Open Journals of Environmental Research (OJER)
ISSN: 2734-2085
Article Details:
DOI: 10.52417/ojer.v5i2.782
Article Ref. No: OJER0502003-735
Volume: 5; Issue: 2, Pages: 32 – 46 (2024)
Accepted Date: December 30th, 2024

Open Journals Nigeria (OJN)
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REVIEW ARTICLE **OJER0502003-735**

EVALUATION OF VENTILATED CAVITY WALL DESIGN FOR PASSIVE COOLING OF INDOOR SPACES.

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ABSTRACT

The function of building facades includes the regulation of solar-radiated heat. It also includes regulating the ranges of heat transfer from the exterior to the interior of a building. The primary functions of building facades promote energy conservation, hence making the art of façade design a vital energy-efficient option in sustainable building. The concept of a ventilated cavity wall is presented in this paper as an option that functions as a barrier for trapping excessive heat radiated naturally through building envelopes, while at the same time utilizing ventilation of the cavity space in its double layer to control the heated façade through aeration of the cavity space. A review of modern active multi-skin façade systems adopted by designers reveals the climate-responsive ideas associated with double-skin facade designs. This study emphasizes the function of the ventilated cavity wall as a climate-responsive system that passively enables the cooling of indoor spaces. For this purpose, a study of a sample of this design was conducted to ascertain the thermal control properties. The study includes an experimental evaluation and thermal simulation of the sample model using the Phoenix-VR application. The results of the interior air temperature and internal façade cavity conditions reveal that this façade system may substantially reduce the thermal effect on building walls. This is seen in the significant decrease of the indoor room temperature by up to 5°C compared to the cavity air temperature. The result provides a good premise for designers to adopt the principles of the ventilated cavity wall system in building designs. For application, residential homes that adopt the ventilated cavity wall option may further improve indoor thermal conditions through whole building orientation or by indoor space orientation. The indoor spatial orientation if properly managed during the building design process may add to the energy conservation potential.

Keywords: *Circulation configuration, Flow patterns, Hospital design, Principles of circulation, Visibility graph analysis*.

INTRODUCTION

Building fabrics like walls, floors, roofs, and various internal elements are often placed in buildings mainly to influence the interior climate of the building spaces. For this reason, façades of buildings serve as separators between the internal space and the external environments. The role of building facades also includes air infiltration, air ex-filtration, solar temperature management, ventilation, thermal load regulation, noise control as well as design aesthetics (Kamal, 2020). Generally, designers of building envelopes consider the external building envelope as barriers that bridge the conditions of the regulated interior environment and the fluctuating outdoor climate. Based on these, the effectiveness of a building façade is determined by its ability to shield against outdoor environmental conditions, to allow for the effective control of the indoor air system. Conversely, owing to advancements in recent technology, the modern concept of facade designs practically regards building façade systems as filters that regulate internal space conditions and the external environment (McClintock *et. al.* 2003; Yaman, 2021; Sultan, 2023).

Modern building façade designs found in most of the developing countries around the world are often attributed to Western architectural concepts. These concepts in most cases disregard the indigenous climatic conditions of the building's location thereby triggering unfavorable impacts on the building and its occupants. This culture and actions are often noticed in the insignificant concern observed in design relative to the climate, appropriate materials, and adoption of passive design strategies that should be targeted towards the reduction of energy consumption. The resultant effect of this is reflected through the high energy demands for indoor cooling, leading to huge pressures on economic and energy resources. This paper therefore seeks to identify a façade design system that may counter the climate-related concerns that are indigenous to tropical environments.

Research identifies strategies targeted toward the innate potentials of the building envelopes and façade systems as significant for energy saving in buildings (Saelens, 2008). Notably, the fundamental aim for adopting building façades in any region (hot or cold) is the reduction of solar heat gain, enhancement of solar gain, and provision of daylighting. The concept of ventilated facades and multi-skin facade systems is picking up in many countries, especially in European regions. The concept of multi-skin facades has been practiced for years, however, the design idea of this system on its own is currently affiliated with the adoption of glazed or transparent architecture. Conventionally, the features of a double-skin façade system are typically referred to as a pair (or more) of glazed panels that are separated using a cavity space referred to as air-corridors. This air space within the glass panels performs the functions of thermal insulation, sound insulation, and wind resistance with regular application of controlled shading devices for improving thermal control (Yaman, 2021).

Concept of the Ventilated Cavity Wall

Most intelligent building skin systems known in modern times, originated as double-layered facades. These façade types consist of three components that include an external façade layer, followed by the intermediate cavity (air space), and finally an internal façade layer. The primary function of the outer layer includes protection against natural weather conditions, as well as acoustic and thermal insulation. On the other hand, the design of the façade is crafted to allow for ventilation of the intermediate cavity layer, either by passive or active means (Oesterle, 2001).

