# HEAT RESPONSIVE SOLAR SHADING IN DOUBLE SKIN FAÇADE FOR TROPICAL CLIMATES

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# HEAT RESPONSIVE SOLAR SHADING IN DOUBLE SKIN FAÇADE FOR TROPICAL CLIMATES

by

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## LIST OF SYMBOLS

| | |
|---|---|
| $\Delta l$ | Increase in length |
| $\Delta t$ | Increase in temperature |
| $\alpha_L$ | Coefficient of linear thermal expansion |
| $R^2$ | Coefficient of determination |
| $M_i$ | Measured value at one point |
| $R_O$ | Radius at temperature $T_O$ |
| $R_T$ | Radius at temperature T |
| $S_i$ | Value obtained by simulation |
| °F | Degree Fahrenheit |
| ∞ | Infinity |
| Af | Tropical rainforest climate |
| Am | Tropical monsoon climate |
| As | Tropical savanna climate with dry summer |
| Aw | Tropical savanna climate with dry winter |
| BTU | British thermal unit |
| ft | Feet |
| h | Hour |
| in | Inch |
| K | Kelvin |
| mm | Millimeter |
| Mn | Manganese |
| Ni | Nickel |
| ºC | Degree Celsius |
| % | Percentage |
| W | Watt |

| | |
|---|---|
| $A$ | Angular deflection |
| $CV$ | Coefficient of variation |
| $E$ | Moduli of elasticity of the component alloys |
| $L$ | Length of the component alloys |
| $MBE$ | Mean Bias Error |
| $N$ | Arithmetic value/mean of measured data |
| $NMBE$ | Normalized Mean Bias Error |
| $R$ | Bending radius, radius of arc |
| $RMSE$ | Root Mean Square Error |
| $T$ | Temperature |
| $k$ | Flexivity; specific curvature |
| $l$ | Initial length of object |
| $n$ | Total number of measurements |
| $s$ | Thicknesses of the component alloys |
| $\varphi$ | Bending angle at the free end of the component alloys |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| BLAST | Building Loads Analysis and System Thermodynamics |
| BTU | British Thermal Unit |
| CV | Coefficient of Variation |
| DGF | Double Skin Glazed Façade |
| DIN | Thermostat Metals; Technical Delivery Conditions |
| DOE | Department of Energy |
| DSF | Double Skin Façade |
| DSF-CL | Double Skin Façade with Conventional Louver |
| DSF-HBL | Double Skin Façade with Heat-Responsive Bimetal Louver |
| DSF-NBL | Double Skin Façade with None-Heat Responsive Bimetal Louver |
| DSF-NL | Double Skin Façade without/no Louver |
| EAF | Exhaust Air Façade |
| EMS | Engineering Materials Solutions |
| EP | EnergyPlus |
| EPW | EnergyPlus Weather File |
| G-Value | Solar Gain |
| HAVC | Heat, Air Ventilation and Cooling |
| IDA ICE | Indoor Climate and Energy |
| IES-VE | Integrated Environmental Solutions-Visual Environment |
| JKT | Jakarta |
| KL | Kuala Lumpur |
| MAE | Mean Absolute Error |
| MBE | Mean Bias Error |
| NBN | The Bureau for Standardization |
| NHA | Nha Trang |
| NMBE | Normalized Mean Bias Error |
| NVDSF | Natural Ventilated Double Skin Façade |
| OEI | Omege Engineering Inc |
| OTTV | Overall Thermal Transfer Value |
| PCM | Phase Change Material |
| PNH | Phnom Penh |

| | |
|---|---|
| PV | Photovoltaic |
| QUEST | Quick Energy Simulation Tool |
| RMSE | Root Mean Square Error |
| RTU | Remote Terminal Unit |
| R-Value | Thermal Resistance |
| SAF | Supply Air Façade |
| SMA | Shape Memory Alloys |
| TRNSYS | Transient System Simulation Software |
| TYP | Typical Year File |
| UAE | United Arab EmiratesDSF |
| UNDP | United Nation Development Programme |
| USA/US | United Nation of America |
| U-Value | Thermal Transmittance |
| VDF | Ventilated Double Façade |
| WHO | World Health Organization |

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**TEDUHAN SURIA RESPONSIF HABA DALAM SISTEM FASAD KULIT BERGANDA UNTUK IKLIM TROPIKA**


## ABSTRAK

Fasad kulit berganda (DSF) telah muncul sebagai strategi penting untuk meningkatkan prestasi terma dan kecekapan tenaga di dalam bangunan pejabat, terutamanya dalam iklim tropika. Walau bagaimanapun, keupayaan penuh DSF masih belum dapat direalisasikan, dan penjimatan tenaga mungkin tidak begitu ketara. Kajian ini menyiasat potensi DSF untuk penambahbaikan terma bangunan dan penjimatan tenaga, menggabungkan teduhan suria responsif haba menggunakan kisi-kisi dwilogam- termo di dalam rongga terma DSF dalam iklim tropika pengelasan Köppen. Penyelidikan ini menggunakan pengiraan dan simulasi perkomputeran perisian EnergyPlus. Penemuan menunjukkan bahawa kedua-dua fasad kulit tunggal (SSF) dan DSF memberikan prestasi yang berbeza dalam kategori iklim tropika masing-masing, mempengaruhi prestasi terma dan tenaga DSF dengan sewajarnya. Walau bagaimanapun, DSF bagi setiap kumpulan iklim tropika berpotensi untuk meningkatkan prestasi terma di dalam bangunan dengan perbezaan kadar kecekapan tenaga tahunan yang sedikit. Kajian itu juga mendedahkan bahawa peranti teduhan memberi kesan ketara terhadap prestasi terma dan tenaga DSF. Tambahan pula, kisi-kisi dwilogam-termo di dalam rongga DSF bukan sahaja mengurangkan keperluan untuk cahaya buatan dalam DSF, bahkan meningkatkan prestasi terma dan kecekapan tenaganya. Secara keseluruhannya, DSF yang direkabentuk dengan baik, dengan perintegrasian teduhan suria responsif terma berkemanpuan untuk meningkatkan tingkah laku terma dan kecekapan tenaga dari segi penyejukan dan pencahayaan di dalam bangunan pejabat dalam iklim tropika.

