantly glazed façade fronts. Its function is dependent on a mechanical system of operating secondary shading devices attached to the skin which can be adjusted according to the demands of the climate. The success of a changeable façade can be dependent on the thermal factors of the material used for the adjustable system and the design method applied. In the past and presently too, the use of adjustable louver systems are seen to be the most maneuverable system for applying the adjustable member on the façade [11].

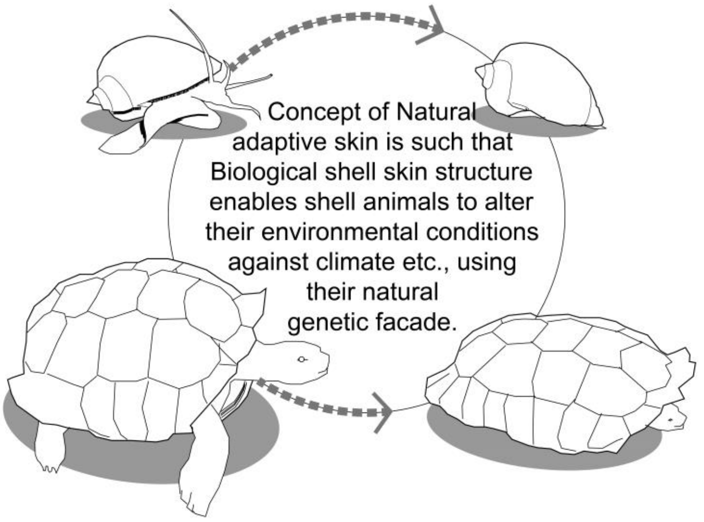


Figure 5. Concept of biological façade on shell organisms

This study presents a design scheme made to combine the changeable façade concept and the adaptive bionic concept in the Adaptive Shell Design of a 'Climate-active Smart house' (figure 6). This smart house was designed to mechanically adjust its shading skin when necessary (according to weather conditions).

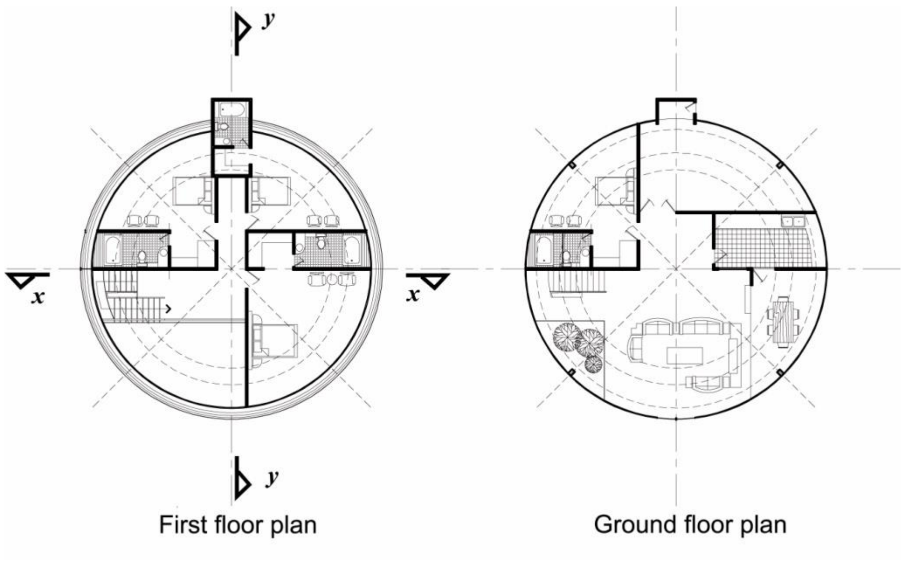
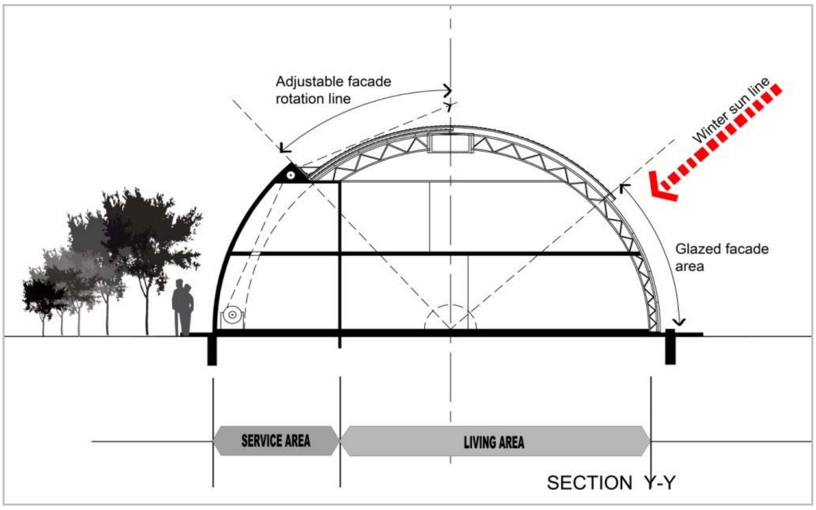


