Inspiration for the Morphology of the South-Oriented Double-Skin Façade to Enhance Air Movement in Office Buildings of Cairo

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Abstract. Energy consumption in buildings is approximately 40% of the total world annual consumption. In hot climate, crucial percentage of energy consumed due to the cooling loads in buildings. Wherefore, tendency towards decreasing the energy demand rises through the revival of passive strategies and encouraging the development of innovative initiatives in different fields. Double skin facade (DSF) is a promising passive strategy to enhance the thermal comfort while decreasing energy consumption. The DSF promotes the convective strategy in the cavity as an additive force to enhance air movement the occupied spaces. The study will introduce a proposed skin inspired from parametric pattern movement and exploit the features of the pattern mutation. The movement of the parametric pattern demonstrates changes in the cavity configuration revealed at the outer skin through the entire height of the façade. The proposed facade generates a special species of fluctuation for air distribution covering larger area of the occupied space by applying the principle of Venturi’s effect. The results show enhancement in the magnitude and distribution air velocity inside the occupied space, which assists in improving thermal comfort range inside by natural means.

Keywords: Double Skin Facade, Air flow in buildings, Computational fluid dynamics

1. Introduction
Double skin facade is composed of external and internal skin separated by the cavity channel. It acts as a mediator between internal and external climatic conditions. Implementation of the DSF is one of the developed strategies for improving air velocity inside the space that affects the energy use in buildings in log-term perspective. The impact of DSF on the air movement is affected by the complexity of the thermal behavior together with the air movement phenomena evolved inside the cavity. In ventilated DSF, the air movement occurs due to buoyancy effect, where the chimney effect acts as an additive force to warm the air at the upper part. The air becomes less dense and so more buoyant, which will subsequently boost air movement inside the occupied space. The paper will monitor the movement of air velocity generated due to alternative cavity configuration. The study will focus on the notion of the cavity configuration to at the outer skin of the cavity generated from the principle of venturi’s effect that creates difference in pressure between inflation & constricted portion to improve air velocity in the occupied space.

1.1. Aim of the research
Competence in amalgamation between double skin facade and the parametric pattern arise potential for boosting air movement inside the building to attain thermal comfort requirements. A non-uniform
A cavity is proposed inspired from analyzing the features of the origami pattern movement. Diversity in the cavity thickness observed generating different configuration alternative. The paper will monitor the influence of pressure difference generated due the alternative cavity configuration on the air velocity through the cavity and its influence on the adjacent spaces.

2. Literature Review

2.1. Factors affecting air movement inside the cavity

Several factors affect the air movement through the cavity of the double facade. These factors classified into building form, site factors and facade factors. The site factors are concerned with the orientation of the facade with respect to sun path and wind direction. The facade factors are classified into cavity components and cavity configuration. Comparatively, the influence of cavity components rely on creating temperature gradient that subsequently generate pressure difference that allow the movement of air. The study will focus on the notion of the cavity configuration that directly creates pressure gradient at the cavity channel.

2.1.1. Building form. The building geometry has an influence on the flow pattern on the building. Different flow pattern is generated based on the influence area of the building exposed to the windward side. Downward & frontal vortex occurs at wide & high buildings. Meanwhile, the air will move along the buildings sideways in slender & high buildings, and over the building in a low-rise & wide building. This will lead to variation in the wind pressure coefficient at different height of the building.

2.1.2. Site factor. The level of solar incidence, external temperature and wind direction affect the orientation of DSF within the building. For warm climate, precedent studies show that locating DSF at the south facade with 45° variations together with proper shading elements is more effective for boosting rate of airflow at the north latitude (Gratia & De Herde, 2007). Wind is crucial natural element affecting airflow behavior of DSF. Locating the double skin façade at the leeward side of the building has a better influence on the quantity of airflow rate as it acts as an additive strategy due to the stack effect and assists in removing larger amount of trapped heat. (Stec & Van Paassen, 2003).