The concept of double skin construction had existed earlier in the form of traditional applications, but Mike Davies produced the first demonstration of the principle as an intelligent application to building skins through his design of the ‘polyvalent wall’ shown in Figure 1. In his article published in the RIBA journal (A Wall for all Seasons), regarded as the foremost documented manifestation of the concept of intelligent building skins, he suggested several ways that glass could be used in buildings (Davies, 1981). This concept has now evolved through the emergence of new technologies.

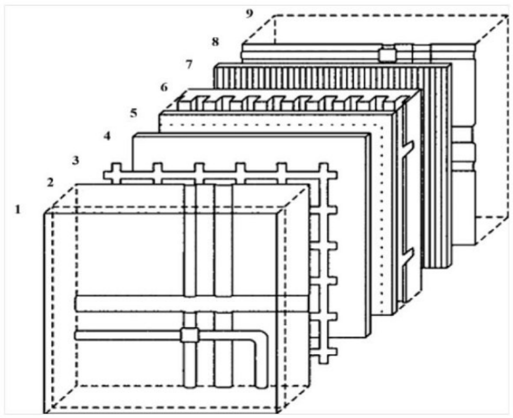
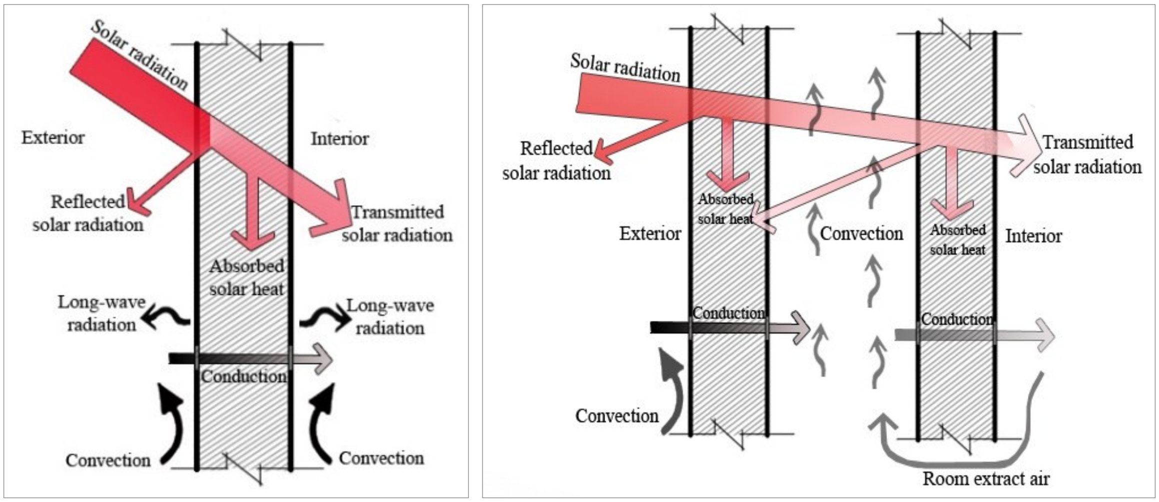


Figure 1: Polyvalent Wall concept
(Source: Saelens, 2003)

Amongst the major ideas borne by the foremost users of multi-layered façade system, includes its ability to control ambient climate conditions, for the sole purpose of improving indoor thermal comfort. However, owing to the huge fluctuations in temperature conditions between seasons, which pose different actions on the façade system, the design efficiency transformed the expected advantages of the façade system into a disadvantage when attributed to energy efficiency. Several design features have been applied to the facade system to optimize its function for energy-saving. Optimizing the design includes considerations towards improving the external façade of the double skin system owing to its exposure to the outdoor environment. When this occurs, the temperature of the internal surface then becomes a subject of concern, because any glazed surface is a basic source of infrared radiation during the hot seasons. Studies suggested that the challenges of the application of the glazed systems could be solved if the inner pane surface temperature of the glazed double skin façade is leveled with the indoor room temperature (Arons, 2000). However, this solution option is considered ineffective especially when the façade system’s cavity layer is not a ventilated type, or if the glazed panel temperature rises owing to heat transmitted through elements like shading devices (Khoshbakht, 2017). Factors that affect the functions of this façade system include natural occurrences like forms of heat transfers (Safer, 2005), direct radiation, conduction, convection, and air infiltration (figure 2).

In the case of direct solar radiation, this is determined by the heat gain coefficient, which is defined as the proportion of the solar radiation transmitted through a façade, absorbed through the system, and subsequently released inwards to the interior space. This heat gain coefficient through solar radiation is required to determine the heat gain through a facade. Equally for thermal convection where heat gain through solar radiation is transferred through the movement of air, the application of a transit layer for trapping air to receive the thermal gains becomes significant. The interplay of conduction and movement of air (figure 2) in the cavity space creates temperature variations. These changes in temperature and air movements thus form a pattern that is significant in designing ventilated facade systems (cavity walls).