# HEAT RESPONSIVE SOLAR SHADING IN DOUBLE SKIN FAÇADE FOR TROPICAL CLIMATES


## ABSTRACT

Double skin façade (DSF) has emerged as a pivotal strategy for enhancing thermal performance and energy efficiency in office buildings, particularly in tropical climates. However, the full aptitudes of DSF have yet to be realized, and energy savings may not be substantial. This study investigates the potential of DSF for building thermal enhancement and energy saving, incorporating heat-responsive solar shading using thermo-bimetal louvers in the thermal cavity of DSF in Köppen-classified tropical climates. The research adopts calculation and computational simulation, EnergyPlus software. Findings indicate that both single skin façade (SSF) and DSF perform differently in respective tropical climate categories, influencing the thermal and energy performance of DSF accordingly. However, the DSF of each tropical climate group has the potential to enhance thermal performance in buildings with slightly varying annual energy efficiency rates. The study also reveals that the shading device significantly impacted the thermal and energy performance of DSF. Furthermore, thermo-bimetal louvers within the DSF cavity not only reduce the need for artificial light in DSF but also improve its thermal performance and energy efficiency. Overall, a well-designed DSF with the integration of heat-responsive solar shading has the capacity to enhance thermal behavior and energy efficiency in terms of both cooling and lighting in office buildings in tropical climates.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

A double skin façade (DSF) is a façade system comprising of at least two layers of glass façade with an intermediate space, which can extend over several meters and be operated by different ventilation systems (Arons, 2000; Chan et al., 2009). Over the years, numerous approaches have been explored and proposed to enhance the energy performance of modern buildings (Hong et al., 2013; Yang et al., 2020). DSF, one of the approaches, has garnered positive attention in various studies that have examined different DSF typologies and their impact on thermal and energy performance across diverse climatic conditions (Aksamija, 2016; Barbosa & Ip, 2017; Faggal, 2017). Owing to its numerous advantages, the utilization of DSF has become a prominent design approach pursued by researchers to this day (Inan & Basaran, 2019; Saroglou et al., 2020; Hou et al., 2021).

Besides building façades, the shading device is also significant in controlling thermal influence in tropical buildings (Gavan et al., 2007; Li et al., 2019). Consequently, various researchers have been working to improve the overall performance of the shading device (Sung, 2011; Lee et al., 2015; Yang et al., 2020). In 2011, Sung investigated the mobility of the metal in terms of solar shading and natural ventilation in architectural design, believing that it may improve the indoor environment. The thermo-bimetal, a heat-responsive composite material, has been now one of the approaches discovered to optimize the performance over the conventional shading device recently. Thermo-bimetals are a combination of two components with different coefficients of thermal expansion, and as the temperature changes, the bimetal begins to curl due to the differences in thermal expansion of the two composites (Kretzer, 2015). Thermo-bimetal could be implemented into the DSF system to enhance building façade performance in terms of energy savings and indoor environment enhancement. In hot climates, hot air is trapped between the DSF layers and exhausts via the outlet, so heat-responsive bimetallic could act as a thermal enhancer in the cavity.

## 1.2 Gaps of Study

Recently, DSF has gotten more attention from researchers on its applications in various climates. Several studies were conducted to prove its advantages, typically on building energy efficiency and thermal enhancement. Even though DSF positively affects building thermal and energy performance, it still needs further investigation and improvement to guarantee the fullest potential of the façade. Momentarily, DSF does not entirely perform as an environmentally friendly façade when other negative factors have not been disclosed.

There were statements in numerous studies that the effects of DSF on the building’s performance would be different from one location to another location and from one climate to another climate (Rahmani et al., 2012; Azarbayjani, 2013). However, no exclusive investigation has ever been conducted in a broader climatic context, as most studies have only focused on specific locations. Thus, it could be a consequence when straightforwardly employing the system on the buildings in a broad climate without a proper DSF design. On the other hand, the need for natural light was accomplished by utilizing glass façades or windows, but an extra layer of a glass wall or window could be the component that reduces the indoor light quality (Joe et al., 2014; Manubawa et al., 2020). Alternatively, the lighting performance of DSF has not been explored by most studies.

Despite the existence of some research studies that have explored new passive shading devices, such as the work conducted by Sung (2016) on thermo-bimetal, the widespread awareness and practical application of this technology remain limited. Sung's study highlighted the potential of thermo-bimetal in enhancing the performance of building façades in terms of ventilation and natural light. However, its utilization as an energy-efficient shading device in DSF has not been extensively investigated or implemented. The incorporation of thermo-bimetal into DSF systems holds significant importance as it can contribute to the reduction of heat transfer and the augmentation of natural light within the building. Remarkably, despite the passage of a decade, no notable advancements have been made in this area. Consequently, there exists a promising opportunity to enhance DSF systems by leveraging the potential of thermo-bimetal.

## 1.3 Problem Statement

In the modern design world, building envelopes play an important role in the functionality, desirability and sustainability of a whole building. Based on the United Nations Environment Programme (UNEP), buildings make use of over 40% of the world's energy, and roughly 60% of the world’s electricity is consumed by residential and commercial buildings. In tropical countries, cooling and lighting accounted for 56% and 16%, respectively, of the whole typical building energy (Katili et al., 2015). Even though the technology of DSF has been developed over recent decades to tackle extreme energy consumption in glass buildings, issues still arise when energy saving has not been extensively obtained, and its full aptitudes are yet to be discovered (Barbosa et al., 2017). Correspondingly, in a tropical climate, heat and glass façade are the most critical influences on a building's energy performance. Glass façade retains a high solar radiation rate, heating the building and causing thermal discomfort and excessive energy consumption for air cooling systems. In warm climatic zones, the primary challenge associated with DSF is the issue of excessive solar gains, as aforementioned (Mohammed & Alibaba, 2018).

Initially, DSF could positively impact building thermal performance, which defines the efficiency of the whole building. Even though various benefits have been discovered and scientifically proven, there are still some negative impacts found in some specific studies (Table 2.2). Furthermore, even though the naturally ventilated DSF has been broadly employed, the thermal performance of the system is not thus far entirely understood (Aleksandrowicz & Abraham, 2018). For instance, Inan & Basaran (2019) found both positive and negative effects of DSF in their investigation that DSF could usually provide positive effects while it showed better energy performance in July; yet, it could still offer unfavourable results for the external airflow mode in the cavity in January. Even though DSF could effectively control heat gain caused by the differences in indoor and outdoor surface temperatures, it could still not prevent internal heat gain caused by direct solar radiation in tropical climates (Li et al., 2019).

