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Natural Ventilation Techniques as a Base for Environmental Passive Architecture

With Special Reference to Residential Buildings in Greater Cairo

A Thesis Presented in Partial Fulfillment of the Requirements for Master of Science Degree in Architecture Engineering

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STATEMENT

This thesis is submitted to Ain Shams University for the M.Sc. degree in Architecture.

The work included in this thesis was carried out by the researcher at the Department of Architecture, Faculty of Engineering, Ain Shams University, and During the Period from September 2007 to May 2012.

No Part of this thesis has been submitted for a degree of a qualification at any other university or institute.

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DEDICATION

To my father's pure soul; may ALLAH have mercy upon him

To my mother's kind heart

To my loving wife

To my country to have a rising and bright future

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First of all, I am thanking *Allah* Almighty for accomplishing this modest work, hoping that holds the good for the scientific researchers and students locally and internationally.

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ABSTRACT

The research aimed to evaluate the efficiency of applying the natural ventilation passive techniques within a residential space on the indoor ventilation rates and thermal comfort within local hot summer climate. The research revealed that the techniques that depend on thermal buoyancy effect, as a working principle, could achieve significant high ventilation rates within local hot summer climate of high temperatures and solar radiation.

Double wall technique, with variables of air gap, construction material, technique opening dimensions, and position, was investigated using EnergyPlus as a CFD simulation engine to study system efficiency on flow rate and thermal comfort using only passive convective strategy. Investigation was conducted within both day and night conditions and all orientations of solar exposure (east, south, and west orientations). This simulation included testing other passive techniques already existing as a reference case to define natural ventilation passive techniques that are suitable and appropriate to be applied into the local climate of Cairo.

CFD simulations showed that applying double wall technique with the given configurations enhanced ventilation rates at all orientations by mean values that vary from 68.9% to 85.9%, with maximum recorded mean air velocity of 0.3 m/s. In case of high quality of outdoor supply air, these high ventilation rates improve the indoor air quality levels.

The results also revealed that applying technique within eastern façade can enhance thermal comfort levels inside a space by a maximum mean operative temperature value of 3.65°C at night, which met thermal comfort acceptability limits.

Within southern and western orientations, applying system did not enhance the thermal comfort levels at day or night conditions. A supplementary study revealed that reducing incoming air temperature while applying double wall technique can reduce the indoor mean operative temperature by around 0.3°C to 0.4°C for each reduction in incoming air temperature of 1.0°C. This gives promising indicators that applying double

wall technique during warm season may enhance the thermal comfort conditions through high levels of ventilation rates.

ABBREVIATIONS

ACH	Air Changes per Hour
Amb.	Ambient
AVG	Average
CFD	Computational Fluid Dynamics
DSF	Double Skin Facade
ECC	Evaporative cooling cavity
EMA	Egyptian Meteorological Authority
ETMY	Egyptian Typical Meteorological Year
IAQ	Indoor Air Quality
IWEC	International Weather for Energy Calculations
LMA	Local Mean Age of air
PPD	Predicted Percentage of Dissatisfied
PMV	Predicted Mean Vote
SC	Solar Chimney

KEYWORDS

Natural Ventilation Techniques

Passive Techniques

Ventilation Rate

Thermal Comfort

Residential Space

Indoor Air Quality

CFD Simulations

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Overview

Environmental design aims to save the natural balance between man and surroundings, and to turn back the relationship between man, architecture and environment to the stage of equilibrium.

Passive design depends on the building design and materials to control the environmental conditions within the inner spaces of the building without need of consuming energy. In other words, passive architecture is that one of innate environmental harmony. Passive architecture gets its potentials from location, society, and human who applied innately the simplest principles of passive architecture since he started to build a house for himself and his family to protect them from the outside environmental conditions.

Local traditional architecture was applying the environmental passive principles in building designs that were a pure reflection of the local life and society and of the economic, social and climatic conditions of the region.

Because of contemporary westernization, the local contemporary architecture appeared losing the principles of passive design and harmony with the surroundings. This environmentally distorted output results in directing the users to the active solutions that need more energy just to provide comfortable living conditions.

From here, this research tries to be a step on the way of track readjustment by studying a major factor of passive design concerning the thermal comfort and indoor air quality, which is indoor natural ventilation through analyzing and evaluating the natural ventilation passive techniques. The research will study the possibility of applying these techniques within the local climate of Greater Cairo region.

Problem Statement

Usage of mechanical air conditioning as an active cooling solution has heavily expanded recently due to many reasons. Also, operation hours of air conditioners have increased through summer season, and sometimes during spring and autumn seasons. This recent heavy dependence on such active solution for achieving thermal comfort has many dangerous impacts on indoor air quality and energy consumption. Passive strategies in architectural design may help minimizing the operation hours of active solutions in very hot regions like Egypt. Within Egyptian hot summer climate, efficient convective strategy that achieves comfortable thermal conditions and high indoor air quality is missing. So, research will go through studying the convective applications to evaluate the efficiency of passive techniques of natural ventilation in local hot climate.

Research Hypothesis

Application of natural ventilation passive techniques within a residential space in local hot climate may affect positively the thermal comfort levels and indoor air quality by enhancing ventilation rates within this space.

Research Objectives

The Main goal of the research is to define natural ventilation passive techniques that are suitable and appropriate to be applied into the local climate of Greater Cairo. This goal can be reached through some partial objectives:

- Defining the natural ventilation process and passive techniques.
- Analyzing the residential applications of natural ventilation passive techniques within similar climates to the local one.
- Evaluating local reference case performance.
- Evaluating the efficiency of applying the natural ventilation passive techniques within the residential reference case on the indoor ventilation rates and thermal comfort of space.

Research Methodology

Research will go through successive stages of study:

1. Theoretical study

- Theoretical study of natural ventilation process.
- Theoretical study for the most common passive techniques of natural ventilation (the operation principle and applications)

2. Analytical study

- Analytical study for natural ventilation passive techniques applications within the residential buildings in climates similar to the climate under study (case studies).

3. Comparative applied study

- Definition of local reference case and natural ventilation passive technique of the study.
- Analyzing the application of the passive technique by thermal and CFD (Computational Fluid Dynamics) simulations, then evaluating and comparing the results with the reference case.

Research Structure

Organization of the research connects to the methodology as shown in the diagram in figure 0.1.

- *Chapter one: Natural Ventilation Passive techniques*

Chapter one states a background of passive cooling strategies and approach of natural ventilation theoretical concepts, and illustrates the passive techniques of natural ventilation according to the proposed classification through studying working principle and applications of each.

- *Chapter two: Natural Ventilation Passive Techniques for Contemporary Housing Applications*

Chapter two analyzes four case studies of applying natural ventilation passive techniques into residential buildings through studying their performance and evaluating the results.

- *Chapter three: CFD Simulation Analysis*

Chapter three discusses the local issues beginning with the local climatic conditions of Greater Cairo, and then goes through the selection process with its dual phase of selection (reference case and passive technique for study). Through determining the limitations of input data of CFD simulation analysis, chapter three deals with the CFD analysis phases of simulating the reference case and passive technique.

- *Chapter four: CFD Simulation Results*

Chapter four has been assigned to demonstrate the simulation results, and to discuss, evaluate and compare the results of technique application to the reference case.

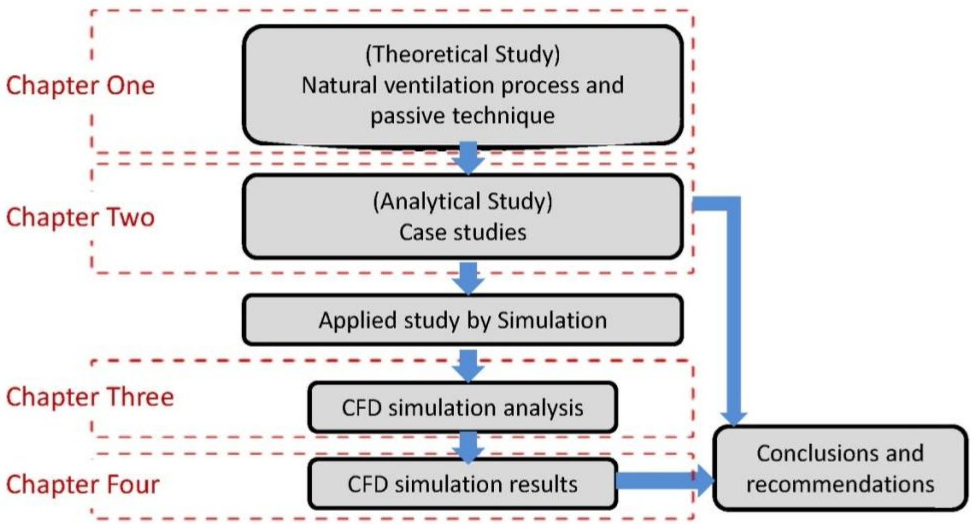

Figure 0.1 - Research main structure

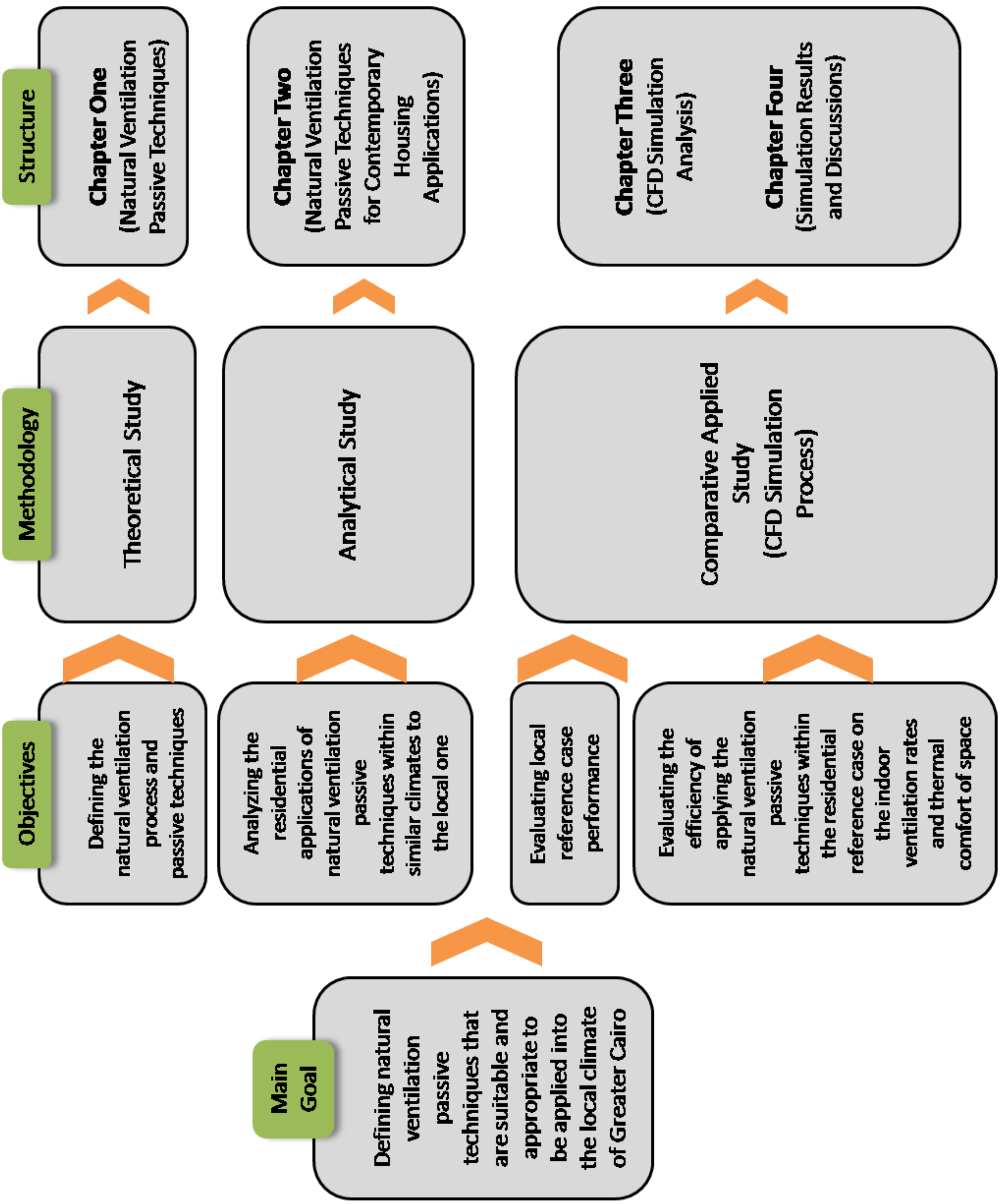

Figure 0.2 - Research organization network

Literature Review

This review is to briefly highlight the previous work and researches related to passive cooling techniques, building envelope passive design, and exterior openings configurations. This review was carried out in the early stages of the study in order to clarify the main ideas of this research.

A. Researches related to natural ventilation and passive cooling design and techniques

- *Passive Cooling Techniques for Enhancing the Building Sustainability Development (M.Sc. thesis, Ain Shams University, Cairo, 2010)*

This research had classified the passive techniques due to the cooling strategies. Then, it discussed the passive considerations focusing on the principles and applications of natural cooling techniques through theoretical review and analysis[1].

- *The possibility of using conventional climatic treatments within contemporary architecture in Egypt (M.Sc. thesis, Ain Shams University, Cairo, 2002)*

This research had introduced an analytical study for the conventional passive techniques and their functional performance. Study also evaluated the application of these treatments within contemporary local climate and architecture. It also focused on the climatic performance of applying courtyard and lathe-turned wooden lattice windows on the built environment[2].

- *Natural Ventilation as a Design Approach for Passive Architecture (M.Sc. thesis, Ain Shams University, Cairo, 1999)*

This research introduced an analytical study of natural ventilation passive techniques for cooling and heating within different climates[3].

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[1] (Hammad, Passive Cooling Techniques for Enhancing the Building Sustainability Development, 2010)

[2] (مصطفى، إمكانية استخدام المعالجات المناخية التقليدية في العمارة المعاصرة في مصر، 2002)

[3] (الدبركي، التهوية الطبيعية كمدخل تصميمي في العمارة السالبة، 1999)

B. Researches related to opening configurations and building envelope

- *Air flow through louvered openings: Effect of louver slates on air movement inside a space (M.Sc. thesis, University of Southern California, USA, 2010)*

This research had performed a wind tunnel testing and CFD simulation to study the effect of different louvered openings that provide natural ventilation on indoor air velocities, air flow characteristics, and thermal comfort conditions inside space[1].

- *Impact of Building Envelope Design on Thermal Gain and Comfort, An approach for environmental design of building envelope (M.Sc. thesis, Cairo University, Cairo, 2003)*

This research had studied the effect of architectural solar design on building envelope, producing a numerical approach to study the effect of window configurations on thermal behavior of building. Research also proposed an analytical methodology for designing the building envelope[2].

- *Passive Solar Architecture in Hot Climates, Economic Evaluation for its climatic treatments (M.Sc. thesis, Cairo University, Cairo, 1994)*

This research had introduced a theoretical study for the effect of passive solar features on building envelope with an analytical study of passive techniques economic evaluation. Study ends with a methodology for simulating building envelope with solar passive techniques[3].

- *Architectural Approach to the Energy Performance of Buildings in a Hot-Dry Climate with Special Reference to Egypt (PhD thesis, University of Bath, UK, 1986)*

This research had submitted an evaluation of energy performance of buildings within hot dry climate of Egypt. Part of the research focused on natural ventilation through a theoretical methodology for ventilation

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[1] (Chandrashekaran, Air flow through louvered openings: Effect of louver slates on air movement inside a space, 2010)

[2] (العيسوي، تأثير تصميم الغلاف الخارجي للمبنى على الاكتساب الحراري والراحة الحرارية للمستعملين - منهج لعملية التصميم البيئي للغلاف الخارجي للمباني، 2003)

[3] (الزعفراني، العمارة الشمسية السالبة في المناطق الحارة - تقييم لاقتصاديات معالجتها المناخية، 1994)

principles and analytical study for the effect of opening ratios on indoor environmental conditions[1].

Literature Review Conclusion

The previous researches had illustrated the passive cooling techniques in a theoretical analysis methodology, taking all passive strategies into consideration. The researches dealt with simulation analysis for evaluating passive techniques had focused on window configuration to study the indoor air flow and thermal comfort.

This research will study the performance of natural ventilation techniques related to building envelope within local climate using a simulation analysis methodology to study both thermal comfort and ventilation rates within indoor environment.

[1] (Hamdy, Architectural Approach to the Energy Performance of Buildings in a Hot-Dry Climate with Special Reference to Egypt, 1986)

CHAPTER
ONE

Natural Ventilation Passive Techniques

- Introduction
- Passive Cooling Strategies
- Natural Ventilation
- Natural Ventilation Design Guidelines
- Natural Ventilation Approaches
- Traditional Natural Ventilation Strategies
- Passive Techniques of Natural Ventilation
- Conclusion

1.1. Introduction

This chapter mainly discusses the working principles and application of the most common passive techniques of natural ventilation according to the proposed classification based on theoretical fundamentals studied herein. Through explaining natural ventilation main approaches, this chapter is going to study natural ventilation as a passive strategy, as shown in figure 1.1, used for achieving both: indoor air quality and thermal comfort.

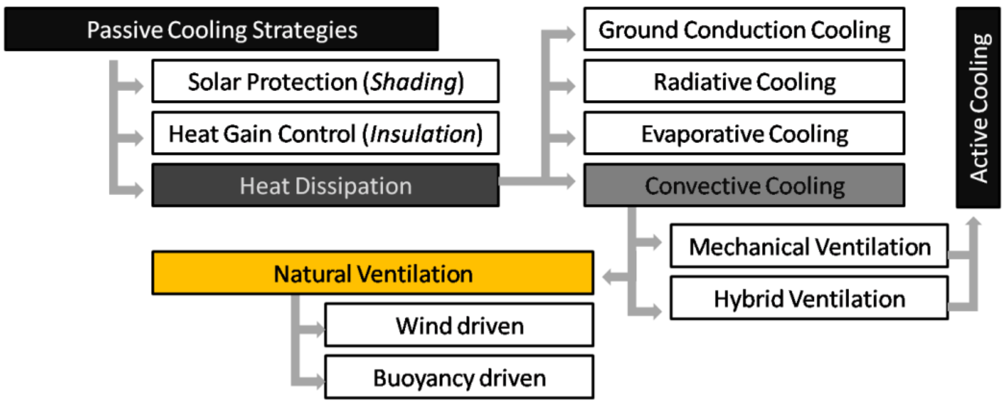

Figure 1.1 – Passive cooling strategies[1]

Using active solutions for achieving thermal comfort has many negative impacts on indoor air quality and energy consumption. The use of air conditioning in the residential buildings sector is rapidly increasing, causing a highly intensive increase in energy consumption needed for residential cooling. This wide use of air conditioning is a result of many reasons:

1- Adoption of a universal style of buildings that does not consider local climatic issues. This results in increasing energy demands during summer period.

2- Increase of ambient temperature, particularly in the urban environment, due to the heat island effect, which expands the cooling demand in buildings. The heat island has a tremendous impact on air-conditioning demand, and then peak power supply[2].

[1] The researcher

[2] (Santamouris M. , Advances in Passive Cooling, 2007, pp. xx - xxiii)

3- Summer heat waves that are striking Egypt are gradually, year after year, increasing in intensity and number of occurrence resulting in higher consumption of electricity loads needed for air conditioning. This led in some instances to power failures leaving some districts of Cairo in full darkness[1].

4- Changes in consumer behavior and expectations. It should be underlined that during the summer of 2005, Japanese prime minister proposed an intensive campaign to encourage Japanese office workers to take off their ties to decrease their thermal comfort levels and save air conditioning loads[2].

5- Improvement of living standards which has an important impact on the energy consumption of buildings due to increase in the buildings internal loads[3].

All these issues result in a great expansion in air conditioning market, and considerable problems associated to the wide use of air conditioning, like:

- Increase in the peak electricity load.
- Environmental problems like ozone depletion and global warming.
- Indoor air quality problems.

1.2. Passive Cooling Strategies

Energy conservation and passive cooling/heating are the most efficient and cheap alternatives to conventional energy sources. Most studies in hot climates have revealed that the most energy efficient spaces are those which use passive techniques for cooling[4]. The term "passive" implies that energy-consuming mechanical components like pumps and fans are NOT used. Passive cooling building design attempts to integrate principles of physics into the building envelope to slow heat transfer into a building and remove unwanted heat from a building[5].

Passive cooling strategies can be classified in three main categories as follows:

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[1] (Egypt hit by power cuts amid Ramadan heat wave, 2010)
[2] (Santamouris M. , Advances in Passive Cooling, 2007, p. xxv)
[3] (*Ibid.*, p.xix)
[4] (*Ibid.*, p.xxix)
[5] (http://en.wikipedia.org/wiki/Passive_cooling, Passive Cooling, 2010)

1.2.1. Solar protection

Protection from direct solar radiation may involve: Landscaping, building form, and solar shading of building surfaces.

1.2.2. Heat gain control

Control of heat gain deals with the insulation properties and thermal capacity of the building materials and structure. The cycle of heat storage and discharge must be combined with means of heat dissipation strategy, like night ventilation, so that the discharge phase does not add to overheating.

1.2.3. Heat dissipation

This strategy deals with the potential for disposal of excess heat of the building to an environmental sink of lower temperature. Dissipation of the excess heat depends on two main conditions: the availability of an appropriate environmental heat sink; and the establishment of an appropriate thermal coupling between the building and the sink as well as sufficient temperature differences for this transfer of heat. The main processes of heat dissipation strategies are: ground cooling using the soil as the heat sink, convective and evaporative cooling using the air and/or water as the sink, and radiative cooling using the sky as the heat sink. The potential of heat dissipation techniques strongly depends on climatic conditions[1].

Convective cooling by ventilation is one of the most effective heat dissipation strategies, and a very effective method to improve indoor comfort, indoor air quality and reduce temperature. Higher air speeds inside the building may enhance thermal comfort when they do not exceed certain values, as it will be explained later. This strategy is usually limited to night time ventilation, however daytime ventilation may be used when ambient temperature is lower than indoor temperature.

Convective cooling may be natural, mechanical or hybrid. Natural ventilation is due to wind forces, temperature differences or both. Careful positioning of

[1] (Santamouris M. , Passive Cooling of Buildings, 2005, p. 15)

the openings in naturally ventilated buildings is a vital parameter that determines the effectiveness of the process[1].

1.3. Natural Ventilation

Ventilation can be considered one of the main requirements for the thermal comfort by controlling temperature, humidity, air motion, and quality of air with regard to contaminants.

The main functions of ventilation are related directly to both comfort and health. As ventilation is important to introduce suitable thermal conditions by achieving good air movement, and removing extra-heat generated within spaces, Ventilation can also be considered a vital factor to introduce clean air into building by removing air contaminated by occupants and their activities[2].

Natural ventilation is achieved by using the available natural resources of wind power and solar and thermal energy. Although these natural resources are free; they are difficult to control, hence, the challenge becomes to provide and develop the suitable control mechanisms to reach the required indoor air quality[3]. To achieve that, it is necessary to understand the terms related to ventilation explained in detail within appendix A.

1.3.1. Natural ventilation for indoor air quality

One of the main purposes of ventilation is to provide acceptable indoor air quality by removing contaminants generated within inner volume. This process can be achieved by obtaining acceptable levels of ventilation rates[4] inside space with comfortable conditions of temperature and humidity[5]. According to ASHRAE Standard 62.2-2007, the required ventilation rate for achieving acceptable indoor air quality in residential buildings depends on unit floor area and number of bedrooms, the whole-building required ventilation rates are shown in appendix A. For around 100 m^2 apartment with

[1] (*Ibid*., p. 18)
[2] (ASHRAE-Standard, ASHRAE Standard 62.1.2007 (Ventilation for Acceptable Indoor Air Quality), 2007)
[3] (Linden, The Fluid Mechanics of Natural Ventilation, 1999, p. 202)
[4] Total amount of air passing into or out of the room per unit time (litters/second)
[5] (ASHRAE-Standard, ASHRAE Standard 62-2-2007 (Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, 2007, p. 3)

2 bedrooms, the minimum ventilation rate is 21 L/s[1]. Generally, natural ventilation can achieve the required indoor ventilation rates. Anyway, in case of high outdoor air quality, higher value of ventilation rate inside space is preferable.

1.3.2. Natural ventilation for thermal comfort

Natural ventilation performance criteria are related to the objectives of ventilation: air quality control and thermal comfort. Criteria for air quality control are defined in terms of minimum ventilation rates, while criteria for thermal comfort depend on air velocity, indoor air temperature, and mean radiant temperature[2].

Due to the multi-parameters of thermal comfort, precise value of ventilation rate required for achieving thermal comfort is hard to be determined. So, air velocity is more applicable parameter when talking about thermal comfort. For low air velocities, mean radiant temperature and room air temperature equally affect the comfort temperature (operative temperature). At relatively high air velocities operative temperature can be described as the room air temperature, reducing the impact of mean radiant temperature.

When night ventilation is applied, daytime natural ventilation should normally be limited to the minimum rate required for air quality control to avoid convective overheating of the building. Thus, by reducing air velocity, radiant impact will be maximized to achieve acceptable thermal comfort temperature.

On the other hand, when air temperature is within acceptable ranges for achieving indoor thermal comfort, natural ventilation by convection should be magnified to make best use of outdoor air temperature. Thus, by increasing air velocity, air temperature effect will be maximized to achieve required comfort temperature.

When natural ventilation is used for cooling, the upper limit of thermal comfort zone may be exceeded from time to another due to random variations

[1] *Ibid*. p.4
[2] (Santamouris M. , Solar Thermal Technologies for Buildings (The State of The Art), 2003, p. 117)

of the natural driving forces. The BRE (Building Research Establishment, UK), Environmental Design Manual 1988, places limits on the mean and standard deviation of summer indoor comfort temperatures of 25 ± 2 °C for informal spaces[1].

1.3.3. Acceptable thermal conditions

General acceptable thermal conditions deal with those internal conditions that achieve an accepted indoor environment, whether or not the space is naturally ventilated. There are six primary factors that define conditions for thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity[2]. Clarifications for these thermal conditions are explained within appendices B, C, and D.

Occupant-controlled naturally ventilated spaces are those spaces where the thermal conditions of the space are regulated primarily by the users through opening and closing the windows. In such spaces, occupants' thermal responses depend on the outdoor climate, with no mechanical cooling system for the space.

Requirements at this section apply only to spaces where the users are acting light physical activities, and may freely adapt their clothing to the indoor and outdoor thermal conditions.

Required indoor operative temperatures for spaces that meet these criteria may be determined from figure 1.2. This figure includes two sets of operative temperature limits: one for 80% of users' acceptability and the other for 90% acceptability. The 90% acceptability limits may be used when a higher standard of thermal comfort is desired. This figure is based on an adaptive model of thermal comfort that is derived from a global database of 21,000 measurements taken primarily in office buildings[3].

The allowable operative temperature limits may not be extrapolated to outdoor temperatures above and below the end points of the limits in this

[1] (*Ibid.*, p.118)
[2] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 2)
[3] (*Ibid.*, p.9)

figure. Thus, if the mean monthly outdoor temperature is less than 10°C or greater than 33.5°C, this requirement may not be used.

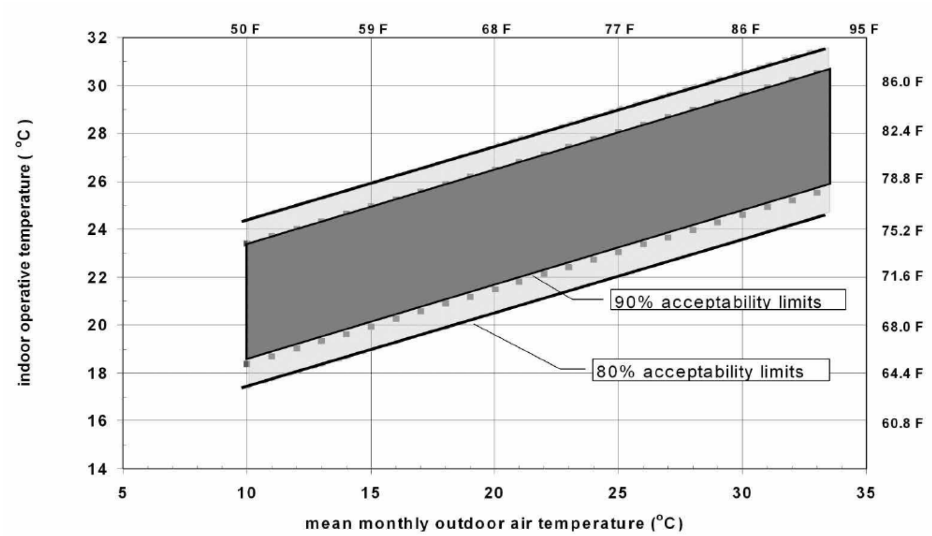

Figure 1.2 - Acceptable operative temperature ranges for naturally ventilated spaces[1]

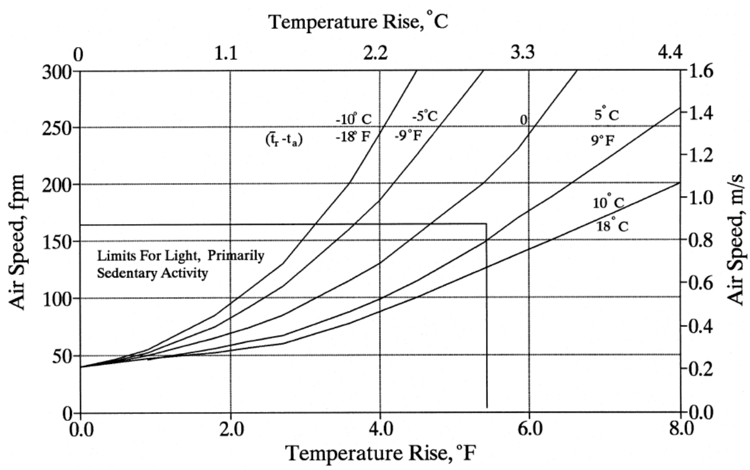

Figure 1.3 - Air speed required for offsetting increased temperature[2]

Elevated air speed may be used to offset an increase in the air temperature and the mean radiant temperature, but not by more than 3.0°C above the values for the comfort zone without elevated air speed, as shown in figure 1.3. The required air speed may not be higher than 0.8 m/s. As, with higher air speeds, large individual differences exist between people with regard to

[1] (*Ibid.*, p.10)
[2] (*Ibid.*, p.6)

the preferred air speed. Therefore, the elevated air speed must be under the direct control of the affected occupants[1].

1.4. Natural Ventilation Design Guidelines

The effectiveness of natural ventilation is being measured by its ability to ensure indoor air quality and passive cooling in a building. This effectiveness greatly depends on the design process.

Ventilation systems that use only natural forces like wind and thermal buoyancy need to be designed together with the building, since the building and its elements are the factors that can affect air movement, heat gain, and even air contaminants[2]. General design guidelines and criteria for natural ventilation depend on the following aspects:

1.4.1. Site constrains

The design of the site factors, as location, orientation, distribution, and landscaping, affects the overall airflow pattern, and thus ventilation rates within the spaces through monitoring:

- Topography and surrounding buildings.
- Building orientation due to airflow paths.
- Landscaping elements design

1.4.2. Building design program

The information needed to define proper requirements for natural ventilation, related to whole building and spaces design, include:

- Type of building (residential, commercial, …)
- Type of space (living room, bedroom, bathroom, office, kitchen, …)
- Time schedule of use for each space.
- The amount of fresh air needed hourly in each space (ventilation rate) and accepted indoor operative temperature.
- Climatic Data, like mean monthly outdoor temperature and relative humidity ranges.

[1] (*Ibid.*, p.6)
[2] (Allard, Natural Ventilation in Buildings (A Design Handbook), 2002, p. 195)

- Form of building envelope (building height, roof form, building aspect ratios, overhanging, wing-walls, and recessed spaces)
- Plan and sectional distribution of spaces due to wind direction, as shown in figure 1.4.
- Type of structure, and dimensions of exposed thermal mass.

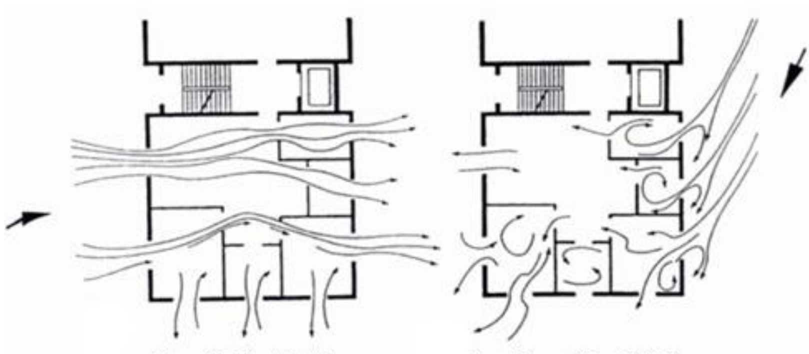

Figure 1.4 – Cross ventilation airflow patterns within an apartment with different wind direction[1]

1.4.3. Design of opening

Opening design, that is considered the core of this study, concerns the selection of the types of windows, screens and their operational features. Also, choosing the appropriate design elements (windows, screens, doors, vents, and ventilators) are important for applying the suitable technique to achieve the required rates of ventilation:

- *Windows*; that have multiple integrated functions like viewing, daylighting, solar gain, and ventilation, are signified due to some variables: the plane of placement (horizontal, vertical, or tilted), the position on building envelope, and the opening system.
- *Screens;* are basically used as shading devices, but can also be designed for ventilation purposes, or modifying the opening size, and aerodynamic performance of the window.
- *Doors;* that basically be functioned as interconnectors between spaces, can also be used in solar transmittance, and interzonal airflow control[2].

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[1] (Allard, Natural Ventilation in Buildings (A Design Handbook), 2002, p. 208)
[2] (*Ibid.*, pp. 196-225)

1.5. Natural Ventilation Approaches

The hybrid variations of natural ventilation techniques classifications that have been proposed in recent years are complicated. Nevertheless, these techniques are always stated as variants into three fundamental approaches to natural ventilation that can be merged into an integrated system. These three main approaches are:

- Wind-driven ventilation.
- Buoyancy-driven stack ventilation.
- Single-sided ventilation[1].

1.5.1. Wind-driven ventilation

A significant difference in wind pressure between inlet and outlet openings and a minimal internal resistance to flow are needed to ensure sufficient air flow. The effect of wind on a building is dominated by the shape of the building and the proximity of other buildings and surrounding landscaping elements. Wind-driven ventilation occurs via ventilation openings on opposite sides of an enclosed space. Pressures are higher on the windward side of the building and lower on the leeward side and on the roof and so will tend to drive a flow within the building from the windward vents to the leeward vents. Figure 1.5 shows a schematic of cross ventilation serving a multi-room building. The building floor plan depth in the direction of the ventilation flow must be limited to effectively remove heat and pollutants from the space by typical driving forces[2].

1.5.2. Buoyancy-driven stack ventilation

Temperature, and pressure, differences between the inside and outside of a building and between different spaces within a building produce buoyancy forces that drive flow. Figure 1.6 shows a schematic of stack ventilation for a multi-room building. A chimney or atrium is frequently used to generate sufficient buoyancy forces to achieve the needed flow. However, even the smallest wind will induce pressure distributions on the building envelope that

[1] (Steven J. Emmerich, Natural Ventilation Review and Plan for design and Analysis Tools, 2001, p. 3)
[2] (*Ibid.*, pp. 3,4), (Linden, The Fluid Mechanics of Natural Ventilation, 1999, p. 204)

will also act to drive airflow. Indeed, wind effects may well be more important than buoyancy effects in stack ventilation schemes, thus the successful design will seek ways to make full advantage of both[1].