Figure 6 Climate-active Smart house design (floor plans)



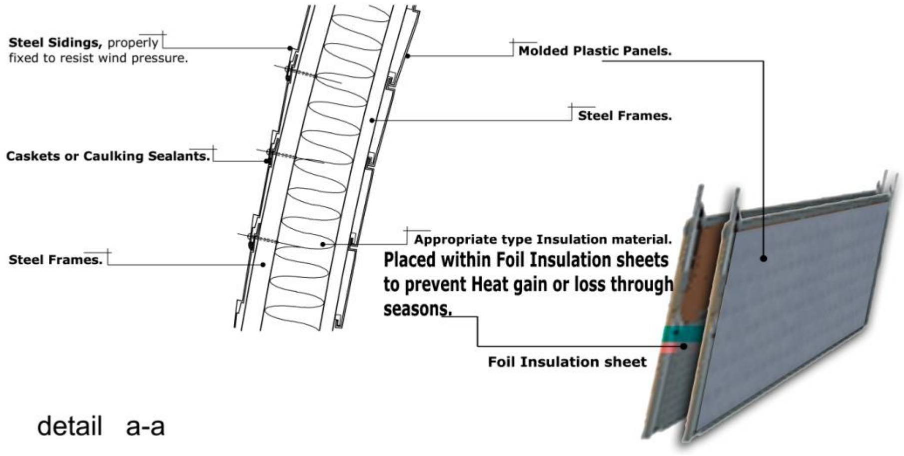


Figure 8. Climate-active Smart house design (section/detail of facade)

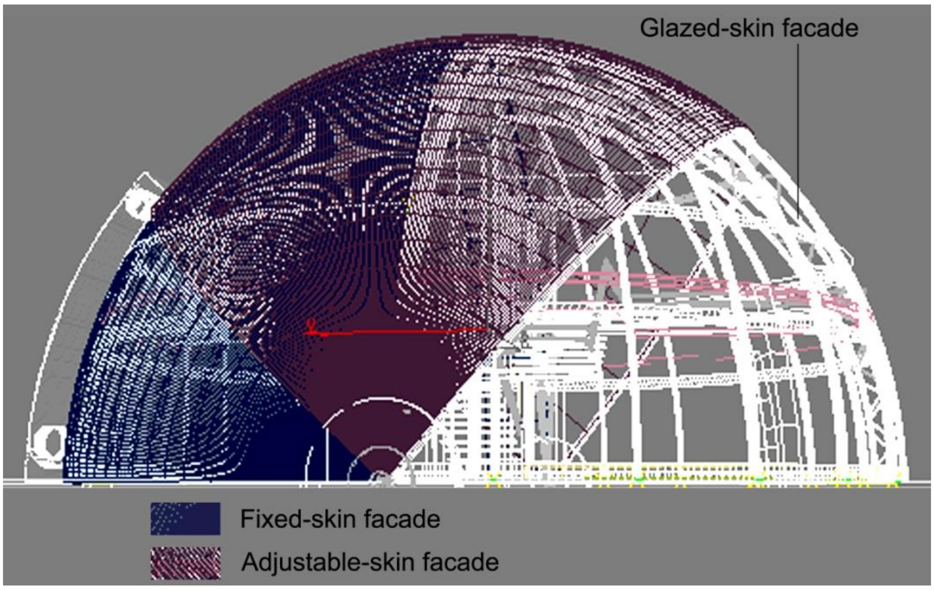
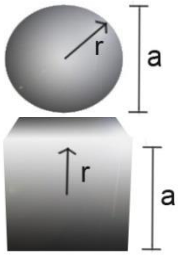


Figure 9. Its climate-active (x-ray view showing the façade structure)