On the contrary, the second layer of DSF minimizes the natural light in the buildings, thereby necessitating an increased reliance on artificial lighting. The implications of this drawback have also been addressed in several specific studies. According to Azarbayjani (2013), lighting loads in DSF fell during the summer due to the longer daytime, which means lighting loads may also vary from daily climatic variations. Aksamija (2018) also signified the application of all DSF varieties in various climatic conditions for building thermal improvement, but all types of DSF cause energy consumption increases for lighting. Comparably, Manubawa et al. (2020) investigated the natural light quality of the building with a DSF system, following the standard lighting level. There were findings that the additional skin to the glass wall tends to shade the building interior and causes insufficient lighting levels, leading to below the standard as required. However, without the second skin to the exterior wall, the lighting level in the building interior is way too high than the standard lighting limit, which causes glare and discomfort visual. Therefore, enhancing the performances of DSF and making the system viable in the overall tropical context is another outcome to achieve.

## 1.4 Research Questions

The research questions that can be derived from the problem statement are:

1. What is the comparative thermal performance of DSF and single skin façade (SSF) in an overall tropical climate, particularly in terms of thermal enhancement and energy efficiency?

2. What is the impact of shading configuration inside the DSF cavity on the thermal behavior and energy consumption of DSF in a general tropical climate context?

3. How does the configuration of thermostatic bimetal shading influence and enhance thermal performance and energy saving, particularly in terms of cooling and lighting, of DSF in tropical climates?

## 1.5 Research Objectives

The main goal of this research was to enhance the overall performance of DSF for the high-rise office building in terms of thermal enhancement and energy efficiency by adopting thermostatic bimetal as a zero-energy shading system in DSF for an overall tropical climate context. To achieve the research goal, three main objectives were intended for investigation.

i. To investigate the potential of DSF by analysing its thermal behaviour and energy consumption in an overall tropical climate.

ii. To assess the impact of shading configuration inside the DSF cavity on the thermal performance and energy efficiency of DSF in the general tropical climate context

iii. To determine the influence of heat-responsive shading, thermo-bimetal louver, on the thermal performance and energy efficiency of DSF in terms of cooling and lighting in an overall tropical climate.

By exploring these aspects, this research aimed to provide insights into the most effective façade system, particularly DSF, for enhancing thermal behavior and energy efficiency in office buildings in tropical climates.

## 1.6 Research Significances

Research outcomes will be the additional pieces of knowledge and understanding of the performances and benefits of DSF in tropical climate countries where demand for building cooling energy is high. More importantly, developing a new design approach is the key to sustainable and green building design, which lowers global and environmental impacts.

This study introduced a new approach providing thermal enhancement and energy saving in office buildings with environmentally friendly façade and shading devices with heat-responsive bimetal louver. Also, this could be an early design knowledge for developing office buildings in a tropical climate environment.

## 1.7 Research Scopes

This research study aimed to investigate the thermal performance and energy efficiency enhancements, in terms of cooling and lighting, of DSF in high-rise office buildings in tropical climates, classified by Köppen-Geiger climate classification (Köppen, 1998; Peel et al., 2007; Beck et al., 2018), by incorporating heat-responsive shading, thermo-bimetal louvers. The study focused on a typical square-shaped building, which is practical for the thermal investigation of standard four orientations. The study employed the calculation and simulation tool, EnergyPlus, for whole building investigation and analysis, which only required specific data collection based on simulation requirements. Thermo-bimetal shading was assumed to be similar to typical louvers applied on DSF in terms of width and length. On the other hand, curvatures or deflections of the bimetal were obtained from calculations and thermal simulation within the tropical climate context. The investigation was conducted during the proposed working hours from 7 am to 5 pm. The goal of this research was to enhance the performance of DSF by adopting thermostatic bimetal as an energy-free automated shading device. Therefore, the bimetal was integrated into only optimal classifications and technical aspects of DSF for tropical context for analyses and enhancement.

## 1.8 Research Methodology

This research study employed a quantitative approach combined with computational simulation using EnergyPlus and calculation methods to address the research objectives. The primary focus of the study was to examine a typical tropical office building as a base case study for the application of DSF in the tropical climate region. In order to encompass a broader range of tropical climate contexts, four countries with distinct tropical climate characteristics, as classified by the Köppen system, were selected as representative models for other tropical countries within the same category.

The investigation was structured into three main strategies.

- Strategy One aimed to investigate the thermal performance of DSF alone by categorizing the case study into two scenarios: SSF and DSF without any shading device. Building orientation was taken into consideration for the thermal analysis.
- Strategy Two assessed the impact of the shading device in the DSF by comparing it to the DSF from Strategy One.
- Strategy Three aimed to determine the influence of thermos-bimetal louvers on the thermal performance and energy efficiency of the DSF, specifically in terms of cooling and lighting, within the context of the tropical climate. The shading device used in Strategy Two was replaced by thermos-bimetal louvers, assuming the same size as the conventional shading device. The curvatures of the thermos-bimetal louvers were determined through calculations correlated with the range of air temperature in the DSF cavity of Strategy Two.

The research methodology employed in this study aims to provide a comprehensive understanding of the thermal performance and energy efficiency of

DSF in tropical climates. It takes into account different shading configurations and the integration of thermos-bimetal louvers.

## 1.9 Organization of Dissertation Chapters

The dissertation was organized into six chapters as described below:

- **The first chapter** gave an introduction to this research by including the background of the study, the study gaps, the problem statement, research questions, research objectives, the significance of the research, the scope of the study and a brief research methodology.
- **The second chapter** presented a review of the literature and previous research on DSF and thermo-bimetal, focusing on application, thermal and energy performances.
- **The third chapter** presented the adopted approach and methods, including design strategies to act in response to research objectives.
- **The fourth chapter** presented the analysis of the results and discussions.
- **The fifth chapter** presented the conclusion and recommendation.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The chapter reviewed the literature on DSF and thermo-bimetal, which were the main focus of this research study. It covered the history, classification, performance, application, and other important aspects of DSF and the bimetal material. The review provided a comprehensive understanding of the background and characteristics of DSF and thermo-bimetal louvers, laying the foundation for the subsequent analysis and investigation.