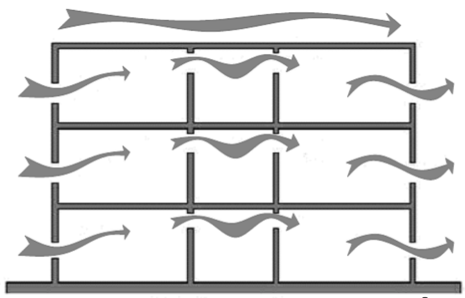

Figure 1.5 – Wind-driven Ventilation[2]

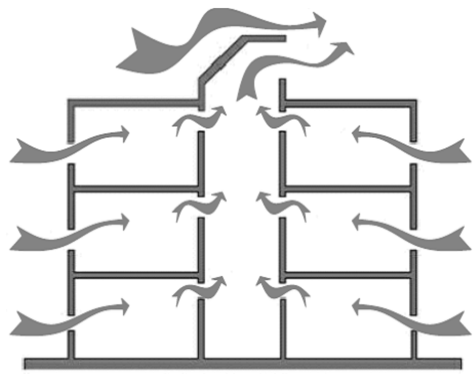

Figure 1.6 – Buoyancy-driven stack ventilation[3]

1.5.3. Single-sided ventilation

Single-sided ventilation is a special case of both wind-driven and buoyancy-driven ventilation, because ventilation airflow in this case is driven by room-scale small differences in envelope wind pressures, and buoyancy effects. Consequently, driving forces for single-sided ventilation tend to be relatively small and highly variable. This approach is one of the most common forms of natural ventilation and occurs when there is a single opening into a space. This strategy typically serves single rooms and thus provides a local ventilation solution. Figure 1.7 shows a schematic of single-sided ventilation in a multi-room building. Compared to the other alternatives, single-sided ventilation offers the least attractive natural ventilation solution but, nevertheless, a solution that can serve individual spaces[4].

1.5.4. Merging of basic approaches

Many built examples employ elaborations of these basic schemes. In some instances these three schemes have been used in a mixed manner in single

[1] (*Ibid.*, p.206), (Steven J. Emmerich, Natural Ventilation Review and Plan for design and Analysis Tools, 2001, p. 4)
[2] (*Ibid.*, p.4)
[3] (*Ibid.*, p.4)
[4] (*Ibid.*, p.5), (Linden, The Fluid Mechanics of Natural Ventilation, 1999, p. 218)

buildings to handle a variety of ventilation needs. Figure 1.8 shows a schematic of mixed (local/global) stack/wind ventilation strategy[1].

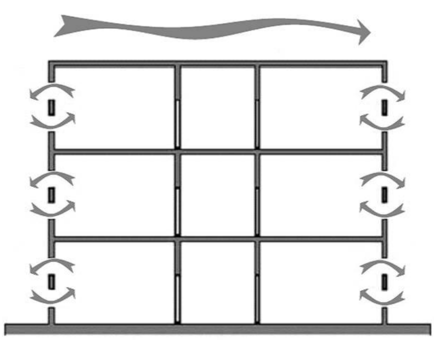

Figure 1.7 – Single-sided ventilation[2]

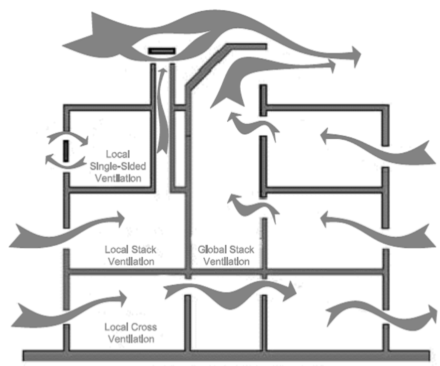

Figure 1.8 – Mixed Natural Ventilation Strategies[3]

1.6. Traditional Natural Ventilation Strategies

One of the most significant features of traditional architecture is the true reflection of the local environment and culture. Traditionally, building knowledge was being used to adopt buildings to the outdoor environment. Vernacular buildings in hot climates are commonly specified with thick walls, narrow vents, wind catchers, courtyards, ponds, fountains, rich gardens and vaulted chambers.

Traditional design is characterized by physical functionality, low-energy use, thermal comfort, durability and affordability. Such buildings used local construction materials, passive cooling and heating techniques, and renewable energies. All vernacular technologies and forms are generally found to be well adapted to local climate conditions, and are often considered an appropriate base for environmental design[4].

[1] (Steven J. Emmerich, Natural Ventilation Review and Plan for design and Analysis Tools, 2001, p. 6)
[2] *Ibid.*, p.5
[3] *Ibid.*, p.6
[4] (Ahmadreza Foruzanmehr, Towards new approaches for integrating vernacular passive-cooling systems into modern buildings in warm-dry climates of Iran, 2008)

Natural ventilation strategies in traditional applications, mostly, depend on solar protection, heat insulation, and heat dissipation by wind driven forces. Regional traditional architecture did understand the effect of the sun factor in air movement, and did make the best use of wind as a natural resource to achieve the internal thermal comfort by using the natural ventilation techniques that depend on the same physical, theoretical aspects of today, but within different forms of application. Although most of these vernacular techniques are energy efficient and sustainable, some of them are currently no longer used because of changing cultural and social aspects[1].

1.7. Passive Techniques of Natural Ventilation

The exact analysis of air flow in buildings is extremely complex because it involves three dimensional modeling. However, the actual entry of air into the building is influenced by size, shape, type, location, and operation of the window, and inlets and outlets of the space through various openings, or single opening[2]. The pure classification of ventilation techniques due to operation principles mentioned herein is only a theoretical method of arrangement. In real conditions, the different driving forces (wind and buoyancy) work together within each technique for achieving indoor natural ventilation as instructed at this chapter.

However, the techniques will be classified into three main categories, as shown in figure 1.9, due to the most effective driving force that achieves natural ventilation by this technique. Other effective driving forces within actual operation will be discussed separately within each technique. These three main categories are techniques that mainly depend on:

- Direct displacement by wind-driven force.
- Wind pressure differences and suction effect.
- Solar or thermal buoyancy effect.

Each technique will be discussed due to main operation principle, applications, and traditional forms of applications, if any.

[1] (Ibid.), (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 63)

[2] (I. F. Hamdy, Passive Solar Ventilation, 1998, p. 382)

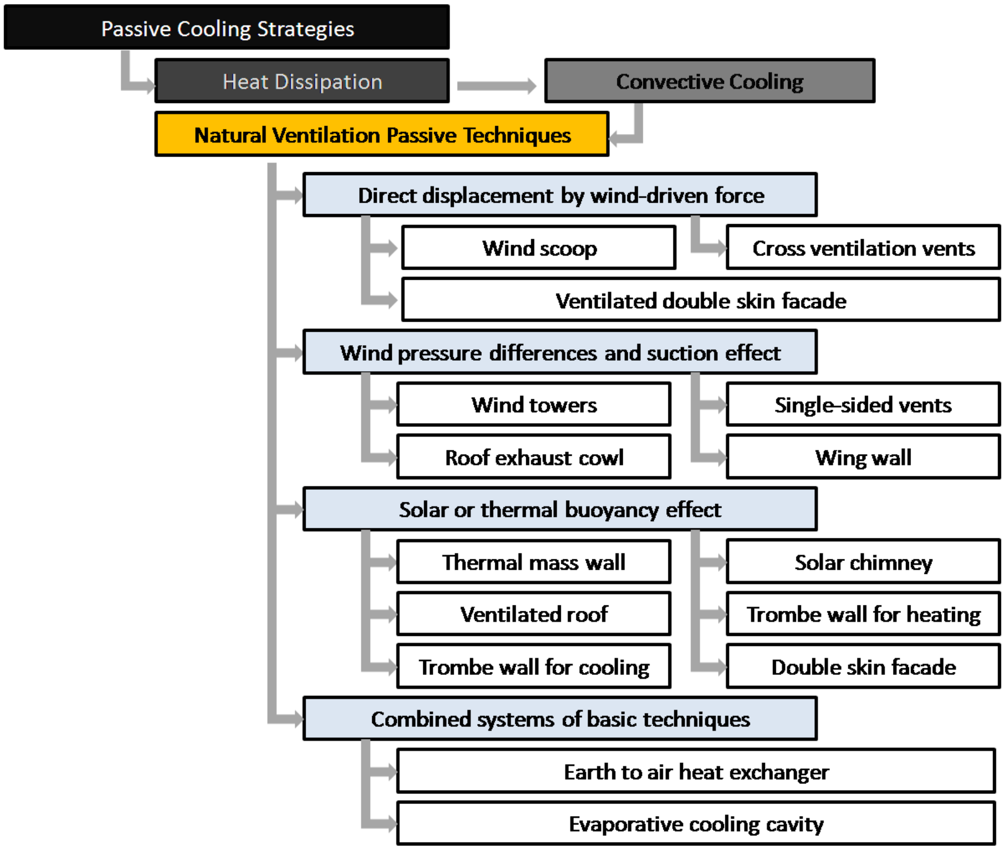

Figure 1.9 – Natural ventilation passive techniques classification[1]

1.7.1. Direct displacement by wind-driven force

This section illustrates techniques that depend on direct displacement by wind-driven force.

1.7.1.1. Cross ventilation vents

Cross ventilation vents system is commonly used in dwellings due to its low-tech nature, low cost and manual operability.

A. Operation principle

In such system, airflow through openings is mainly wind driven. Changes in ventilation flow rates, efficiency, thermal comfort and indoor air quality vary due to configurations of openings positions, as shown in figure 1.10, openings sizes, external sunshades, and types of window openings[2].

[1] The researcher
[2] (Naghman Khan, A review on wind driven ventilation techniques, 2008, p. 1587), (Baker, Passive and Low Energy Building Design for Tropical Island Climates, 1987, p. 108)

There are situations where the wind and buoyancy forces reinforce one another to ventilate a space, as shown in figure 1.11(a), and others where the buoyancy and wind forces oppose one another, as shwon in figure 1.11(b). The two situations result in very different air flows within the space[1].
The experiments have shown that, at case (a), air flow through space depends on wind speed and vertical distance between the two openings. In low and medium wind speeds, air flows through space by displacement achieving cross ventilation effect. But at high wind speeds, mixing mode of ventilation is observed doing short circuits of flow that negatively affect ventilation and numbers of air exchanges[2].

1- High inlet and outlet do not produce good air movement at body level.

2- Low inlet and outlet produce a good pattern of air movement required for cooling.

3- Low inlet and high outlet produce a low level wind pattern.

4- Air flow at ceiling height produced by high inlet is hardly affected by low level outlet.

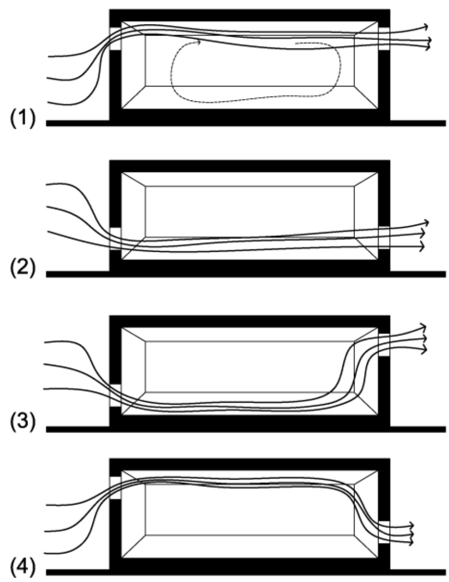

Figure 1.10 – Air flow within space due to openings positions[3]

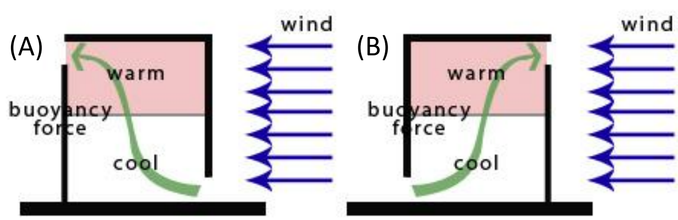

Figure 1.11- Wind and buoyancy forces according to opening positions[4]

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[1] (G.R. Hunt, The fluid mechanics of natural ventilation-displacement ventilation by buoyancy-driven flows assisted by wind, 1999, p. 708)
[2] *Ibid.*, p.709
[3] (Baker, Passive and Low Energy Building Design for Tropical Island Climates, 1987, p. 108)
[4] Hunt, *op. cit.* p. 708

B. Applications

Cross ventilation system plays the most important role achieving the required ventilation rates. It is only a matter of special design that gives a due care to space organization. So, cross ventilation technique has to be, intentionally, considered and designed in the planning of any residential unit, according to prevailing wind direction and site constrains.

Experiments conducted by Chia R. Chu and partners, Taiwan 2009, using a wind tunnel and scale model have showed that cross ventilation system performance depends mainly on wind incidence angle and direction of air flow due to pressure differences and driving forces[1]. Also, as it will be discussed in detail in chapter two, studies made in MIT (*Massachusetts Institute of Technology*) have indicated that the mean age of air inside space varies due to wind direction, angle of incidence, and position of space openings, and regardless the air velocity that may not truly indicate the indoor air quality. Designer should consider such reactions in indoor air flow design[2].

Energy studies were conducted on a residential building in Tricase, south of Italy within Mediterranean climate testing the performance of passive techniques strategies on achieving zero energy building concepts. Results showed that zero energy balance and zero CO_2 emission houses can be totally obtained with high levels of feasibility through cross ventilation system and combining passive strategies like: thermal mass wall, shading devices, reflective finishing materials, and PV panels. Cross ventilation design, as shown in figures 1.12 and 1.13, depends on courtyard concept to provide spaces on northern façade with required ventilation[3].

Courtyards consider a vital approach in achieving the cross ventilation strategy. As shown in figure 1.13, contemporary designs of courtyards

[1] (Chia R. Chu, Turbulence effects on the discharge coefficient and mean flow rate of wind-driven cross ventilation, 2009, p. 2071)

[2] (Chen, Using computational tools to factor wind into architectural environment design, 2004, p. 1206)

[3] (A. Ferrante, Zero energy balanceand zero on-site CO2 emission housing development in the Mediterranean climate, 2011, p. 2009)

provide large open atrium that daylights the interior, provides cross ventilation, and serves as a peaceful enclosed outdoor living area[1].

Figure 1.12- Cross ventilation strategy through building design[2]

Figure 1.13- Providing cross ventilation through courtyard [3]

C. Traditional forms of applications

Most of environmental vernacular designs depend on cross ventilation flow of air within spaces, and afford a due care to space planning and organization,

[1] (http://archnewhome.com/, Home Architectural Design, 2009)
[2] (A. Ferrante, Zero energy balanceand zero on-site CO2 emission housing development in the Mediterranean climate, 2011, p. 2004)
[3] *Ibid.*, p. 2004

respecting the environmental issues, to make the best use of air motion to achieve maximum possible cross natural ventilation. So unique architectural forms and spaces had been generated in the traditional architecture to satisfy such targets like: Courtyard, *Sahn*, the inner garden and *Takhtabush*. Figure 1.14 illustrates the plan of *Al-Suhaymi* House showing the courtyard, the inner garden, and *takhtabush*[1].

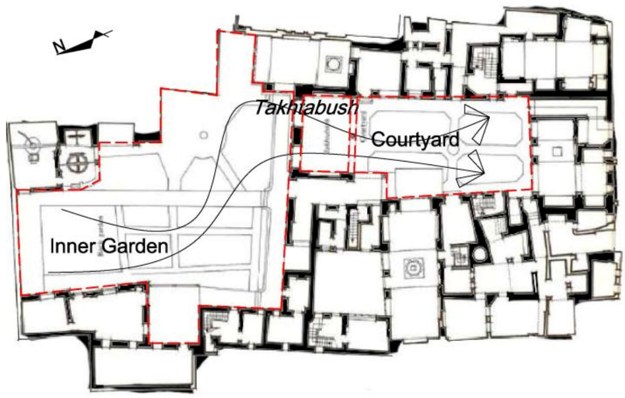


Figure 1.14- Plan of *Al-Suhaymi* house, *Darb Al-Asfar*, Cairo showing courtyard, back garden, and *takhtabush* situated inbetween[2]

1.7.1.2. Wind scoop (wind catcher)

A wind catcher is an architectural device used for many centuries to create natural ventilation in buildings.

A. Operation principle

Wind scoop, as illustrated in figure 1.15, is designed to catch the wind at the area of greatest positive pressure, and direct fresh air into the building. Scoop has to be multi-directional when the desired wind heavily changes its directions. At the angle of 30° (deviation away from the head-on wind) the scoop starts to become ineffective. At 50° it is completely ineffective, and starts to act as an exhaust.

B. Applications

The design of the scoop has to be sensitive to wind direction changes and be able to move easily towards wind, see figure 1.16. The opening for the wind

[1] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 138)
[2] *Ibid.*, p. 140

scoop can be arc-shaped to help catch wind that deviates away from the head-on axis[1].

Experimental wind tunnel investigation was conducted in Yazd, Iran to study performance of two-sided and multi-openings wind catchers. The results showed that the air flow rate decreases by increasing the number of opening. Two-sided wind catcher showed best performance for lower values of air incident angle with no short-circuiting. With increasing air incident angle, the short-circuiting appeared into the wind catcher system and reached its maximum value at 60°, as shown in figure 1.17. The results also showed that the wind catchers with rectangular cross section provided a higher induced air flow than any other forms of wind catchers[2].

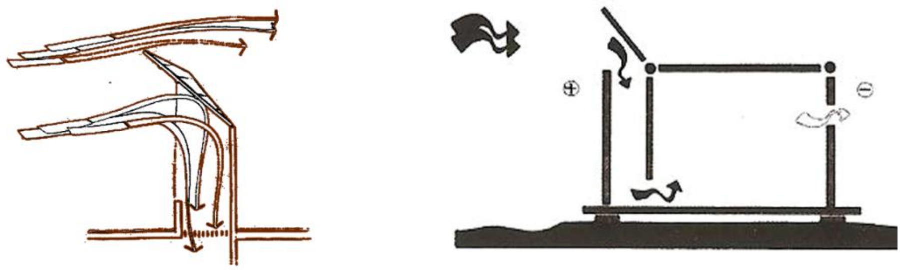
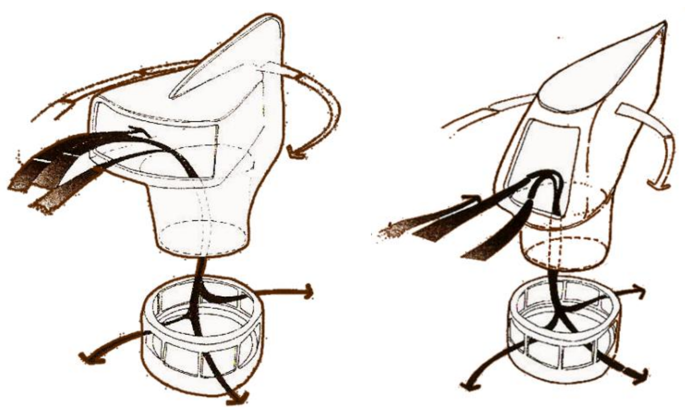


Figure 1.15 – schematic diagrams illustrating design principal of wind scoop[3]

Figure 1.16 – Design of multi-directional wind catcher with arc-shaped scoop that helps catching wind that deviates away from the head-on axis[4]



[1] (Battle-McCarthy-Consulting-Engineers, Wind Towers, Detail in Building, 1999)

[2] (Montazeri, Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers, 2011, p. 378), (H. Montazeri, Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling, 2010, p. 1435)

[3] Battle-McCarthy-Consulting-Engineers, *op. cit.*

[4] *Ibid.*

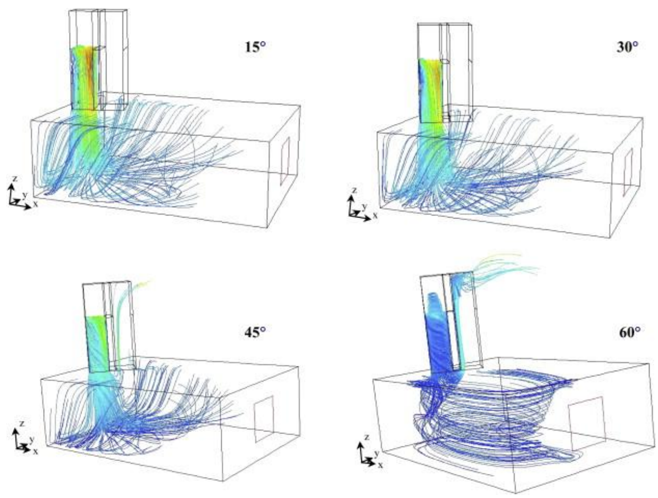


Figure 1.17 – Two-sided wind catcher shows its best performance with low values of air incident angles[1]

C. Traditional forms of applications

Wind catching system was applied in the vernacular architecture in the form of *Malqaf*. The '*Malqaf*' is one of the most famous natural ventilation techniques in traditional designs. *Malqaf* is a shaft rising high above the building with an opening facing the prevailing wind, acts exactly like a wind scoop[2].

Also, the multi-directional wind scoop was applied in the traditional architecture with the form of *Badgir*. It was developed in Iran and the countries of the Gulf as a specific type of *malqaf*. *Badgir* is a shaft with the top opening on four sides, and with two partitions placed diagonally across each other down the length of the shaft to catch air from any direction. An example from *Bastakiya* Quarter of Bur Dubai, United Arab Emirates is shown in figures 1.18, and 1.19[3].

Wind scoops can be used in combination with wind towers or solar chimneys to enhance the ventilation process as it will be discussed later.

[1] (H. Montazeri, Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling, 2010, p. 1432)

[2] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, pp. 56, 116, 117)

[3] (*Ibid.*, p.60)

Figure 1.18 – *Badgir* (wind catchers) at the *Bastakiya* Quarter traditional buildings, Dubai, UAE[1]

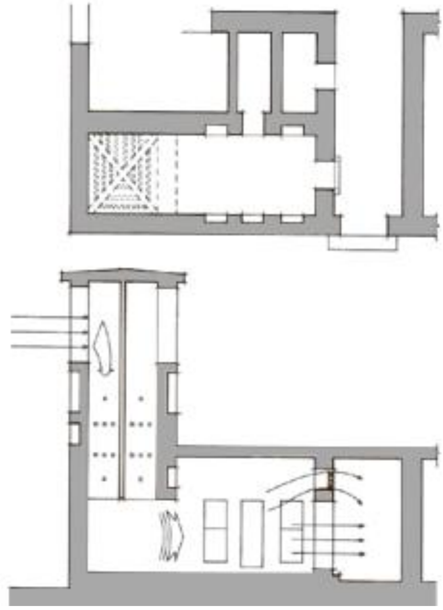


Figure 1.19 – Plan and Section of typical *Badgir* in *Bastakiya* buildings, Dubai[2]

1.7.1.3. Ventilated double skin facade

A. Operation principle

Ventilated double skin façade (DSF) is one of double wall forms that depend on wind-driven forces in dissipating heat generated in the air gap by radiation. Through drawing warm air outside the building, system helps in preventing heat transition into building spaces.

B. Applications

In one of ventilated DSF forms the space can be isolated from the massive structure with a lightweight screen, as shown in figure 1.20[3]. In other forms, light DSF may be designed with double layers of glass with sun breakers in-between, as shown in figure 1.21[4]. Enhancements were carried out on ventilated light DSF with a movable integrated shading system, as shown in figure 1.22, to serve in different summer and winter configurations. In summer, exterior layer provides complete shading and ventilation. In winter,

[1] (US-Dept-of-State-Geographer, Google Earth, 2011)

[2] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 134)

[3] (Baker, Passive and Low Energy Building Design for Tropical Island Climates, 1987, p. 59)

[4] (Wilmer Pasut, Evaluation of various CFD modelling strategies in predicting airflow and temperature in a naturally ventilated double skin facade, 2012, p. 273)

exterior layer has been closed to lock up the air in the air gap to provide heating and provide low altitude sun radiation[1].

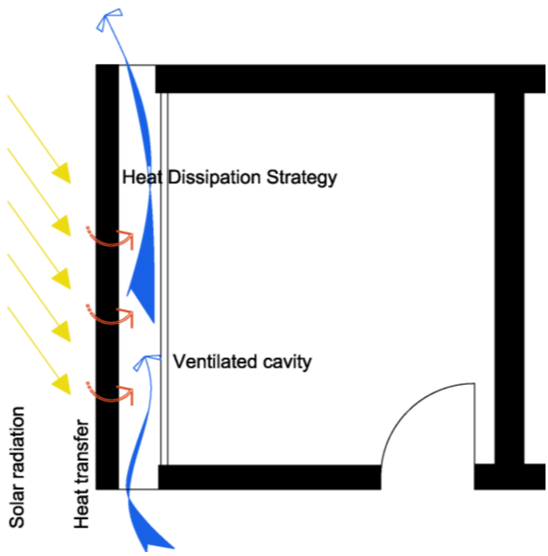


Figure 1.20 – Ventilated DSF with massive exterior wall[2]

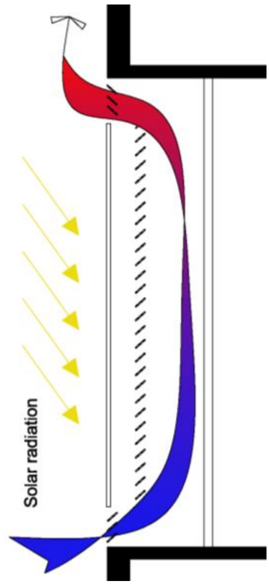


Figure 1.21 – Ventilated lightweight DSF[3]

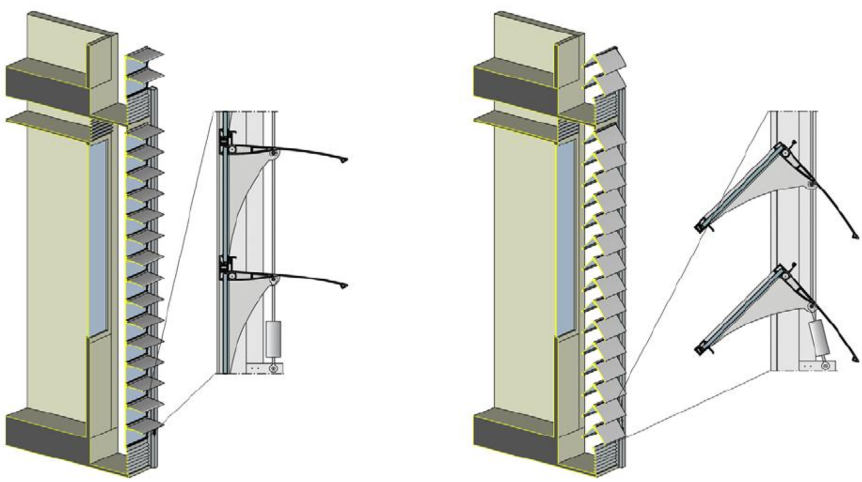


Figure 1.22 – Enhancements of ventilated DSF by adding a movable integrated shading system [4]

[1] (Baldinelli, Double skin facades for warm climate regions: Analysis of a solution with an integrated movable shading system, 2009, p. 1117)
[2] (Baker, Passive and Low Energy Building Design for Tropical Island Climates, 1987, p. 59)
[3] (Wilmer Pasut, Evaluation of various CFD modelling strategies in predicting airflow and temperature in a naturally ventilated double skin facade, 2012, p. 273)
[4] Baker, *op. cit.* p. 59

1.7.2. Wind pressure differences and suction effect

This section includes the second classification of passive techniques. It illustrates the techniques which depend on wind pressure differences or suction effect (indirect wind forces)

1.7.2.1. Wind towers

A. Operation principle

Wind tower is a vertical construction that projects above the building to draw air out of the space, by inducing negative pressure and providing suction effect with all wind directions, as shown in figure 1.23. Thus, the effectiveness of wind towers depends on producing the maximum pressure difference between the air inlet openings and the wind tower. The air movement around the building will determine the size and position of the tower and openings to maximize the pressure difference. Tower height also affects the ventilation rate. The taller tower has stronger winds passing through it, creating a greater negative pressure[1].

Wind towers can be used in combination with wind scoops to create a system by which cool air is provided by wind scoops, and warm air is then extracted by wind towers, as shown in figure 1.24. By collecting and extracting air at high levels, there will be a greater pressure difference between devices, producing more air flow through the building.

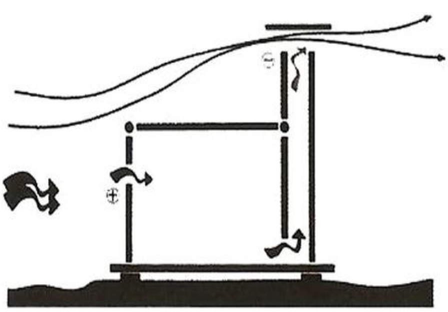


Figure 1.23 – Typical wind tower design[2]

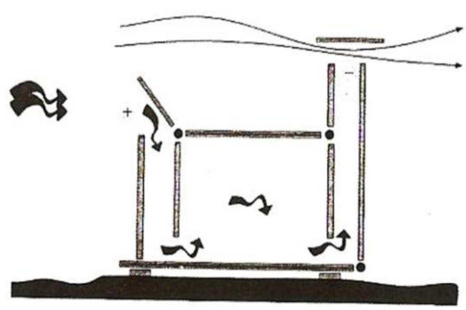


Figure 1.24 – Merging wind towers and scoops produces more air flow throw the space[3]

[1] (Battle-McCarthy-Consulting-Engineers, Wind Towers, Detail in Building, 1999)
[2] *Ibid.*
[3] *Ibid.*

B. Applications

Wind towers were merged in contemporary forms within different types of buildings. Figures 1.25 and 1.26 show some of the contemporary forms of wind towers. Solar collectors can be part of wind tower to promote stack effect ventilation in times of little wind speeds to enhance the airflow. Also double skin façade system can be merged with wind tower, as shown in figure 1.27, to achieve better air flow through tower by increasing stack effect[1].

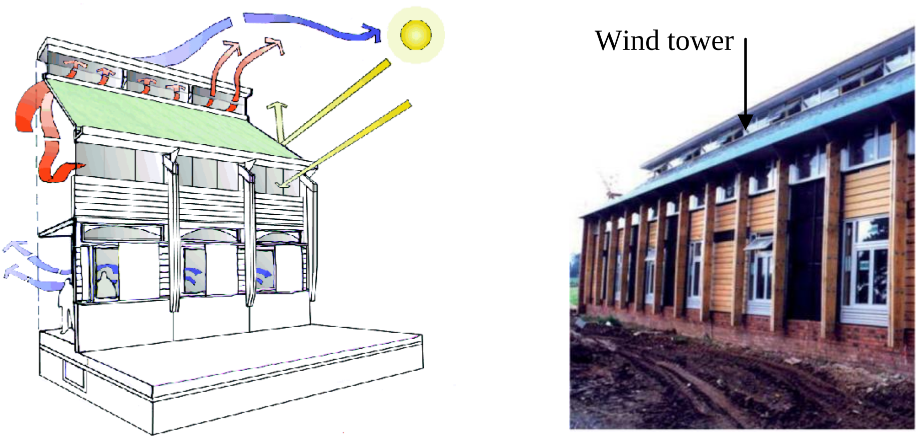


Figure 1.25 Merging wind tower concepts within contemporary low rise buildings[2]

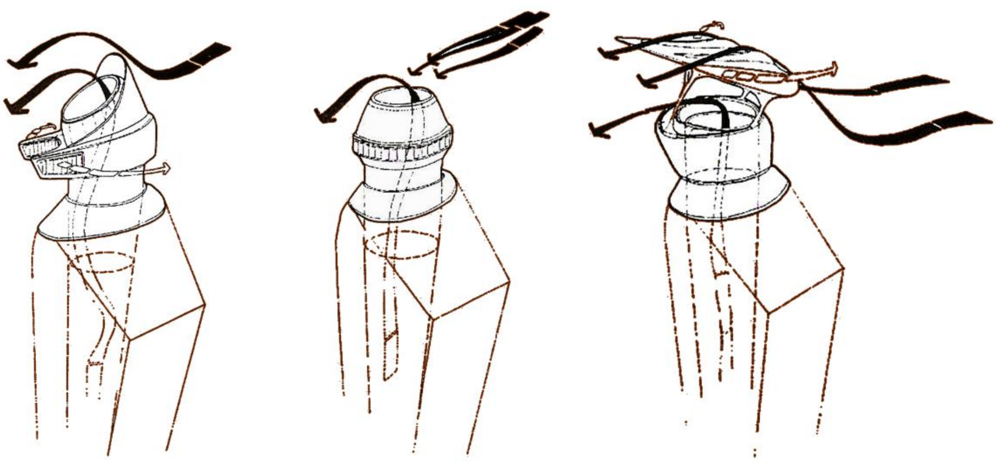


Figure 1.26 – Modern Applications of wind towers[3]

[1] (Naghman Khan, A review on wind driven ventilation techniques, 2008, p. 1593)

[2] (Battle-McCarthy-Consulting-Engineers, Wind towers for the article (The design of wind driven ventilated buildings))

[3] (Battle-McCarthy-Consulting-Engineers, Wind Towers, Detail in Building, 1999)

Enhancements have been operated on tower form, using aircraft wing theory, to accelerate air flow on the leeward of the tower causing a greater negative pressure which exhausts air. This system is called '*Wing Jetting system*'[1] and shown in figure 1.28.

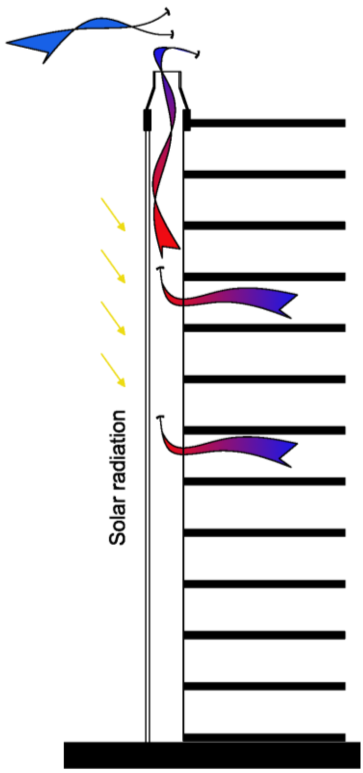


Figure 1.28 – Merging Double skin façade system with wind tower enhances air flow in spaces[3]

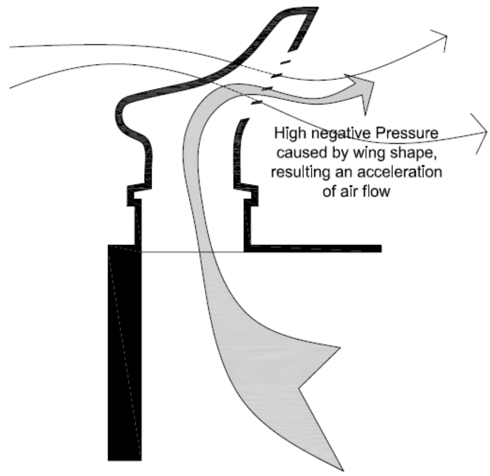


Figure 1.27 – Wing Jetting System[2]

C. Traditional forms of applications

The merging between wind towers and scoops can be seen in vernacular techniques. The wind tower is being acted by *Dur-qa'a* which is a shaft extracting air from spaces causing the air flow. *Malqaf* and *Dur-qa'a* did work together to enhance the air movement inside space, as found in *Muhibb al-Din al-Muwaqqi'* Palace in Cairo, shown in figures 1.29, and 1.30[4].