2.1.3. Façade factors Cavity. Constituents. Comprehensive understanding for the glazing properties system is required to deduce the effect of the solar radiation transmission on the vertical temperature gradient and its influence on the airflow regime. Higher flow rate was observed at the implementation of high-absorbing inner material combined with an equal transmitted absorbance glazing 0.4 at the outer layer (Pérez-Grande, Meseguer, & Alonso, 2005). Precedent study shows that double glazing at the outer glazing of DSF provides better thermal insulation through prevention of heat gain into the cavity for better thermal condition and energy consumption (Mingotti, Chenvidyakarn, & Woods, 2013). To reduce the radiative and conductive components heat transferred an equilibrium between glazing system is generated through applying glazing properties with high transmittance at the outer layer in conjunction with double glazing (higher thermal insulation) at the inner layer (Barbosa & Ip, 2014). Positioning shading devices inside the cavity is substantial to reduce the amount of solar heat transfer. In warm climate, it’s recommended to locate the shading devices near the outer skin to attenuate the transmitted heat inside the cavity which consequently influence the thermal comfort conditions (Gratia & De Herde, 2007). The venetian blinds inside the cavity assist in enhancing airflow due to generation of an upward buoyancy momentum around the heat absorbed by the blinds. Implementation of slats tilted 80° boosts the air velocity up to 35%.

Cavity configuration. The cavity height affects the magnitude of the stack effect in DSF due to the difference in height between inlet and outlet openings of the cavity (Pappas & Zhai, 2008). Increasing the height of the thermal storage space leads to increase in the pressure difference between the upper and lower inlets resulting in higher rate of airflow (Ding, Hasemi, & Yamada, 2005). The cavity height is one of the prime factors that influenced the magnitude of the thermal buoyancy in DSF.
When the height of the chimney of double façade exceeds 5m, the air flow is enhanced inside the cavity (Gratia & De Herde, 2004). As the width of the cavity decreases the stack effect increases, leading to a robust air movement inside the cavity and extract of the trapped heat from the upper part of the cavity. (Rahmani, Kandar, & Rahmani, 2012). The cavity ranges from 0.7 to 1.2 m is recommended to improve the stack effect creating equilibrium between air extraction and heat transmission (Radhi, Sharples, & Fikiry, 2013). Simulation lags behind in providing an understanding of how non-uniform cavities will have an impact on the volume flow rates inside the cavity. Hamza, discussed an attempt in changing the design of the outer surface of a Double skin facade configuration to examine the impact of changing the flow channel configuration on buoyancy and heat stratification in the double skin facade. Three configurations proposed; a raked, a necked (constricted flow) and a straight facade, as a possible architectural variation to the external surface while maintaining the air volume inside the cavity. The test shows similar in behavior for the three configurations and their influence on indoor thermal and air quality conditions that give architects more freedom to design the external surface (Hamza, Cook, & Cropper, 2011).

Another attempt introduced by Hamza proposing three alternatives for the DSF configuration, straight, raked and staggered, extended over the first and the second floor. The research examined the impact of the architectural configuration on the volume flow rates that affect thermal performance inside the cavity for natural ventilation. The thermal performance of the straight and raked cavity was the same, while the staggered one managed to lower thermal stratification profile due to the reduced solar radiation generated from overshadowing (Hamza & Abohela, ).

3. Methodology

3.1. Parametric structure inspiration

Origami is a tectonic study authorizes the mutation of two-dimensional surface to three-dimension, through folding techniques. It generates a wide range of design, patterns and objects that generate functional and aesthetical diversity (Jackson, 2011). After analyzing the movement, several geometrical parameters featuring the configuration are deduced, variation in the cavity depth due to pattern movement and variation in the percentage of solar radiation falling on the façade. The pattern movement provides diversity in the cavity configuration generating variation in the thickness through the entire height, Fig. 1. Origami inspiration pattern integrates the idea of movable panels into one large system, the envelope; act as an integral part of the whole façade.