In buildings, the correct design of the surfaces can be used to gain energy and to preserve heat. This is particularly important in regions, where temperatures extremes occur. The logical solution is in minimizing surfaces in order to keep undesired transmission heat gains or losses as low as possible. One useful value in determining an optimized building form for effective low surface area is the so-called ‘A/V-ratio’, which expresses the relationship between the heat-radiating surfaces of a building (A) and its volume (V) [15]. A low A/V-ratio saves costs and energy. A sphere by the composition of its form appears to have the best A/V-ratio. Since a sphere is not practical as a building form and poses problems for use due to intricacies in generating its plan, the half-sphere (hemisphere) comes closest to the ideal as a building shape being its reason for use in the Climate-active Smart house design. An instance is the igloo, which utilizes an optimum A/V-ratio and is particularly suitable for the climate conditions in cold regions [16].



Sphere: $V = \frac{4}{3}\pi r^3$ $A = 4\pi r^2$

Cube: $V = 8r^3$ $A = 24r^2$ $r = \frac{1}{2}a$

Figure 10. A/V ratios of curved surfaces (Spherical) and plane surfaces (Cuboid).

Table 1. A/V ratio-shape factor analysis

Shape	A/V Ratio	Shape to Surface factor	Design factor
Cube	Larger A/V ratio, maximizes surface exposure	The plane surfaces here imply more direct surface exposure to surrounding conditions.	Angular formed shapes are easier to design and construct and less expensive to build
Sphere	Lower A/V ratio, minimizes surface exposure	Curvy surface factor indicating less direct effects on surface from surrounding conditions.	Due to its non angular shape factor, involves some intricacies in design and construction hence, more construction cost.

2.1 Tectonics of Double skin facades and its Optimization theory of for improving performance

The design concepts of Double skin façade (DSF) designs is such that the double layers of envelope with a cavity space in form of an internal ventilation corridor that functions like a barrier used to trap excessive heat radiated through the building walls in hot climates and utilizes the double layer to preserve the indoor cool conditions. Numerous design features have been applies in the past and presently for the purposes of optimizing the DSF function. In as much as the external façade of the DSF is given major consideration in design due to its exposure to the external environment, the temperature of the inside surface of glazing systems needs to be taken into consideration too; as this surface is a source of infrared radiation during hot seasons. This problem can be solved if the surface temperature of the inner pane is leveled with the room temperature, improving the thermal comfort near the window [17]. However, this may not always be true especially when the façade is not inside ventilated, or when the glass temperature rises due to the reradiated heat absorbed by the shading devices. User comfort is also linked with the aspect of being able to control the rays with louvers/shades and the ability to control air movement with operable windows [18].

Studies identifies that optimizing the function of a DSF varies with different situations and these can be classified according to the form in which the intermediate space is divided and the nature of air flow within the space [17]:

2.1.1. Based on the origin of the air flow into the intermediate space the following should apply:

I. Supply: fresh outside air flows into the cavity
II. Exhaust: inside air flows through the cavity to outside.
III. Air curtain: air leaves the cavity the same side it came in (Figure 11 c and d]; there is no exchange between the air outside and inside (exterior and interior air curtain).

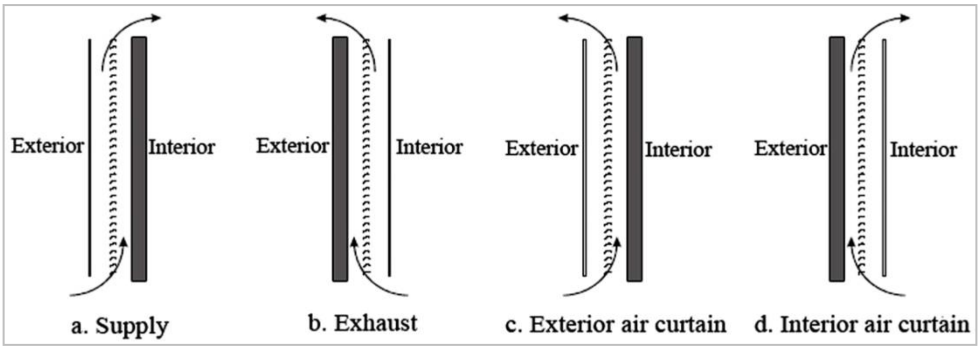


Figure 11. Optimization of DSF based on origin of air flow

2.1.2. Based on the driving force of the air flow of the façade:

I. Mechanically ventilated systems: In these systems air flow is generated by fans, making it much more controllable.
II. Naturally ventilated systems: Here, the driving forces are thermal buoyancy and wind pressure differences. In this case air flow rate is not a known quantity but depends on climatic conditions. However, this may not be very suitable for extremely hot climates and also where the temperature difference between the outside pane and inside space is not great enough to allow the stack effect to take place.