[1] (Naghman Khan, A review on wind driven ventilation techniques, 2008, p. 1598)
[2] *Ibid.*, p.1593
[3] *Ibid.*, p.1598
[4] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 56)

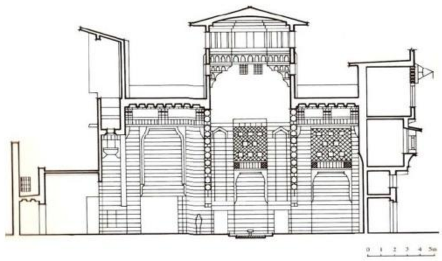


Figure 1.29 – Cross section through palace showing the *Malqaf* and central location of the *Dur-Qa'a*[1]

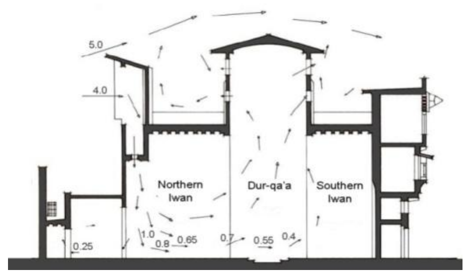


Figure 1.30 – Air flow and speeds (m/s) through *Iwans* trapped by *Malqaf* and extracted by *Dur-Qa'a* that acts like a wind tower[2]

1.7.2.2. Roof exhaust cowl

A. Operation principle

Exhaust cowls, shown in figure 1.31, are an effective means of facilitating ventilation by dissipating exhaust air into the atmosphere. The external wind movement through the cowl generates a rarefaction effect at the internal air volume, and causes the warmer upper layers of inner air mass to be pulled out through the cowl towards the external wind direction, as it can be called 'the suction effect'. Thus, the space can be provided by cooler air through normal openings. This suction effect depends upon three primary factors: prevailing wind conditions, type of cowl, and the flow rate[3].

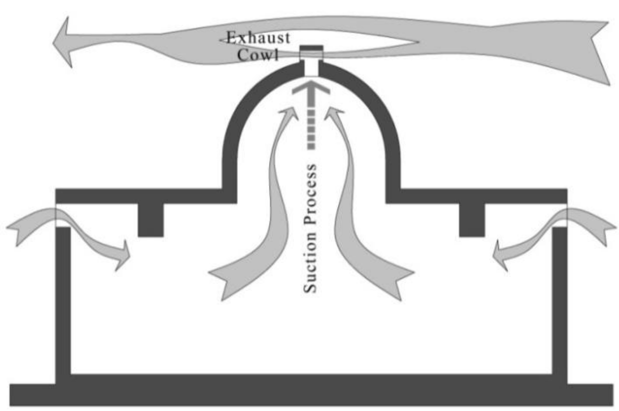
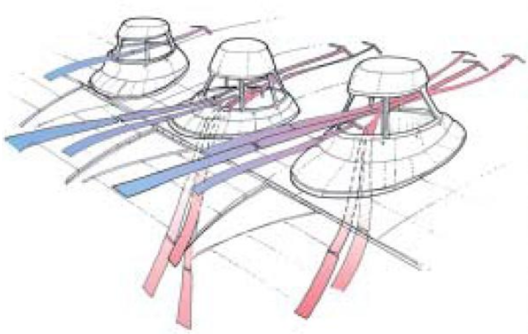


Figure 1.31 – Suction effect through roof exhaust cowl[4]

[1] *Ibid.*, p.116
[2] *Ibid.*, p.117
[3] (Naghman Khan, A review on wind driven ventilation techniques, 2008, pp. 1588, 1590)
[4] *Ibid.*, p.1590

B. Applications

Through applying contemporary architectural forms of exhaust cowls, extracting worm air from spaces through roof by suction effect can be noticed in many applications in single floor residential and public buildings. Figure 1.32 shows some of these applications.



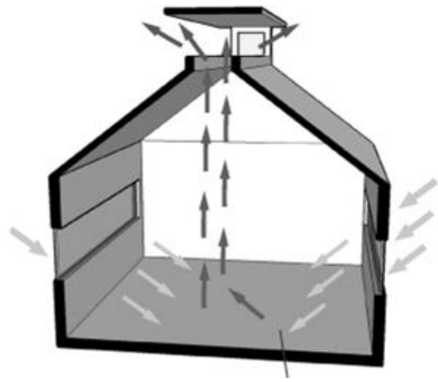
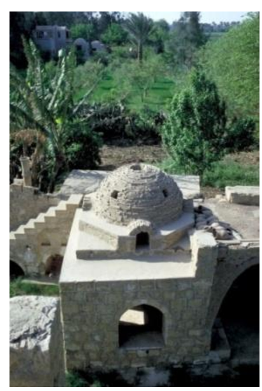


Figure 1.32 – Contemporary applications of roof exhaust cowls[1]

C. Traditional forms of applications

This working principle can obviously be figured out in the vernacular architecture with the application of the dome. Dome, or *Qubba* as shown in figure 1.33, is mostly being noticed as a primary element used to add an extra volume to the space for stimulate the hot air to move upwards into the volume of the dome. By adding an upper opening to the dome, hot air is being extracted out of space by suction effect to accelerate indoor air flow[2].

Figure 1.33 – *Fouad Riad* house, Giza, Egypt, by *Hassan Fathy*[3]



[1] (Battle-McCarthy-Consulting-Engineers, Wind towers for the article (The design of wind driven ventilated buildings))

[2] (Aga Khan Trust for Culture, Digital Library / Publications, 2011)

[3] *Ibid.*

1.7.2.3. Single-sided vents

Single-sided natural ventilation is achieved by the exchange of air between indoor and outdoor environment through alongside openings at the same height on one side of a space or with the flow of air into a space through more than one inlet at different levels on one side of a space.

A. Operation principle

The driving forces for such system are wind and buoyancy. The air exchange between indoor and outdoor air is achieved by differences in wind pressure and temperatures along the façade. The ventilation rate depends on the strength and direction of these forces and temperature difference across the opening(s) between an indoor and outdoor space.

In real cases, buoyancy and wind-driven flows exist together. The influence of temperature and wind on the ventilation process at the window is very complicated because wind and stack forces reinforce or counteract each other. As shown in figure 1.34, the studies showed that air flow direction, and driving forces depend on wind speed[1].

B. Applications

Experiments, operated by A.Munir and S.Wonorahardjo using a CFD (Computational Fluid Dynamics) software, have studied how the performance of single-sided ventilation influenced by window type and the position of openings. Figure 1.35 shows how the air flow inside space varies due to type of window used[2].

Studies operated in Cambridge using CFD software to analysis air flows performance on typical room with facade consists of an upper and lower windows within three floors, as shown in figure 1.36.

The experiments have been conducted under two scenarios: (1) buoyancy-driven scenario (windless condition), (2) combined wind and stack scenario. The results showed that single-sided vents can provide sufficient natural ventilation rates values inside space. The results also stated that ventilation performance depends on values of air velocity and temperature that vary

[1] (Abdul Munir, The Performance of Single-Sided Natural Ventilation induced by Wind-Driven Flow, 2005)

[2] *Ibid.*

according to driving force and position of space in the building, as shown in figures 1.37 and 1.38[1].

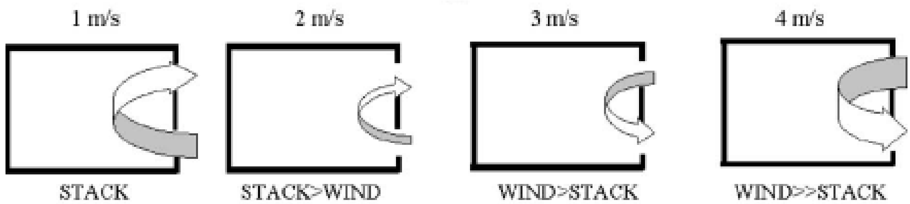


Figure 1.34 – Changing in driving forces due to wind speeds (m/s)[2]

Figure 1.35 – Air flow performance due to type of window operation[3]

(a) HP *Horizontal Pivot*

(b) VP *Vertical Pivot*

(c) SH *Side Hung*

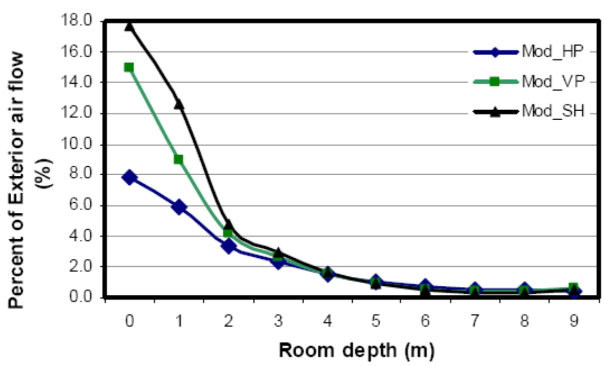
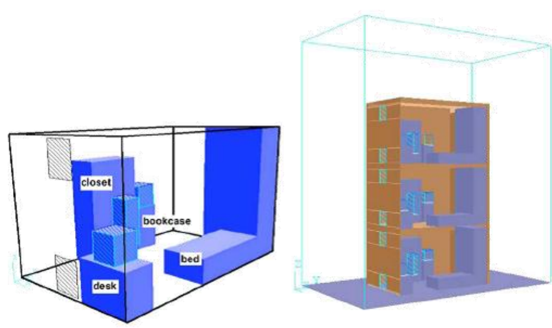
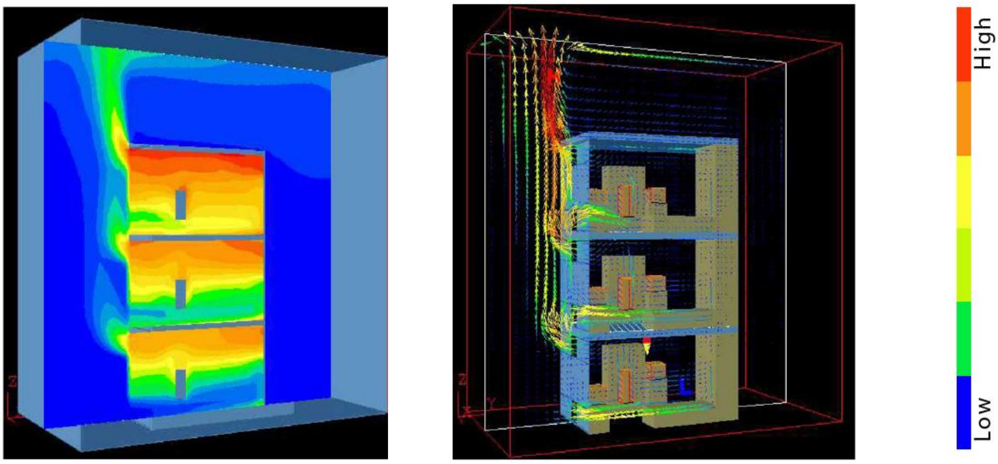


Figure 1.36 – The study building consists of three floors, each is a typical room with the furniture shown[4]



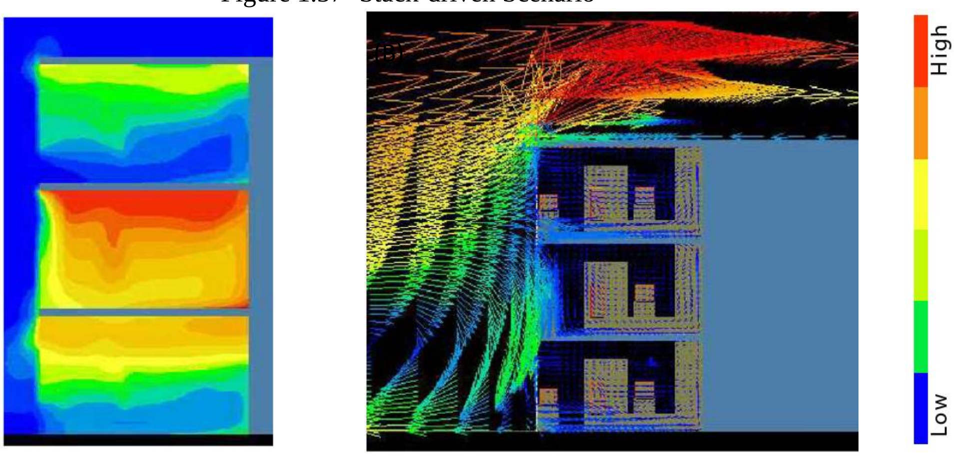
[1] (Chen, Using computational tools to factor wind into architectural environment design, 2004, p. 1208)
[2] *Ibid.*, p.1208
[3] (Abdul Munir, The Performance of Single-Sided Natural Ventilation induced by Wind-Driven Flow, 2005)
[4] Chen, *op. cit.* p.1207



(a) Air temperature (b) Air velocity

Figure 1.37- Stack-driven Scenario[1]

(A)



(a) Air temperature (b) Air velocity

Figure 1.38 – Combined wind and stack Scenario[2]

C. Traditional forms of applications

The exchange of air between indoor and outdoor may happen through same opening, if it is a ceiling to floor large opening. In this case, lower part of opening operates a supply process, and higher part operates an extracted one. Such case can be found clearly in vernacular architecture in two applications: Large scale *mashrabiya*, and *Claustra*, figures 1.39 and 1.40[3].

[1] *Ibid.*, p. 1207
[2] *Ibid.*, p. 1208
[3] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 54), (Aga Khan Trust for Culture, Digital Library / Publications, 2011)

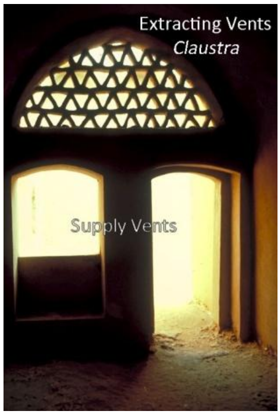


Figure 1.39 – Installing *claustra* at high level openings in New *Baris* Village for extracting hot air[1]

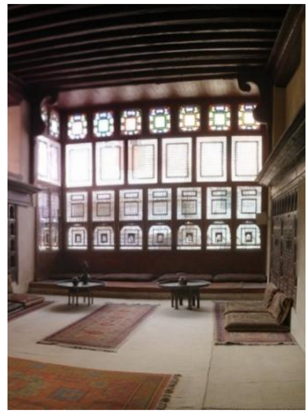


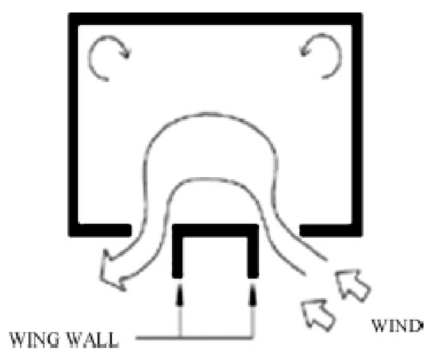
Figure 1.40 – Indoor space with full height façade of *mashrabiya* with two different patterns, for supplying and extracting air through same opening[2]

1.7.2.4. Wing walls

A. Operation principle

Wing wall is usually used to aid single sided ventilation on windward facing facades by using positive and negative pressures on either side of two wings. Through enhancing the flow rate, wing wall results in increasing average air velocity in the room to 40% of the outside incident wind velocity, with percentage of only 15% without applying wing wall system. Best performance is noticed during incident wind angles of 45°. Wing walls can be used as sun shading devices, and can be made from transparent materials and used as an architectural integration[3].

Figure 1.41 – Using wing walls enhances air flow resulting from single-sided ventilation by 25%



[1] *Ibid.*
[2] *Ibid.*
[3] (Naghman Khan, A review on wind driven ventilation techniques, 2008, p. 1588)

B. Applications

Investigations that have been conducted using CFD software to study wing wall performance have shown that applying wing wall increases the air change per hour and the mean indoor air velocity that would promote natural ventilation inside space. No significant improvement of natural ventilation performance is shown in the case of longer wing wall as shown in figure 1.42.

The simulation results also showed that wing wall performance is greatly affected by the wind directions. The results showed that the wing wall reaches its best performance at wind angle of around 45°[1].

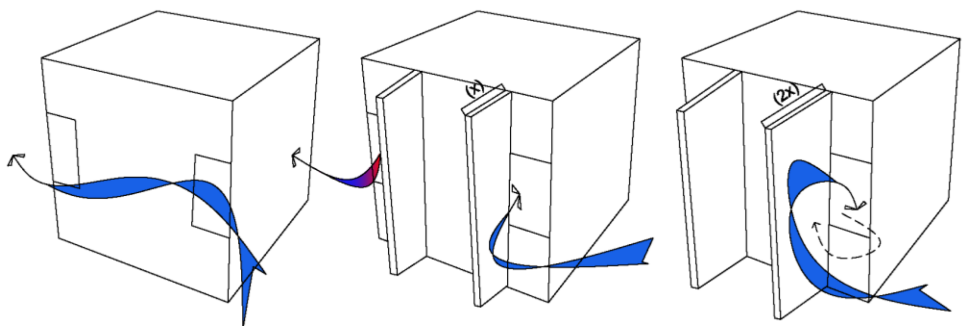


Figure 1.42 – Simulation cases for investigating wing wall performance[2]

1.7.3. Solar or thermal buoyancy effect

This section discuses the third classification of passive techniques that depend on solar or thermal buoyancy effect.

1.7.3.1. Solar chimney

A solar chimney is one of construction technologies used to promote air movement throughout the building by using solar energy to achieve ventilation. The stack effect principle has already been described in relation to air flow within a building. A solar chimney depends on the same effect but here the air is designed to be heated by solar radiation in order to create an exhausting effect.

1 (C.M. Mak, A numerical simulation of wing walls using computational fluid dynamics, 2007, p. 999)
2 *Ibid.*, p. 998

A. Operation principle

A solar chimney is essentially divided into two parts: the solar air heater (collector) and the chimney, as shown in figure 1.43. The system was designed to maximize solar gain and thereby the ventilation effect. The critical design parameters are the stack height, cross section area and the difference in temperature at the inlet and the outlet level of the solar heating system. Air in a solar collector is heated during the day, as it heats, it expands and rises. In turn, it starts pulling the indoor air up and out. One of the advantages of the system is its ability to self balance. The hotter the day, the hotter the solar air heat collector and faster the air movement[1].

Buoyancy effect occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences. A chimney that is heated by solar energy can be used to drive the chimney effect without increasing room temperature[2].

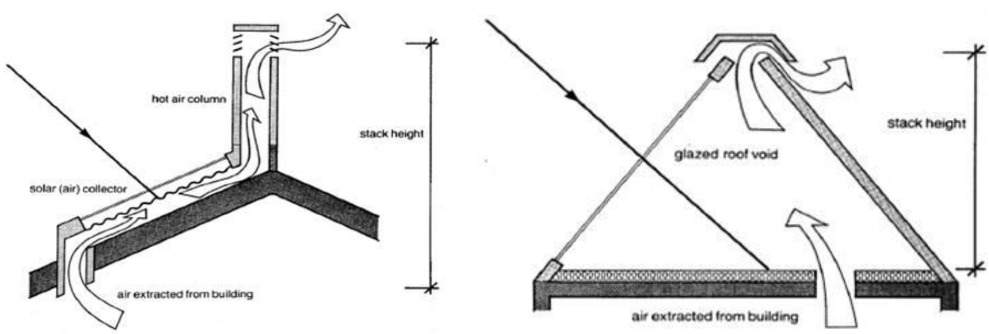


Figure 1.43- solar chimney operation principle[3]

B. Applications

Solar chimney is widely used for contemporary residential applications. Passive sustainable home redesign of row house, shown in figure 1.44, done by iSTUDIO Architects can reduce the energy consumption by 65% through applying solar chimney to the existing design winning the presidential

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[1] (Santamouris M. , Advances in Building Energy Research, 2009, p. 22), (Baker, Passive and Low Energy Building Design for Tropical Island Climates, 1987, p. 125)

[2] (I. F. Hamdy, Passive Solar Ventilation, 1998, pp. 382, 383), (M. Maerefat, Passive Cooling of Buildings by using integrated earth to air heat exchanger and solar chimney, 2010, p. 2320)

[3] Baker, *op. cit.* p. 126

citation for sustainable design from the American Institute of Architects (AIA)[1]. Solar chimney as a passive technique can be a part of a complete smart sustainable housing. Figure 1.45 shows an example of application of solar chimney in smart houses[2].

Enhancements have been conducted on contemporary chimneys to be similar to conventional ones except that the south wall is covered by a glazing, and coated by an absorber material. Figure 1.46 shows that solar radiation passes through glazing and is absorbed at the wall surface. Thus, air in the chimney is then heated by radiation from sunrays, and radiation from the absorber.

The enabling of solar energy collection leads to an increase in the air temperature inside the chimney channel and in the stack effect and, also, to thermal energy storage in the walls, which can be released later on during night periods[3].

Figure 1.44- Residential solar chimney of row house by iSTUDIO Architects[4]

[1] (http://greendcdaily.com/, Green dc Daily, 2012)
[2] (http://www.drexelsmarthouse.com/, Drexel smart house, 2010)
[3] (D.J. Harris, Solar Chimney and Building Ventilation, 2006, p. 136)
[4] http://greendcdaily.com/, *op. cit.*

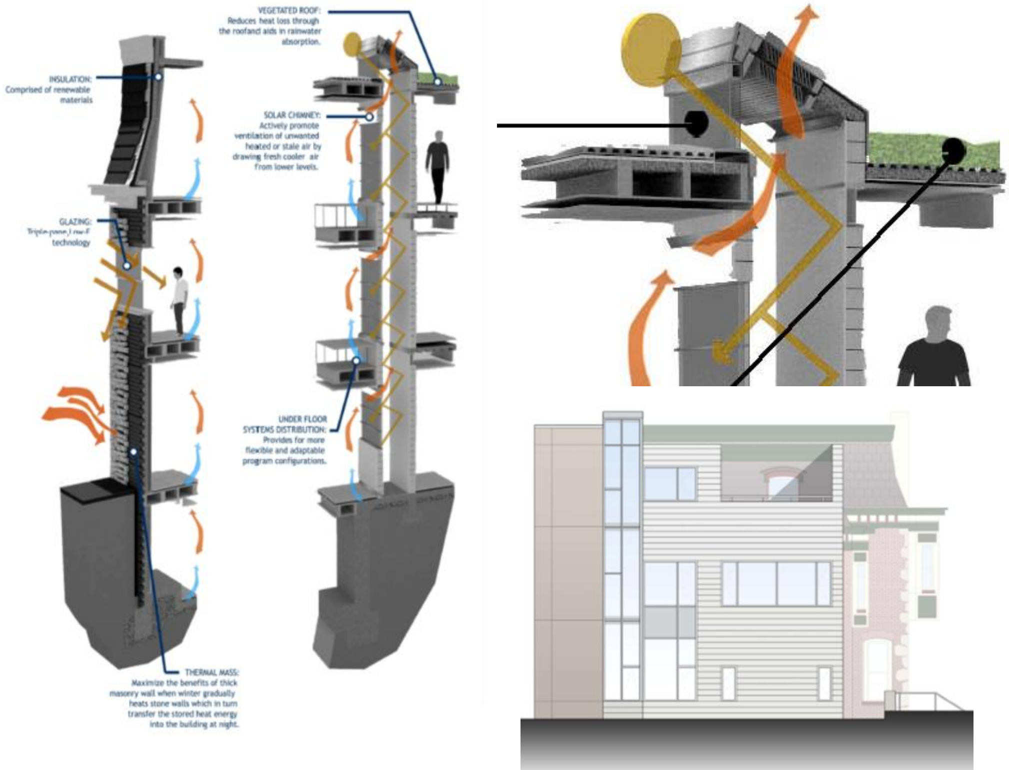
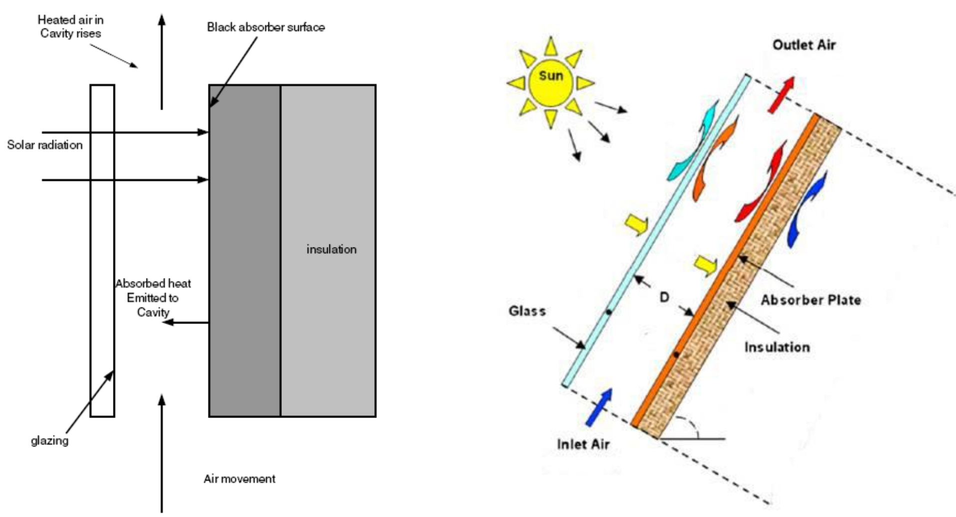


Figure 1.45- Wall solar chimney application within Drexel smart house[1]



Figures 1.46 - Enhancements conducted on solar chimney design[2]

[1] (http://www.drexelsmarthouse.com/, Drexel smart house, 2010)

[2] (M. Maerefat, Natural Cooling of stand-alone houses using Solar Chimney and Evaporative Cooling Cavity, 2010, p. 2042)

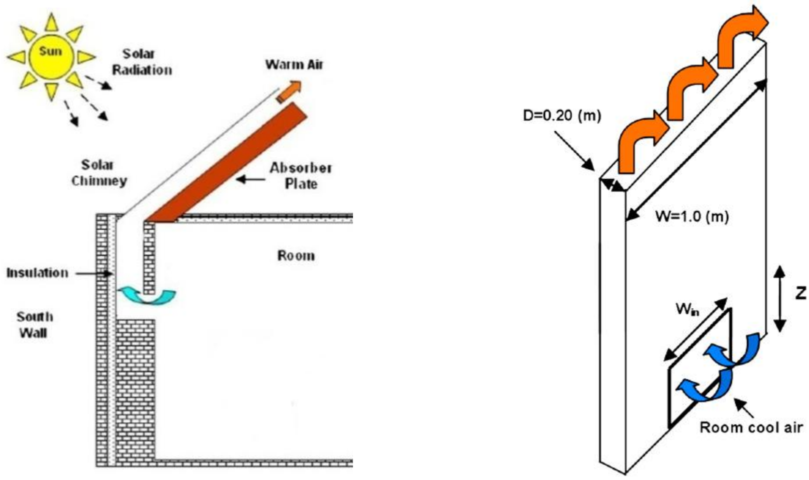


Figure 1.47 – Schematic diagram of solar chimney studying effect of air gap and chimney inlet dimensions on chimney performance[1]

Numerical experiments, conducted by M.Maerefat and A.P.Haghighi *(Tarbiat Modares University, Tehran, Iran)* and published in the international journal *"Renewable Energy"*, showed that the effect of air gap depth on the air changes per hour becomes significant when the gap reaches 0.2 m. But beyond 0.2 m, the air changes per hour remain almost constant. Accordingly, as shown in figure 1.47, air gap of 0.2 m is considered as the maximum required value of the air gap. Also, the results showed that a better performance would be achieved at a higher solar radiation heat flux. This means that around the noon, when the cooling effect is most needed, the system reaches its highest effectiveness. The results also showed that the air changes per hour are increased by adding the absorber material along wall length.

Another parameter that affects the system performance is the chimney inlet dimensions. The results showed that by increasing chimney inlet width (W_{in}), the air changes per hour increases due to the decrease in friction forces[2]. Solar chimneys at the leeward facades can be combined with wind scoops, as shown in figure 1.48, to enhance the stack effect[3].

[1] *Ibid.*, p. 2048
[2] *Ibid.*, pp. 2048, 2049
[3] (N.K.Bansal, A study of Solar Chimney assisted Wind Tower System for Natural Ventilaiton in Buildings, 1994, p. 496)

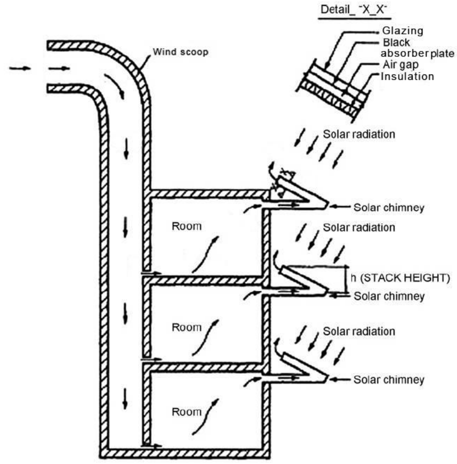


Figure 1.48 - Merging Solar Chimneys with wind Scoop enhances air flow in spaces[1]

1.7.3.2. Ventilated roof

In climates where the solar altitude is large, a sloping roof collector can be more effective in collecting solar energy as shown in figure 1.49.

The advantage of a roof collector is that a large surface area is available for collecting the solar energy and hence higher air exit temperatures can be achieved than those for a solar chimney[2].

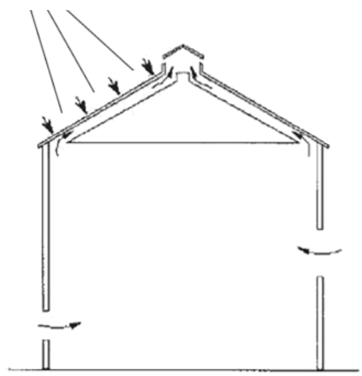


Figure 1.49 – Ventilated roof system[3]

1.7.3.3. Double skin façade

A. Operation principle

One promising development of advanced façade systems is the double skin façade (DSF). DSFs have many types that vary due to installation method, like: box window façade, corridor façade, and multi-storey façade. All of

[1] *Ibid.*, p.496
[2] (Awbi, Ventilation of Buildings, 2005, p. 337)
[3] *Ibid.*, p.337

these types can be applied to all types of airflow concepts that are shown in figure 1.50[1].

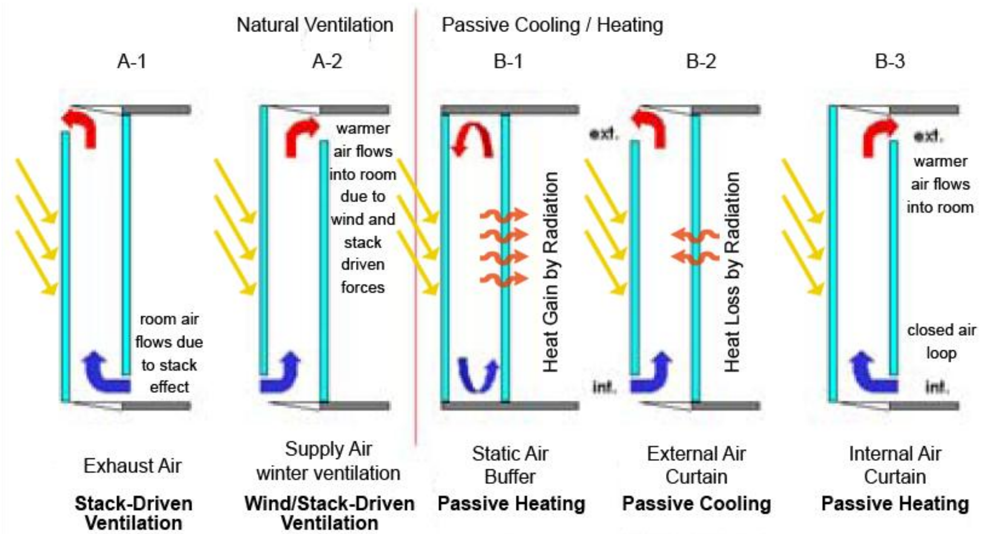
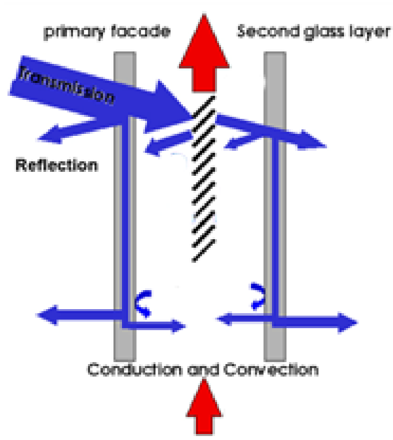


Figure 1.50 – Air Flow Different Concepts of Double Skin Facade[2]

Applying DSF system can provide thermal, visual, and acoustic comfort. Improvements may be done on DSF system to control the impact of solar radiation on the air flow through double-skin air gap, as shown in figure 1.51[3].

Figure 1.51 – Advances in DSF design to control solar radiation[4]



[1] (M.Haase, Ventilated Facade Design for Hot and Humid Climate, 2006)
[2] *Ibid.*
[3] (M.Haase, Design Considerations for Double-Skin Facades in Hot and Humid Climates, 2006)
[4] *Ibid.*

B. Applications

Simulations, done by CFD software and conducted on multi-storey double-skinned façade, have shown that in case of very low wind speeds, the dominant driving force is only buoyancy effect, and DSF system acts like a solar chimney in design principle, but by different application, as shown in figure 1.52. In considerable wind speeds, wind-driven force affects buoyancy-driven force according to position of DSF via wind. DSF works best on the leeward side**,** as wind force combines with stack effect and enhances air flow in spaces, as shown in figure 1.53. In this case, the multi-storey DSF acts like wind tower as shown before.

If the DSF is on the windward side, the pressure driving force of the stack effect is positioned opposite to wind driving forces**.** The stack effect may be lower than the wind effect**,** but would be still strong enough to make a problem in the air flow. The simulation results in figures 1.53, 1.54, and 1.55 show how the used DSF system affects air changes rate (ACH) at each floor[1]. Diagram of conceptual application of DSF smart system on multi-storey building is shown in figure 1.56. In these smart systems, the air cavity provides good air circulation, high thermal and acoustic performance, and conversion of solar energy hitting the façade to electrical energy[2]. Another example of intelligent facades that provide natural ventilation, shading, and daylighting control is shown in figure 1.57.

When replacing the inner light layer of double skin facade system by a wall of considerable thickness, and keeping the external light layer, the system then is called the mass wall system. To be effective, the mass wall needs to face the south or south-west direction. Mass wall has different types of applications due to position of openings, heat gain, and air flow[3].