Figure 1. Section of the Surface when activated in different Configuration.

3.2. Building description

The simulation held for a prototype office building at Cairo, Egypt, of latitude 30.13 & longitude 31.40. It is a four story building, with curtain wall facing south west, with no obstacles from the vicinity or influence from the typography. The temperatures at inlet are assumed equal to outdoor
temperatures, where walls U-value are 0.34 W/m²K, floors U-value are of 0.27 W/m²K, roofs are of U-value 0.27 W/m²K while Floors/Ceilings are 100mm reinforced-concrete of U-value 2.3 W/m²K. The simulation carried along a fragmented period showing diversity in the climatic conditions. 21st of May and August at 13:00 are nominated for having variation in the temperature and solar radiation that influence indoor temperature, where the dry bulb temperature equal to 30°C and 33.5°C respectively. The simulation applied on the south West facade. The analysis will offer a comparison between applying a normal double skin facade and the proposed alternatives.

3.3. Modeling proposed facade
The model generated at Rhinoceros- grasshopper plug-in, where the geometrical design parameters affecting the performance of the facade are the cavity configuration. Alternatives in the cavity configuration occur at the external glazing layer through the entire height of the cavity.

![Diagram showing alternative cavity configurations](image)

**Figure 2. The geometrical design parameters for alternative cavity configuration**

Upper inflation: The first proposal creates an inflation portion at the upper part of the facade. The thickness of the cavity ranges from 0.7m to 1.5m.
Lower inflation: The second proposal is to reverse the channel configuration, creating this inflation at the lower part of the channel inception to be sucked through the constricted upper part of the cavity. Double inflation: The third proposal creates two inflations at the upper and lower part of the facade, joined by a constricted part. Two other proposals introduce altering the location of the inflation portions, Fig. 2.

3.3.1. Factors affecting air movement.

The cavity configuration generates several factors that affect the air movement & pattern inside the façade. Variation in the inflation portion inspired pattern generates different inflation in count & volume which are aligned differently with the outlets in the cavity. Also, the height of the constricted part at the chimney changes according to the inflation portion position. Alternative volume & count of the inflation portion, the height of the constricted part at the chimney & the alignment of the inflation portion with the outlet generate different impact on the air movement & pattern in the cavity and the adjacent spaces. The influence of these factors is examined through the CFD simulation.

3.3.2. Façade design parameters

Glazing properties: The glazing layer defines the cavity configuration through the entire height with specific properties, double-glazed with low e-coating to decrease the heat transfer by reducing conductive heat transfer Low emissivity coating of U-value equals to 1.76 W/m2K used to reflect heat back to its source, so it reflects the heat gain from outside reducing heat gain through the glass during summer. Low emissivity coating of U-value equals to 1.76 W/m2K used to reflect heat back to its source, so it reflects the heat gain from outside reducing heat gain through the glass during summer.

Openings: The air directed inside the space through a lower inlet-velocity with speed 0.6 m/s from the North East facade to be extracted through the upper outlet after crossing the space at the opposite side. The bottom opening of the cavity is located 2.5 m above the ground level avoided from any obstructions to the airflow enhancing air quality intake.

The temperature at the inlet estimated as the outdoor temperature. The inlet opening at each floor is equal in size to the outlet.

Cavity height and depth: In our simulation, the cavity height is 3m above the roof height for influential enhancement on airflow. The cavity depth ranges from 0.7 to 1.5m.

4. Simulation & Results

4.1. CFD Simulation

The proposed design uses a graphical algorithm editor, Grasshopper, for modelling. Together with environmentally conscious architectural analysis tool, Ladybug plug-in, that introduces a variety of interactive 3D graphics. Honeybee plug-in is used for building thermal & energy simulation in a parametric approach. For airflow analysis, ANSYS fluent 17.2 used as a widely validated code that support buoyancy driven natural ventilation in buildings.

CFD simulation used with limitations in modelling buoyancy-driven flows to simulate the influence of variation in the cavity configuration on the air movement through the cavity and its consequents.