2.2.3 Based on compartmentalization of the cavity along the façade:

I. Buffer system: In this system, the two layers of skin are sealed, fresh air is allowed into the building through additional controlled means-either a separate HVAC system or box type windows which cut through the overall double skin.

Shading devices may be included in the cavity (figure 12).

II. Extract air system: This comprises of a second single layer of skin placed on the interior of a main façade of double-glazing. Air space between the two layers of glazing becomes a part of the HVAC system. The heated used air between the glazing layers is extracted through the cavity with the use of fans and thereby churns the inner layer of glazing while the outer layer of insulating glass minimizes heat transmission loss.

III. Twin face system: Consists of a conventional curtain wall or thermal mass wall system inside a single glazed building skin. Interior space of at least 500-600 mm is needed to permit cleaning. Openings in the skin allows for natural ventilation. The outer skin protects the air cavity contents from weather effects and blocks wind in high-rise situations allowing interior openings access to fresh air without associated noise or turbulence. Ventilation openings in the outer skin also moderate temperature extremes within the façade. Internal skin offers the insulating properties of minimized heat loss. Use of windows allows for night-time cooling of the interior thereby lessening the cooling loads of the building's HVAC system.

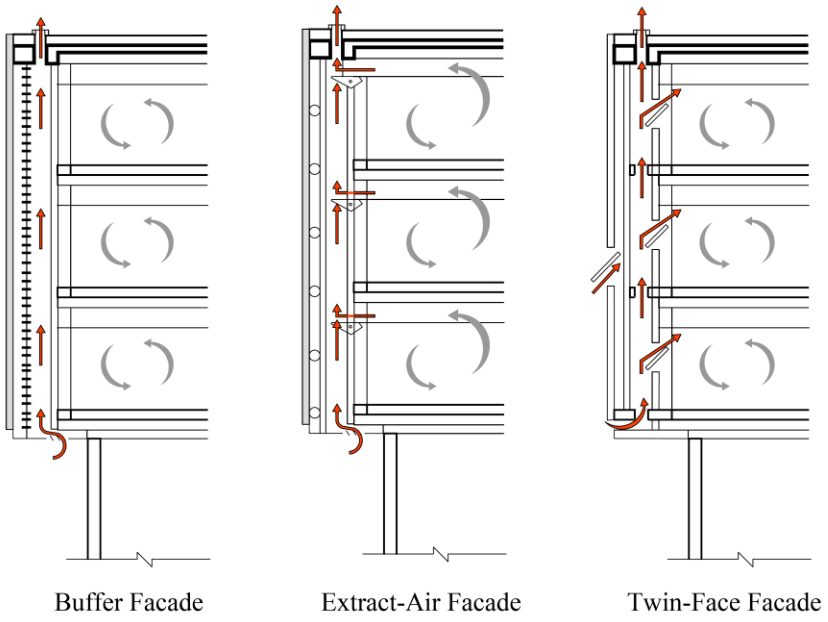


Figure 12. Optimization of DSF based on compartmentalization of the cavity along the façade

3. TECTONICS OF THE CLIMATE ADAPTIVE FAÇADE EXPERIMENTAL MODEL

Here, this report discusses the design model (figure 13, an experiment house) of a double skin climate-active façade and the analysis of its application in residential design. In concept, the design is a double solid wall system (figure 14). The model is an approximately 4.2m high by 12sqm sized building box with double layers of conventional brick inner wall (150mm thick) and exterior wall panel of sandwich type polyurethane-foam insulation wall of about 75mm thickness (comprising of 50mm thick polyurethane-foam board, coated on both sides with 12.5mm thick sandcrete mortar). The cavity space (air corridor) between the double layers is 700mm wide for the North facing walls and 800mm for the south facing façade and is finished with reflective coating to enhance the insulation ability of the cavity space. The south facing façade comprises of three cavity (air corridor) units. It has a glazed window area on the exterior skin for lighting and ventilation when necessary and a glazed door in the interior skin that opens into the central cavity unit. The cavity units are open-able at the floor level and roof level for passive ventilation of the cavity air in hot and sealed in cold weather. The experimental model was developed in order to justify the functionality of the components for physical application. Following the development of a design model for experimental purposes, the thermal performance of the model was performed using CFD tool in order to identify the potentials of the façade tectonics in mitigating thermal impacts on building facades in hot climates.