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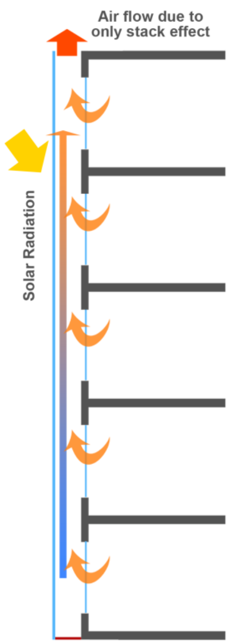
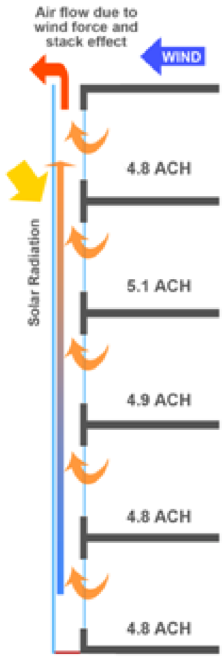
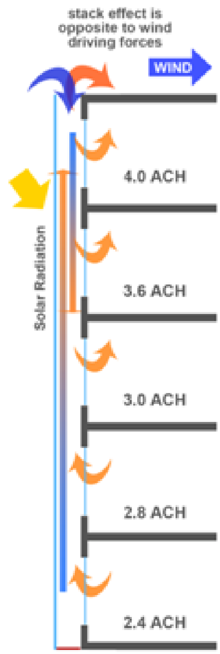
[1] (Naghman Khan, A review on wind driven ventilation techniques, 2008, p. 1593), (Zhao, A Decision support framework for Design of Natural Ventilation in Non-Residential Buildings, 2007, pp. 14-16)

[2] (http://www.theislingtonestate.com, Sustaining tower blocks, 2004)

[3] (S.R.Hastings, Passive Solar Commercial and Institutional Buildings, A source book of examples and Design Insights, 1993, p. 114)







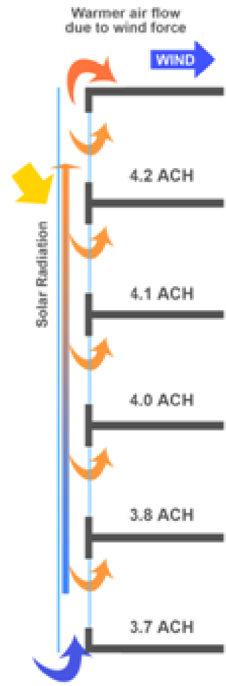


Figure 1.52 – Regardless wind force, DSF system acts like a solar chimney, as driving force is only buoyancy effect[1]

Figure 1-53– DSF at leeward side acts like wind tower, as wind force combines with stack effect and enhances air changes in spaces[2]

Figure 1.54– DSF at windward side, stack effect is opposite to wind force, resulting reducing air changes in spaces[3]

Figure 1.55 – Spaces are ventilated with the high temperature air through the DSF, resulting reduction in indoor air quality[4]

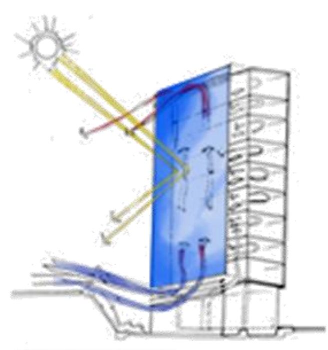


Figure 1.56 – Application of DSF smart system on multi-storey building[5]

[1] (Zhao, A Decision support framework for Design of Natural Ventilation in Non-Residential Buildings, 2007, p. 16)
[2] *Ibid.*, p.16
[3] *Ibid.*, p.16
[4] *Ibid.*, p.16
[5] *Ibid.*

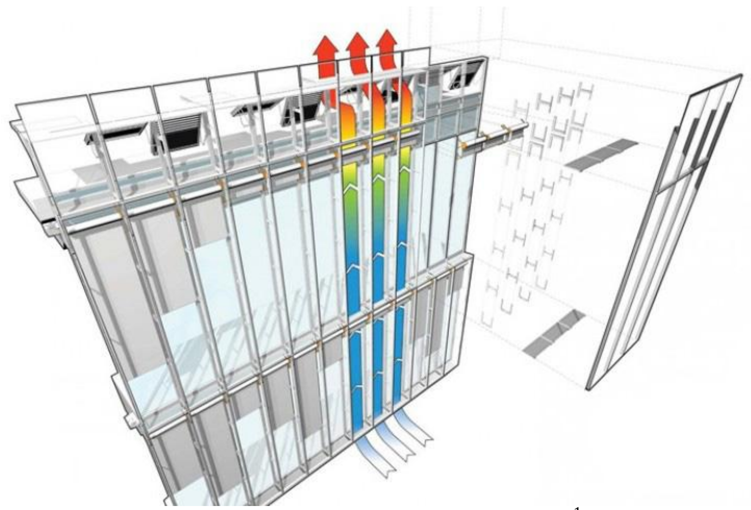


Figure 1.57 – Intelligent DSF facades[1]

1.7.3.4. Thermal mass wall

The thermal wall is a simple solar collector with no openings in the mass wall. This system is almost used for passive heating by radiation, while heat transfers from heated closed air gap through thermal wall into space. Thermal wall is also used for passive cooling when using high thermal mass material and modifying the outer light layer to make an air flow process, as shown in figure 1.58. The system then is called ventilated façade and lets the heat radiates from the wall into air gap. Figure 1.58 shows the two types of thermal mass walls[2].

1.7.3.5. Trombe wall for heating

Trombe wall[3], also called vented mass wall, has traditionally been used for space heating by allowing air from the room to enter at the bottom of the wall into air gap which is heated by solar radiation and then returned back to the room at high level of the wall, as shown in figure 1.59[4].

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[1] (Vaglio, jeff vaglio, 2011)
[2] (Santamouris M. , Advances in Building Energy Research, 2009, p. 24), (Green-Building-Program, Sustainable Building Sourcebook, Supplement to the Green Building Program, 2000, p. 48)
[3] The system is called *Trombe* wall, on the name of *Felix Trombe*, the architect who designed and built the system for the first time in southern France.
[4] (Awbi, Ventilation of Buildings, 2005, p. 336), (S.R.Hastings, Passive Solar Commercial and Institutional Buildings, A source book of examples and Design Insights, 1993, p. 114)

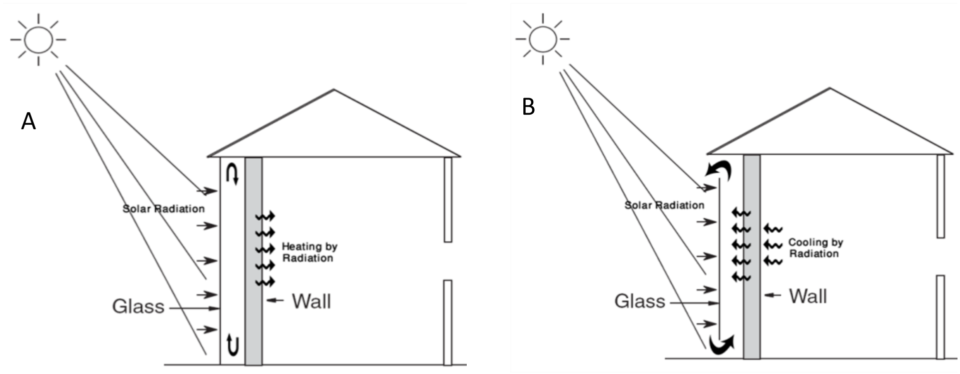


Figure 1.58 – Thermal mass walls types: A- Thermal wall used for heating by radiation, B- Ventilated façade system used for passive cooling by radiation[1]

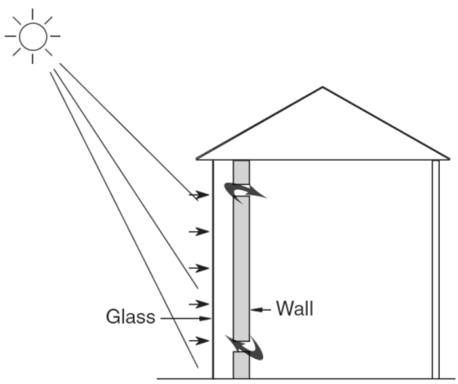


Figure 1.59 – Trombe wall system for heating[2]

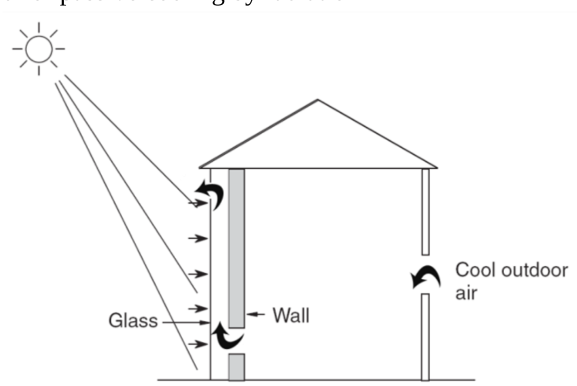


Figure 1.60 - Modified Trombe wall system for cooling[3]

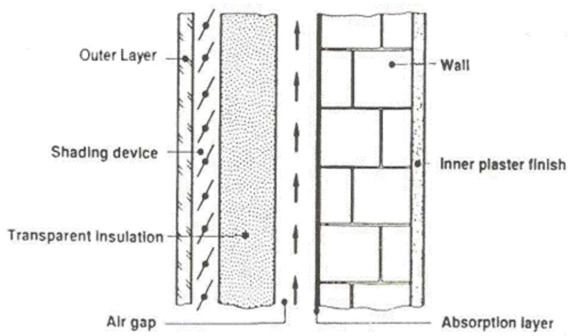
1.7.3.6. Trombe wall for cooling

This system is operated with a modification by putting a high level external opening on the glazing, and closing the top opening to the room. This device can be used for cooling by drawing outdoor air from another opening into the room, and then warm room air is extracted out through the system, as shown in figure 1.60[4].

[1] (Santamouris M. , Advances in Building Energy Research, 2009, p. 24)
[2] (Awbi, Ventilation of Buildings, 2005, p. 336)
[3] *Ibid.*, p.336
[4] *Ibid.*, p.336

A transparent insulation material (organic plastics) and shading device can be added to this system, as shown in figure 1.61, to control solar radiation and air flow through gap, and provide usage flexibility for heating or cooling[1].

Figure 1.61 – Addition operated on the system to enhance system flexibility[2]



For cooling cases, shading controls solar radiation falling on wall to avoid excess heat transfer. For heating cases, system gets maximum solar radiation, while insulation keeps air gap warm. A damper then is provided at the bottom opening of the wall. When it is closed the air gap is confined, and the system then acts like thermal mass wall.

1.7.4. Combined systems of basic techniques

This section shows some combined system of the major techniques to study the efficiency of combining more than one technique within single system.

1.7.4.1. Earth to air heat exchanger system

A. Operation principle

In order to take advantage of the fact that the soil temperature falls within comfort conditions, direct contact between supply air and soil allows excess heat of air to be dissipated into the earth.

The whole system consists of: 1- the heat exchangers, which are pipes, buried beneath earth surface, and through which air is drawn into the building, and 2- the solar chimney which is fixed inside space. The driving force then for the air flow through the space is function of the pressure difference between the inlet of the heat exchanger and the chimney outlet. The stack effect, due

[1] (S.R.Hastings, Passive Solar Commercial and Institutional Buildings, A source book of examples and Design Insights, 1993, p. 137)

[2] *Ibid.*, p. 137

to increasing air temperature in solar chimney, sucks the cooled and heavy air through the heat exchanger causing ventilation. See figure 1.62[1].

The same system can be applied with wind-driven forces, by adding a wind catcher at the inlet of heat exchanger, and replacing the solar chimney by wind tower as shown in figure 1.63[2].

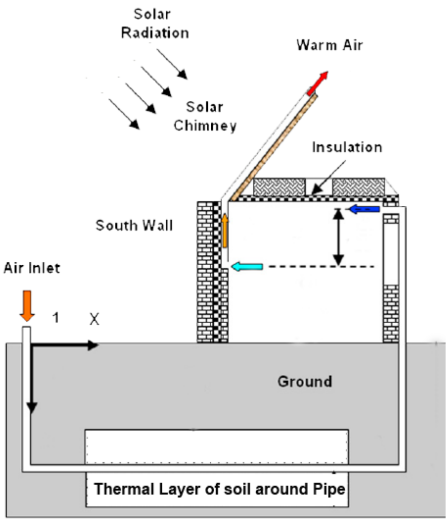


Figure 1.62 – Heat exchanger/ solar chimney system works on stack concept with wall air inlet inside space[3]

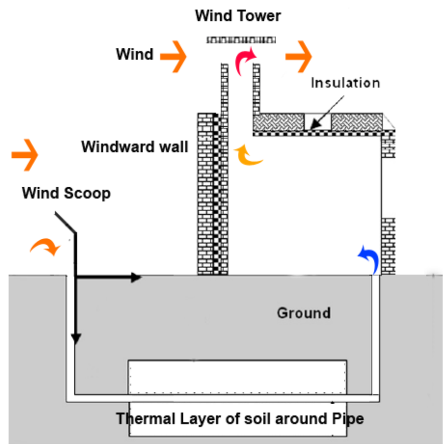


Figure 1.63 – Heat exchanger/ wind tower system works on wind-driven forces with floor air inlet[4]

1.7.4.2. Evaporative cooling cavity (ECC)

A. Operation principle

At dry climates, when outdoor temperature is high, evaporative cooling cavity system is used to reduce ambient air temperature by passing air over a water falling film. Water is sprayed on the top of the wall, where it flows as a thin film along the wall surfaces of the air passage, as shown in figure 1.64. The water then may be recycled again to the nozzles by means of a pump[5].

[1] (M. Maerefat, Passive Cooling of Buildings by using integrated earth to air heat exchanger and solar chimney, 2010, p. 2317), (Eicker, Low Energy Cooling for Sustainable Buildings, 2009, p. 83)
[2] M. Maerefat, *op. cit.*, p. 2317
[3] *Ibid.*, p.2317
[4] *Ibid.*, p.2317
[5] (M. Maerefat, Natural Cooling of stand-alone houses using Solar Chimney and Evaporative Cooling Cavity, 2010, p. 2041)

A mass transfer of evaporated water into the air is occurred, also, heat transfer takes place due to the temperature difference between the water and the air, introducing humid cooled supply air into the room.

B. Applications

The numerical experiments, have been conducted by M. Maerefat, and A.P. Haghighi, have revealed that this integrated system is capable of providing good indoor conditions at the daytime (room air temperature of 27°C), when high ambient air temperature is 34°C. So, this technique is suitable to supply the cooling load in the arid climates[1].

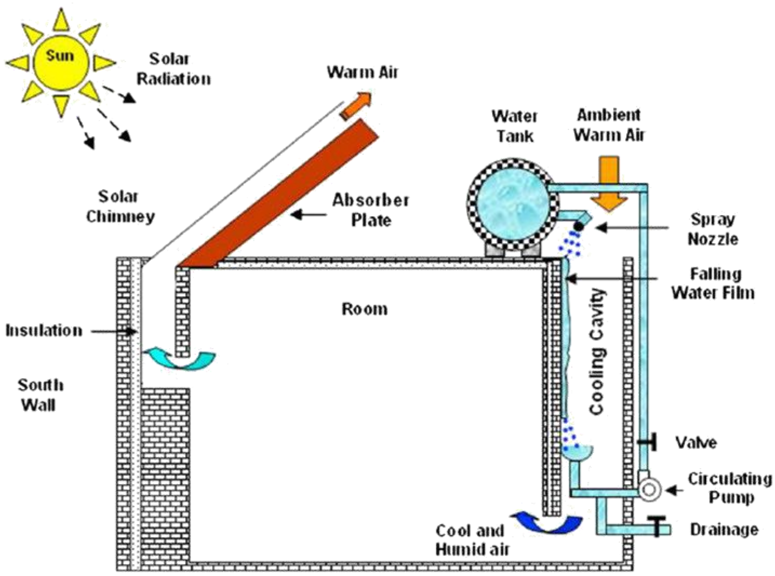


Figure 1.64 – Evaporative cooling cavity / solar chimney integrated system[2]

C. Traditional forms of applications

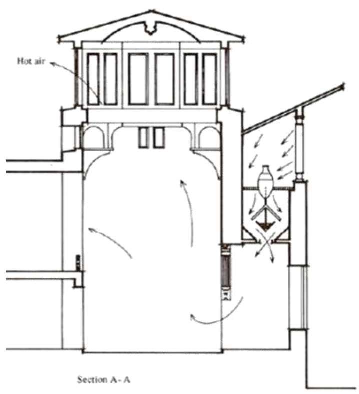
Evaporative cooling cavity can be noticed in some applications in traditional architecture. The simplest application of ECC is the *Mashrabiya* with its familiar form. *Mashrabiya,* as a supply vent, is a cantilevered space with a wooden lattice screen. Usually, small water jars were placed into the *mashrabiya* to be cooled by the air. These water jars provide space by cool

[1] *Ibid.,* pp. 2048, 2051

[2] (M. Maerefat, Natural Cooling of stand-alone houses using Solar Chimney and Evaporative Cooling Cavity, 2010, p. 2041)

humid air via evaporation effect when air flows around them. Whole system then acts like an ECC[1].

More sophisticated applications of ECC in traditional architecture are these enhancements, shown in figure 1.65, that were added to *Malqaf* design by *Hassan Fathy* to supply spaces with cool humid air by passing the air draft flowed through the *Malqaf* over baffles of wetted charcoal panels placed inside the *Malqaf*. Also these baffles are effective in filtering dust and sand from the air[2].



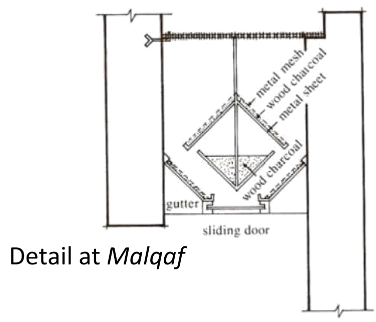


Figure 1.65 – *Malqaf* with wetted baffles designed by Hassan Fathy[3]

1.8. Conclusion

Chapter one defined and explained the different passive techniques used for natural ventilation, through studying the working principles and contemporary and traditional applications of each technique. The illustration used classification criteria that depend on the primary operating principles of natural ventilation concepts.

According to ASHRAE Standard 62.2-2007, chapter one determined that the required natural ventilation rate for achieving acceptable indoor air quality in residential buildings depends on unit floor area and number of bedrooms (for

[1] (Fathy, Natural Energy and Vernacular Architecture - Principles and Examples with reference to Hot Arid Climates, 1986, p. 46)

[2] *Ibid.*, p. 60

[3] *Ibid.*, p. 125

around 100 m^2 apartment with 2 bedrooms, the minimum required ventilation rate is 21 L/s). Generally, natural ventilation can achieve the required indoor ventilation rates for air quality.
Chapter one also stated that due to the multi-parameters of thermal comfort, precise value of ventilation rate required for achieving thermal comfort is hard to be determined.

This chapter determined that thermal comfort due to drafts depends on air velocities inside spaces. Elevated air speed may be used to offset an increase comfort zone upper limits up to 3°C. The required air speed may not be higher than 0.8 m/s. As, with higher air speeds, large individual differences exist between people with regard to the preferred air speed. Therefore, the elevated air speed must be under the direct control of the affected occupants.

Theoretical information analysis for natural ventilation techniques indicates that the efficiency of first and second classification techniques mainly depends on intensity and direction of prevailing wind. While indicators state that third classification techniques efficiency depends on high direct solar radiation environment, and the temperature differences between indoor and outdoor.

CHAPTER TWO

Natural Ventilation Passive Techniques for Contemporary Housing Applications

- Introduction
- Contemporary Housing Case Studies
- Passive Techniques Performance in Hot Arid Climate
- Conclusion

2.1. Introduction

Chapter two introduces a brief for local housing typology to identify the different passive techniques applications. Due to the classification mentioned within chapter one, four cases of contemporary housing applications for natural ventilation passive techniques are selected, discussed and analyzed within this chapter. Through the analysis of different cases, this chapter aims to evaluate the performance of different passive applications on residential buildings.

The United Nations estimated that more than one billion urban citizens live in inappropriate houses, mostly in squatter and slum settlements. While in most of cities in less developed countries; between one and two thirds of the population live in poor quality and overcrowded housing.

One of the most important characteristics of the inappropriate housing is the poor indoor environmental conditions such as extremely low or high temperatures, lack of ventilation, etc. In parallel, heat island conditions in dense urban areas increase ambient temperatures and the thermal stress to buildings, especially during the summer period.

Therefore, conventional air cooling techniques have to be adopted in order to improve the environmental conditions of low-income households. The idea is not to maintain temperatures within the ASHRAE defined comfort zone using energy driven systems, but to create buildings that will not threaten the lives of their occupants under adverse conditions even when power is lost or if citizens cannot afford to pay for it[1].

2.2. Contemporary Housing Case Studies

By monitoring the contemporary local housing and the applications of natural ventilation techniques used, it is found that Egypt housing sector totally depends on passive natural ventilation techniques to supply living spaces with the required fresh air with no mechanical ventilation methods. That is because the Egyptian building code requires a natural ventilation vent in each

[1] (M. Santamouris, Recent progress on passive cooling techniques (Advanced technological developments to improve survivability levels in low-income households), 2007, p. 860)

space directly to the outdoor for supplying natural ventilation to all residential spaces.

The passive natural ventilation techniques in contemporary local housing are mostly limited on the first and second classification mentioned at the previous chapter (techniques that depend on direct displacement by wind-driven force, and those that depend on wind pressure differences and suction effect). The cross ventilation vents, single-sided ventilation, and sometimes wing walls are the most common techniques due to their low cost, technicality, and maintenance, with obvious absence of wind scoops and towers, or roof cowls. That is because of the differences between the contemporary residential type, and the traditional one that had different design, planning, and organization of types.

Regarding the third classification of passive techniques (techniques that depend on solar or thermal buoyancy effect) which make use of solar energy to induce ventilation process, it was expected to find such techniques in a hot sunny region like Egypt. But on the contrary, there is complete absence of such techniques. This absence may go back to high technicality, or higher initial cost of such techniques. So the next sections will concentrate on studying the effect of applying this classification in residential buildings in hot climates.

Within the next sections, four case studies will discuss the application of passive natural ventilation techniques in residential buildings in regions of hot climate (dry or humid). They were chosen according to the classification of passive techniques as follows:

- One case study for the techniques of the first and second classifications, which already exist in local housing, to evaluate their performance.
- Two case studies for the techniques of the third classification in hot humid climates to study the effectiveness of applying such techniques within residential buildings.

- One case study for the techniques of the third classification in hot arid climates to study how successful applying these techniques in hot arid climates like Egypt will be.

The case studies can be related to the main classification of natural ventilation passive techniques proposed within chapter one as shown in figure 2.1.

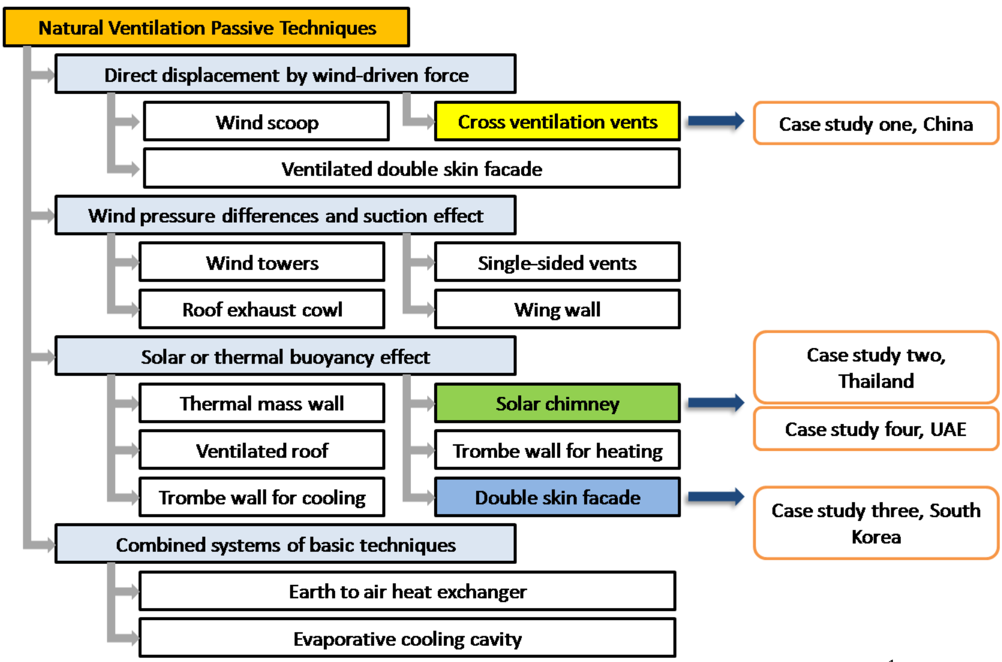


Figure 2.1 - Research case studies due to passive techniques classification[1]

2.2.1. Taidong residential quarter, Shanghai, China (evaluation of cross ventilation system)

Many applications of contemporary cross ventilation techniques meet some success in achieving the indoor air quality and thermal comfort. A design team from MIT (Massachusetts Institute of Technology) implements a CFD simulation analysis on design of three mid-rise buildings in a residential compound development project in Shanghai, China, to evaluate the cross ventilation design and monitor the air flow within the chosen unit.

[1] The researcher

2.2.1.1. Project details

A study was conducted by a collaboration between (MIT group of Sustainable Urban Housing in China, Construction Engineering Department, *Tongji* University), (Architectural Design and Research Institute, *Tongji* University), and (Shanghai Housing Development Company).

Project	Three mid-rise buildings for *Taidong* Residential Quarter
Location	*Taidong*, Shanghai, China
Climate	warm, humid summer climate
Year	Fall 2000

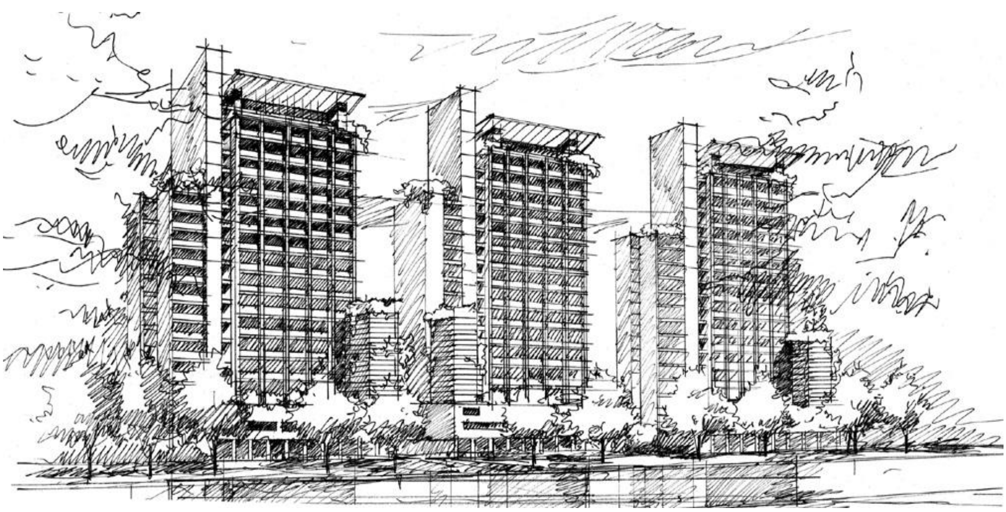


Figure 2.2 – Architectural rendering for Taidong residential project, Shanghai, China[1]

There were two design proposals in this project: Two-building proposal, and three-building proposal, shown in figure 2.2, which has been selected by developer as it promoted better indoor natural ventilation within the studied units. Each building consists of nearly ten floors. Each two floors consist of five duplex units and two single units. Within duplex units, natural ventilation was provided for the kitchen and dining rooms by utilizing the space over the corridor, which allowed airflow into the units, as shown in figure 2.3. Within the single-floor units, located at the end of each corridor,

[1] (Lin, Case Study Three - Shanghai Taidong Residential Quarter, 2006, p. 172)

all windows were carefully located beneath balcony overhangs to provide shading.

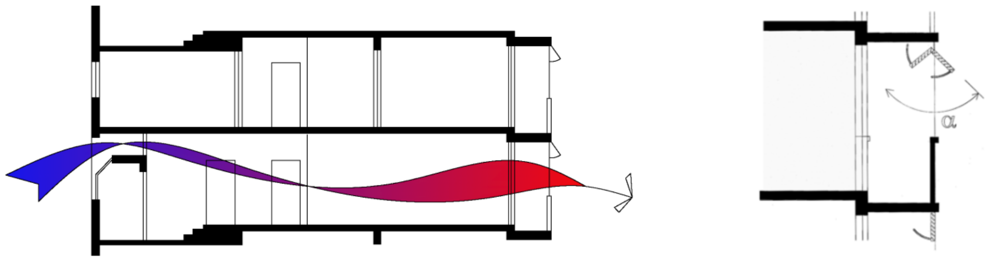


Figure 2.3 – Sections showing airflow by high-level ventilation above the corridor– (Right) moveable shading system on southern facade[1]

2.2.1.2. Passive technique and strategy *(Direct displacement by wind-driven force / cross ventilation vents)*

Cross ventilation system is the technique under investigation in this study. Study went through passive strategy of reducing the summer cooling load and associated energy for cooling by: (1) controlling initial solar gains by using fixed and operable overhang shading systems and (2) removing excess moisture by encouraging cross airflow for cooling[2]

2.2.1.3. Testing methodology

Natural ventilation studies were performed through simulation of indoor and outdoor airflow by CFD software using the following outdoor ambient recorded data:

Wind speed	3 m/s at 10 meters above the ground
wind direction	southeast
Outdoor Air temperature	24°C
Air relative humidity	70%
CO_2 concentration	400 ppm

Table 2.1 – Simulation input outdoor site data

Indoor airflow was simulated to evaluate design decisions for openings, and partitions locations. These simulations were conducted for all duplex units and single units. Only the single-floor unit, shown in figure 2.4, is described in this case study. The single-floor unit studied was unit G.

[1] *Ibid.*, p.174
[2] *Ibid.*, p.160, (MIT-Building-Technology-Group, Sustainable Urban Housing in China, 2001)

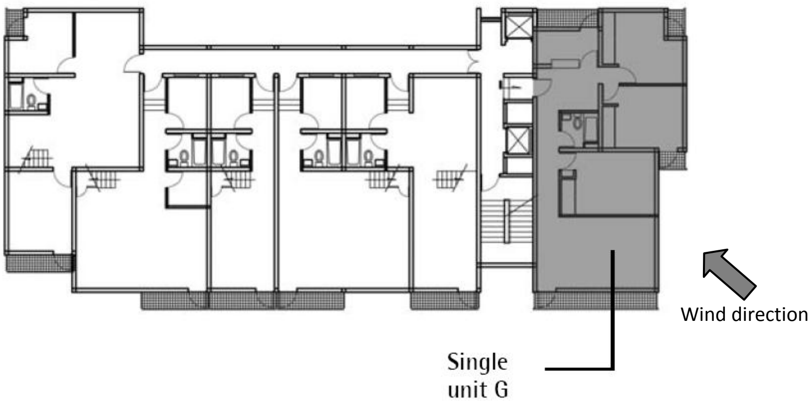


Figure 2.4 – Floor Plan diagram, showing location of single unit G[1]

2.2.1.4. Study results

Indoor airflow simulations results are shown in table 2.2, and figure 2.5. These results indicate that the average air velocity in the unit was less than 1.0 m/s, which is a comfortable value for cross ventilation. The air exchange rate varies from 16 ACH on the first floor to a maximum of 40 ACH at approximately two-thirds of the maximum height of the building. With the minimum air exchange rate of 16 ACH, the indoor air temperature increased by less than 1.0°C, although there were heat sources in the unit. The relative humidity was around 70 percent, which was close to that of the outdoors. Since the air exchange rate was high, the mean age of air was less than 120 seconds. Therefore, the air quality would be very good when outdoor air quality was high[2].

Result Parameter	*Results*
Indoor temperature	24 – 25°C
Air velocity	0.01 – 1.2 m/s
PPD	5 – 30%
Relative humidity	70 – 75%
CO_2 concentration	400 – 500 ppm
Ventilation effectiveness	20 – 100%
Age of air	0 – 102 sec

Table 2.2 - Result parameters for CFD simulation of single unit (G)

[1] (Lin, Case Study Three - Shanghai Taidong Residential Quarter, 2006, p. 179)
[2] *Ibid.*, pp. 176-181

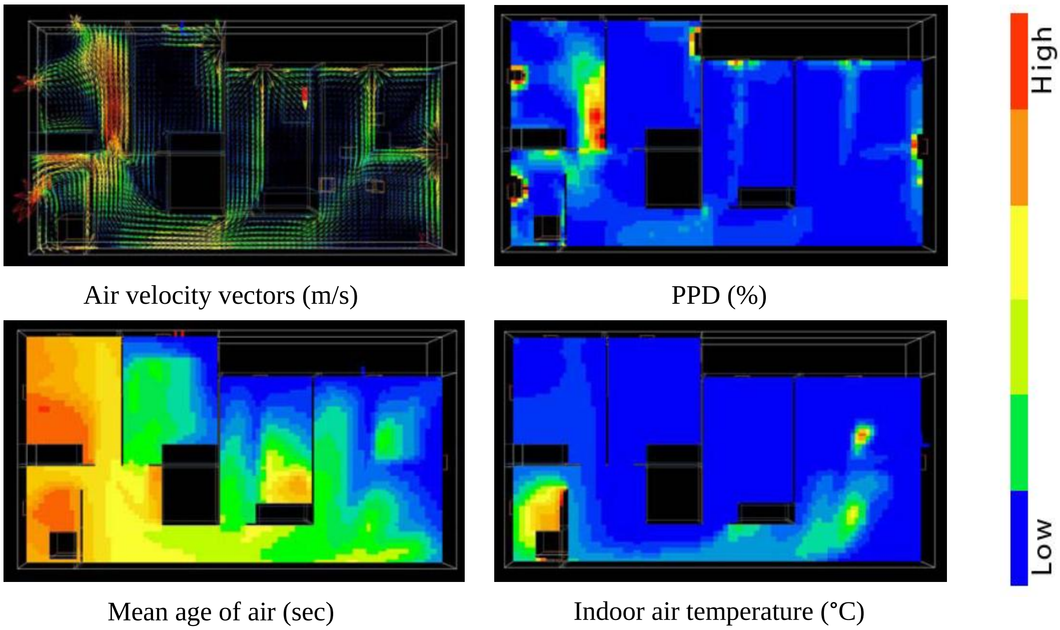


Figure 2.5 – Cross ventilation performance analysis[1]

The design team was able to create a design that improves the occupant comfort levels and microclimate conditions at each building, while reducing the overall need for mechanical systems for cooling.

The results also illustrated that the air velocity may not truly indicate the indoor air quality. Within left-hand bedroom, air flows into room through the door with high air velocity. But mean age of air is also high due to pressure differences on external windows which cause a semi-static air movement condition that affects indoor air quality[2]. Figure 2.6 shows the air flow directions due to simulation results.

[1] *Ibid.*, p. 180

[2] (Chen, Using computational tools to factor wind into architectural environment design, 2004, pp. 1206-1208)

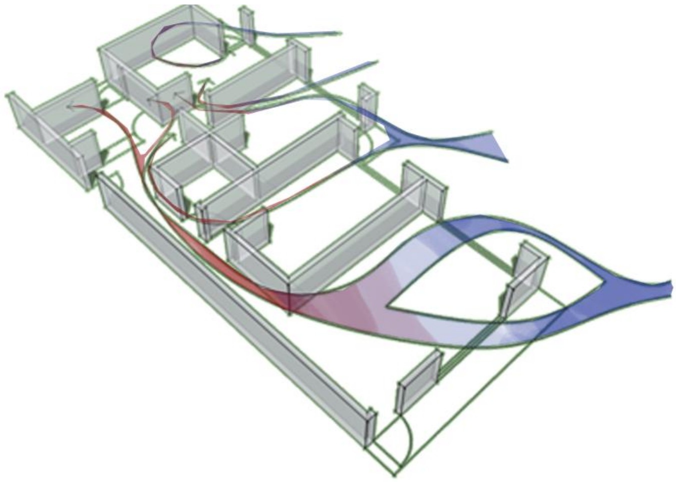


Figure 2.6 – Air flow directions due to simulation results[1]

2.2.2. Typical Thai sub-urban residential unit, Thailand (evaluation of solar chimney and roof pond system)

Using field measurements and digital simulation study by CFD software, a combined passive system of solar chimney and roof pond has been investigated in *Sirindhorn* International Institute of Technology (SIIT), *Thammasat* University, Bangkok, Thailand. This system was applied on true scale physical model (test unit) for the typical single-storey residential unit to study the performance of passive systems on indoor environmental conditions.

2.2.2.1. Project details

The typical residential type of sub-urban settlements of Thailand for small families (one or two children) consists of one or two storeys as maximum. Obviously, this type is heavily spread regardless the economic level of users, as shown in figure 2.7.