## 2.2 Double Skin Façade

### 2.2.1 History of Double Skin Façade

There were different claims from different sources on the history of DSF's appearance and utilisation (Streicher et al., 2005). An early known ventilated multiple skin façade with a mechanical system was depicted by the proprietor of Brussel's industrial museum, Jean-Baptiste Jobard, in 1849, as claimed by Crespo and Saelens (2002).

Ana Maria Leon Crespo described an early commencement of the system that the double skin wall was first applied on the three-storey building of the Steiff Factory in 1903 in Giengen/Brenz, which was nearby Ulm, Germany, to exploit the quality of the daylight and to get the extra shield from strong wind in cold weather in Giengen as shown in Figure 2.1. In the following years, the other two buildings with the same structural system were duplicated and built after the first one was successfully beneficial (Fissabre & Niethammer, 2009).

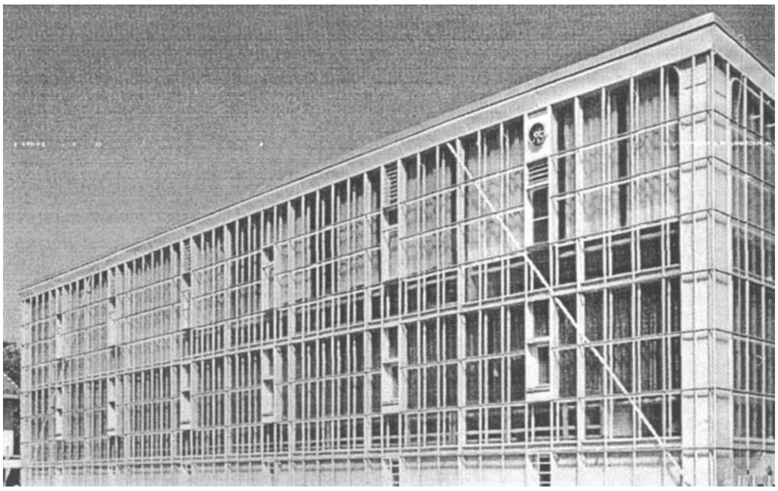


Figure 2.1 Steiff Factory, Giengen / Brenz, Germany (Streicher et al., 2005)

In 1912, the Post Office Saving Bank, which was a winning project earned by Otto Wanger, also had a double skin system that appeared right in the main banking hall as a double skin skylight (Streicher et al., 2005; Kerékgyártó, 2017). Then, in the late 1920s, there were significant projects that were known. The Narkomfin building in Russia was developed and experimented with by Moisei Ginzburg in 1928. He had applied double skin stripes on the communal housing block for maintenance and then pushed the idea for the window. Le Corbusier spent several years designing a few buildings, including Centrosoyus in Moscow, Cite de Refuge in 1929 and Immeuble Clarte in 1930 in Paris. However, none of these buildings had a double curtain wall system. Nevertheless, at the end of the 1920s, Le Corbusier started exchanging ideas on the uses of the double skin system with Ginzburg as they met and found similarities between their projects, Narkomfin and Cite de Refuge. The momentum gaining of double skin façades in the 80s and the 90s had increased attention from various architects and developers to adopt the system regarding the response to environmental concerns and political influences. The first double-skin curtain wall incorporated the ventilation idea of Le Corbusier had been seen when a collaboration project, the Hooker Office Building, by Cannon Design and HOK Design, was to be constructed in Niagara Falls, New York, in 1978. The building façade was structured with a roughly 20-centimeter cavity depth with a solar cell equipping louver to create a stack effect to provide the desired temperature. As popularity gained, there were also similar approaches adopted in other locations in Europe like Lloyd’s Building, designed by Richard Rogers and Partners, Leslie and Godwin office, also known as the Briarcliff House, designed by Arup Associates and the SUVA building, designed by Herzog and De Meuron (Crespo; Streicher et al., 2005; Schiefer et al., 2008). In Addition, the set of windows with an airflow system was patented in Scandinavia in 1957 and 1967, and the system of the ventilated window had been operated in the office building of EKONO company in Helsinki, Finland (Barnaś, 2014).

As its popularity has grown, the double-layer wall not only caught the attention of cold countries but also of hot and warm countries in the 2000s since there were many experiments had been made and provided a lot of positive results with the system (Pollard, 2000). In the recent decade, there have been many applications of DSF adopted in a so-called warm climate worldwide (Saroglou et al., 2020). The most remarkable one might be the Shanghai Tower in China, with the largest detachment between the outer curtain wall system and the inner main structure at 15 meters (Gu, 2014).

### 2.2.2 Definitions of Double Skin Façade

The term "double skin façade" was defined in a variety of ways based on its applications and benefits. Even the system's name had also been labelled inversely from any perspective on its benefits (Table 2.1).

Table 2.1 Various labels of double skin façade, (Poirazis, 2004; Loncour et al., 2005)

| | |
|---|---|
| - Double-Skin Façade<br>- Active Façade (usually when the air cavity ventilation is mechanical)<br>- Passive Façade (usually when the air cavity ventilation is natural)<br>- Double Façade<br>- Double Envelope (Façade)<br>- Dual-Layered Glass Façade<br>- Dynamic Façade<br>- Wall-Filter Façade<br>- Environmental Second Skin System<br>- Energy Saving Façade | - Ventilated Façade<br>- Double-Leaf Façade<br>- Energy Saving Façade<br>- Environmental Façade<br>- Multiple-Skin Façades<br>- Intelligent Glass Façade<br>- Second Skin Façade/System<br>- Airflow Window<br>- Supply Air Window<br>- Exhaust Window/Façade<br>- Double Skin Curtain Wall<br>- Twin Skin Façade |

Arons (2000) gave a short definition of the system as a twin skin façade consisting of two divided planar walls that allow air to move in it. Oesterle et al. (2001) stated that a double skin façade has two main layers called interior and exterior façade with an air space in between, which allows ventilation to travel through while providing climatic and acoustic protection from the exterior layer. Comparably, Harrison & Meyer-Boake (2003) defined it as *"Essentially a pair of glass "skins" separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes"*. To provide ventilation movement, the distance of the intermediate air space can range from 20 centimeters up to 2 meters, which can be operated naturally or mechanically depending on the climatic location of the buildings (Poiraziz, 2004). Nevertheless, the outer skin of the DSF usually is transparent glazing, which can be far from the inner skin of the building up to 80-100 centimeters, which is slightly different from the statement above on the cavity depth (Safer et al., 2005a).