4.1.1. Requirements for CFD modeling

- Surface temperature as a fluctuation of incident solar radiation
- Outside dry bulb temperature
- Air velocity impinging the facade at inlet-velocity opening

Mesh. The geometry modelled at ANSYS Fluent defining the unity of the whole space and cavity where the fluid simulated as an ideal gas. Meshing divides the whole component into number of elements to distribute the load uniformly where each element having its own stiffness. The element type distribution along the mesh are 8 node Linear Hexahedron & 6 Node Linear Wedge(prism), to
allow clustering of cells in selected area of the flow domain. For the shift between large and small
cells, a large amount of cells is required with a total amount of cells through the modelling. *Fig. 3.*

![Figure 3. Meshing: Cell size & quality](image)

**Solver Setup**
- For the numerical sub-model, the simulation is solved in 3D steady state, RNG k-epsilon
turbulence model is chosen for all the cases, with a pressure-based, double precision transient
solver
- The fluid imposed as ideal gas in the turbulent flow regime.
- Navier equation with energy conservation equation is resolved, where the convergence
criterion is realized at about 500-600 iteration.

**Boundary Conditions.** The dry bulb temperature is recorded 30°C and 34°C at May and August
respectively. Through simulation, a slight variation recorded for the internal surface temperature,
which counted around 0.2-0.5°C degree difference through different floors that will not have a
substantial influence on air velocity.

The internal surface temperature of the glazing system generated from Honeybee plug-in, integrated at
ANSYS fluent to compute solar heat transmitted. The thermal boundary of the walls defined with a
fixed temperature extracted from Honeybee. A constant surface temperature will set to be 28°C and
27°C during May, and 33°C and 32°C during August for the external and internal glazing system
respectively. These temperatures coincide with the values of the operative temperature of the static
façade of shading percentage equals to 70%, resulted from thermal simulation, to produce a
comparative result for the several cavity configurations.

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Extracted from ladybug plug-in_ grasshopper; the results shows that the wind direction is from the
North East with variation from 0.5 to 1.2 m/s during the summer season (from May to August).
Analysis carried where the velocity specification method for the inlet velocity is normal to the
boundary with magnitude varied from 0.2 to 0.6 m/s. The paper focuses on the inlet velocity condition
with magnitude 0.6 m/s as it shows significant variation in the species of air fluctuation in different
proposal & provides the prescribed velocity distribution. The lower opening at the cavity assigned as
an inlet-pressure for unconfined flow. The air pressure at the flow inlet considered for buoyancy
driven flow. The upper opening of the cavity allocated as pressure outlet considering the specification
of static pressure at the outlet boundary, where the flow quantity extrapolated from the flow in the
interior.
4.2. Results
From CFD simulation, the generated temperature contour at the lower inflation & double inflation (especially 1st and 2nd proposal) recorded lower temperature degree, from 33.3°C at the static façade to be reduced to 32.0°C when apply with the double inflation prototype in August, while from 28.6°C to 27.2°C during May. Such decrease in temperature occurs directly related to the cavity configuration morphology. The simulation results emphasize on the prominence of the cavity configuration influence, Fig. 4&5.

![Figure 4. Velocity values inside the cavity in August, Contour](image1)

![Figure 5. Velocity values inside the cavity in August, pathlines](image2)

4.2.1. The volume of inflation portion
The morphology of the cavity configuration assists in the generation of Venturi’s effect, which consequently has a substantial impact on air velocity. A difference in pressure between the constricted...
and the inflation portion created to boost the air movement. The increase in the air velocity supports the connotation of decreasing the operative temperature in the channel & the adjacent spaces. Through monitoring the results of air velocity, increase in the large cross-section area of the inflation portion didn’t show more influence on the speed of air other than the quantity grabbed out from the occupied space except for a stream air velocity of 0.5m/s and the rest ranges around 0.2m/s, on contrary more amount of air is sucked through the smaller inflation that reaches 0.7m/s with the majority of 0.5m/s. The simulation results emphasize on the prominence of the cavity configuration, Fig. 6.