	Project	Typical type of single- storey residential unit
Location	*Original unit*	Sub-urban settlements in Thailand
	Experiment	*Thammasat* University, Bangkok, Thailand
	Climate	Hot-Humid summer climate (Tropical Wet Climate)
	Year	2004 - 2005

[1] The researcher

Kanchanaburi Province, Sub-urban of Bangkok

Sub-urban of *Undon Thani*

Figure 2.7 – Different economic levels of typical single-storey Thai sub-urban housing[1]

2.2.2.2. Passive technique and strategy *(Solar and thermal buoyancy effect / solar chimney)*

Using field measurements, experiment aimed to analyze the performance of combined system of solar chimney and roof pond carried out in a specific designed test residential unit, comparing the results with that of the original unit. The test unit has the same construction pattern as the original one. The experiment aims to study the effect of both techniques one by one as well as the combined system. So, the original unit was sealed (all openings were closed) and a wind shield was used around the test unit during the experiment to neutralize the wind effect, and that for monitoring the stack effect of solar chimney and radiation effect of roof pond separately. An illustration of the combined system is shown in figure 2.8.

2.2.2.3. Testing methodology

The experiment aimed to simulate the typical residential unit into a test unit with the same specifications of the original unit to evaluate the passive strategy chosen for enhancing the indoor thermal conditions. The interior dimensions of the chosen unit for experiment are 3.8m x 2.8m x 2.4m, with same wood structure as the original unit. The unit has a pitched roof with tilt angle of 45°, which is divided into two parts, as shown in figure 2.9. The south part is utilized as a solar chimney of 0.15m in width. There is an air gap under the south roof to reduce heat transfer. The north roof consists of two

[1] (US-Dept-of-State-Geographer, Google Earth, 2011)

layers, the outer zinc louvers and the inner flat zinc sheet on where water pipes are mounted to act as a roof pond.

The experiments were carried out on selected days during June – July, September – October, and February – March (2004–2005). The measurement data were recorded every 2 min during 24 h[1].

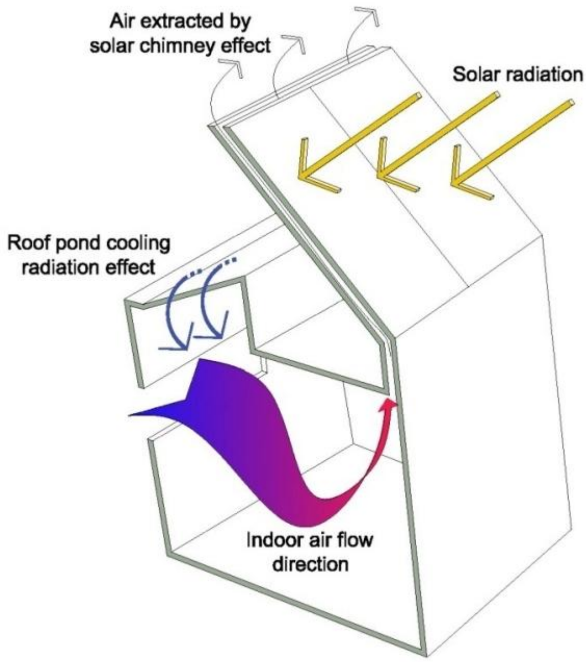


Figure 2.8 – Solar chimney and roof pond combined system illustration[2]

(a) (b)

Figure 2.9 – (a) Roof pond facing north direction, (b) Solar chimney facing south direction[3]

[1] (Sudaporn Chungloo, Application of passive cooling systems in the hot and humid climate (The case study of solar chimney and wetted roof in Thailand), 2006), (Sudaporn Chungloo, A numerical study of natural ventilation in buildings - Utilized solar chimney and cool ceiling, 2006)

[2] The researcher

[3] Sudaporn, *op. cit.*

2.2.2.4. Study results

The results were divided due to test strategy into two phases: 1- only solar chimney results and 2- combined system of solar chimney and roof pond.

A. Experiment results for only solar chimney application

1- First observation was that airflow rate during February–March (warm season) is higher than that during June–July and September–October (hot season). The experiment showed that the main changing parameters are ambient temperature (T_{amb}), indoor average temperature of test unit (T_{in}), and solar chimney temperature (T_{sc}). The results showed the following relationships.

At warm Season: $T_{amb} > T_{in}$, $T_{sc} > T_{amb}$ (due to heat storage), $T_{sc} >> T_{in}$

At hot Season: $T_{amb} \approx T_{in}$, $T_{sc} \geq T_{amb}$, $T_{sc} > T_{in}$

The results assured that the airflow depends on the temperature difference between T_{sc}, and T_{in}. The greater the difference is, the more flow the air will be, because of increasing thermal buoyancy force.

2- During hot outdoor air (12.00 pm – 4.00 pm, July 1, 4), the ambient temperature ranged from 32°-39°C. The results revealed that the average temperature in the test unit is lower than that in the original unit by 1°-1.3°C, and lower than the ambient air temperature by 1°-3.5°C.

B. Experiment results for both solar chimney and roof pond application

The results showed that when roof pond was applied in addition to solar chimney, the average temperature in the test unit is lower than that in the original unit by 1.4°-3.0°C, and lower than the ambient air temperature by 2.0°-6.2°C. Figure 2.10 shows changes in indoor temperature contours when applying roof pond to the system.

The recorded volume flow rates through solar chimney were 0.008–0.012m^3/s in July and 0.012–0.016m^3/s in September. The recorded values of ACH were 1.13 and 2.26 for same period.

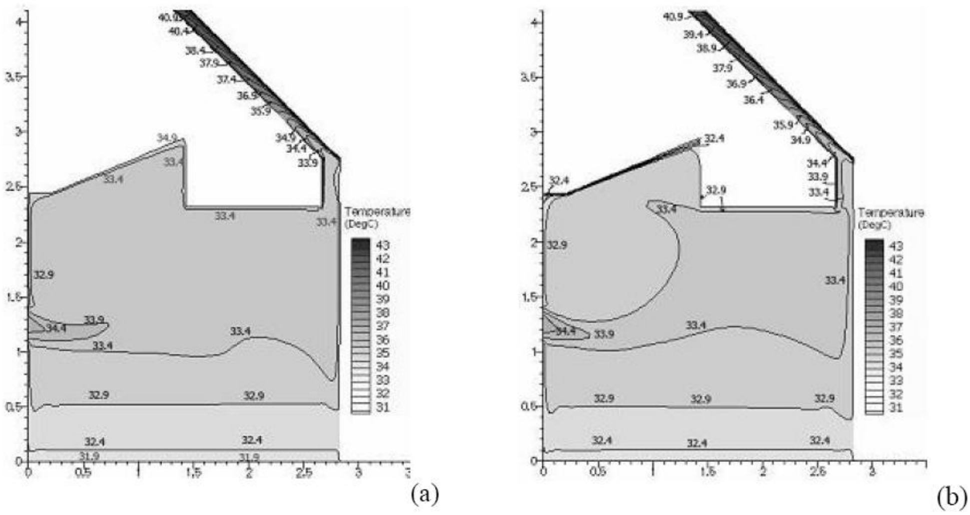


Figure 2.10 – Simulated Indoor temperature distribution for: (a) solar chimney, (b) combined solar chimney and roof pond[1]

During hot season when effect of wind was considered (real conditions), the experiments showed that the values of air velocity inside test unit were 0.02 - 0.08 m/s, and ACH was 4 to 15[2].

It can be concluded from the results that in the worst case (zero wind velocities), applying solar chimney combining with roof pond system can achieve a reduction in unit temperature of 6.2°C lower than outdoor temperature, with better performance in warm season than in hot one. Also, it can be concluded that the affecting factors on test unit inner temperature are:

- The high ambient temperature of hot season.
- The cooling loads by radiation generated from roof pond, which increase the difference between T_{sc} and T_{in}.
- The high induced solar chimney temperature by the solar radiation.

2.2.3. Residential complex, Mapo district, Seoul, South Korea (evaluation of double skin façade system -DSF-)

As the multi-functional residential complexes become popular in Korea, more comfortable indoor conditions are needed. Spreading such building typology increases the energy usage for cooling, because of solar heat

[1] (Sudaporn Chungloo, A numerical study of natural ventilation in buildings - Utilized solar chimney and cool ceiling, 2006)

[2] *Ibid.*

transfer due to large areas of glass façades supplying daylighting. Thus, a study was performed aiming at reducing the cooling energy requirements of a residential complex by maximizing the possibilities of natural ventilation strategies through Double Skin Façade.

2.2.3.1. Project details

Project	Multi-functional residential building shown in figure 2.11
Location	Mapo District, municipal of Seoul, South Korea
Climate	warm, humid summer climate, with west/southwest wind
Year	2004

The chosen unit is 204.96m^2 apartment, with south-facing façade, as shown in figure 2.12. The double façade typically consists of two separate glass skins with an air cavity between with a width of 0.50 m. Shading and light directing devices may be situated between the two skins.

Figure 2.11 –Mapo district urban pattern and example of residential typology in Mapo[1]

2.2.3.2. Passive technique and strategy *(Solar and thermal buoyancy effect / double skin façade)*

A study was conducted to evaluate double skin façade performance through three successive stages: 1- choosing the building of study, 2- using ESP-r simulation software for calculating building loads when DSF system is

[1] *Ibid.*

applied, and 3- changing the building skin and evaluating the building loads for each change[1].

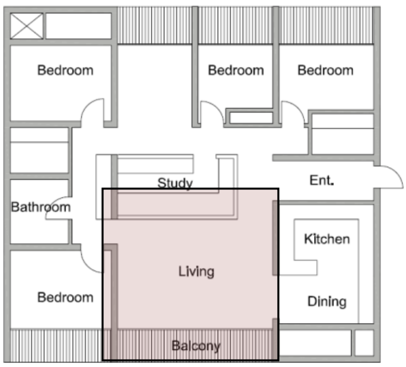


Figure 2.12 – Study unit plan, with the southern space selected for study[2]

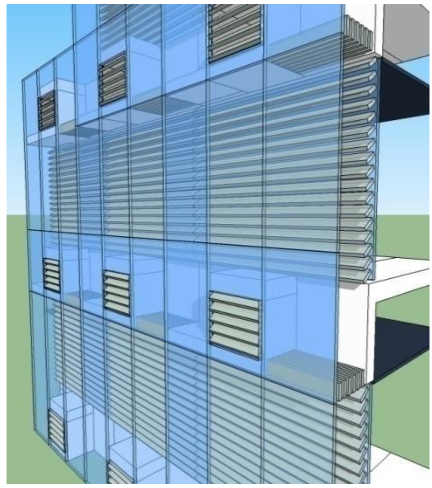


Figure 2.13 – 3D model of DSF system used showing stack effect ventilation, and direct cool air supply[3]. See figure 2.14 for more details

2.2.2.3. Testing methodology

This study proposes a box type double skin system that makes use of buoyancy for creating ventilation. In hot summer days, the air temperature of the cavity becomes higher than temperature outside, resulting in a stack effect. Grills then are opened to let outside air to flow directly inside, as shown in figure 2.13. The complete control algorithm of the system is shown in figures 2.14, and 2.15.

In order to compare the cooling energy performance of double skin system, three other skin designs were selected and compared, as shown in figure 2.16. An energy analysis was conducted for a peak cooling load on August 22, and with outside average temperature was over 26°C. It was assumed that the cooling system started when the temperature rise over 26°C. Figure 2.17 shows the energy consumption of each skin design.

[1] (Seung-Bok Leigh, A Study on Cooling Energy Savings Potential in High-Rise Residential Complex Using Cross Ventilated Double Skin Facade, 2004, pp. 275, 276)
[2] *Ibid.*, p. 274
[3] The researcher

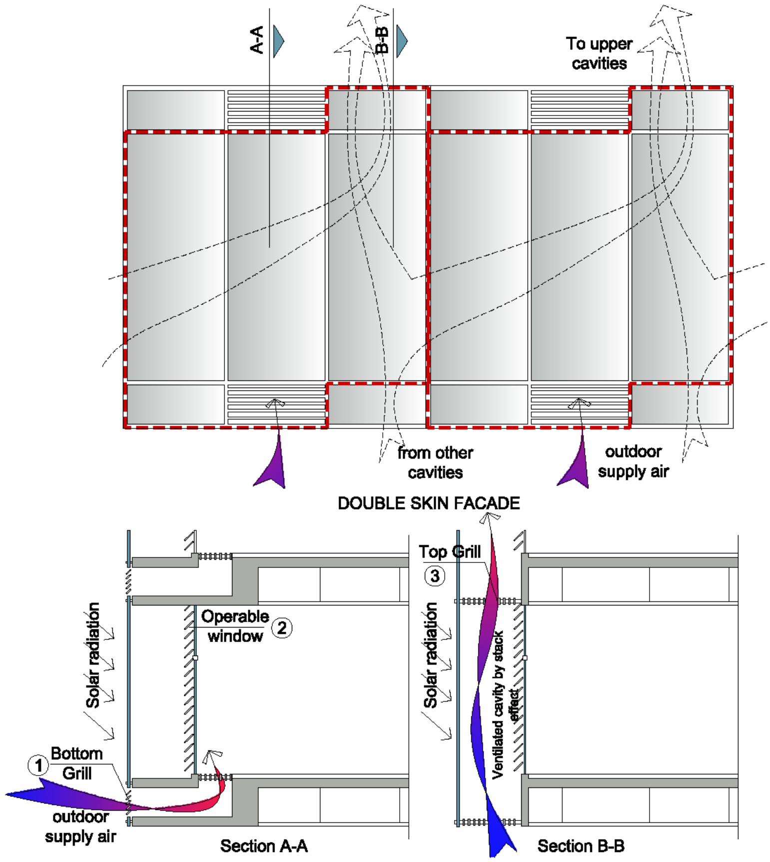


Figure 2.14 - Double skin façade working process[1]

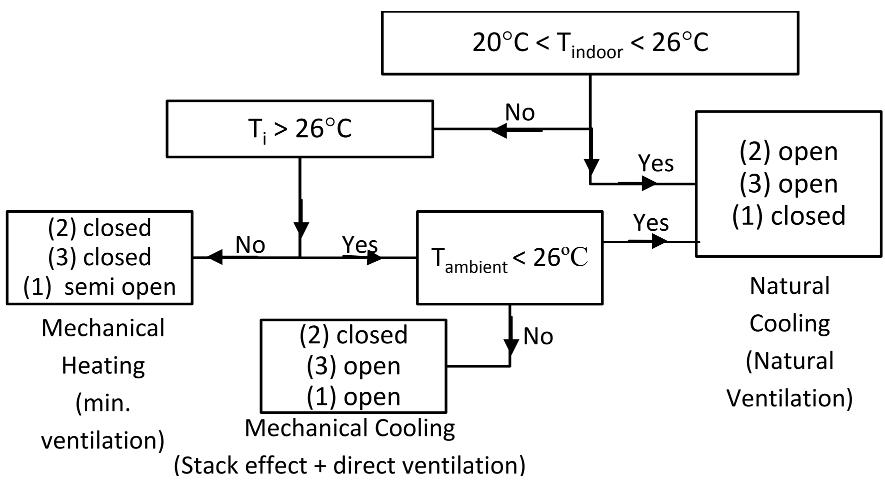
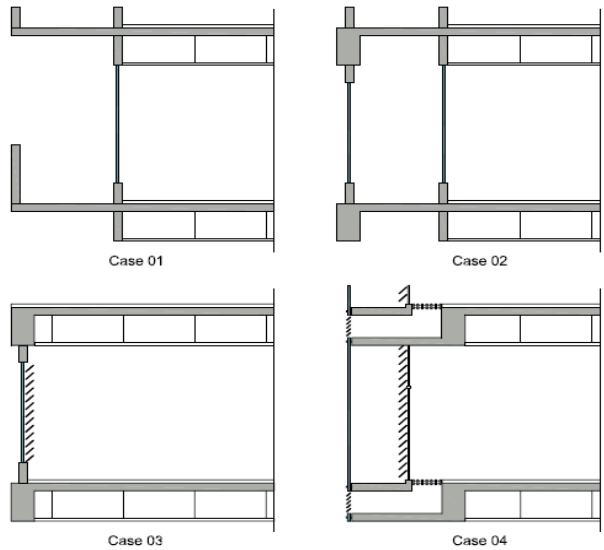


Figure 2.15 – Full control algorithm of double skin facade system[2]

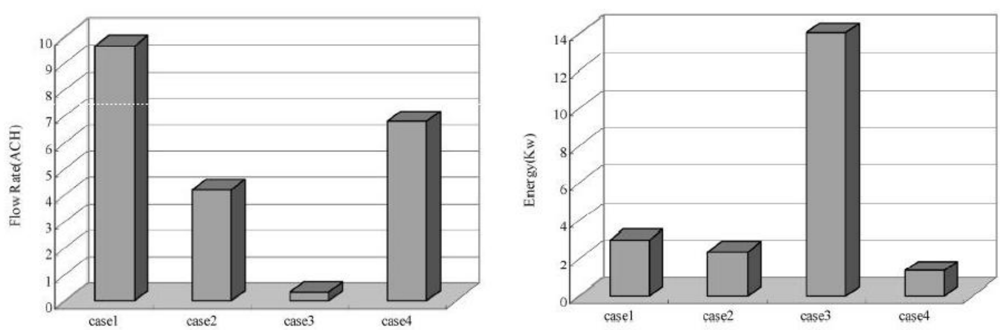
[1] (Seung-Bok Leigh, A Study on Cooling Energy Savings Potential in High-Rise Residential Complex Using Cross Ventilated Double Skin Facade, 2004, p. 278)
[2] *Ibid.*, p. 277

Figure 2.16 – Outer skin study alternatives. Case (01) open balcony, Case (02) enclosed balcony, Case (03) extended interior space, Case (04) double skin façade (reference case)[1]



2.2.3.4. Study results

The average ventilation rate for case 4 was 6.7 ACH ranged from minimum of 0.7 ACH to maximum of 24.5 ACH. When wind speed was zero, cavity's buoyancy still produced the required minimum level of ventilation. The electricity consumption for each skin design is shown in figures 2.18.



flow rate energy consumption

Figure 2.17 – Skin alternatives results[2]

According to the survey by Korea Electric Power Corporation (KEPCO), it could be said that 30% of cooling cost would be saved with the application of

[1] *Ibid.*, p.278
[2] *Ibid.*, p.279

DSF system. It was shown that case 4 had the lowest cooling energy consumption level with 2nd position in flow rate.

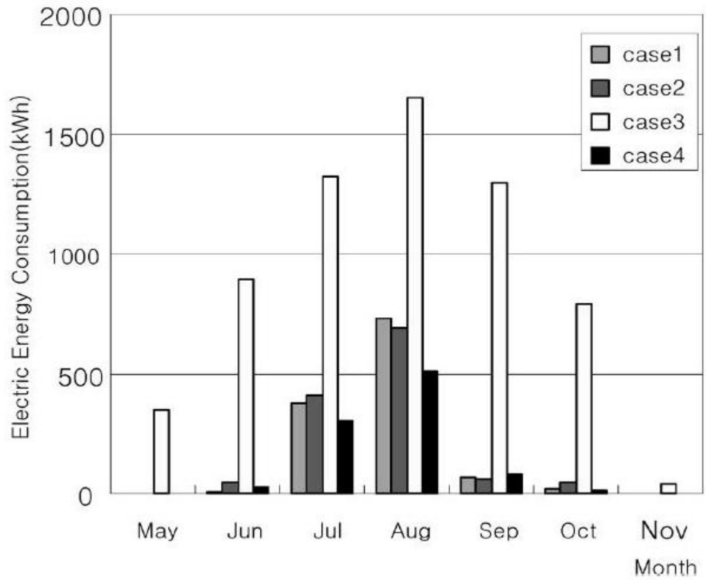


Figure 2.18 – Electric energy consumption during hot season for the four skins[1]

There are some assumed weakness points of the double skin façade. First is the temperature increase in the cavity during the summer season. It turned out to be an average increase of about 1.1°C when compared with the outside temperature, which is not such a significant difference. The second point is the interior space usage. The double skin façade takes only 7.00 m^2 of floor area[2].

2.2.4. Low-rise residential type, Al-Ain city, UAE (evaluation of only roof and wall-roof solar chimney)

In hot-arid regions with ambient air temperatures between 42° to 47°C during the hottest period, only direct ventilation is not recommended. So, parametric analytical study of wall-roof solar chimney coupled with wind evaporatively cooled cavity was operated into building external envelope to promote natural cooling, using a spread-sheet computer program.

[1] *Ibid.*, p.281
[2] *Ibid.*, pp. 279 - 281

2.2.4.1. Project details

One very common type of residential buildings in Al-Ain city with Spanish roofs style, shown in figure 2.19, has been chosen. This type includes two floors with two apartments located symmetrically in each floor.

Project	Two floors Private residential unit
Location	Al-Ain, UAE
Climate	Hot arid climate
Year	1998

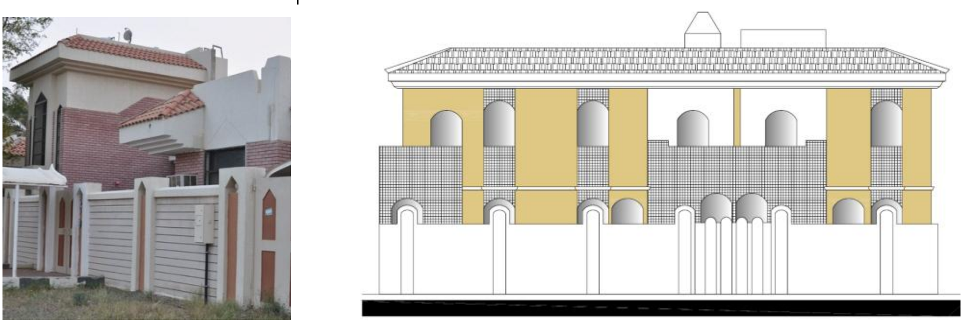


Figure 2.19 – Common building style in Al-Ain city, UAE[1]

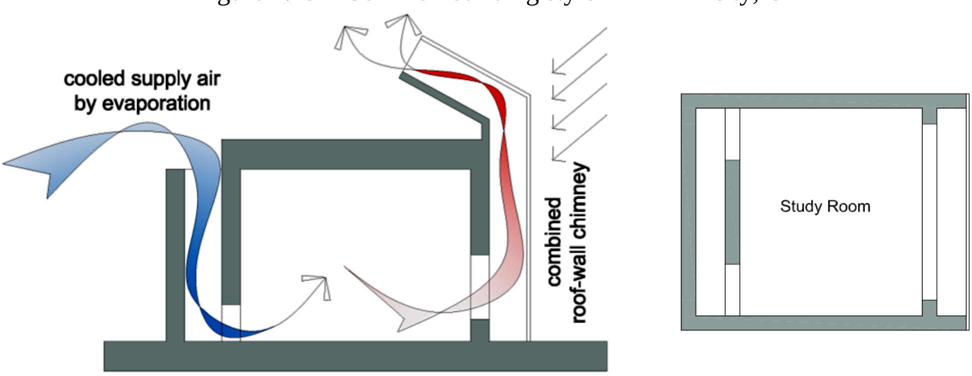


Figure 2.20 – Selected room for study

The selected room for conducting study is 4.80m x3.60m x 3.60m, with volume of 62m^3, as shown in figure 2.20. Evaporative cooling cavity was applied on northern façade. The solar chimney is integrated on inclined roof,

[1] (M.M. AboulNaga, Improving night ventilation into low-rise buildings in hot arid climates exploring a combined wall-roof solar chimney, 2000, p. 49)

with absorbing black metal external plate on south facade, with air gap that varies from 0.08m to 0.25m. The roof inclination is taken to be 25-40°[1].

2.2.4.2. Passive technique and strategy *(Solar and thermal buoyancy effect / solar chimney)*

Using psychometrics spread-sheet Software, the study aimed to evaluate solar chimney performance through two steps: only roof chimney stage, and combined wall-roof chimney stage to increase the induced air flow rate

2.2.4.3. Testing methodology

A study was conducted under an ambient air temperature of 27°C. In such extremely hot climates, direct day ventilation may affect negatively the indoor thermal environment. In order to supply the space by a cooled air, an evaporative cooling cavity was attached to the northern supply façade.

2.2.4.4. Study results

According to the study strategy, results were displayed through two steps:

A. Only roof solar chimney results

For room inlet height of 0.15m, and slope of roof of 30°, the air velocity in the room was found to be 0.27 m/s. In the chimney, it was 0.9 m/s. At an average solar radiation on an inclined surface of 850 W/m^2, the maximum mass flow rate was 1.60 kg/s (with volume flow rate of 0.81 m^3/s). The results show that the higher ambient air temperature increases volume flow rate.

The maximum mass flow rate had increased from 1.50 kg/s at slope angle of 25° to 1.60 kg/s at slope angle of 30°. It had reached the maximum value of 1.75 kg/s when the slope angle was 35°. When the slope angle was taken as 40°, no additional increase occurred to the mass flow rate, but a drop to 1.70 kg/s has been recorded. The above results indicate that the best performance of the roof solar chimney was at slope angle of 35°.

[1] (Aboulnaga, A roof solar chimney assisted by cooling cavity for natural ventilation in buildings in hot arid climates - an energy conservation approach in Al-Ain city, 1998, p. 359)

B. Combined wall-roof solar chimney results

By applying the wall chimney with the roof, air velocity in the room reached a maximum of 0.3 m/s. Air speed in the wall-roof solar chimney was increased to the maximum value of 2.6 m/s. Wall chimney showed an increase in the air flow rate of 2.30 m^3/s. By inlet height of 0.15 m, air change per hour up to 26 could be achieved, with an increase three times greater than that of the roof solar chimney alone[1].

2.2.5. Discussion

This chapter analyzed four contemporary housing applications for natural ventilation passive techniques. Table 2.3 shows a full comparison between the four case studies.

A. Cross ventilation technique analysis (case study one)

1- Ventilation rates: system succeeded in achieving high rates of air flow inside space ensuring high indoor air quality.

2- Air velocity: system analysis proved that high values of air velocities did not necessarily provide high value of ventilation rates, due to indoor pressure differences.

3- Thermal comfort: system did not provide cooler indoor conditions than outdoor thermal environment. The best performance the system could reach is to achieve near values to outdoor conditions of temperature, CO_2 concentrations, and relative humidity.

B. Solar chimney with roof pond analysis (case study two)

1- Ventilation rates: system shows better performance within warm season than hot one.

2- Thermal comfort: system could reduce the indoor temperature by maximum value of 3.5°C than outdoor temperature for only solar chimney and 6.2°C for whole system application.

[1] (M.M. AboulNaga, Improving night ventilation into low-rise buildings in hot arid climates exploring a combined wall-roof solar chimney, 2000, p. 54)

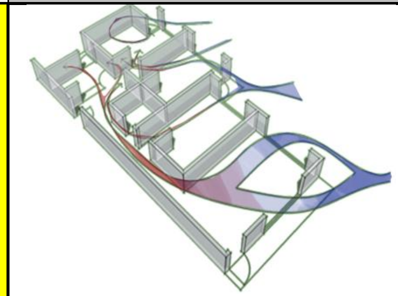
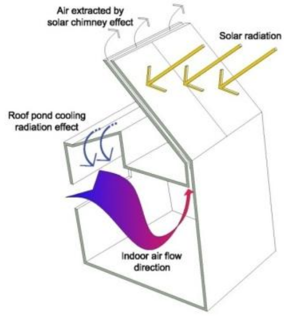
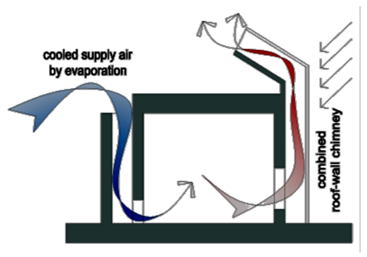
		Passive technique illustration	Project	Location	Climate	Year	Passive technique	Testing type	Test conditions	Analysis results		Remarks
										Ventilation rates performance	Thermal comfort performance	
	1		three mid-rise buildings for *Taidong* Residential Quarter	Shanghai, China	warm humid summer climate	2000	cross ventilation system	CFD simulations	incoming air temperature of 24°C	High ventilation rates of 40 ACH	-rise in indoor temperature up to 1°C -rise in relative humidity up to 5%	high values of air velocities did not necessarily provide high value of ventilation rates
	2		Typical type of single-storey residential unit	Sub-urban settlements of Thailand	Hot humid summer climate (tropical wet climate)	2004 - 2005	Solar chimney and roof pond system	field measurements + CFD simulations	Within hot and warm seasons	ventilation rates of 15 ACH within hot season	reduction in indoor temperature up to 3.5°C for only solar chimney and 6.2°C for whole system	better performance within warm season than hot one
	3		Multi-functional residential building	Mapo District, municipal of Seoul, South Korea	warm, humid summer climate	2004	Double skin façade	ESP-r simulation software	-incoming air temperature of 26°C -west /southwest wind directions	Maximum ventilation rates of 24.5 ACH	saving 30% of energy consumption assigned for cooling	-
	4		Two floors Private residential unit	Al-Ain, UAE	Hot arid climate	1998	Solar chimney with evaporative cooling cavity	Numerical study with psychometrics spread-sheet software	-high solar radiation of 850 W/m^2 -ambient air temperature of 27°C	ventilation rates of 26 ACH	evaporative cooling cavity was applied to system to achieve comfortable thermal conditions	-results increased three times when applying wall-roof chimney -higher ambient air temperature increases volume flow rate

Table 2.3 - full comparison between the four case studies

C. Double skin façade analysis (case study three)

1- Ventilation rates: system could achieve significant results for indoor air flow.

2- Thermal behavior: system could save 30% of energy consumption assigned for cooling.

D. Solar chimney with evaporative cavity analysis

1- Ventilation rates: with high solar radiation, system could achieve high values of ventilation rates with roof chimney; results increased three times when applying wall-roof chimney.

2- Thermal comfort: in order to achieve comfortable thermal conditions, evaporative cooling cavity had to be applied to system.

From cases two and four it is obvious that to achieve better thermal indoor conditions, solar chimney has to be combined with another passive cooling strategy, like evaporative or radiative techniques.

2.3. Passive Techniques Performance in Hot Arid Climate

Within the hot arid climate, some studies were conducted to evaluate the performance of natural ventilation passive techniques that depend on solar buoyancy for promoting ventilation.

A numerical study was conducted within hot arid climate of Egypt and considered the effect of geometrical parameters of the solar chimney design like inlet height and air gap width on ACH. The study concluded that at inlet height of 0.10 m and increasing chimney width from 0.10 to 0.30m, ACH increases by 22.5%. At inlet height of 0.30m and increasing chimney width with same quantity, ACH increases by 71%. But when fixing the chimney width at 0.10m and increasing inlet height from 0.10 to 0.30m, ACH increases only by 9.5%. This means that the chimney width has a more significant effect of ACH compared to the inlet height[1].

[1] (Ramadan Bassiouny, An analytical and numerical study of solar chimney use for room natural ventilation, 2008, p. 872)

In another study to evaluate the thermal performance of double skin façade within hot arid climate of Tehran, Iran, results showed that in countries with high solar radiation, especially in summer and because of high ambient temperature, night ventilation for the DSF system is essential to cool down the air gap of double facade. The results also revealed that installing shading devices inside the cavity can reduce the cooling loads in a building with DSF in comparison to the same building with normal facade[1]. Other thermal simulations using APACHE-Sim software in hot arid climate of Egypt indicated that a reflective double skin facade can achieve better energy savings than a single skin with reflective glazing[2].

2.4. Conclusion

This chapter discussed four case studies for different application of natural ventilation passive techniques:

1- Case one. Taidong Residential Quarter, Shanghai, China (Evaluation of cross ventilation system):

With an incoming air temperature of 24°C, cross ventilation system achieves maximum ventilation rates of 40 ACH (mean age of air of 90 seconds). Due to thermal comfort, the system causes a rise in the indoor air temperature of 1°C (to be 25°C). The system also causes a rise in indoor relative humidity of about additional 5%.

2- Case two. Typical Thai Sub-Urban Residential Unit, Thailand (evaluation of solar chimney and roof pond system):

Solar chimney as a technique depends on thermal buoyancy concepts proved that it gets a better performance in ventilation rates within warm season than the hot one. Within hot season, the system achieves ventilation rate of 15 ACH (age of air of 240 seconds). About thermal conditions, applying only solar chimney reduces the indoor air temperature by maximum value of 3.5°C than the outdoor air temperature. Applying whole system (roof pond

[1] (N. Hashemi, Thermal behaviour of a ventilated double skin facade in hot arid climate, 2010, p. 1832)
[2] (Hamza, Double versus single skin facades in hot arid areas, 2008, p. 240)

plus solar chimney) reduces the indoor air temperature by maximum value of 6.2°C than the outdoor air temperature

3- Case three. Residential Complex, Mapo District, Seoul, South Korea (evaluation of Double skin façade system -DSF-):

Within this case, a passive system is used not to go without active solutions, but to reduce energy consumption. Applying double skin façade (DSF) system achieves a maximum ventilation rate by 24.5 ACH (age of air 147 seconds), and shows best energy consumption levels by saving 30% of cooling cost.

4- Case four. Low-rise residential type, Al-Ain city, UAE (Evaluation of solar chimney within hot arid regions):

A combined system of solar chimney and evaporative cooling cavity was tested within hot dry climate; for high solar radiation of 850 W/m^2 and ambient air temperature of 27°C; roof solar chimney system achieved ventilation rate of 76.5 seconds as age of air inside space, while wall-roof solar chimney system achieved ventilation rate of 26.96 seconds as age of air inside space.

Chapter two showed that to achieve better thermal indoor conditions, solar chimney has to be combined with another passive cooling technique, like evaporative or radiative techniques. Within hot arid climates in countries of high solar radiation, applying solar buoyancy techniques could achieve significant high ventilation rates.

CHAPTER
THREE

CFD Simulation Analysis

- Introduction
- Climatic Features of Greater Cairo Region
- Local Case Study
- Simulation Software
- Input Data
- Reference Case
- Application of Natural Ventilation Passive Technique
- CFD Grid Statistics
- Comparison Methodology
- CFD Simulation Phases
- Conclusion

3.1. Introduction

This chapter is considered with studying the application of the natural ventilation passive techniques for residential buildings within the local field. The previous chapter described the application of passive techniques in both hot humid and hot arid climates with different techniques. In this chapter a reference case and a passive technique will be selected for performing research investigation. Referring to natural ventilation passive techniques classification illustrated in chapter one and shown in figure 3.1, the local case study discussed within this chapter belongs to first classification (direct displacement by wind-driven force). The reference case is derived from the case study and belongs to the second classification (wind pressure differences). The selected passive technique for study belongs to the third classification (thermal buoyancy effect)

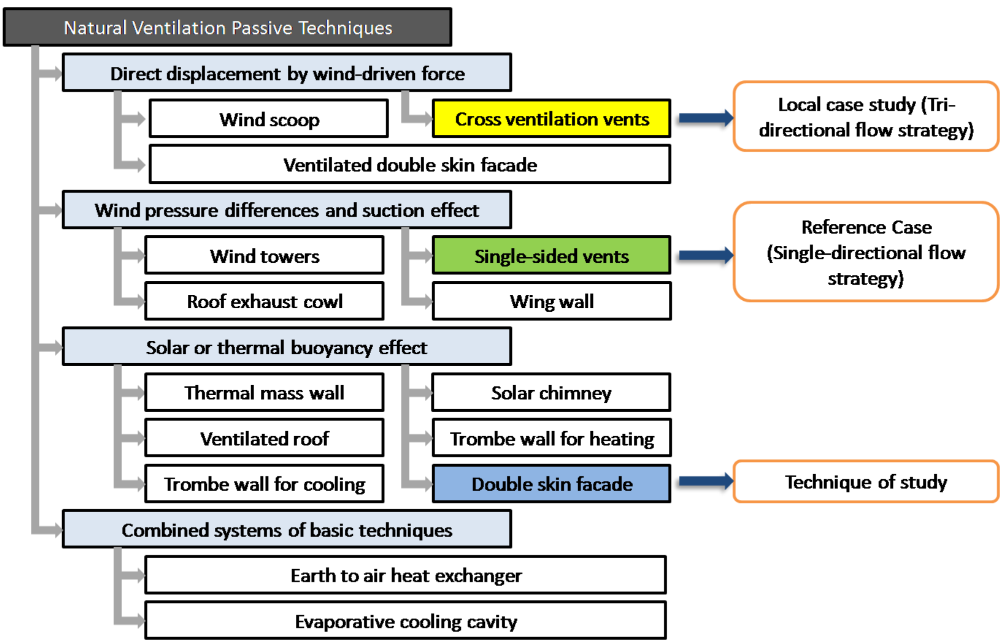


Figure 3.1 – Selection of techniques of study due to research classification[1]

Then, Reference case and passive technique with its study variables will go through dual phase of simulation processes: 1- Thermal simulation process,

[1] The researcher

then 2- Computational Fluid Dynamics (CFD) simulation process to evaluate the technique performance. Before proceeding into local application, this chapter presents a brief overview for the local climatic conditions.