Defined by Loncour et al. (2005). *"A ventilated double façade can be defined as a traditional single façade doubled inside or outside by a second, essentially glazed façade. Each of these two façades is commonly called a skin (Whence the widely used name "ventilated double-skin façade"). A ventilated cavity - having a width which can range from several centimetres at the narrowest to several metres for the widest accessible cavities - is located between these two skins. There exist façade concepts where the ventilation of the cavity is controllable, by fans and/or openings, and other façade concepts where this ventilation is not controllable (the ventilation is produced in this case via fixed permanent ventilation openings)".*

Another similar explanation by Chan et al. (2009) defined that *"Double skin facade refers to a building facade covering one or several stories with multiple glazed skins. The skins can be airtight or naturally/mechanically ventilated. The outer skin is usually a hardened single glazing and can be fully glazed. Inner skin can be insulated by double glazing and is not completely glazed in most applications. The width of the air cavity between the two skins can range from 200mm to more than 2m. An air-tightened double-skin facade can provide increased thermal insulation for the building to reduce heat loss in the winter season. On the other hand, moving cavity air inside a ventilated double skin facade can absorb heat energy from the sun-lit glazing and reduce the heat gain as well as the cooling demand of a building".*

Even though definitions of double skin façade have some similarities and contrasts among each explanation, a concluded perspective is that the system usually consists of two glass layers creating a cavity to deliver ventilation, which can be operated naturally or mechanically based on the context of a specific climate where the system is adopted.

### 2.2.3 Perceptions of Double Skin Façade

DSF is one of the attractive elements of a building's wall regarding its environmentally responsive profits with a good esthetical presence (Hendriksen et al., 2000; Streicher et al., 2005; Barbosa & Ip, 2017). The transparency of the exterior double skin layers is considered the design principle in architecture because it has a close interaction with nature and has also influenced the indoor environment and space utilization. Moreover, glass wall addiction issues could also be unravelled toward business trends and excitement of glass envelop Hendriksen et al. (2000). DSF normally overlaps its advantages perceptions and applications in both architectural and engineering design (Loncour et al., 2005). Back in the old days, the value of architecture mostly relied on the composition of shape, proportion, aesthetics, material and natural light. Later, global environmental concerns changed many ways of view of good architecture in the late 20th century. DSF has taken the main role in architecture as an aesthetically environmentally friendly façade since it could fulfill exterior desires and positively respond to ecological issues at the same time (Streicher et al., 2005; Preet et al., 2022).

For engineering, DSF is mainly considered advantageous regarding technical constructions and the physical environment. As explained by Waldner et al. (2007), DSF is formed by combining the conventional curtain walls and window system to guarantee the wind and water tightness of the building, which was employed in many of the projects that are normally studied and designed by the engineering firm. It has also been explained that *"Curtain walling usually consists of vertical and horizontal structural members, connected and anchored to the supporting structure of the building and infilled, to form a lightweight, space enclosing continuous skin, which provides, by itself or in conjunction with the building construction, all the normal* *functions of an external wall, but does not take on any of the load-bearing characteristics of the building structure" and "The main difference with windows is that curtain walls are built in front of the building structure, while windows are built into the building openings.".*

Therefore, the system of the double glass wall is widely considered in architecture and engineering in terms of its benefits. Principally, aesthetics, ventilation, cost saving, acoustic, client control, comfort, productivity and security were all positively explained by Arons (2000). It can allow ventilation to circulate inside the cavity predominantly and to stipulate great acoustic insulation for the building (Lee et al., 2002), and the second layer of the glazing skin can be partially or entirely extended all over the building structure while the distance from the internal layer can be up to several meters (Regazzoli, 2013). Furthermore, the system can also provide natural light (De Carli et al., 2014), energy efficiency and improvement in occupant's thermal sensation in the building (Barbosa & Ip, 2014; Ghaffarianhoseini et al., 2016).

### 2.2.4 Classification of Double Skin Façade

From various pieces of literature, the classification of double skin façade was made based on their characteristics and performances. Loncour et al. (2005) classified a double skin façade by three main criteria, namely type of ventilation, the partition of the façade and modes of ventilation of the cavity (Figure 2.2).

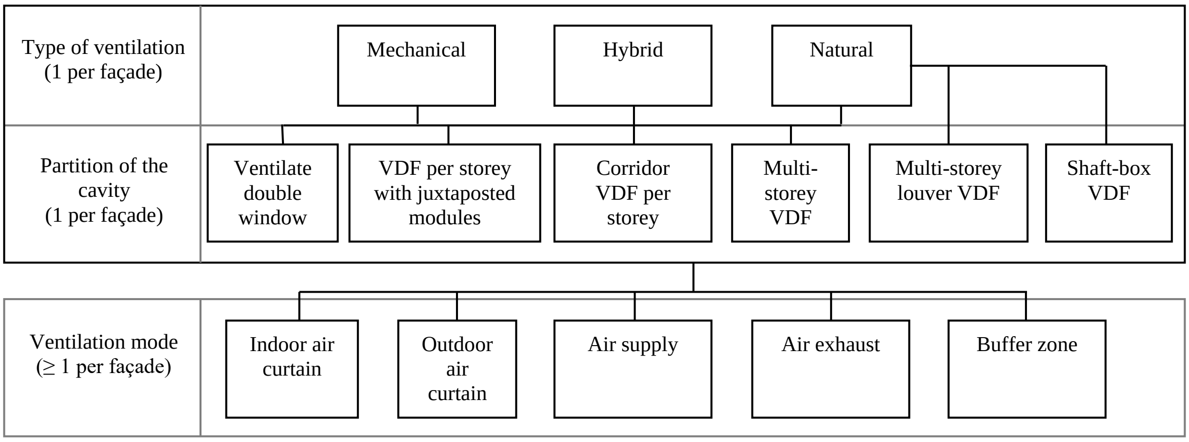



Figure 2.2 Double skin façade classification overview, Loncour et al. (2005)

#### 2.2.4(a) Ventilation type

This classification emphasizes ventilation of the cavity, which can be operated naturally, mechanically, or even both, which is called a hybrid system (Figure 2.3). There are similarities in explanations of ventilation varieties as follows:

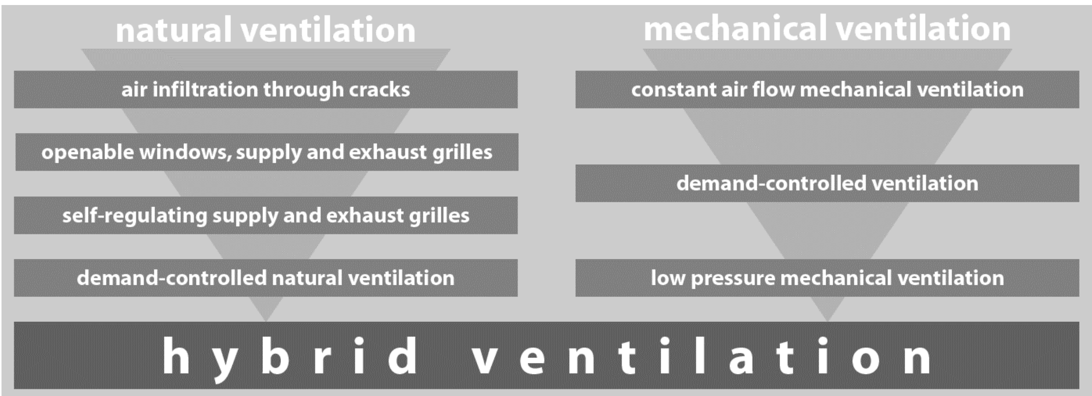



Figure 2.3 Development of natural and mechanical systems (Heiselberg, 2002)

- ***Natural ventilation***: Loncour et al. (2005) defined this classification based on the standard NBN EN 1279 as *"ventilation (...) which relies on pressure differences without the aid of powered air movement components."*. It is also called passive ventilation due to the absence of mechanical support to ventilate the building (Autodesk, 2016). Natural air is blown into and out of the building through the opening of the wall, whereas temperature and humidity take roles in performing stack effect by the discrepancy of its properties (Walker, 2016).

**- *Mechanical ventilation***: Active ventilation is a system that requires the support of forced air circulating mechanisms (Loncour et al., 2005). Unlike natural ventilation, mechanical ventilation is motorized by mechanical fans or blowers to provide fresh air in the building when there is insufficient regular air circulating in the building. On the other hand, various types of mechanical ventilation could be equipped on any part of the building where needed according to the respective climate (WHO, 2009).

**- *Hybrid ventilation***: Also known as mix-mode ventilation, hybrid ventilation is a system driven by both natural and mechanical ventilation to ventilate buildings. The two systems are combined and switched based on different climatic conditions to enhance the thermal environment while providing energy efficiency (Heiselberg, 2002; Loncour et al., 2005).

#### 2.2.4(b) Partitioning

Another classification of double skin façade is defined by the partition of the cavity. Partitioning tells us how ventilation performs between the two glazing walls and how it is used in different situations. Based on Loncour et al. (2005), partitioning of DSF cavity can be classified as ventilated double window, ventilated double façade per story with juxtaposed modules, corridor ventilated double façade per story, multi-storey ventilated double façade, multi-storey louver ventilated double façade and shaft-box ventilated double façade (Figure 2.2). Similarly, Poiraziz (2004) provided the four most clearly defined DSF systems by their geometry, including Box Façade, Corridor Façade, Shaft-Box Façade and Multi-Storey Façade (Figure 2.4).

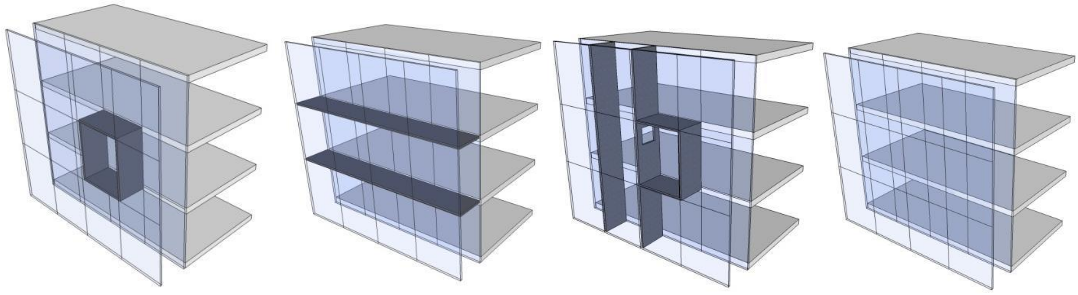



Figure 2.4 Classifications of double skin façade, (Regazzoli, 2013)

#### 2.2.4(b)(i) Ventilated double window/ box façade

To provide passive ventilation for both intermediate space and living space, the opening of the exterior skin is purposefully provided to introduce fresh air by removing stale air inside the cavity. Due to the requirement of acoustic insulation to prevent noise from both exterior and interior, the box façade system becomes one of the most DSF to be established and employed in such circumstances (Oesterle et al., 2001). Similarly, the box façade is said to be useful in terms of preventing sound from transmitting through additional glass vertically and horizontally. On the other hand, it performs better than natural ventilation regarding the level of fire security (Uuttu, 2001). According to Loncour et al., 2005, it may use windows double inside or double outside by single glazing or by a second window, and it has similarities with a box façade. A box façade is a system where the cavity is separated both vertically and horizontally at each level of the façade, as shown in Figure 2.5. The system works by composing two parallel windows, forming a gap that allows air circulation (Carlos et al., 2011).