(a) (b)

Figure 2: Heat transmission (a) through Single-skin walls, (b) through Double-Skin facades
(Source: Mohtashim *et. al.* 2022)

Another factor that influences thermal transfer through double-skin facades is the air infiltration process (Roig, 2023). The process of air movement causes the flow through the façade owing to wind forces (Fayed, 2019), (Hensen, 2007). The air pressure forces cooler air in through openings (inlets) on the windy side and through buoyancy effects, it draws heated air out of the opposite side (outlets) as seen in Figure 3. This process is required in the ventilation of the cavity air space in the ventilated (double skin) wall (Pelletier, *et. al.* 2023).

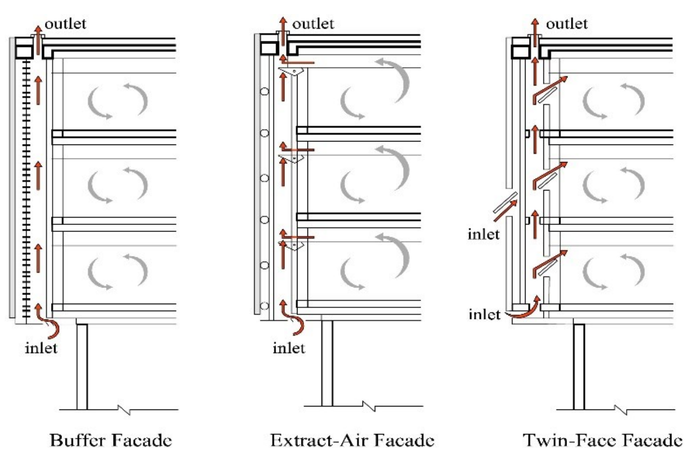


Figure 3: Air infiltration process in three different double-skin (ventilated) façade configurations
(Source: Boake, 2003)

This study reviewed the various concepts adopted by the original designers of double skin façades, which utilized the cavity wall ideas. Having examined the theoretical concepts and principles that affect the application of the ventilated façade system, two major concepts are identified including a traditional/conventional concept and modern concepts applicable in hot and cold climates.

Traditional Concept

The concept of double-skin façades could be attributed to the earliest traditional concepts of Box windows (figure 4), which are amongst the oldest forms of two-layered façade applications (Memari, 2022). The box window concept comprises a frame that houses a casement system that opens inwardly. This casement system is combined with a single external glazed skin that opens to allow the flow of fresh air, as well as permit the outflow of exhaust air, thereby serving the purpose of ventilating both the intermediate cavity space and the indoor spaces (Oesterle, 2001; Pelletier *et. al.* 2023). According to the design, the cavity space can be partitioned horizontally or vertically to prevent the passage of smells and sounds from one space to another, thus dividing the façade structure into smaller boxes. Each of the components of the box window system required individual air intake and extract openings for ventilation of the air cavity space.

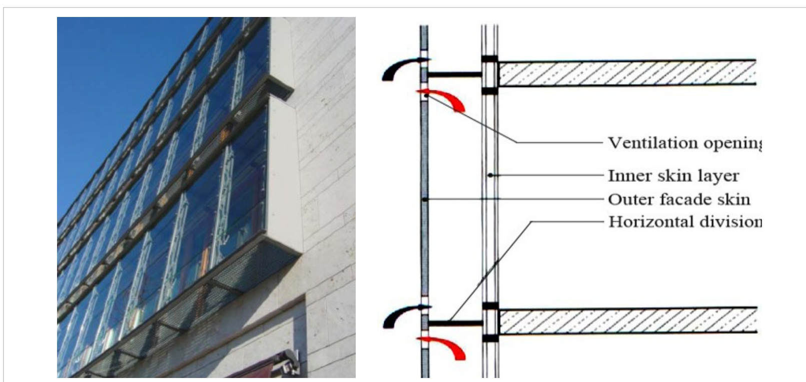


Figure 4: Function of a typical Box window façade
(Source: Oesterle, 2001)

Modern Concept

The first documented concept of a modern double skin façade was the Steiff Factory in Giengen Germany designed by Richard Steiff (Tascon, 2008). The three-story building comprised welded T-sections that made use of cleats fixed to the internal and external sides of the building's columns. The T-section framework was then used as support for the layers of the double skin, thereby creating a cavity space of 25cm in between the two layers. The building which is still in use today as a museum was viewed as a success story for double-skin facades (Figure 5).

Figure 5: The Steiff Factory Museum as it is in present day
(Source: Tascon, 2008)

Similar to the Steiff Factory building, Le Corbusier adopted a second glazing skin in his Swiss 'Villa Schwob' house called the La Chaux de Fonds (Tascon, 2008). It consists of large double-layered windows intended to function across two complimentary building systems as follows:

- One system to generate respiration exaction, with a carefully controlled mechanical ventilation system,
- One neutralizing system consists of walls made of glass, stone, or a combination of forms comprising two membranes with a cavity space between the two layers (Bryan, 1991).
- Within the cavity space and subject to outdoor climatic conditions, the design intends to allow the flow of hot or cold air to ensure that the temperature of internal room spaces is maintained at 18°C (Wigginton, 2002).