3.2. Climatic Features of Greater Cairo Region

Until 2001, Cairo was classified as BSh climate. This classification was set by Egyptian Typical Meteorological Year (ETMY) and International Weather for Energy Calculations (IWEC)[1]. Köppen classification[2] defines BSh climate as hot semi-arid climate, with hot to extremely hot dry summer, and mild to warm wet winter[3]. Updated world maps of Köppen classification, published in 2007 by Copernicus Publications on behalf of the European Geosciences Union, have classified Cairo Region as BWh climate which is defined as hot desert climate[4].

Hot desert climate features hot, exceptionally hot dry summer, unbroken sunshine for the whole year, maximum temperatures of 45°C, and more dry winter[5].

According to reports published by EMA (Egyptian Meteorological Authority) based on reports from Climate Research Unit (CRU), university of East Anglia, UK, monitoring the climatic data in the period from 1996 to 2004, precipitation in Greater Cairo Region is 0.00 mm/day in summer, and 0.20 – 0.50 mm/day in winter. Also reports recorded 40.0-45.0°C as a maximum temperature range in summer, 20.0-25.0°C as a maximum temperature range in winter, 20.0-25.0°C as a minimum temperature range in summer, and 5.0-10.0°C as a minimum temperature range in winter[6].

The weather data used in this research were reported from two stations for climate observation in Cairo. The first is in Cairo International Airport, and the other is in Helwan Observatory. Two recording systems were employed:

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[1] (U.S.Department-of-Energy, EnergyPlus Energy Simulation Software - Weather Data Sources, 2011)

[2] The Köppen climate classification is one of the most widely used climate classification systems. It was first published by Crimea German climatologist *Wladimir Köppen* in 1884.

[3] (Wikipedia, http://en.wikipedia.org/wiki/koppen_climate_classification, 2011)

[4] (M.C.Peel, Updated world map of the Koppen-Geiger climate classification, 2007, p. 1638)

[5] Wikipedia, *op.cit.*

[6] ((EMA), Climate change and biodiversity, 2009)

ETMY and IWEC. ETMY system is provided by U.S. National Climatic Data Center, depending on the period of record from 12 to 21 years, all ends in 2003. IWEC system is the result of 2001 ASHRAE Research Project for period of record of 18 years[1].

According to the previous information, ETMY system was selected because its records end in 2003 two years later than IWEC system. Also, Cairo International Airport observation station was chosen due to the urban context of its location, which provides similar conditions for local urban housing context, compared with the semi-rural context of Helwan station. From the three available weather data files (Cairo_ETMY, Cairo_IWEC, and Helwan_ETMY), Cairo_ETMY was selected for this study according to the previous criteria.

The following section discusses the primary features of typical summer conditions of Cairo climate according to the previous source.

3.2.1. Typical Summer week data

Typical summer week is an average week of summer climate conditions, so it can be used in defining the whole summer behavior. Specifications of typical summer week and extreme summer week differ from observation system to another. According to Cairo_ETMY system, typical summer week is from 5th Jun to 11th Jun.

The following data will concentrate on the climatic conditions of the typical summer week of Cairo_ETMY system.

Max. Temp. (°C)	39	Min. Temp. (°C)	19
Average of Max. Temps. (°C)	33.5	Average of Min. Temps. (°C)	20.6
Max. Rel. Humidity value (%)	88	Max. Direct Solar gain (kW/m²)	1.1
Average of Max. Rel. Humidity values (%)	74.4	Average Max. Direct Solar gains (kW/m²)	0.95

Table 3.1 – Typical summer week data for different observation system

[1] (U.S.Department-of-Energy, EnergyPlus Energy Simulation Software - Weather Data Sources, 2011)

Figures 3.2 to 3.4 show the ambient temperature, relative humidity, and direct solar gains for typical summer week of Cairo_ETMY system.

3.2.2. Summer wind analysis

Cairo_ETMY system records wind direction, speed, average wind temperature, and average relative humidity. The records state that prevailing summer wind direction is northeast to northwest, with average wind speed from 25 to 35 km/h (6.9 – 9.7 m/s)[1].

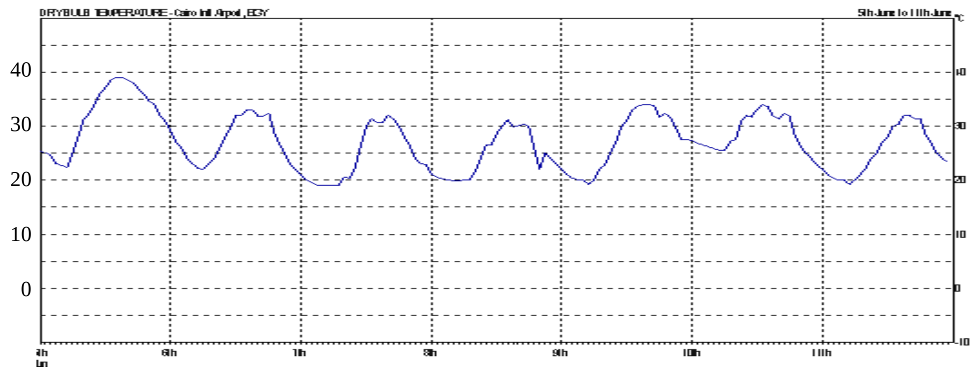


Figure 3.2 – Ambient Temperature (°C) for typical summer week (5th – 11th Jun)[2]

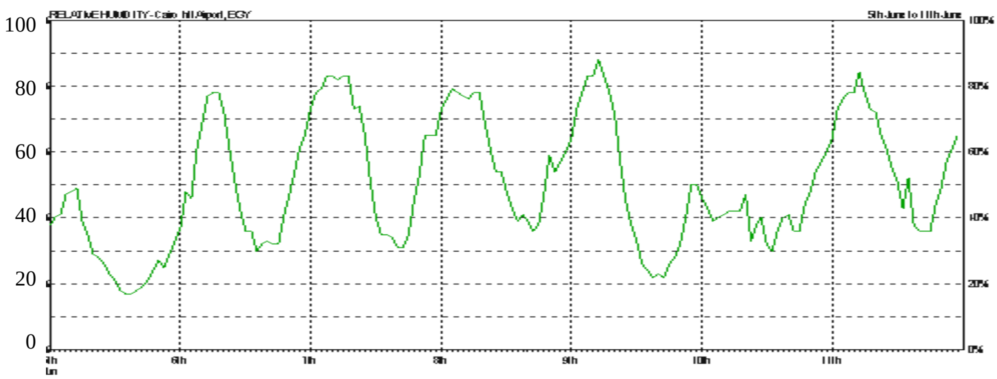


Figure 3.3 – Relative Humidity (%) for typical summer week (5th – 11th Jun)[3]

[1] (U.S.Department-of-Energy, EnergyPlus Energy Simulation Software - Weather Data Sources, 2011)
[2] (DesignBuilder-Software, Energy plus weather data file, 2009)
[3] *Ibid.*

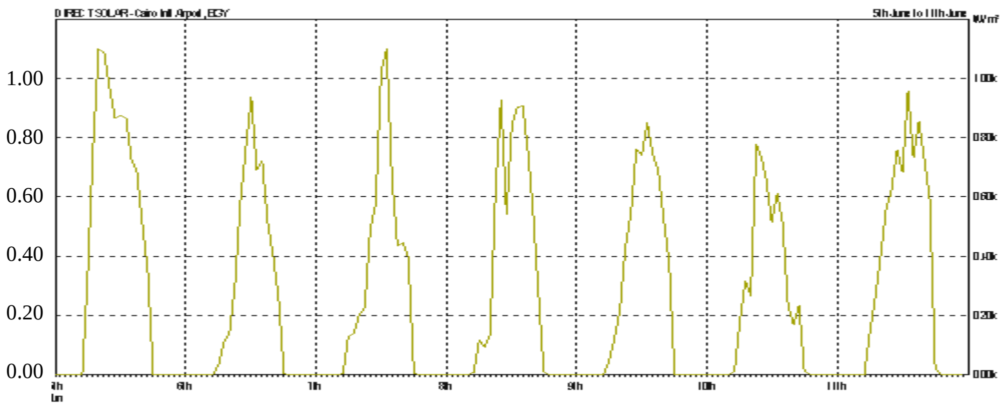


Figure 3.4 – Direct Solar Gains (KW/m^2) for typical summer week (5th – 11th Jun)[1]

3.3. Local Case Study

The case study represents a popular prototype of medium-income housing in Egypt. Referring to the local housing market, medium-income and youth housing sector was selected because it meets the following criteria:

- Expressing medium area of the residential units exist in the local market.
- Reflecting the different housing policies in community (private, social and economic housing).
- Representing the heaviest demand of the market.

Monitoring the local housing, National Youth Housing Project is found to be more popular, and serve wider sector of users, which gives it more importance and effectiveness in housing movement in Egyptian community. This national project provides different types of housing policies with residential areas of 65 to 95 square meters.

National Youth Housing Project consists of three stages, on 15 years, begin at 1996 and end at 2011. The project aimed to build around 75,000 residential units through those three stages. The type of 90 m^2 belongs to the first stage which consists of around 20,000 residential units, all are in Greater Cairo region.

[1] *Ibid.*

The 90 m^2 type of governmental housing project for youth in *Al-obour* city, as an example of economic housing sector, is selected as a local case study for this research.

3.3.1. Case study specifications

Generally, the 90 m^2 type has four different architectural plans. The selected plan is the unit plan of Al-Obour city. *Shabab Al-Obour* residential buildings are urban patterns that consist of compositions of a typical cell unit of three buildings. The selected building is shown in figure 3.5.

Each building consists of 5 floors (G+4). Each floor has two mirrored typical 90 m^2 types. The unit selected for the study is shown in figure 3.6 and table 3.2. All the units are typical with no difference between in-between or end units, because there are no openings on the eastern or western facades of the unit. The unit consists of reception hall, two bedrooms, kitchen, and bathroom. The hall is at north with northern windows, and bedroom 2 is at south with southern window and side one.

The unit selected for study is the 3^{rd} floor unit to be a mid-unit of typical conditions, as shown in figure 3.7. The ground and 4^{th} floor units are excluded because of the special thermal behavior of ground unit due to direct-to-earth conduction, and last floor unit due to roof solar exposure.

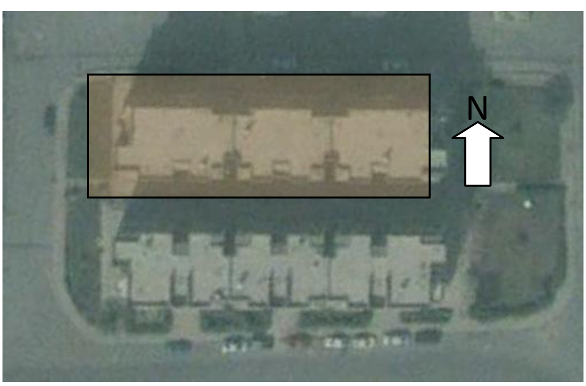


Figure 3.5 – Typical urban cell of *Shabab Al-Obour* district; the building selected for study is one of the buildings of the back raw marked by shadowed rectangle [1]

[1] (US-Dept-of-State-Geographer, Google Earth, 2011)

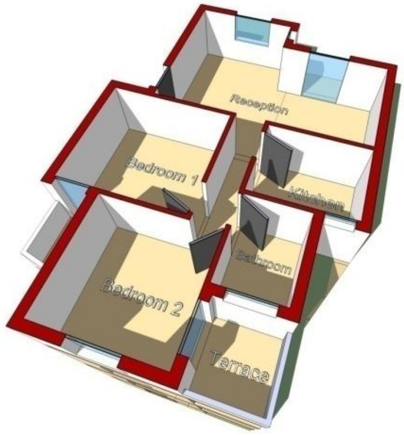


Figure 3.6 – Case study unit[1]

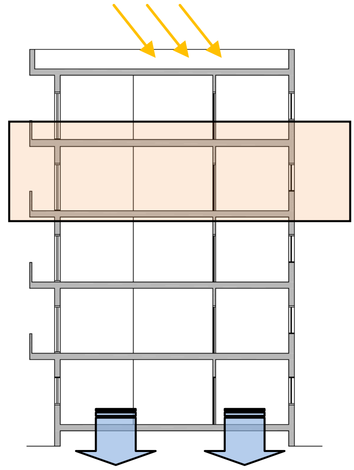


Figure 3.7 – Section in building of study, showing the study unit in the 3rd floor to be within typical thermal and wind conditions[2]

Location	Al-Obour city, Shabab Al-Obour district
Floor	3rd floor
Type market area	90 m^2
Exact net area (excluding terraces)	77.73 m^2
Spaces	Rec. + 2BR.s + Kit. + Bath.
Exposed Facades	North and South facades

Table 3.2 – Selected residential type data

The 3rd floor unit is selected as a typical unit exposed to wind conditions with minimum effects of neighbor buildings that act as wind obstacles.

Bedroom 2, with an area of 3.35m x 3.40m (11.39 m^2) and height of 3.00m (34.2 m^3 in volume), is selected to be the space under study, as shown in figure 3.8, because of:

- Its full exposure to the outside that gives it the ability to apply natural ventilation techniques.
- Its exposure to direct solar radiation.

[1] *Ibid.*
[2] *Ibid.*

Within space of bedroom 2, the southern façade will be selected tfor conducting the simulation. This facade will be considered the simulation variable during the next steps of research.

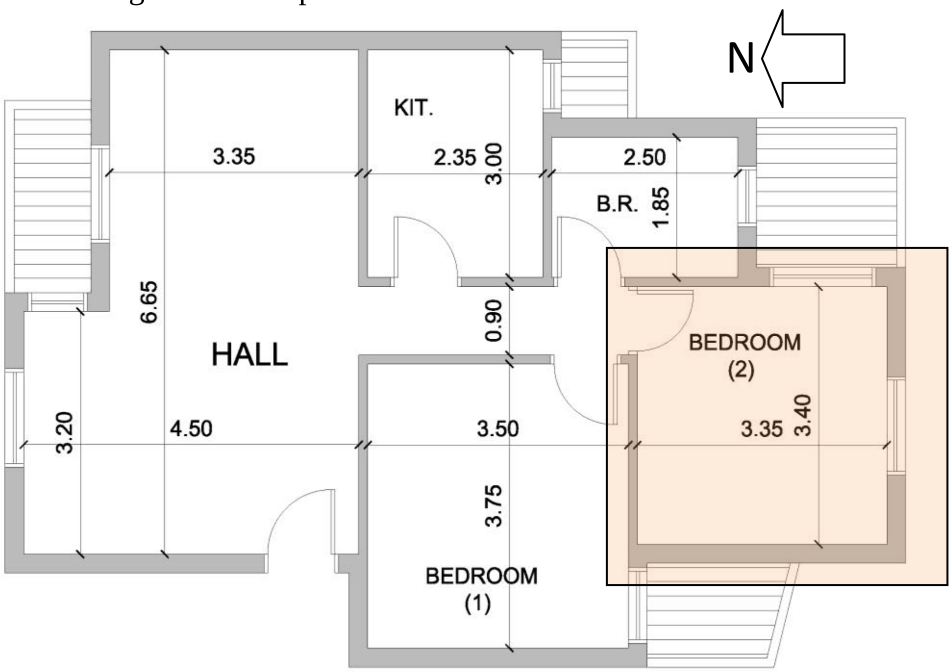


Figure 3.8 – Plan of study unit, with highlighted space selected for study[1]

The whole unit will be under investigation. However, the conclusions will only be focused on space of study.

Bedroom 2 has three openings that can be used for ventilation at three different directions, as shown in figure 3.9. This gives the space a good chance for ventilation that is not noticed within such type of housing. The tri-directional air flow strategy, as a maximum possible flow within space, is achieved when the southern and eastern windows are open, and the door is also open to be used for both access and ventilation.

[1] *Ibid.*

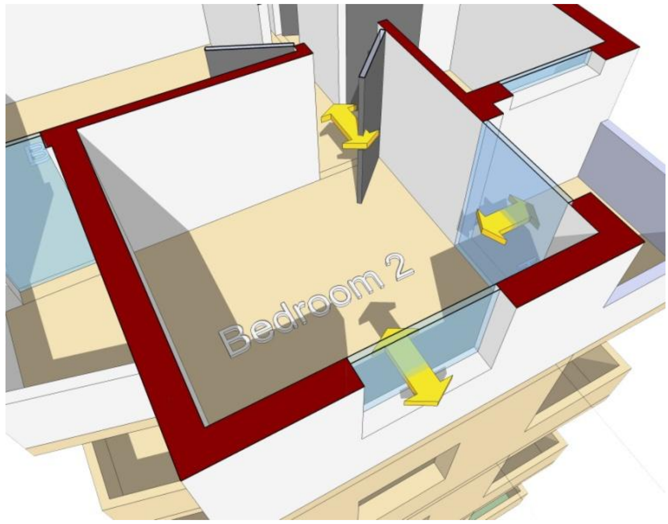


Figure 3.9 – Case study (Tri-directional flow strategy)[1]

3.4. Simulation Software

Using the previously mentioned weather information, the study will be conducted to evaluate the performance of applying a natural ventilation passive technique into a residential building in the local region of Greater Cairo. This evaluation will be operated using digital simulation process through CFD (Computational Fluid Dynamics) software. Any simulation program has two incorporated surfaces: the simulation engine and the program interface.

3.4.1. Simulation engine

The simulation engine used for this study is Energy Plus (e^+) version 4.0.0.024. Energy Plus simulation software has been validated by Energy Efficiency and Renewable Energy (EERE) program, U.S. Department Of Energy (DOE).

Till Jan 10, 2012, Energy Plus software was tested and validated under ASHRAE Research Projects 865 and 1052, ANSI/ASHRAE Standard 140-2007, International Energy Agency Solar Heating and Cooling Program (IEA SHC), and BESTest (Building Energy Simulation Test)[2].

[1] Field survey, 2009

[2] (U.S.Department-of-Energy, EnergyPlus Energy Simulation Software - Weather Data Sources, 2011)

3.4.2. Simulation interface

The simulation engine has to work within an interface characterized by flexibility and stability. Two simulation interfaces were tested and compared for usage by the researcher: Ecotect and DesignBuilder. DesignBuilder software proved to be of better specifications:

- More precise modeling data.
- More accurate and detailed results.
- More flexible interface.
- More compatibility with EnergyPlus engine.

Another vital difference is that DesignBuilder can perform both thermal and CFD simulations, while Ecotect has to depend on other CFD software to perform such simulation like FDS and WinAir. Such exporting/importing process may affect the CFD results accuracy and detailing.

So, DesignBuilder Software is selected as a simulation interface for this study. Design Builder version used is 2.2.5.004, 2009 copyrights.

3.4.3. Weather data file

Weather data file represents the typical long-term weather patterns of the intended region. The weather data file used for this study is (EGY_AL QAHIRAH_CAIRO INTL AIRPORT_ETMY.epw); this file is an EnergyPlus weather file with the summary statistics report (EGY_AL QAHIRAH_CAIRO INTL AIRPORT_ETMY.stat)[1].

Weather Data File	EGY_AL QAHIRAH_CAIRO INTL AIRPORT_ETMY.epw
Type	Hourly weather data
Identity	EnergyPlus weather file
Location	Cairo, Egypt, Africa WMO Region 1
Location Coordinates	(N 30° 7') (E 31° 23')
Elevation	74m above sea level
Standard Pressure	100439 Pa
Source	Egyptian Typical Meteorological Year (ETMY)

[1] *Ibid.*

	system provided by U. S. National Climatic Data Center
Credence Year	2003
Validated by	Energy Efficiency and Renewable Energy (EERE) program, U.S. Department Of Energy (DOE)
Referencing Code	623660
Updated Validation	December 2011

Table 3.3 – Details of Weather Data File used for simulation

3.4.4. Hypothesis and target

Simulation target is enhancing the flow rates and comfort conditions in bedroom 2 by applying the passive technique on the study variable. So, the study hypothesis is as follows:

''Applying double wall system on the southern façade of bedroom 2 in the reference case may affect positively natural ventilation rate and thermal comfort conditions within the space of the room''

3.5. Input Data

Bedroom 2 Dimensions	3.35m x 3.40m x 3.00m
Southern opening dimensions	1.20m x 1.30m
Eastern opening dimensions	1.20m x 2.20m
Door dimensions	0.90m x 2.20m
Space Orientation	South
Activity template	Dwelling (Bedroom)
Occupancy	0.04 people/m2 (nearly 4 persons/flat)
Metabolic rate	0.8 met
Summer Clothing	0.5 clo
HVAC template	Natural ventilation (No heating/cooling)
Natural ventilation scheme	Calculated ventilation (natural ventilation and infiltration air flow rates are calculated based on openings and cracks sizes,

	buoyancy, and wind pressures)
Model infiltration	Zero infiltration (naturally ventilated space)
Percentage of window glazing area opens (Ref. case)	75%
Percentage of door area opens	75%

3.5.1. Thermal simulations

In order to perform a CFD simulation to test the double wall system, a thermal simulation has to be operated first. Hourly thermal simulation was performed within the typical summer week period through Cairo_ETMY weather data file. Thermal simulation results are a vital base to decide the most appropriate day and hour to perform CFD tests. Figure 3.10 shows the complete results of thermal simulation of the typical summer week.

3.5.2. Selecting CFD simulation hour

To perform a CFD simulation, a certain hour at a certain day has to be specified. Based on the results of thermal simulation shown in figure 3.10, specified hours with significant values of ACH, shown in figure 3.11 and table 3.4, were selected in morning, noon, afternoon, and evening periods to represent simulation hours at different day and night simulation orientations.

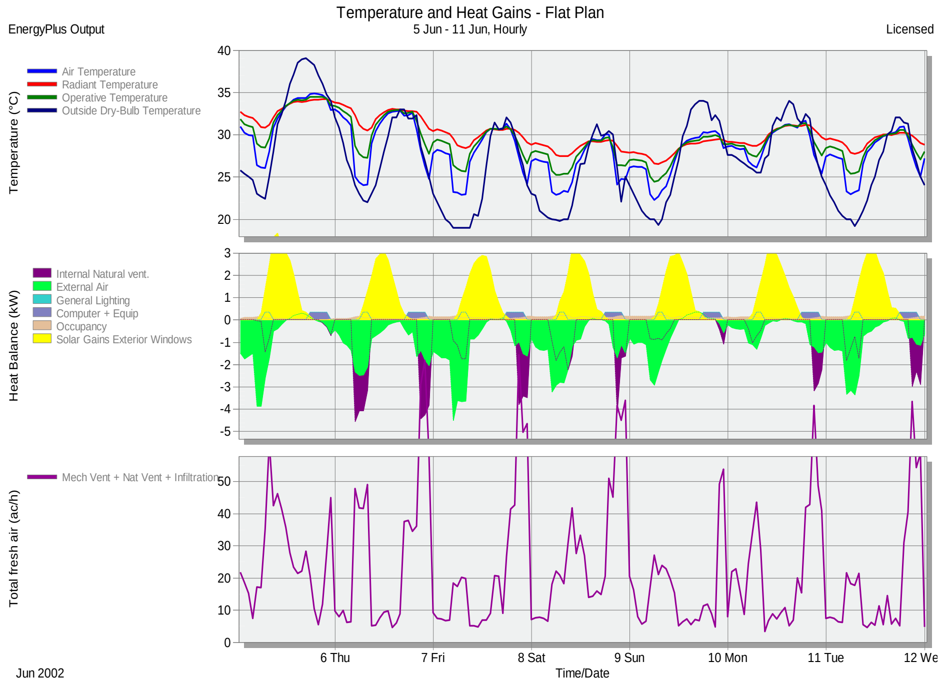


Figure 3.10 – Thermal simulation results set for typical summer week[1]

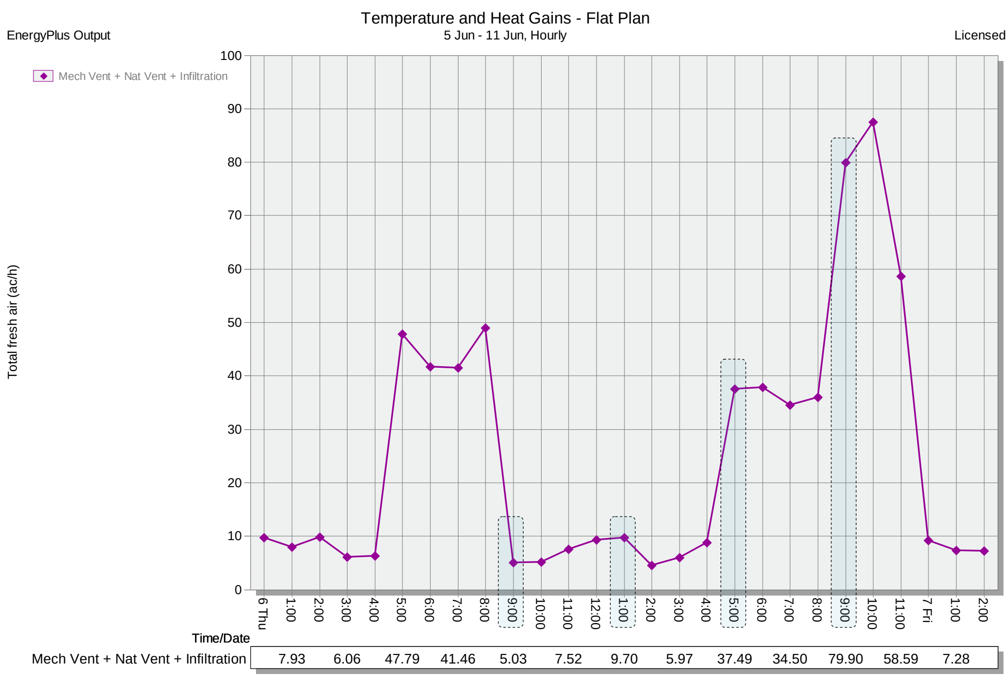


Figure 3.11 – ACH values for Thur. 6 Jun[2]

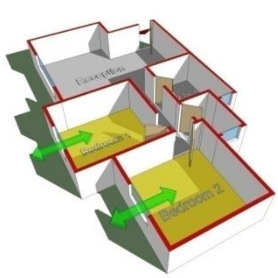
[1] (DesignBuilder-Software, Energy plus weather data file, 2009)
[2] *Ibid.*

<table>
<tr><th>Day</th><th>Hour</th><th>Orientation</th><th>Incoming Air Temp.</th><th colspan="2">Wind Direction</th><th>Wind Speed (m/s)</th></tr>
<tr><td>Thur. 6 Jun</td><td>9.00 AM</td><td>East</td><td>24.0°C</td><td rowspan="4">Northeast</td><td>50° to East</td><td>4.1</td></tr>
<tr><td>Thur. 6 Jun</td><td>1.00 PM</td><td>South</td><td>32.0°C</td><td>20° to East</td><td>4.6</td></tr>
<tr><td>Thur. 6 Jun</td><td>5.00 PM</td><td>West</td><td>31.9°C</td><td>30° to East</td><td>5.7</td></tr>
<tr><td>Thur. 6 Jun</td><td>9.00 PM</td><td>All orientations</td><td>26.9°C</td><td>20° to East</td><td>4.6</td></tr>
</table>

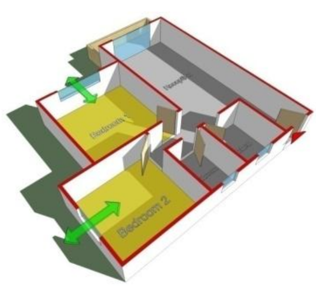
Table 3.4 – Specified hours for CFD simulation

3.6. Reference Case

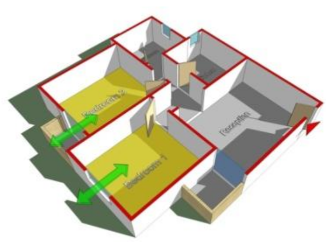
. This situation of tri-directional flow is not common for normal cases. As shown in figure 3.12, most of residential spaces within similar housing typology in local market get their ventilation through single-directional flow strategy with normal conditions when doors are used only for access not for ventilation purposes. So, the tri-directional flow strategy of the case study will be simulated to evaluate the maximum possible condition of ventilation within real case, but a single-directional flow strategy, as a critical air flow system, will be considered the reference case for the next steps of the study. The single-directional flow will be derived from the case study, as shown in figure 3.13, by closing the doors and the eastern window, thus the space depends only on the southern façade for providing ventilation.



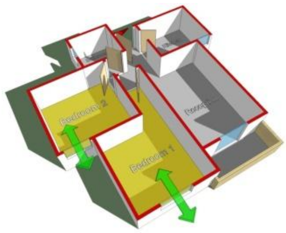
Abeer Gardens Project for youth housing, 6th October (85 m² unit)



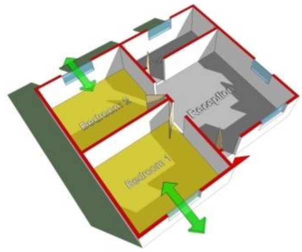
October Gardens Project for youth housing, 6th October (85 m² unit)



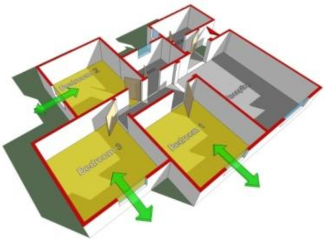
Park Ville Project for youth housing, 6th October (80 m² unit)



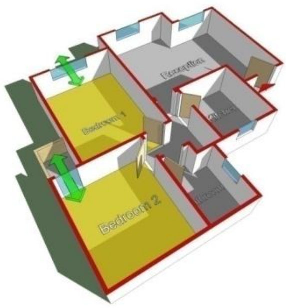
Sanabel Project for youth housing, 6th October (80 m^2 unit)



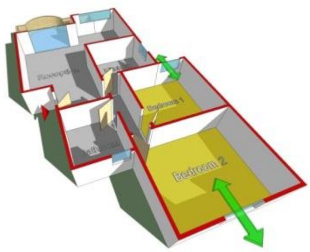
Governmental Youth Housing



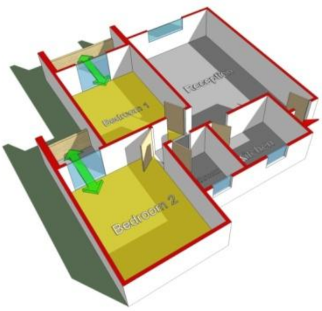
Syndicate of Applicators youth housing - Rawdaty Project (95 m^2 unit)



Syndicate of Commercial Professions youth housing (75 m^2 unit)



Syndicate of Engineers youth housing (95 m^2 unit)



Al-Rehab private housing (90 m^2 unit)

Figure 3.12 – Single-directional flow strategy within local housing different types[1]

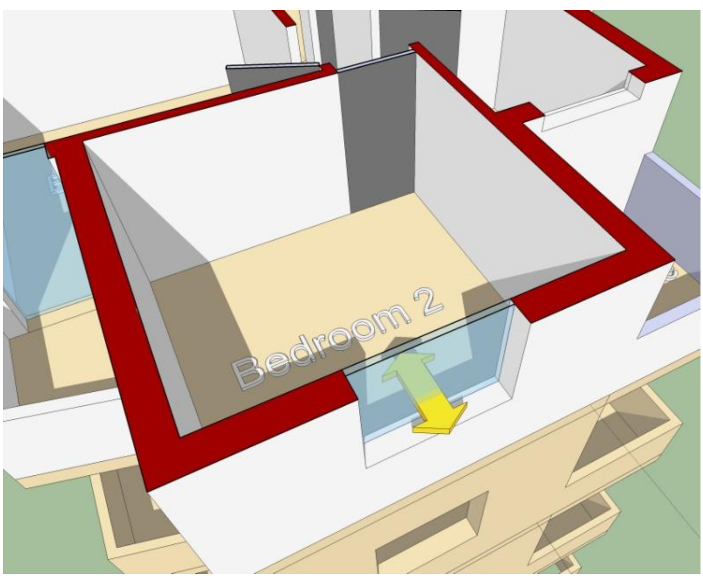


Figure 3.13 – Reference case (Single-directional air flow strategy)[2]

[1])http://www.moh.gov.eg/main/localproject.aspx(2012 ،المشروع القومي للاسكان ،

[2] Field survey, 2009

3.6.1. Modeling the reference case

The reference case had been modeled with the same real construction conditions through successive steps:

1- Modeling of the whole building

2- Modeling of the unit

3- Unit activity template

4- Unit construction template

3.6.1.1. Modeling of the whole building

The whole building has been modeled into two types of zones:

- Adiabatic zones: all the neighbor units were modeled to be thermally adiabatic to facilitate modeling data and save simulation time.
- Standard building zones: the unit of study

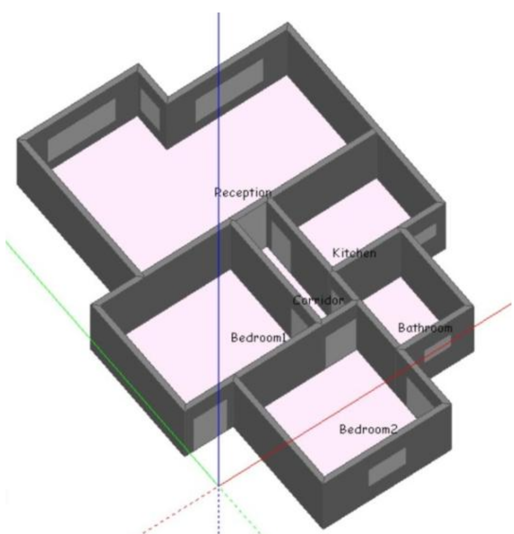
3.6.1.2. Modeling of the unit

Each functional space of the unit has been separately modeled as a standard thermal zone, as shown in figure 3.14, with the following elements:

- Floors and ceilings: conjoint horizontal surfaces between unit and adiabatic neighbors.
- Walls: on-perimeter vertical surfaces between unit and outdoors.
- Partitions: conjoint vertical surfaces between standard zones.

Figure 3.15 shows full dimensions of bedrooms 2 zone plan and elevations.

Figure 3.14 – Six thermal zones that form the unit[1]



[1] (DesignBuilder-Software, Energy plus weather data file, 2009)

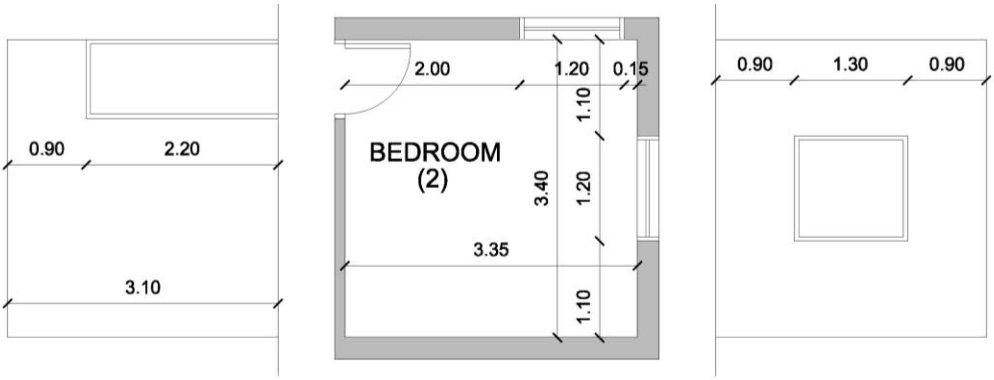


Figure 3.15 – Bedroom'2' zone full dimensions[1]

3.6.1.3. Unit activity template

Because of the selection of bedroom 2 is selected to perform the study on, its activity is also selected to be the main activity template of the study unit. The template chosen is (Bedroom_Dwelling). This template is primarily used for sleeping.