3.1 Methodology of analysis of the climate-adaptive façade model

The analysis of the façade model was conducted for a hot climate condition. For this purpose, a physical model was developed as seen in figure 13. Measurements of the façade thermal conditions were taken alongside the measurements of the cavity (air corridor) inlet air temperature. These external façade surface temperature and inlet temperatures were input as primary data to run the CFD simulation using the PHOENIX-VR modeling tool. The results generated from the runs, were presented in order to graphically reveal the thermal behavior around the model in figure 16.

Table 2. Values of physical measurements taken from the experimental model of the climate-adaptive DSF

FAÇADE	Cavity inlet air temp (°C)	Cavity outlet air temp (°C)	Cavity inlet velocity (m/s)	Cavity outlet velocity (m/s)	Façade surface temp (°C)
North	38	40	3.5	3.8	40
South	-	-	-	-	38.6

Figure 13. Pictures of the climate-adaptive double skin façade experiment model

3.2 Performance of the climate-adaptive façade model

During the hot weather, the outer skin made of high quality heat resistance insulation material (polyurethane-foam board with R-value of 5.8) reduces the heat gain (radiation) from the exterior while the cavity space in between the skins passively (or mechanically) ventilates the hot air that got through the exterior skin as shown in figure 14. By this process it achieves minimizing the overall heat gain by the interior skin; hence containing the indoor air temperature.

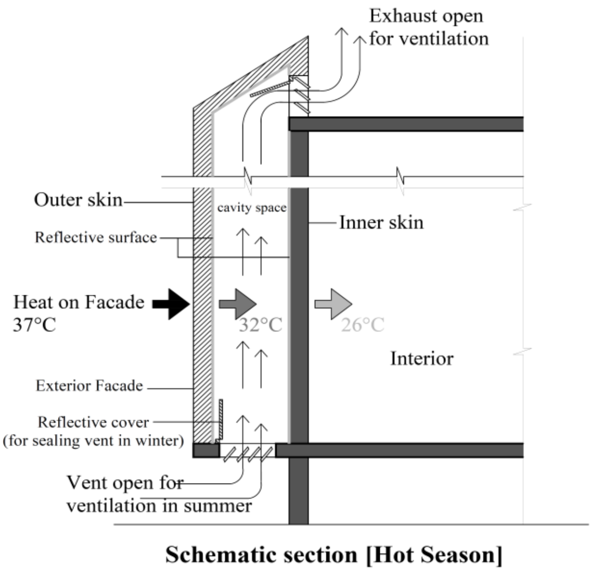


Figure 14. Detailed section of the climate-adaptive double skin façade model

The effectiveness of the climate-adaptive double skin façade was tested in the 3D model of the design using PHOENIX-VR CFD tools. The thermal behaviors were simulated as shown in figure 16. By imputing the key data for inlet air temperatures (38°C), inlet air velocities (3m/s) and the external wall surface temperature (N=40°C, S=39°C), the simulation results revealed a reduction in the internal wall surface temperature to an average of (33 °C). Likewise the cavity space air temperature showed a value of (36 °C), signifying the effectiveness of the cavity space in reducing the excessive heat radiated through the building walls. The final indoor air temperature recorded an average value of (31°C), which is a significant drop from the cavity air temperature. These results demonstrate the thermal control properties of the climate-adaptive DSF.