Another early adoption of the modern double skin façade system is seen in the case of Occidental Chemical Center designed by Cannon and HOK in 1978. This is seen as the foremost case of double skin façade that incorporated ventilated cavity systems originally introduced by Le Corbusier. It is comprised of a 20cm ventilated cavity unit housing a combination of louvers which are assembled in tiers. Each tier of the louver compartment contains a solar cell used to register solar impacts that sets up a reaction that enables the redirecting (tilting) of the entire compartment away from the sun's path (Boake, 2001). The louver system collects radiation energy when the compartment reflects the sunlight, resulting in stack effects, whereby warm air rises above the system to be stored in colder weather or removed as exhaust in hot weather as shown in Figure 6.

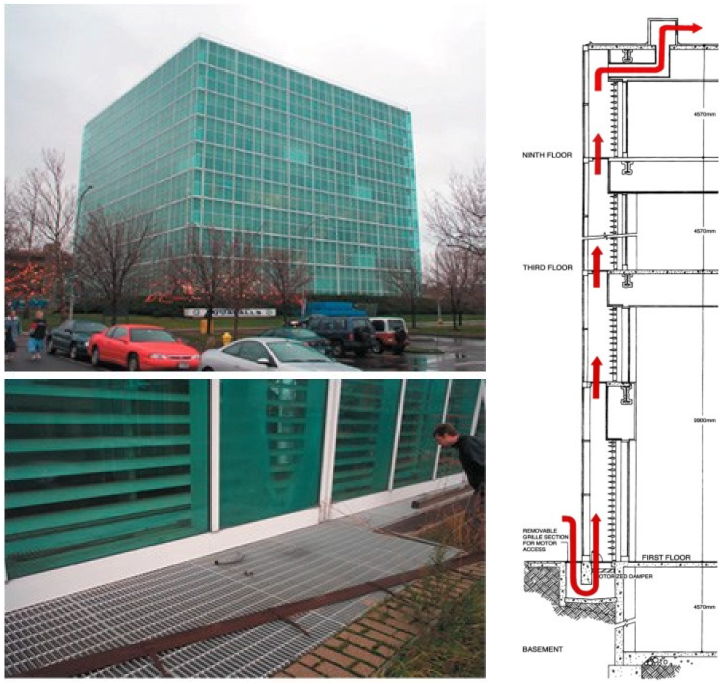


Figure 6: The Occidental Chemical Center by HKO
(Source: Boake, 2001)

Design of Ventilated Cavity Wall Model

For this study, the author developed a physical model (figure 7). It comprises two exterior wall panels with the cavity (air corridor) for ventilation of the cavity air. The study model is 4.2m high and 12 m^2 in area. The building box comprises a double-layer wall system. While the inner layer is made of conventional bricks 150mm thick, the outer layer on the other hand is made of a 75mm thick sandwich polyurethane-foam insulation panel. The sandwich panel comprises a polyurethane foam board (50mm thick) which is coated on each side with cement mortar (12.5mm thick). Between the two layers lies the cavity compartment which is a 700mm air corridor finished with a reflective coating that is intended to boost the thermal insulation capacity of the cavity. A glass window is added on the outer layer for natural lighting and passive ventilation access. Also, a glazed door is fitted on the inner layer and opens into the central cavity/air corridor. The cavity compartments can be opened at both the floor (inlet) and roof (outlet) levels to ventilate the cavity space through buoyancy or stack effects as seen in Figure 8.

Figure 7: Images of the Ventilated Cavity Wall experimental model
(Source: Author’s physical model)

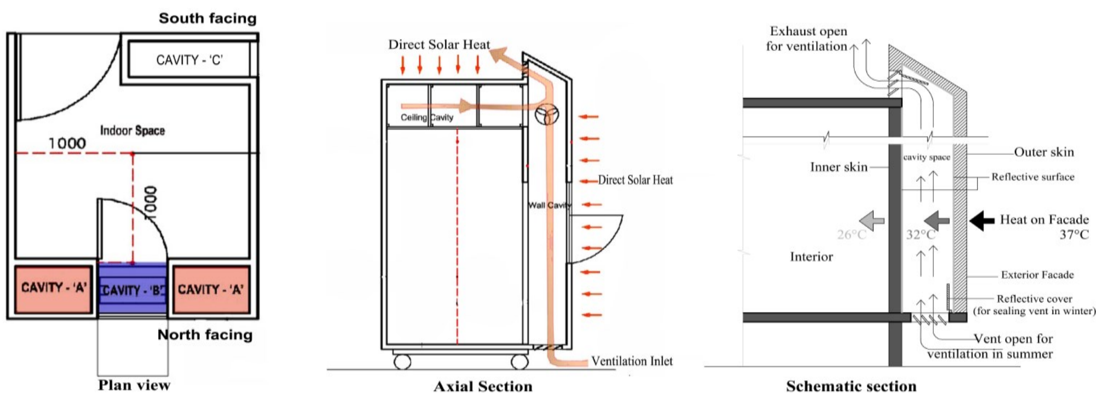


Figure 8: Details of the Ventilated Cavity Wall design model
(Source: Author’s design details)