3.6.1.4. Unit construction template

The construction materials used for study unit are the most commonly used construction materials in Egypt. The detailed construction data are shown in table 3.5 and figure 3.16.

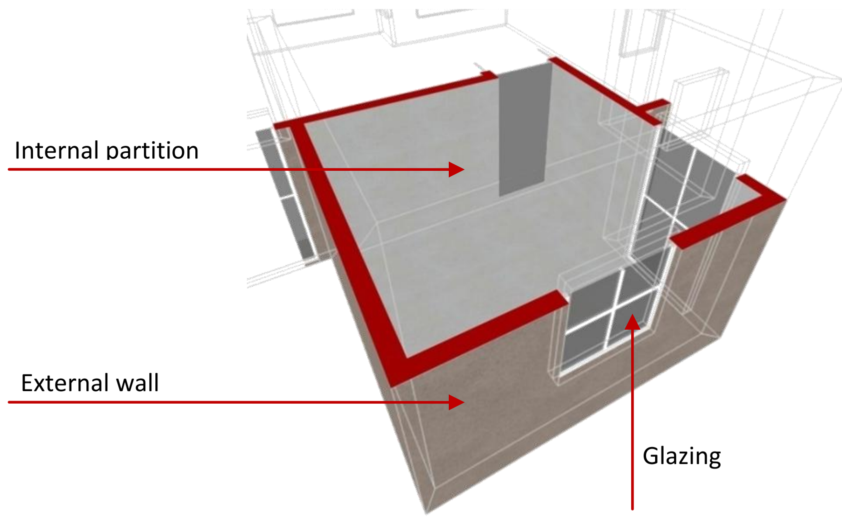


Figure 3.16 – Bedroom 2 construction materials[2]

[1] Field survey, 2009
[2] (DesignBuilder-Software, Energy plus weather data file, 2009)

CONSTRUCTION	SPECs	THICK.s (m)
External walls	Cement sand render (outer leaf)	0.02
	Brickwork	0.25
	Lightweight plaster (inner leaf)	0.02
Internal partitions	Lightweight plaster	0.02
	Brickwork	0.12
	Lightweight plaster	0.02
Intermediate slabs	Dense cast concrete	0.15
	Lightweight plaster	0.09
	Ceramic / Porcelain	0.01
Glazing	Single clear glazing	0.006

Table 3.5 – Construction template details of study unit

3.7. Application of Natural Ventilation Passive Technique

The reference case has a single-directional air flow ventilation technique (single-sided ventilation). It does not contain any active method of cooling or ventilation. The opening area of the space is 1.56 m^2 (13.7% of space area). The opening positioned in the southern façade consists of three simple hinged leaves made of wooden shutters, with internal three simple hinged glass leaves. Then, glass leaves control the ventilation process through this opening.

Natural ventilation passive techniques that depend on solar and thermal buoyancy effect perform perfectly at climates of heavy solar radiation; Cairo has large climatic possibilities to apply such techniques. But referring to section 2.2, these techniques (the third classification) are totally absent from local application. So, initial theoretical indicators refer to an expected success of these techniques when they are applied to buildings in hot climates with high solar radiation like Egypt.

From all the above, the double wall technique is selected to be the alternative in the study variable (the southern façade of bedroom 2).

3.7.1. Passive technique specifications

The selected passive technique depends on thermal buoyancy effect due to heat generated by solar radiation incident on southern façade. The technique is a double wall façade. Technique opening dimensions and position, different construction materials, and air gap between the two walls are assigned to be the study variables that will be used for testing the effectiveness of the technique. The initial condition of the technique is shown in figure 3.17; a pair of double walls is added to the southern façade of the reference case to create a double wall system.

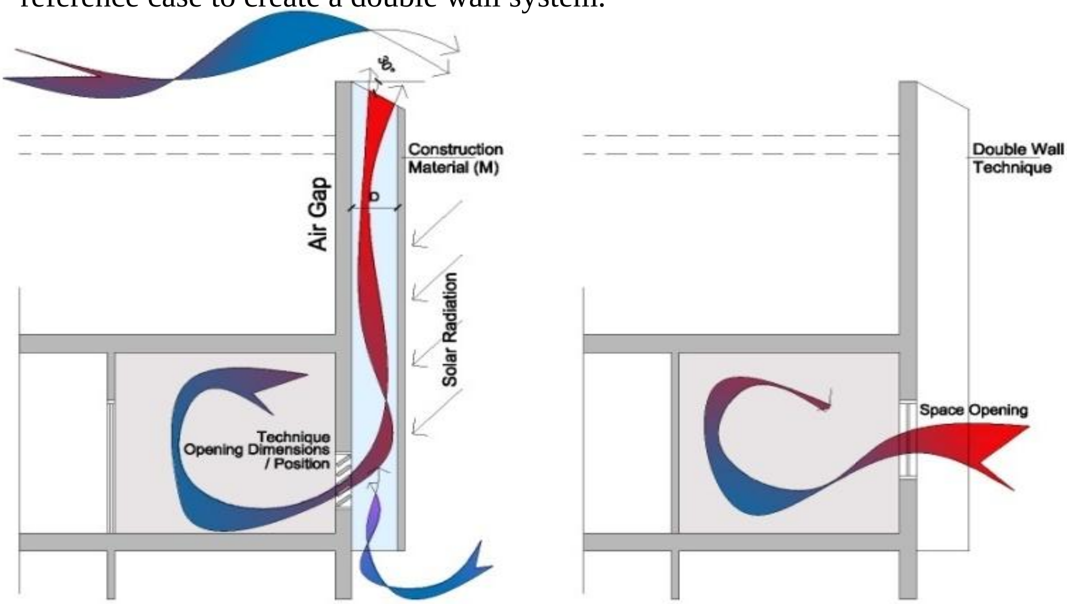


Figure 3.17 – Illustrative diagram of application of double wall system[1]

As shown in the figure 3.18, double wall is connected to the space through an operable louvered opening to control air flow to the space. This system extends up to the end of the building roof parapet to help accelerating the flow rate by suction effect like a wind tower. The air flow directions shown are just illustrative directions to explain the techniques; true flow directions will be studied during simulation analysis.

[1] The researcher

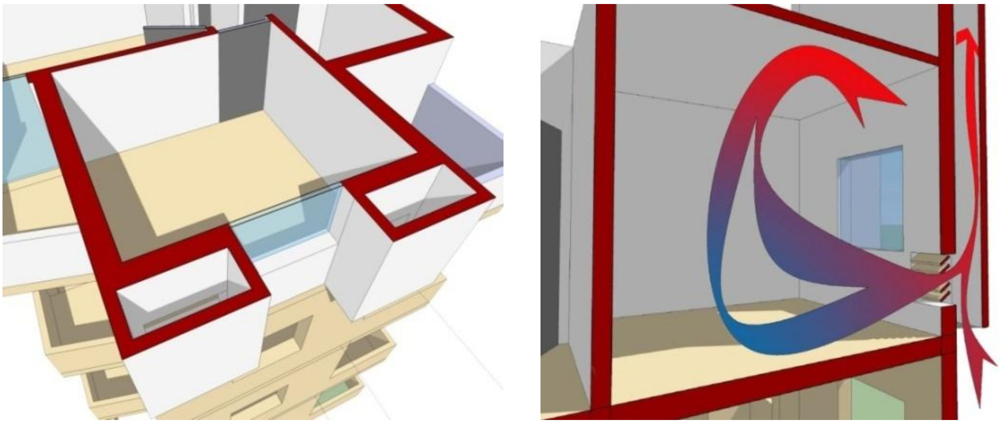


Figure 3.18 – Plan and Section of double wall technique[1]

3.7.2. Modeling of double wall technique

The convection coefficients for the narrow sealed vertical cavity are calculated based on the ISO 15099 standard. The cavity has been fully simulated with the standard zones of the study unit. Figure 3.19 shows that bedroom 2 and cavity zones share the same in-between wall which turns to inter-block partition. As it will be discussed in detail later, the cavity has been modeled with three different construction materials (Glass, brick, and concrete).

3.7.3. Double wall technique construction template

The construction materials used for double wall are standard materials for glass, brick, and concrete constructions as figured out in table 3.6.

[1] *Ibid.*

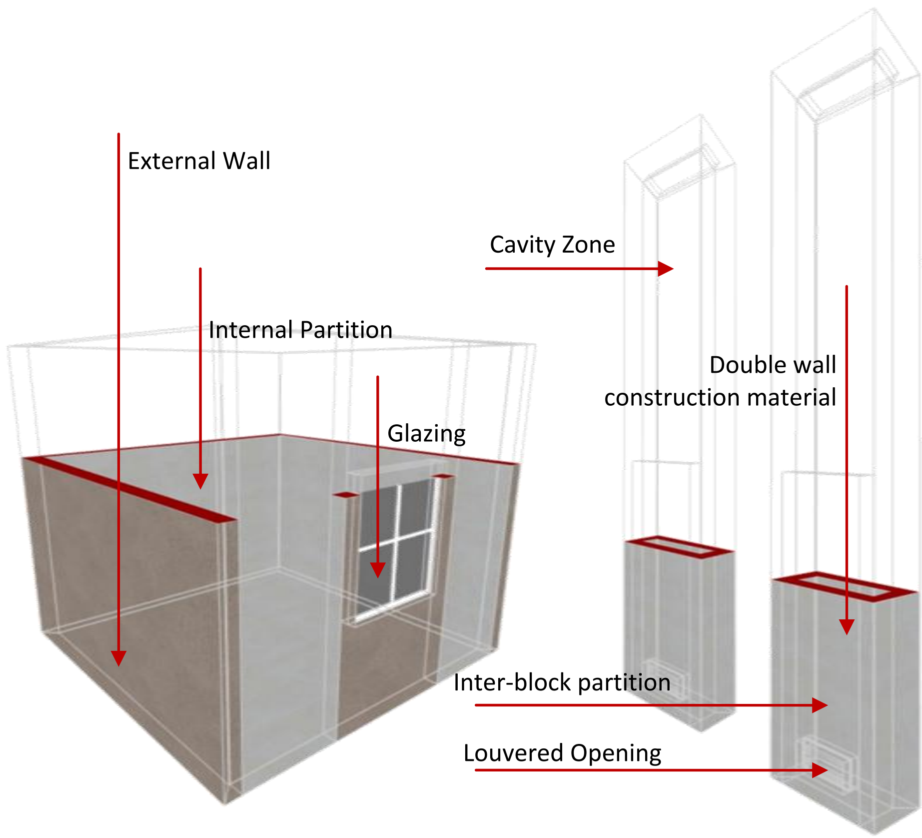


Figure 3.19 – Visualization of construction materials of cavity zone[1]

CONSTRUCTION	MATERIAL layers	SPECs	THICK.s (m)
Glass construction	Soda lime glass - ISO 10456	Conductivity – 1.00 W/m-k	0.01
		Specific heat – 750.00 J/kg-k	
		Density – 2500 kg/m^3	
Concrete construction	Reinforced concrete – ISO 10456	Conductivity – 2.5 W/m-k	0.15
		Specific heat – 1000.00 J/kg-k	
		Density – 2400 kg/m^3	

[1] (DesignBuilder-Software, Energy plus weather data file, 2009)

Brick construction	Lightweight plaster	Conductivity – 0.16 W/m-k	0.02
		Specific heat – 1000.00 J/kg-k	
		Density – 600 kg/m^3	
	Brick work	Conductivity – 0.62 W/m-k	0.12
		Specific heat – 800.00 J/kg-k	
		Density – 1700 kg/m^3	
	Lightweight plaster	Conductivity – 0.16 W/m-k	0.02
		Specific heat – 1000.00 J/kg-k	
		Density – 600 kg/m^3	

Table 3.6 – Construction template details of cavity zone

3.8. CFD Grid Statistics

CFD grid is a 3-D cellular universe of analysis controlling cells in X, Y, and Z axes. Design Builder gives a separate analysis data for each cell; dense grid gives more accurate results but slows down the simulation. So, default grid spacing is taken to be 0.30 m. This grid spacing is the maximum cell dimension. When Design Builder detects any calculations changes within the default spacing, the program then automatically divides the single cell to many cells according to the changes. Gridline merge tolerance is taken to be 0.03 m. (X,Y,Z) grid cells for reference case model are (9,11,9), for double wall technique model are (15,17,23), and for whole case study unit are (29,43,11). Figure 3.20 shows the technique model with simulation origin point and analysis grid.

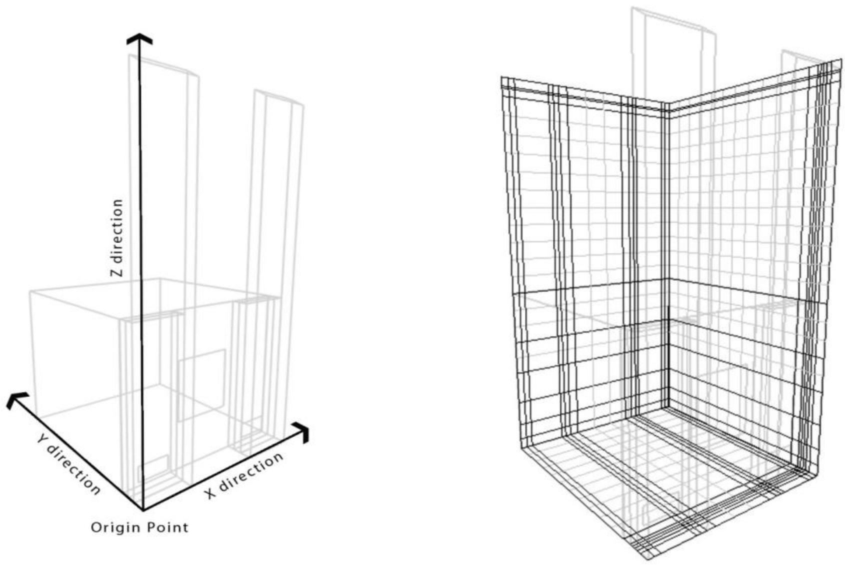


Figure 3.20– Double wall technique CFD model and analysis grid[1]

3.9. Comparison Methodology

In order to compare simulation results, the space under study (bedroom 2) was divided according to two criteria: 1- how far the zone is from southern façade (study variable) that affects the indoor environment of space, and 2- effect of applying the passive technique on space zones. So, the space, as shown in figure 3.21, was divided to nine zones. This dividing process is performed to add more accuracy to study results. The effect of passive technique can be truly expressed by determining the exact changes within indoor environment.

CFD simulation produces a set of values for air velocity, air temperature, mean radiant temperature, operative temperature, air pressure, age of air, PPD, and PMV. The main objective of the research is to compare the ventilation rates and comfort levels within space. Referring to research theoretical introduction, operative temperature expresses both effects of radiation and convection. So, operative temperature can act instead of both air temperature and radiant temperature to represent the indoor comfort levels. Age of air values will be compared to represent the ventilation rate,

[1] (DesignBuilder-Software, Energy plus weather data file, 2009)

and air velocity values will be considered to represent comfort due to air flow.

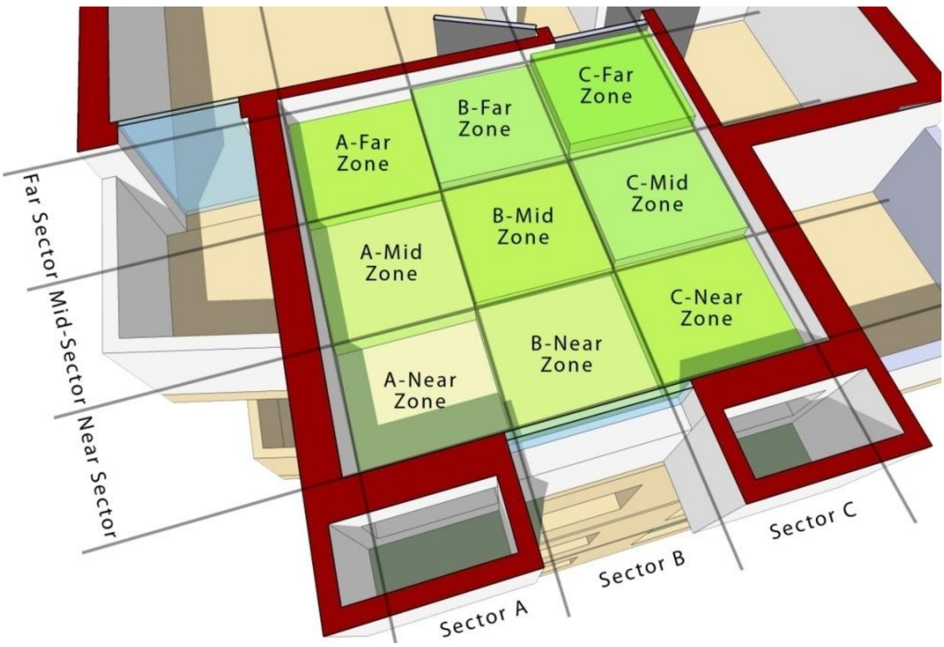


Figure 3.21 – Zones of study room[1]

CFD results can be obtained by slicing the model to get the values of specified feature. The CFD model consists of a 3D net of analysis cells as it will be illustrated within chapter four. The numerical data of each cell can be obtained by exporting a detailed CSV report file for each slice. For all simulation cases, and for standardization, vertical slices will be taken parallel to Y axis at the middle of sectors A, B, and C.

For facilitating the comparison of the results, an average value for each zone will be mathematically calculated from the detailed CSV report to represent the zone value. Each average value will represent all the cells in X, Y, and Z dimensions in each zone. Comparison then will be held between the nine zones for each feature.

[1] The researcher

3.10. CFD Simulation Phases

The simulation analysis will be conducted on:

1-Tri-directional strategy of the space of the study just to evaluate the maximum possible ventilation conditions within actual operating times.

2- Reference case evaluation (single-directional strategy) with different parameters of time and orientations, as shown in figure 3.22. Reference case simulation results will be kept to be evaluated later.

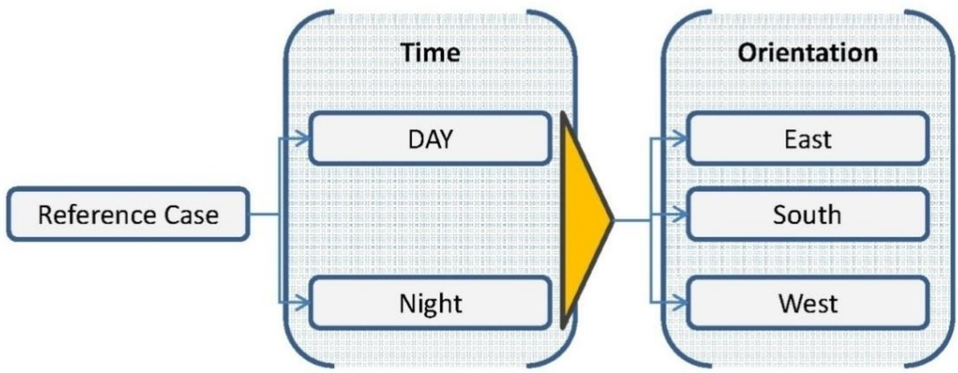


Figure 3.22 – Reference case simulation process[1]

3- Applying the double wall with its variables (air gap – construction material – opening area – opening position) with an initial state shown in figure 3.23. The main process in testing the technique performance is to study the effect of each variable to reach the best performance of technique variables. This best performance will go through same simulation analysis of time and orientations conducted to reference case in order to compare the results.

The final step in simulation process is to test the cavity height effect on indoor ventilation rates by changing the height of the double wall in the case of best performance.

[1] *Ibid.*

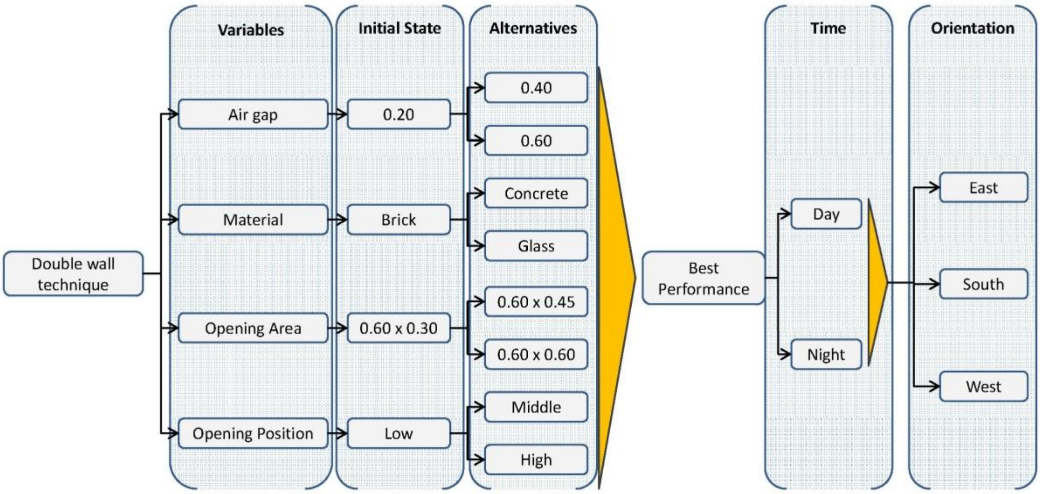


Figure 3.23 – Double wall technique simulation process[1]

3.10.1. Simulation Considerations

Some points have to be taken into consideration while working:

1- Correcting any un-balanced air flow; the total flow in and out must balance to ensure mass balance in the CFD simulation.

2- Resetting the CFD grid on each new case.

3- Within each simulation case, calculations have to be converged or stabilized in order to approve the simulation results.

4- After completing the calculations, CFD comfort calculations have to be separately performed; LMA (Local Mean age of Air) also has to be calculated to complete the results set.

3.11. Conclusion

The research is a comparative study through simulation analysis to test the relative enhancements in indoor ventilation rates and thermal comfort of a residential space within Greater Cairo hot arid climate.

Within typical summer week weather data, chapter three started to set data for CFD simulation process of the research. National youth housing project was chosen to select the local case study from. The selected unit is one of the units in Shabab Al-obour district, Al-obour city with a total area of 90m^2 at

[1] *Ibid.*

the third floor. The space of bedroom 2 with dimensions of 3.35mx3.40mx3.00m was selected to be the research local case study under the daily operation conditions of tri-directional air flow strategy.

Through surveying of other units of national youth housing project, chapter three identified the research reference case by the single directional air flow strategy through the southern façade of study space. Double wall technique was tested as a thermal buoyancy strategy to be applied to the reference case and tested through simulation process to be compared with the reference case under the same simulation conditions of time and orientations.

DesignBuilder software (version 2.2.5.004, 2009 copyrights) is used as an interface, and EnergyPlus (e+) version 4.0.0.024 as an engine. Thermal and CFD simulations were conducted to all research cases under weather data file of (EGY_AL QAHIRAH_CAIRO INTL AIRPORT_ETMY.epw)

The comparative study aimed at proving the hypothesis: ‘*’Applying double wall system on the southern façade of bedroom 2 in the reference case may affect positively natural ventilation rate and thermal comfort conditions within space of bedroom’2’’*.

CHAPTER
FOUR

Simulation Results and Discussions

- Introduction
- CFD Simulation Results
- Conclusion

4.1. Introduction

After specifying the limitations and simulation inputs within previous chapter, simulation was conducted to all simulation cases. This chapter is assigned to display, compare and evaluate simulation results. According to simulation process discussed at the pervious chapter, simulation will be conducted to case study at its tri-directional air flow strategy to evaluate the maximum performance of case study. Then reference case with its single-directional air flow strategy will go under investigation. The reference results will be kept for comparison. Double wall and alternatives of its variables will go under test to explore the best performance of technique different elements. The performance at this stage of evaluation will be measured with the effect of applying the technique on indoor ventilation rates. Technique results will be compared with reference results with similar conditions of time and orientation to monitor the effect of applying the passive technique on both indoor ventilation rates and thermal comfort. First, this chapter illustrates the grid statistics simulation program used for calculations, then goes through the reference case results and the technique results.

4.2. CFD Simulation Results

The simulation results will be displayed according to the comparison methodology of nine zones. While B-Near zone is close to southern opening, C-Near zone is close to eastern opening, and C-Far zone is close to room door.

According to the simulation process discussed in the previous chapter, the results of CFD simulation will be displayed and illustrated on three main successive stages:

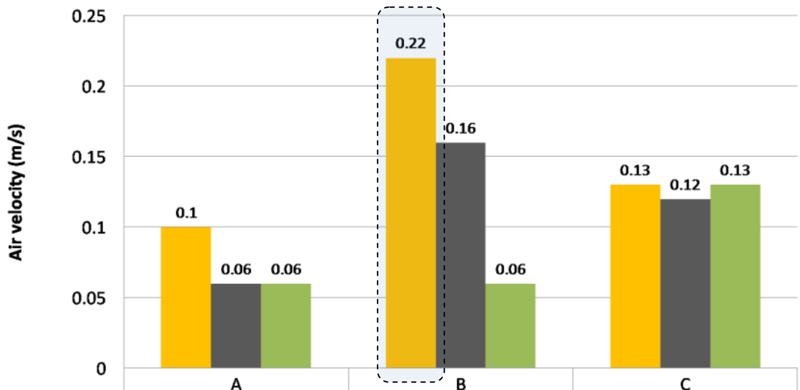
- Case study results (Tri-directional air flow strategy)
- Reference case results (Single-directional air flow strategy)
- Double wall technique results

4.2.1. Case study (tri-directional flow) results

Within case study simulation, a full thermal and CFD simulation was conducted to the whole unit of study with typical day simulation conditions resulting the following values:

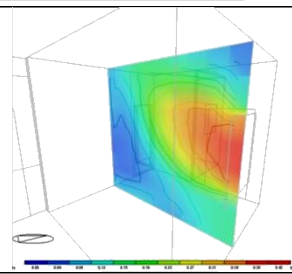
Case study simulation results (Tri-directional air flow strategy)

Air Velocity (m/s)

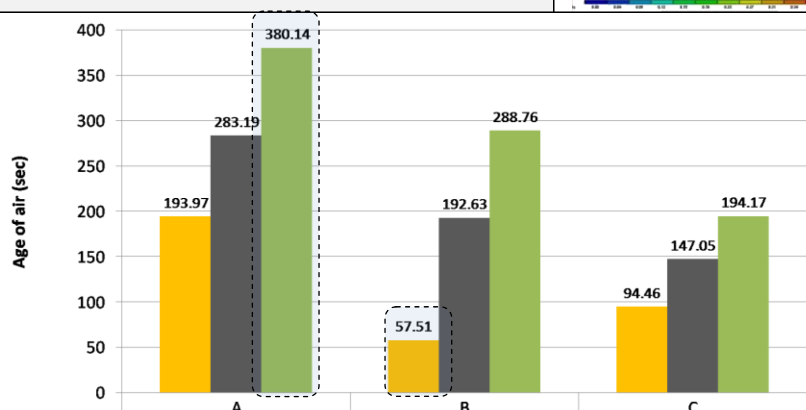


	A	B	C
Near sector	0.1	0.22	0.13
Mid sector	0.06	0.16	0.12
Far sector	0.06	0.06	0.13

Discussion:
Southern opening is the most effective element on air velocity, as zone (B-Near) achieves the highest value of 0.22 m/s close to the southern opening.

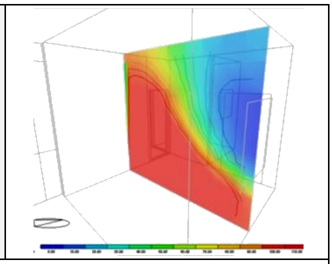


Age of Air (sec)

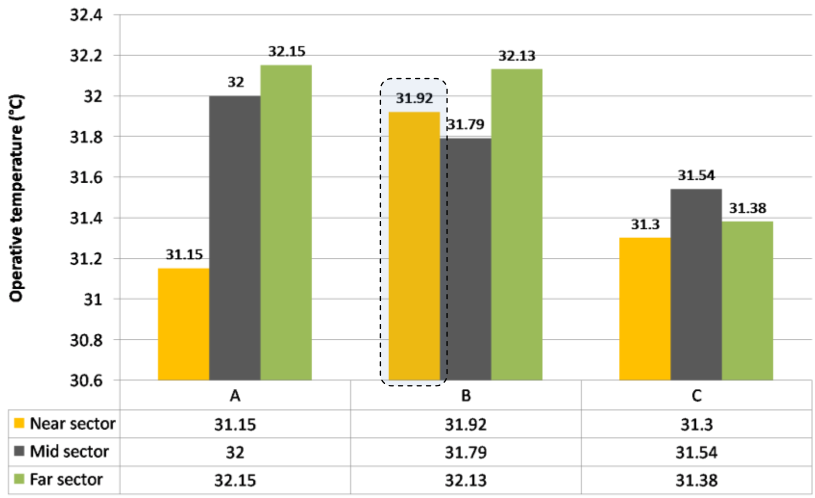


	A	B	C
Near sector	193.97	57.51	94.46
Mid sector	283.19	192.63	147.05
Far sector	380.14	288.76	194.17

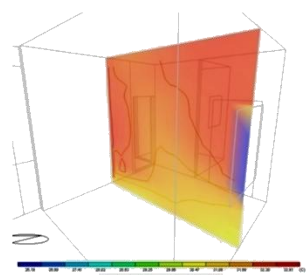
Discussion:
Zone (B-Near), beside the southern window, also achieves the best value in age of air of 57.51 sec, while the far corner of room (A-Mid, A-Far, and B-Far zones) achieves the worst values with highest age of air of 380.14 sec



Operative Temperature (°C)



Discussion:
Although zone (B-Near) achieves the best value in age of air, it does not show a good performance in operative temperature. This is due to the high temperature of incoming air that raises the feeling of discomfort in day periods. Generally sector C (the eastern sector) shows the best values in operative temperature. Zone A-Near achieves the most low operative temperature of 31.15°C down from the outside temperature by 0.85°C



Monitoring the overall performance of all space zones, it is clear that near sector achieves a better overall performance in ventilation rates and thermal comfort. On the other hand, sector A achieves a worse overall performance because of its zones are the most far zones from the three openings of the space.

4.2.2. Reference case evaluation results

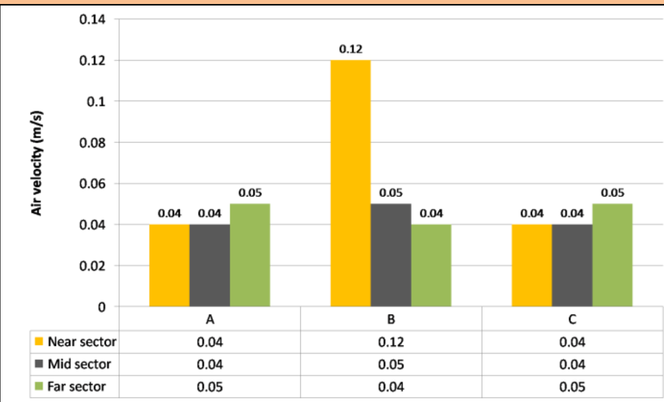
The reference case with single-directional air flow strategy has been investigated according to the simulation process of reference case. It was simulated with the three different space orientations and two different day and night conditions, giving six different simulation cases. Complete set of reference case results is shown in table 4.1.

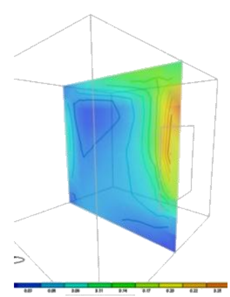
4.2.2.1. South orientation

South day case is the initial simulation condition of reference case derived from case study. Simulation was conducted at 1.00 PM Thur. 6 Jun, incoming air temperature of 32.0°C, and incoming northeast wind of 20° to East and 4.6 m/s in speed.

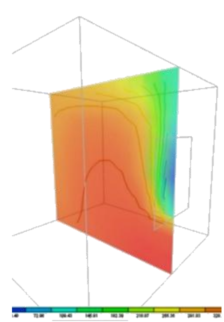
Reference case results (South Day condition)

Air Velocity (m/s)





Age of Air (sec)



Reference case results

Time	Day								
Orientation	South								
Space Temp	32.35								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.04	0.12	0.04	0.04	0.05	0.04	0.05	0.04	0.05
AVG	0.05								
Age of Air	340.93	281.32	340.93	346.85	353.97	346.85	330.12	346.06	330.12
AVG	335.24								
Operative Temperature	29.36	28.45	29.38	29.44	28.96	29.47	29.02	29.17	29.04
AVG	29.14								

Time	Day								
Orientation	East								
Space Temp	28.15								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.03	0.12	0.03	0.03	0.05	0.03	0.05	0.04	0.05
AVG	0.05								
Age of Air	326.6	245.92	328.17	361.75	376.31	363.82	351.44	378.63	351.44
AVG	342.68								
Operative Temperature	28.96	27.65	28.95	29.1	28.27	29.09	28.55	28.75	28.54
AVG	28.65								

Time	Day								
Orientation	West								
Space Temp	34.25								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.04	0.14	0.04	0.04	0.06	0.04	0.06	0.05	0.06
AVG	0.06								
Age of Air	314.57	256.24	314.57	322.53	329.6	322.53	307.92	323.64	307.92
AVG	311.06								
Operative Temperature	31.4	30.28	31.42	31.39	30.81	31.41	30.78	31.03	30.8
AVG	31.04								

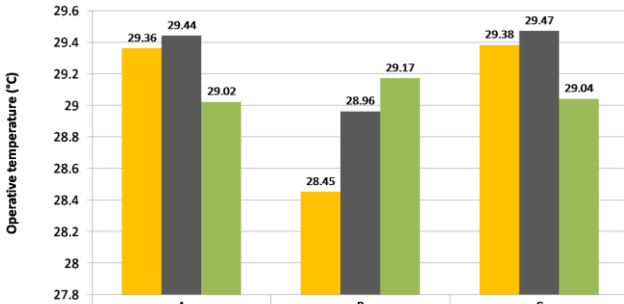
Time	Night								
Orientation	South								
Space Temp	30.41								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.04	0.13	0.04	0.04	0.05	0.04	0.05	0.05	0.05
AVG	0.05								
Age of Air	335.77	263.3	335.77	350.68	361.25	350.68	335.88	356.79	335.88
AVG	336.22								
Operative Temperature	29.34	28.18	29.34	29.37	28.71	29.36	28.82	28.91	28.82
AVG	28.98								

Time	Night								
Orientation	East								
Space Temp	30.50								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.04	0.11	0.04	0.05	0.06	0.05	0.06	0.05	0.06
AVG	0.06								
Age of Air	173.39	148.77	173.62	183.43	187.91	182.67	169.85	182.97	169.97
AVG	174.73								
Operative Temperature	32.09	31.37	32.09	32.04	31.93	32.04	31.94	32.04	31.93
AVG	31.94								

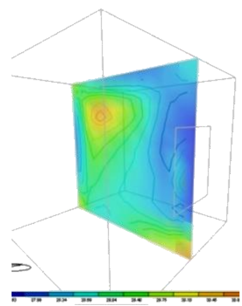
Time	Night								
Orientation	West								
Space Temp	31.27								
Sectors	Near			Mid			Far		
Zones	A Near	B Near	C Near	A Mid	B Mid	C Mid	A Far	B Far	C Far
Air Velocity	0.04	0.13	0.04	0.04	0.06	0.04	0.05	0.05	0.05
AVG	0.06								
Age of Air	312.91	242.7	312.92	330.94	342.49	330.96	317.66	338.88	317.66
AVG	316.35								
Operative Temperature	30.58	29.27	30.59	30.51	29.82	30.52	29.89	30.1	29.89
AVG	30.13								

Table 4.1 - Complete set of results for reference case evaluation

Operative Temperature (°C)



	A	B	C
Near sector	29.36	28.45	29.38
Mid sector	29.44	28.96	29.47
Far sector	29.02	29.17	29.04



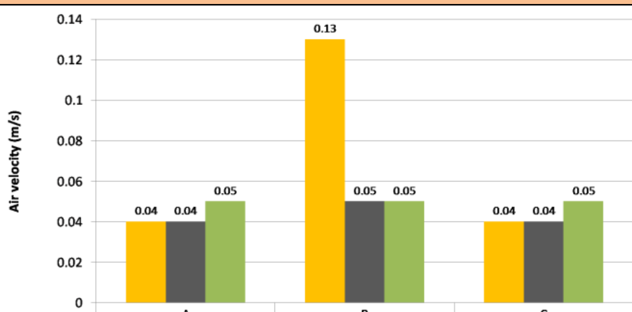
Discussion:

- Results of sector A and C are almost the same.
- Zone B-Near shows the best performance within all values.
- Although the high temperature of incoming air, zone B-Near achieves the best performance in operative temperature, and generally the space behaves better in overall operative temperature than tri-directional strategy.