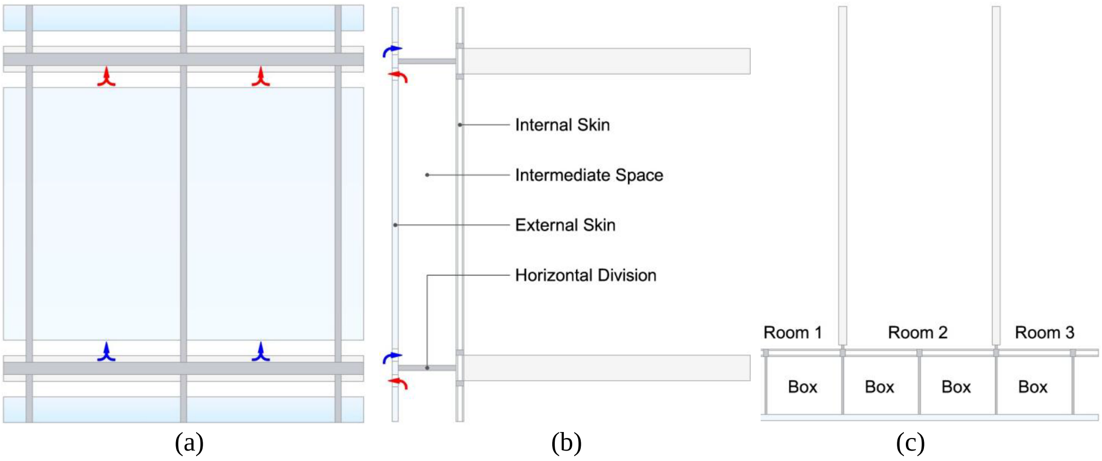


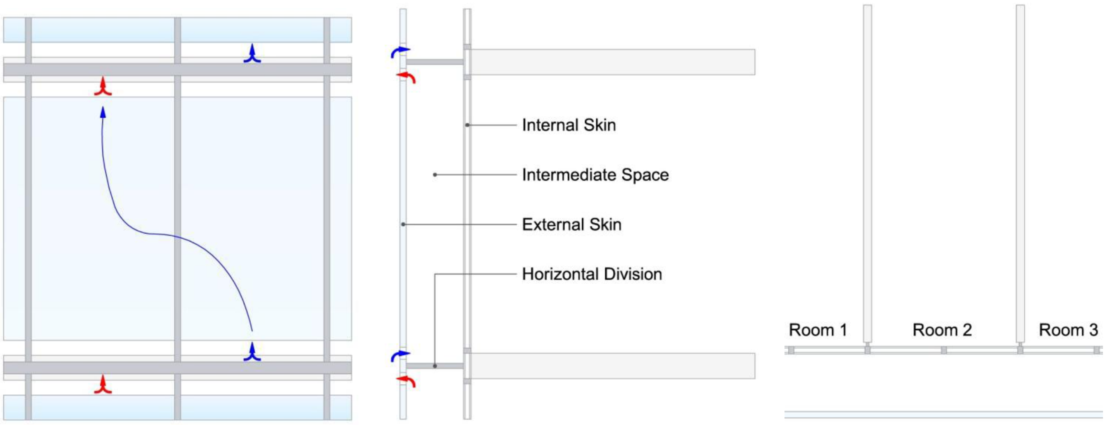

Figure 2.5 Box façade: (a) elevation, (b) section, (c) plan, (Regazzoli, 2013)

#### 2.2.4(b)(ii) Ventilated double façade per story with juxtaposed modules

Based on Loncour et al. (2005), *"In this type of facade, the cavity is physically delimited (horizontally and vertically) by the module of the facade which imposes its dimensions on the cavity."*. This façade type may be referred to corridor ventilated double façade, as presented in Figure 2.6. However, the module of this façade has a height limit to a single floor only.

#### 2.2.4(b)(iii) Corridor ventilated double façade

According to Uuttu (2001), a corridor façade is isolated horizontally between each floor, and the fundamental perception of this façade is decent ventilation, acoustic insulation and a fire security system of the horizontal division platform in the cavity (Figure 2.6). No vertical division is placed in this corridor system except at the angle of the corner of the building or when insulation, security and construction reasons arise (Lee et al., 2002). Fundamentally, it can cover partially or entirely the whole façade, and normally, it is accessible for walking through the corridor cavity (Loncour et al., 2005).

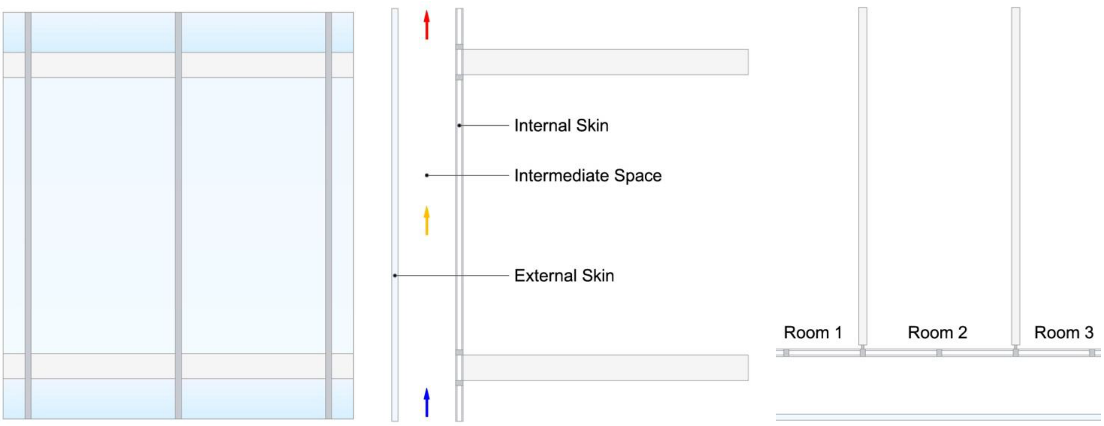



(a) (b) (c)

Figure 2.6 Corridor façade: (a) elevation, (b) section, (c) plan, (Regazzoli, 2013)

### 2.2.4(b)(iv) Multi-storey (louver) ventilated double façade

The intermediate space of this façade system is not separated vertically or horizontally (Oesterle et al., 2001). On a warm day, stale air in the cavity will be warmed up and exhausted through the outlet at the top of the cavity. As a result, cooler air will be introduced through the inlet at the base of the cavity to replace the remaining air (Uuttu, 2001). The exterior layer could cover a great portion of the building façade and allow the extent of air circulation in the cavity (Loncour et al., 2005). The system is demonstrated in Figure 2.7.