Methodology for Analysis of the Experimental Model

An analysis of the ventilated cavity wall model was conducted to ascertain the performance in hot climatic conditions. This experimental study is performed on the physical model built with the details mentioned in Figure 8. Firstly, the thermal conditions of the façade were measured alongside that of the cavity air temperatures. These measurements were taken at different locations of the experimental model as follows:

1. Façade surface (North-facing)
2. Façade surface (south-facing)
3. Façade cavity air space (North facing), when inlets/outlets are active/inactive

4. Façade cavity air space (South facing), when inlets/outlets are active/inactive
5. Cavity air intake velocity (inlet point m/s)
6. Cavity air exhaust velocity (outlet point m/s)

Records were taken at intervals at all the locations stated above from 6:00 am to 12:00 am using a DT600 Data taker and infrared laser thermometer (temperature/humidity measurement tools). The data logging instrument measures Air Velocity/Volume, Temperature, and Humidity. It stores up to 12,000 readings for data analysis. Its Reliability capacities are as follows:

- Velocity (MPS: meter-per sec) 0.1 to 20m/s.
- Air Velocity Accuracy: +/-3% +0.2 m/s, with response time of 1 second
- Air Volume: 0 to 99,999 CFM
- Temperature Range: 0-60 degrees C.
- Temp. Accuracy: +/- 1.1 degrees C.
- Relative Humidity Range 0.1 to 99.9%
- Humidity Accuracy: +/-3%

The mean values obtained (as shown in Table 1) were then input as primary data while ignoring other values (like humidity) and used to run a CFD (computer fluid dynamics) simulation using the 'PHOENIX-VR' modeling tool. These results obtained from the CFD analysis are presented to identify (graphically), thermal conditions within the experimental model. This procedure can be adopted during the design process of real-time buildings to predict the thermal conditions of this façade system (Wang, 2016).

Table 1: Values taken from physical measurements in the Ventilated Cavity Wall experimental model

Façade Direction	**Cavity temperature (inlet ^oC)**	**Cavity temperature (outlet ^oC)**	**Cavity inlet velocity (m/s)**	**Cavity outlet velocity (m/s)**	**Façade-surface Temperature (^oC)**
North facing	38.0	40.0	3.50	3.80	40.0
South facing	37.0	38.0	3.0	3.50	38.60

Analysis and Discussions of the Experimental Model

The study of the model identified the extent of the function of the ventilated cavity wall model. As the external conditions (outdoors) heats up, the outer skin of the double skin wall heats up as well. However, owing to the presence of the heat-resistant insulation material, which is the polyurethane foam board that has an R-value of 5.8 (signifying high thermal retaining value), the thermal gain (through outdoor solar activity) is reduced. Furthermore, the cavity air space in between the double skins which is ventilated from below (inlet region) passively ventilates the warmed-up air inside the cavity space (figure 9). Through the process of air filtration (via buoyancy), the air flows upwards and exits via the outlet aperture. This process minimizes the overall heat gain by the exterior layer before getting to the internal layer of the skin, thereby containing and preventing the heat gain from getting to the internal room spaces.

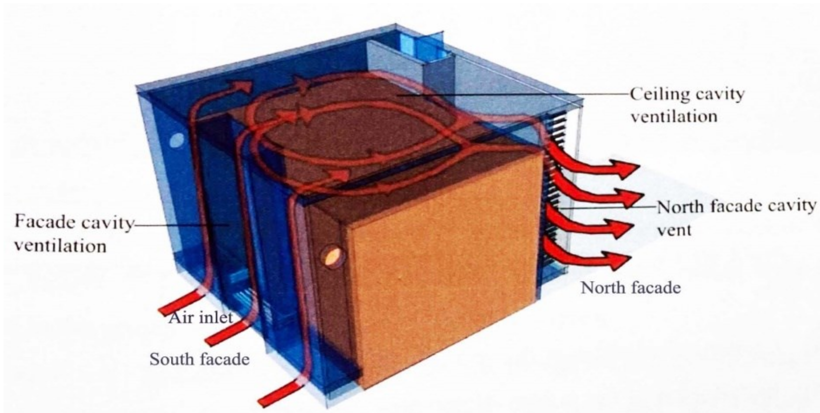


Figure 9: An X-rayed view of the Ventilated Cavity Wall showing the process of ventilation through the inlet and outlet vent points

(Source: Author's sketch)

The experiment conducted for the first part of this study was to identify the impact of the ventilated system when active (the cavity space is ventilated) and when inactive (closed system). As seen in Figures 10 and 11, the process of ventilation (with the opening of the inlet and exhaust vents), permits airflow which reduces the cavity air temperature significantly. This could be observed at the peak of the heated conditions with the external surface indicating 39ºC and the internal layer indicating 34ºC. The internal cavity air temperature in this case recorded 37ºC against an outdoor temperature of 40ºC indicating a significant drop of about 3ºC between the temperatures of the outdoor air and cavity air. However, in the case of the closed ventilation system, the external surface indicated 38.5ºC and the internal layer indicated 37ºC. The internal cavity air temperature in this closed vent scenario recorded 38ºC against an outdoor temperature of 39ºC, signifying a drop of only 1ºC between the temperatures of the outdoor air and cavity air.