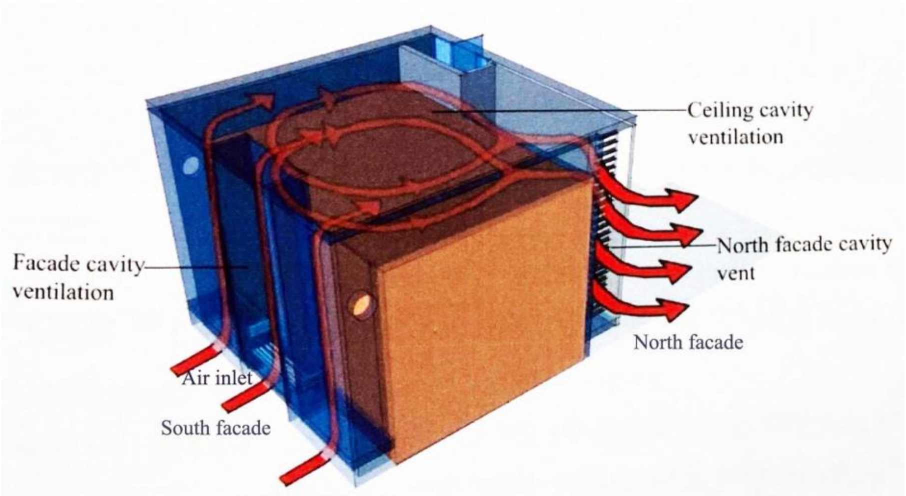
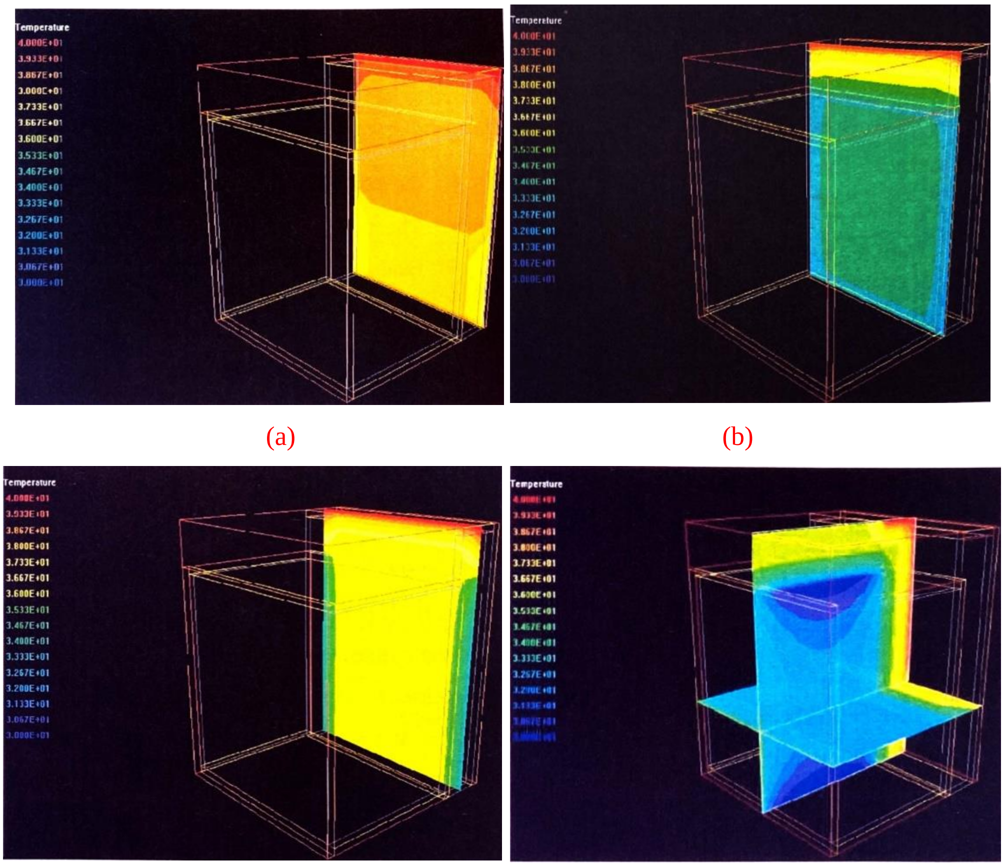


Figure 15. X-ray view of the climate-adaptive DSF, showing the air inlet and vent points



(a) (b)

(c) (d)

Figure 16. Results of the simulation of thermal behaviors in the climate-adaptive DSF.
(a) External wall surface temperature, (b) Internal wall surface temperature, (c) Cavity air temperature, (d) Indoor room air temperature.

4. CONCLUSION

In this study, the relevance of building envelopes in controlling and moderating the thermal conditions in building interior spaces was analyzed. Through the analysis of the climate-adaptive double skin façade model, this paper revealed that the design reduces the thermal impact on the building façade by a significant margin as identified in the interior air temperature and internal façade values. With the idea of natural concepts like solar radiation through the exterior skin, convection in the cavity area creates high stack effect that assures hot air is exhausted by natural ventilation before getting to the secondary skin, which leads to energy saving in cooling needs during the hot seasons. The overall performance of this system can be improved by building and indoor space orientation which if rightly managed and effectively considered in building design, can improve the value of energy conservation and management.

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