4.2.2. The height of the constricted part (chimney).
The connotation of chimney height plays an important role in generating a driving force to enhance the rate of airflow through the chimney. With the increase in height in the constricted part accompanied the inflation portion, the density of the air between the exterior and interior layers of DSF is increased. The lower inflation, records air movement with high speed, of 1.4m/s and 1.73m/s at May and August respectively, that circulate more air outside revealed through the increase in difference of pressure and temperature. A resultant, more air gets out of the outlet to the cavity affecting more air movement through the space adjacent to the cavity. Moreover, the double inflation enhances the fluctuation of air inside the space, grabbing and pulling out more air from the occupied space to the cavity. Due to increase in pressure difference generated at the constricted part, air moves faster with 0.7m/s at the lower part of the cavity and 1.67 m/s at the upper part of the cavity due to the repeated generation low and high pressure. An increase in the quantity of air movement is monitored inside the cavity that is reflected in the occupied space, Fig. 7.

4.2.3. Count of the inflation portion
The air velocity inside the cavity is dictated by the influence of buoyancy force and Venturi’s effect. The pattern of the air movement inside the cavity is significantly improved and an incremental increase in the air velocity and quantity inside the cavity, observed at the chimney height in particular. At every inflation, increase in the quantity of air movement occurred, with consequent pursued by higher increase in velocity in the constricted part of the cavity reaching 1.8 m/s at the upper part of the cavity.

Figure 6. The influence of inflation volume on the quantity of air flow in the cavity
Figure 7. The rate of air flow through the upper part of the cavity (Chimney).

This emphasizes on the connotation, the more inflation portion, the higher air velocity, Fig. 8. As a resultant, a mutation in the air movement pattern in the occupied space revealed covering larger part of the occupied space. Although the lower inflation demonstrate a higher air velocity at the upper part of the cavity similar to that of the double inflation, the double inflation generates a special species of fluctuation for air distribution through the occupied space, Fig. 8.

Figure 8. A special species of air distribution is created when applying the double inflation proposal.
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4.2.4. Positioning outlet with inflation portion
Furthermore, diversity in the inflation angle, confronting the outlets opening, has a great impact on the amount of air grabbed of the space creating a fluctuation in the pattern inside the space. Certain angle assists in grabbing more air out of the space and increasing the air distribution with more rate of ventilation. The more acute angle between the inflation and the outlet, the more the quantity of air pulled out to the cavity, which will consequently affect the distribution of air inside. Comprehensively, the fluctuation of air creates distribution system causes ventilation to flow into and out of a space, Fig. 9.

5. Conclusion
The Understanding the principle of fluid and its response to the alternation of the cavity configuration is substantial to support the passive strategies approach. The result of the air movement inside the cavity is influenced by the buoyancy force and Venturi's effect. The connotation of alternating the cavity configuration through the entire height of the facade relies on creating a pressure difference between the constricted and inflated portions to be added to the buoyancy force to increase the air velocity through the cavity and the adjacent spaces. Moreover, increasing the air velocity in the cavity assists in segregating the heat transfer load to the internal glazing of the DSF.

The results show variation in the pattern of the air movement inside the space adjacent to the cavity. The velocity of air at the static facade is 0.3 m/s through a weak steam airline. The velocity of air increased to 0.5m/s at the lower inflation case distributed along a larger area of the space, together with incremental increase in the air velocity and quantity is at the chimney height in particular that reaches 1.76m/s, which was recorded 1.4 m/s at the static. The double inflation shows enhancement in the air movement pattern with a larger distribution through the occupied space due to the consequent constricted part of the cavity reaching 1.8 m/s at the upper part of the cavity.
The results show how the system manages to increase the air velocity inside the space generating a special species of fluctuation for air distribution especially at the double inflation proposal.

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