The differences observed in the open vent (ventilated wall) with a 3ºC improvement and the closed vent wall with only a 1ºC improvement show the significant impact of the ventilated cavity wall when active.

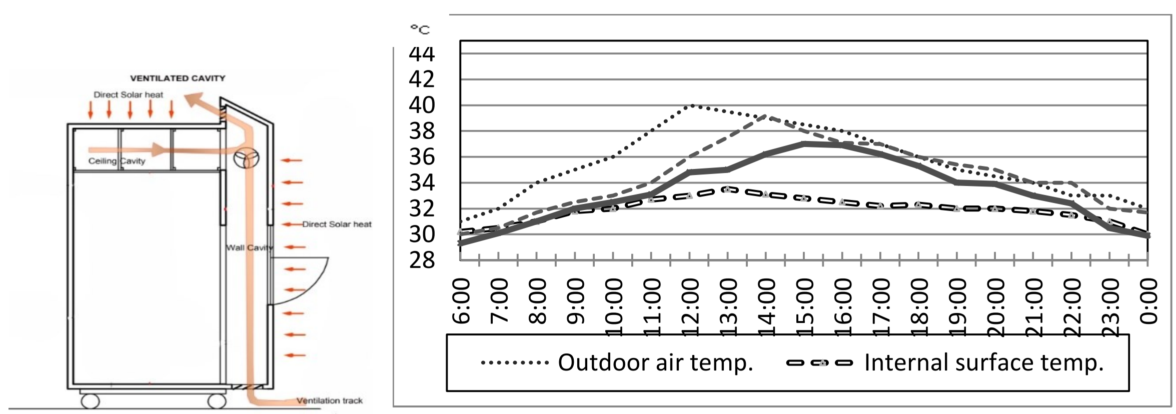


Figure 10: Analysis of the ventilated cavity wall model (north facing) when ventilated with open inlet and exhaust.

(Source: Author's experimental results)

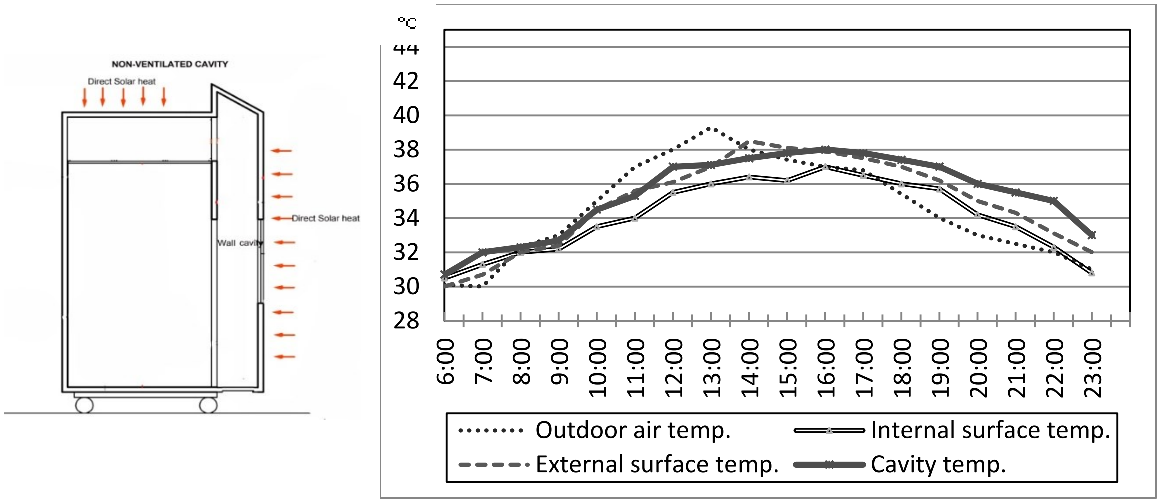


Figure 11: Analysis of the ventilated cavity wall model (north facing) with Closed-vent and exhaust (Source: Author's experimental results)

After acquiring the key data from the measurements, the external wall surface temperatures for the north and south-facing walls, the air temperatures of the inlets into the cavity space, and inlet air velocities were inputted into the PHOENIX-VR CFD modeling tool for the simulation of the thermal conditions (Figure 12 and 13). Despite an external surface temperature of about 38ºC and 40ºC, the simulation results indicated a significant decrease in the ventilated cavity wall's internal surface temperature to an average of 33ºC. Similarly, the ventilated cavity space air temperature recorded a value of 36ºC, which signifies the optimistic impact the ventilated cavity space has in the reduction of heat gained via the eternal facades. Conversely, the air temperature of the indoor space indicated a mean value of about 31ºC, showing a substantial reduction from the cavity space's (36ºC) air temperature. The results from the experiment when compared to that of the simulation, demonstrate the thermal control qualities of the ventilated cavity wall system.