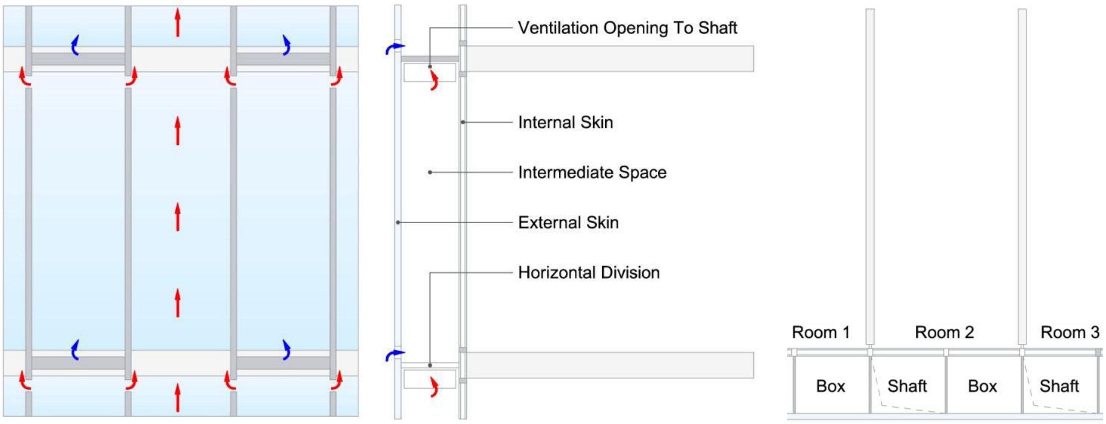

(a) (b) (c)

Figure 2.7 Multi-storey façade: (a.) elevation, (b) section, (c) plan, (Regazzoli, 2013)

Like other façade systems, a multi-storey façade provides great sound insulation, ventilation, fire security, and protection for the device equipped in the intermediate zone (Uuttu, 2001). *"The multi-storey louver naturally ventilated double facade is very similar to a multi-storey ventilated double facade. Indeed, its cavity is not partitioned either horizontally or vertically and therefore forms one large volume. Metal floors are installed at the level of each storey in order to allow access to it, essentially for reasons of cleaning and maintenance. The difference between this type of facade and the multi-storey facade lies in the fact that the outdoor facade is composed exclusively of pivoting louvers rather than a traditional monolithic facade equipped (or not) with openings. This outside facade is not airtight, even when the louvers have all been put in closed position, which justifies its separate classification. However, the problems encountered with these facades are generally comparable to those encountered in the other VDF´s."* (Loncour et al., 2005).

#### 2.2.4(b)(v) Shaft-box ventilated double façade

The shaft-box façade structure provides a very strong buoyancy effect and is normally used as a part of low-rise construction (Oesterle et al., 2001). On top of acoustic insulation, this façade system provides great ventilation and a building security scheme (Uuttu, 2001). This façade system is similar to a single-storey height module or box façade in the way that its modules are linked with the building, as illustrated in Figure 2.8. The circulating air from the box window connects to the vertical shaft, where the air is discharged and drawn to the top of the opening by the thermal stack effect (Lee et al., 2002; Loncour et al., 2005). Each type of DSF has a different role based on the design in response to climate variations.




(a) (b) (c)

Figure 2.8 Shaft box façade: (a) elevation, (b) section, (c) plan, (Regazzoli, 2013)

### 2.2.4(c) Ventilation modes

Another classification of DSF is done by the demonstrative of air circulating in the cavity and how it is introduced into the cavity (Saelens et al., 2003). According to Loncour et al. (2005), five main characteristics of ventilation modes in the intermediate space of double skin façade were categorized as follows (Figure 2.9).

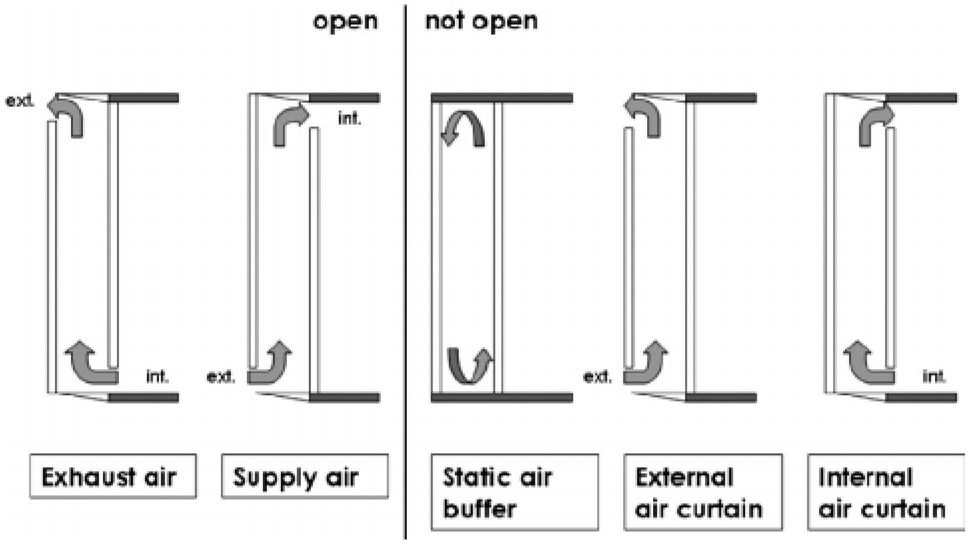



Figure 2.9 Air movements in versatile types of DSF (Haase et al., 2009)

- ***Outdoor air curtain:*** This ventilation mode extracts air from the outside into the cavity and exhausts instantly to the outside, consequently creating an air curtain wall in front of the façade.

- ***Indoor air curtain*:** This ventilation mode works the opposite of the outdoor air curtain mode. The cavity extracts air directly from the room, and air is constantly returned into the room through the ventilating system, therefore creating an air curtain wall inside the façade.

- ***Air supply:*** This system introduces outside air into the interior or ventilation system of the room. The air is supplied constantly through the opening of the exterior layer and drawn into the room through the opening of the interior façade.

- ***Air exhaust:*** This system works the opposite way the Air supply does. The air inside the room is drawn into the outdoor environment through the inlet of the interior façade and the outlet of the exterior layer.

- ***Buffer zone:*** This ventilation mode provides no ventilation system, as the stale air is strapped tightly, creating a buffer zone in the cavity of the façade.

### 2.2.5 Technical Aspects of Double Skin Façade System

In the realm of the DSF system, the common perception often revolves around the notion of double glass walls with a cavity inside. However, there are many aspects of configurations to be considered when designing a DSF system. The three main aspects of a double façade are cavity depths, glass materials and shading devices. These aspects play such an important role in the system and can be designed inversely to enhance the performance of the DSF system.

#### 2.2.5(a) Cavity depth

The intermediate space of the DSF can vary in size, ranging from centimeters to several meters, depending on the desired performance set by the designer. Numerous studies have emphasized the importance of determining the effective depth of the cavity in the context of tropical climates. For example, Aksamija (2009) found that a one-meter air-gap size in a DSF yielded superior results in terms of reducing