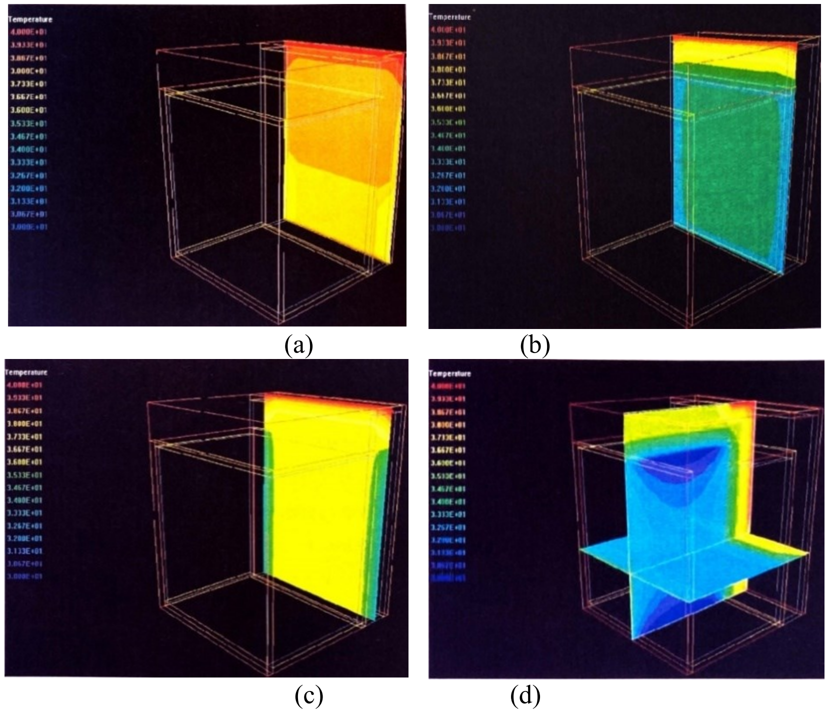


Figure 12: Results from the simulation of the thermal conditions in the north-facing ventilated cavity wall. (a) External wall surface temperature, (b) Internal wall surface temperature, (c) Cavity space air temperature, (d) Indoor room air temperature.

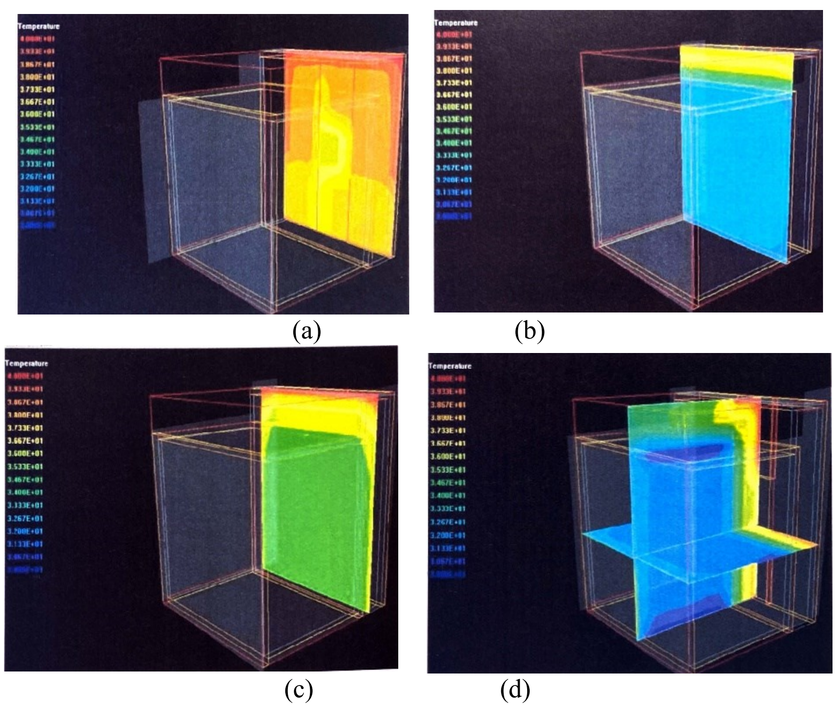


Figure 13: Results from the simulation of the thermal conditions in the south-facing ventilated cavity wall. (a) External wall surface temperature, (b) Internal wall surface temperature, (c) Cavity space air temperature, (d) Indoor room air temperature.

Design Application of the Ventilated Cavity Wall

Following the results of this study, various configurations can be adopted for the application of the ventilated cavity wall in building the design. The foremost consideration in the decision for its application is the building orientation, to exploit the use of natural wind-driven ventilation for activating the cavity airflow. Other options include the addition of mechanical vents at the exhaust points of the façade to raise the airflow rate of the ventilation process. Figure 14 presents the configurations that can be adopted in the design of buildings using this façade type.

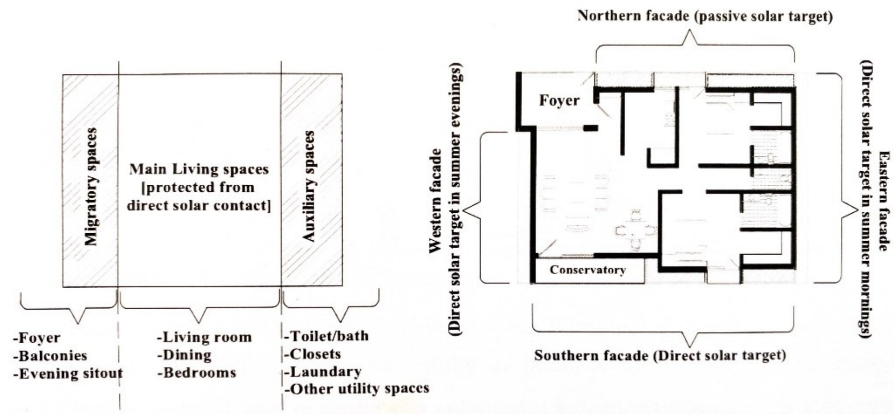


Figure 14: Schematic concept for spatial distribution within an apartment unit adopting the ventilated cavity wall façade system

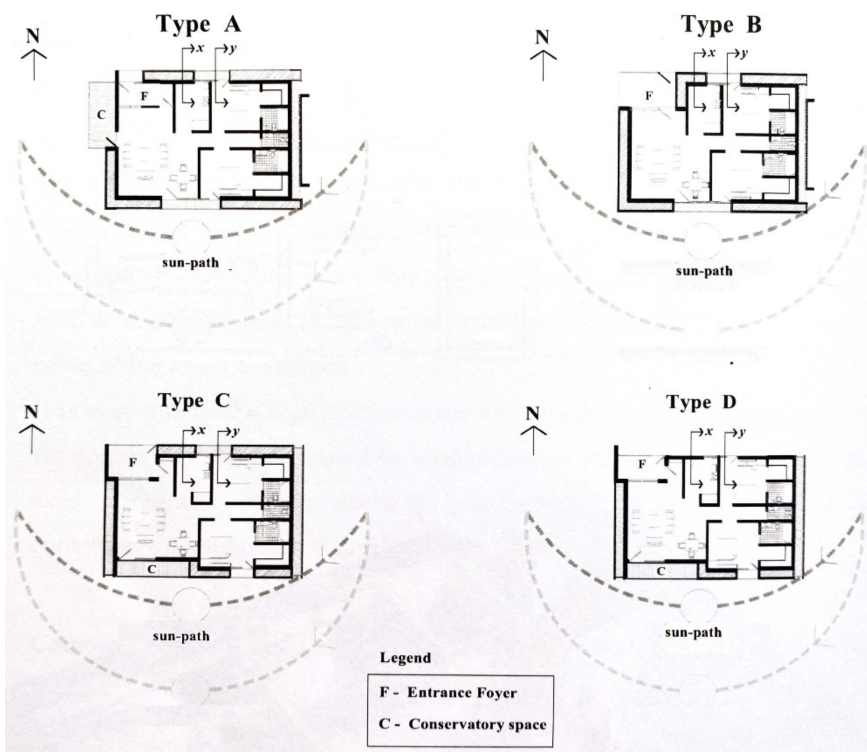


Figure 15: Different configurations for the application of the ventilated cavity wall in an apartment design

CONCLUSION

In this paper, the applicability of a ventilated cavity facade system is analyzed. Through this analysis of the ventilated cavity wall model produced by the author, it is deduced that the system enables reductions of thermal impact in buildings through the façade by significant margins. This is seen in the significant decrease of the indoor room temperature by up to 5ºC compared to the cavity air temperature. This is likewise observed in the reduced thermal values recorded for the cavity air temperatures in each case of closed (inactivated) and open (activated) ventilated systems. The performance of this façade system which in passive mode utilizes buoyancy or stack effects for ventilation of the cavity space may be improved by adopting mechanical systems like simple vent fans solar shading systems or a combination of both. Likewise, designs of homes that adopt the ventilated cavity wall option may further improve indoor thermal conditions through whole building orientation or by indoor space orientation. The indoor spatial orientation if appropriately utilized and properly managed during the building design process may also increase the energy conservation potential.

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