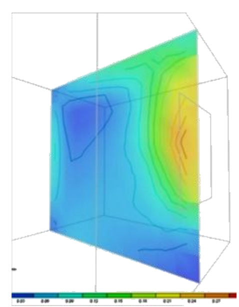
Within night conditions, simulation was conducted at 9.00 PM Thur. 6 Jun, incoming air temperature of 26.9°C, and incoming northeast wind of 20° to East and 4.6 m/s in speed.

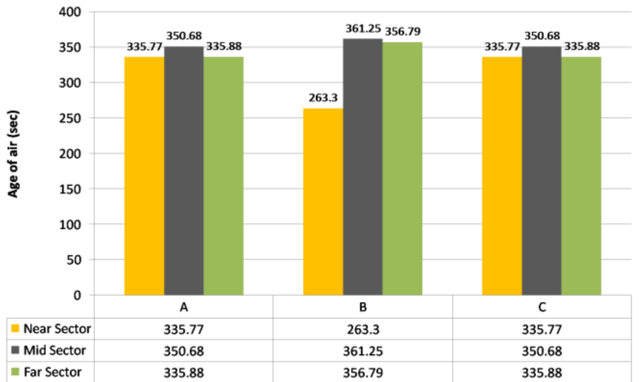
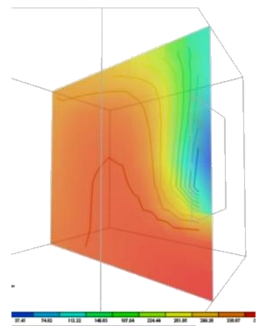
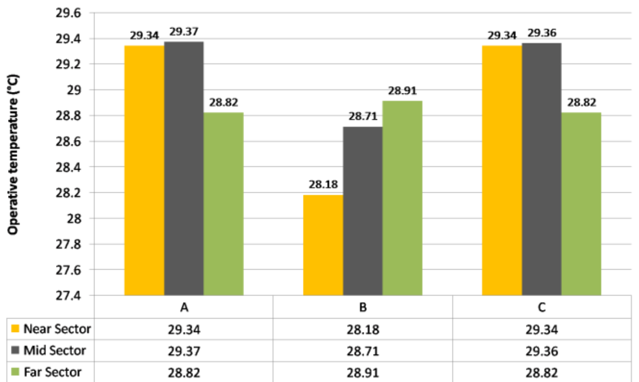
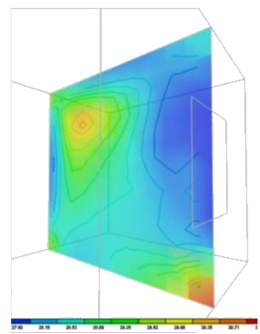
Reference case results (South Night condition)

Air Velocity (m/s)



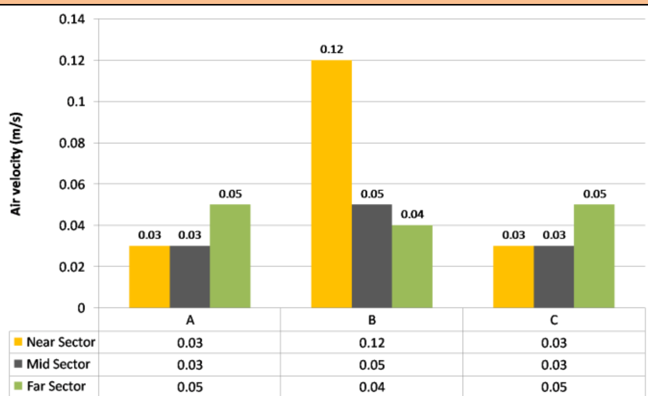
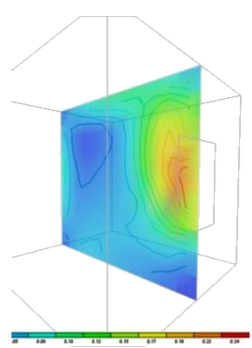
	A	B	C
Near Sector	0.04	0.13	0.04
Mid Sector	0.04	0.05	0.04
Far Sector	0.05	0.05	0.05



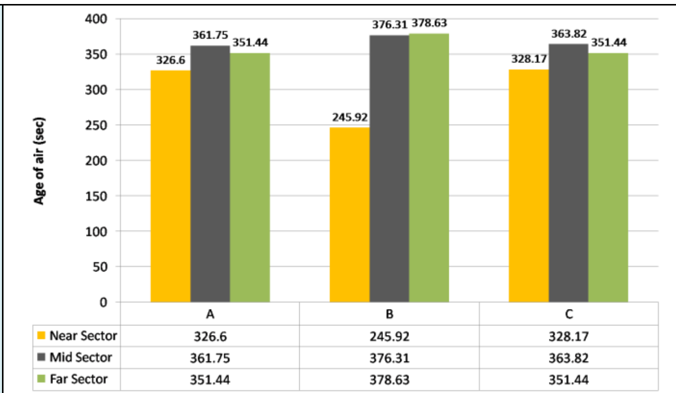
Age of Air (sec)		
Operative Temperature (°C)		

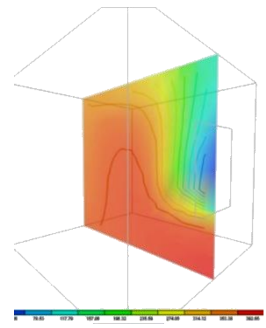
4.2.2.2. East orientation

Within day conditions, space orientation of reference case was changed to east direction. Simulation was conducted at 9.00 AM Thur. 6 Jun, incoming air temperature of 24.0°C, and incoming northeast wind of 50° to East and 4.1 m/s in speed.

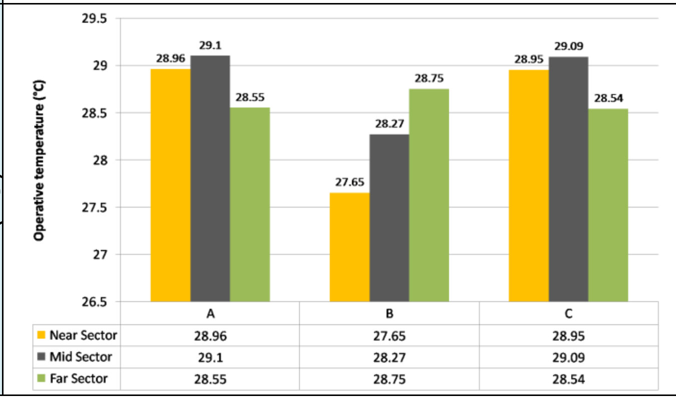
Reference case results (East Day condition)		
Air Velocity (m/s)		

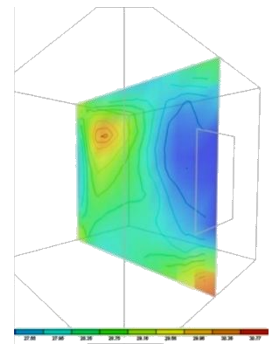
Age of Air (sec)





Operative Temperature (°C)

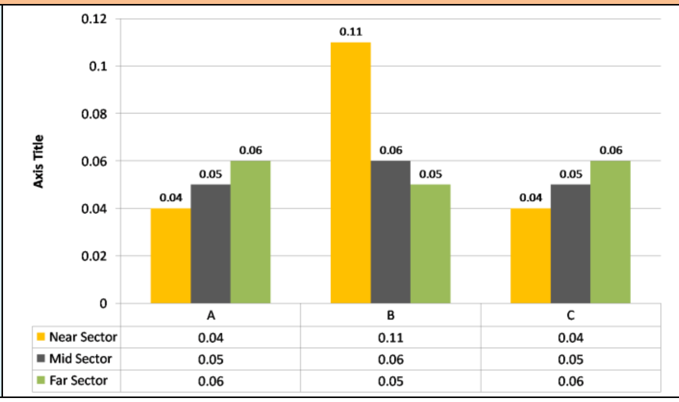


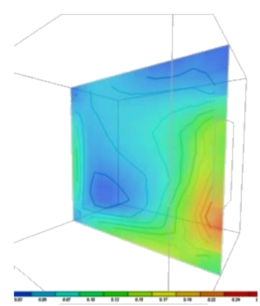


Within night conditions, simulation was conducted at 9.00 PM Thur. 6 Jun, incoming air temperature of 26.9°C, and incoming northeast wind of 20° to East and 4.6 m/s in speed.

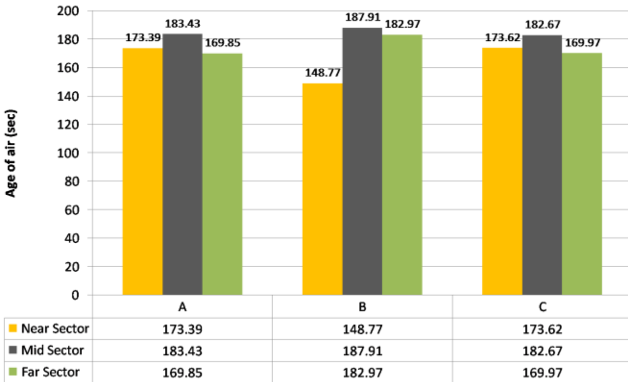
Reference case results (East Night condition)

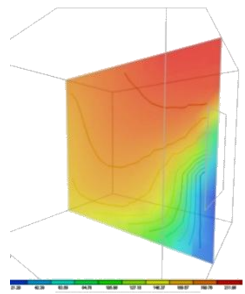
Air Velocity (m/s)



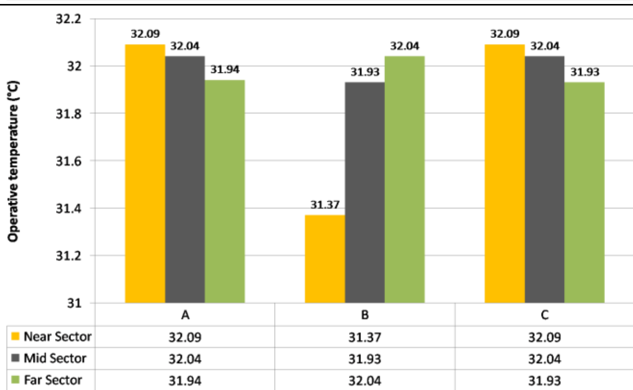


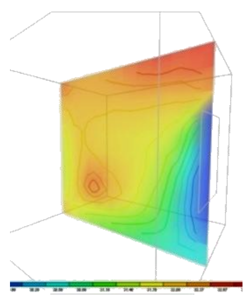
Age of Air (sec)





Operative Temperature (°C)



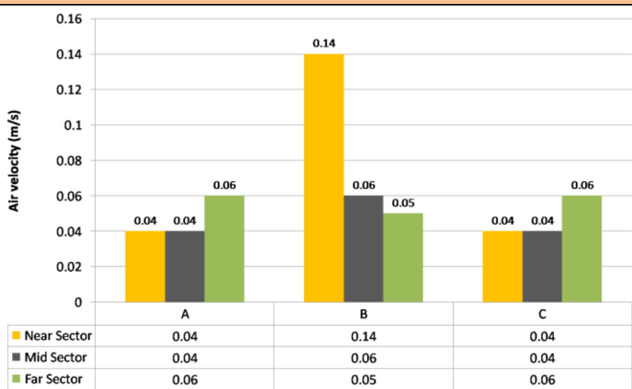


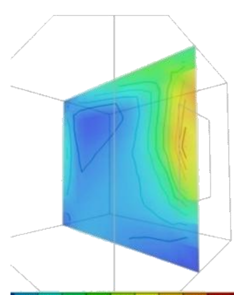
4.2.2.3. West orientation

Within day conditions, space orientation of reference case was changed to west direction. Simulation was conducted at 5.00 PM Thur. 6 Jun, incoming air temperature of 31.9°C, and incoming northeast wind of 30° to East and 5.7 m/s in speed.

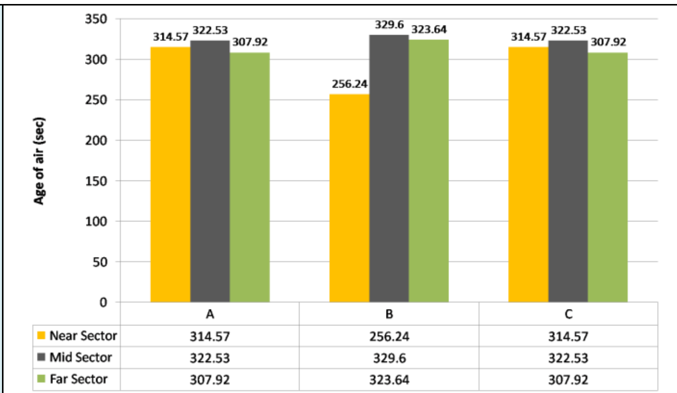
Reference case results (West Day condition)

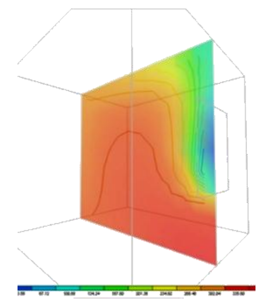
Air Velocity (m/s)



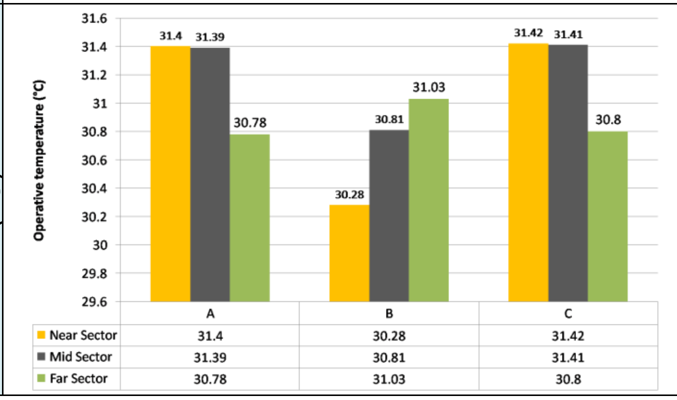


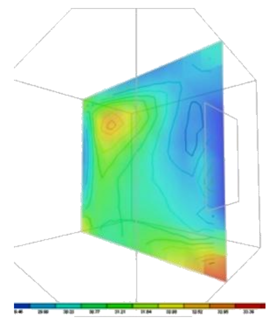
Age of Air (sec)





Operative Temperature (°C)

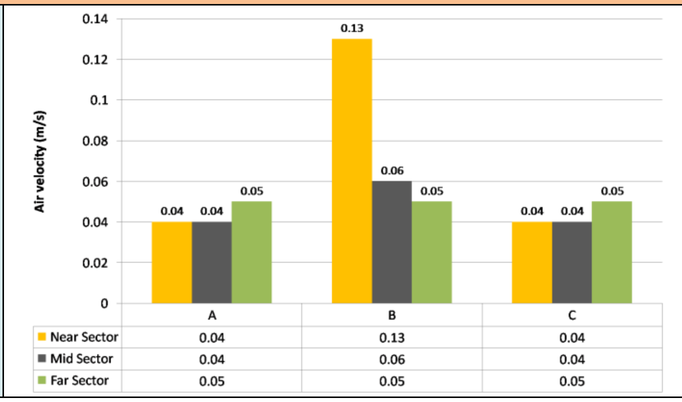


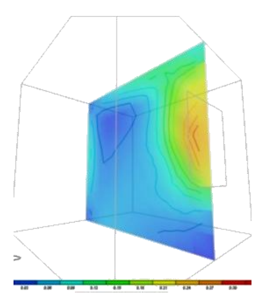


Within night conditions, simulation was conducted at 9.00 PM Thur. 6 Jun, incoming air temperature of 26.9°C, and incoming northeast wind of 20° to East and 4.6 m/s in speed.

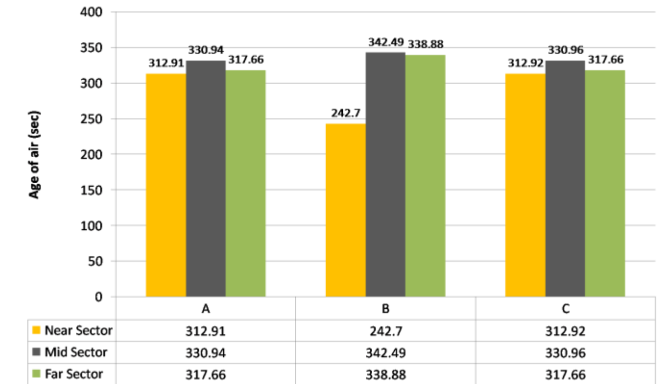
Reference case results (West Night condition)

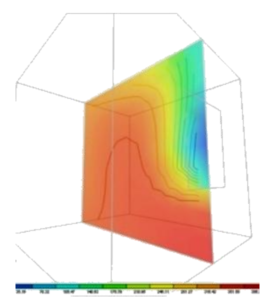
Air Velocity (m/s)



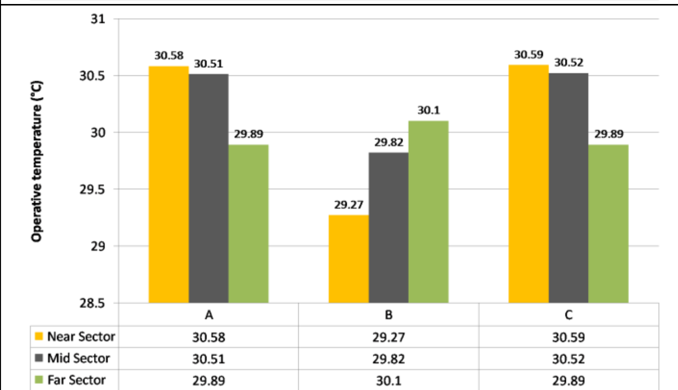


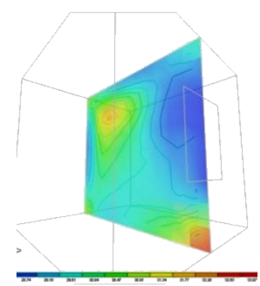
Age of Air (sec)





Operative Temperature (°C)





4.2.3. Double wall technique results

Application of double wall technique went under simulation according to the simulation process of double wall. It was simulated on two stages; first stage is to test the technique variables to pick the alternatives that achieve the best performance of technique in indoor ventilation rates; alternatives were evaluated by comparing the ventilation rates for each variable. This stage was conducted during day conditions while space was oriented towards south direction and compared with reference case at the same time and orientation to evaluate each variable performance. Within the second stage of simulation, best performance case was simulated with two different day and night conditions with three different space orientations similar to the reference case simulation, and then compared with reference case conditions.

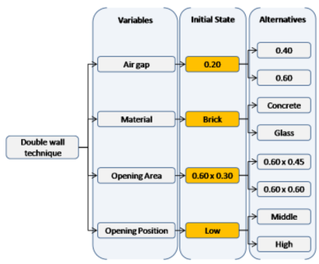
4.2.3.1. First Stage results *(technique variables)*

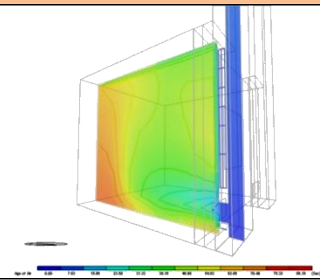
By applying the double wall technique with an initial state, a full thermal and CFD simulation was conducted to the space under study within day condition at 1.00 PM Thur. 6 Jun, incoming air temperature of 32.0°C, and incoming northeast wind (20° to East) and 4.6 m/s in speed.

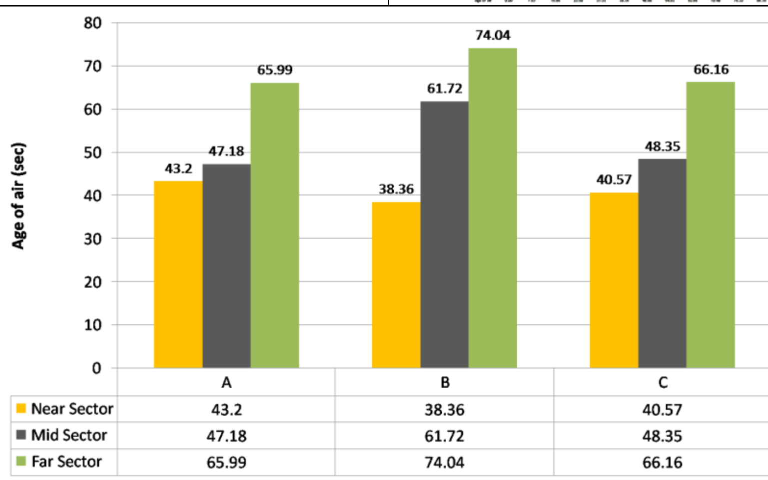
Double wall application results (Initial state)

Double wall / air gap (0.20) / material (brick) / dimensions (0.60x0.30) / position (low)

Age of Air (sec)







	A	B	C
Near Sector	43.2	38.36	40.57
Mid Sector	47.18	61.72	48.35
Far Sector	65.99	74.04	66.16

Then simulation went through testing the variables alternatives one by one

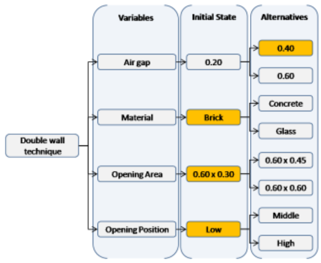
A. Air gap

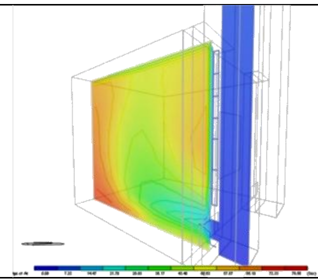
A full thermal and CFD simulation was conducted to the double wall technique according to initial state simulation data with the following alternatives:

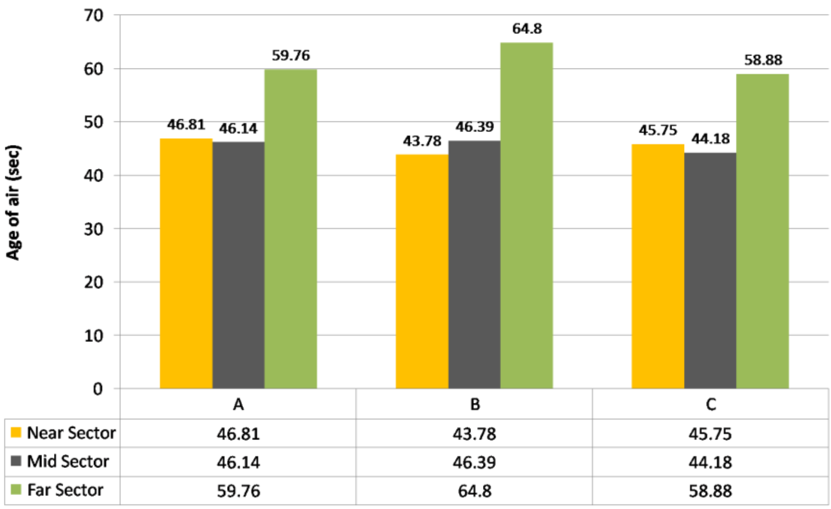
Double wall application results (Air gap of 0.40 m)

Double wall / air gap (0.40) / material (brick) / dimensions (0.60x0.30) / position (low)

Age of Air (sec)



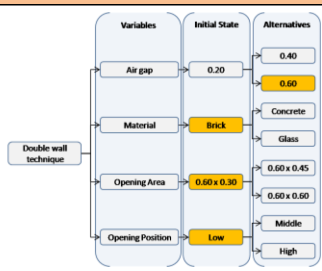


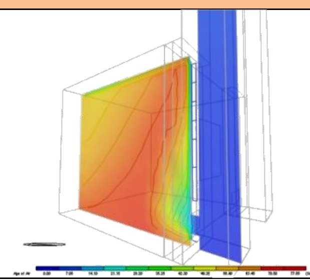


Double wall application results (Air gap of 0.60 m)

Double wall / air gap (0.60) / material (brick) / dimensions (0.60x0.30) / position (low)

Age of Air (sec)





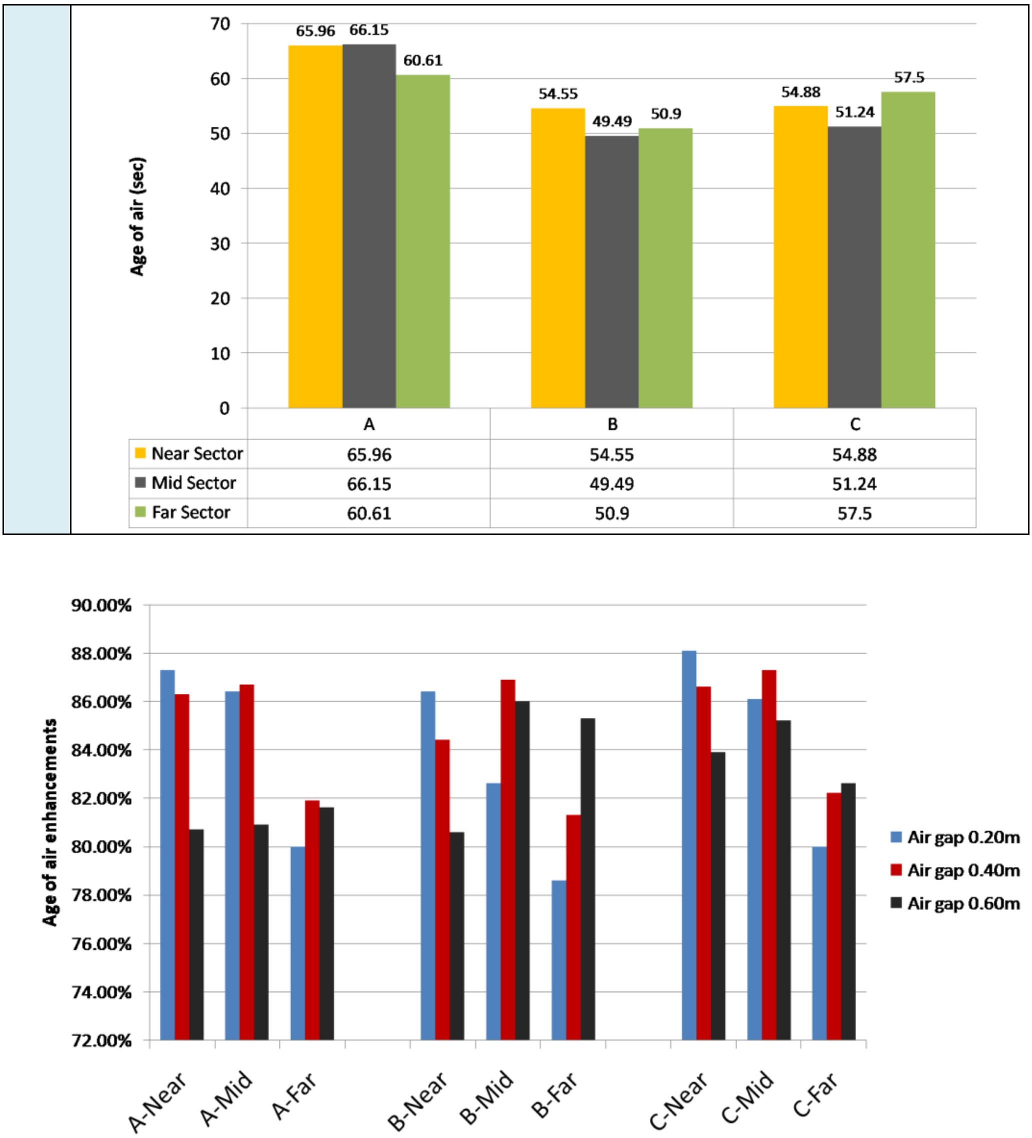


Figure 4.1– Enhancement percentages in ventilation rates for air gaps alternatives when compared with reference case within same time and orientation conditions[1]

Figure 4.1 shows that the performance of an air gap of 0.20m decreases rapidly towards far zones achieving the worst enhancement values. An air gap of 0.60m shows the lowest values in enhancement percentage within near zones, with bad indoor air distribution shown in CFD results. An air gap of 0.40m achieves an overall enhancement percentage of 84.8%, while air gaps

[1] The researcher

of 0.20m and 0.60m achieve an overall enhancement percentage of 83.9% and 83% respectively. Architecturally, air gap of 0.60m achieves the most waste floor area while it achieves the worst overall performance. Although air gap of 0.20m is more appropriate from the architectural point of view, it shows the lowest values within far zones along space depth.

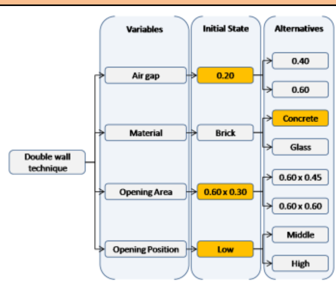
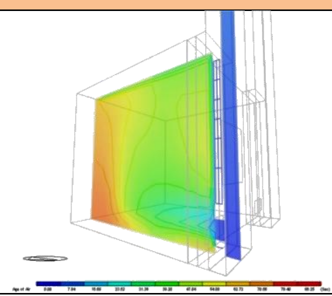
Thus, air gap of 0.40m will be chosen as the best alternative of air gap variable. The results also show that age of air inside air gap decreases when gap gets wider according to table 4.2, but it does not necessarily have a positive effect on indoor ventilation rates. As it was shown, air gap of 0.60m achieves results worse than both gaps 0.40m and 0.20m in overall percentage of enhancement.

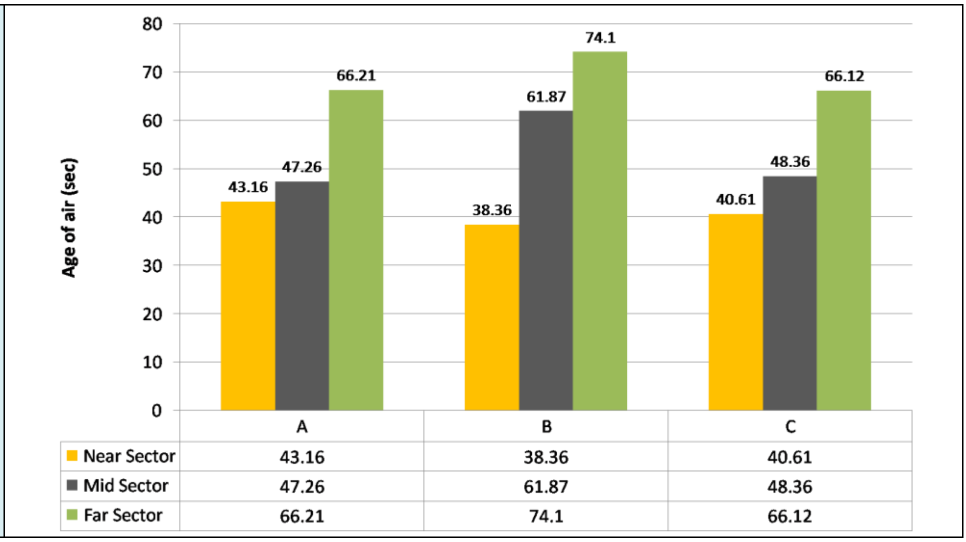
Air gap width (m)	Average age of air inside cavity (sec)
0.20	4.38
0.40	2.46
0.60	2.13

Table 4.2– Average age of air inside cavity due to air gap

B. Construction material

Two different construction materials (concrete and glass) were simulated beside brick main material. While fixed other parameters, a full thermal and CFD simulation was conducted to the double wall technique according to initial state simulation data with the following alternatives:

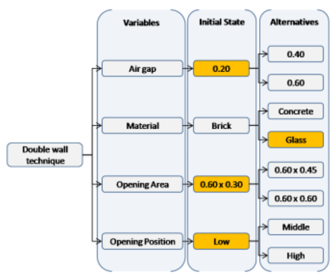
Double wall application results (Concrete material) *Double wall / air gap (0.20) / material (concrete) / dimensions (0.60x0.30) / position (low)*		
Age of Air (sec)		

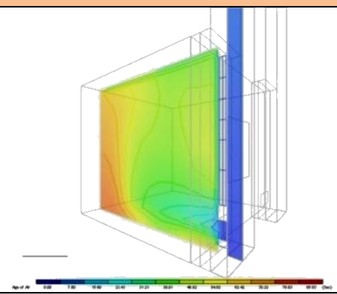


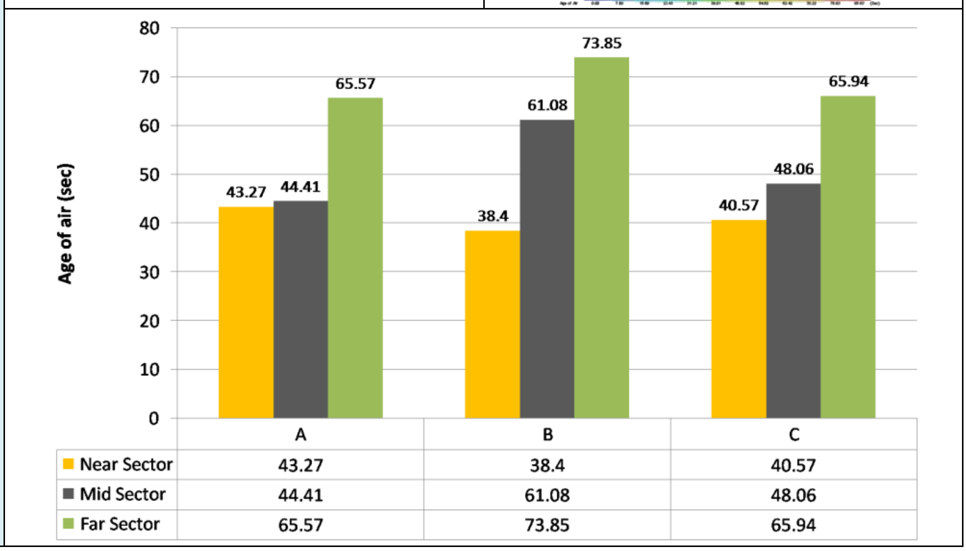
Double wall application results (Glass material)

Double wall / air gap (0.20) / material (glass) / dimensions (0.60x0.30) / position (low)

Age of Air (sec)







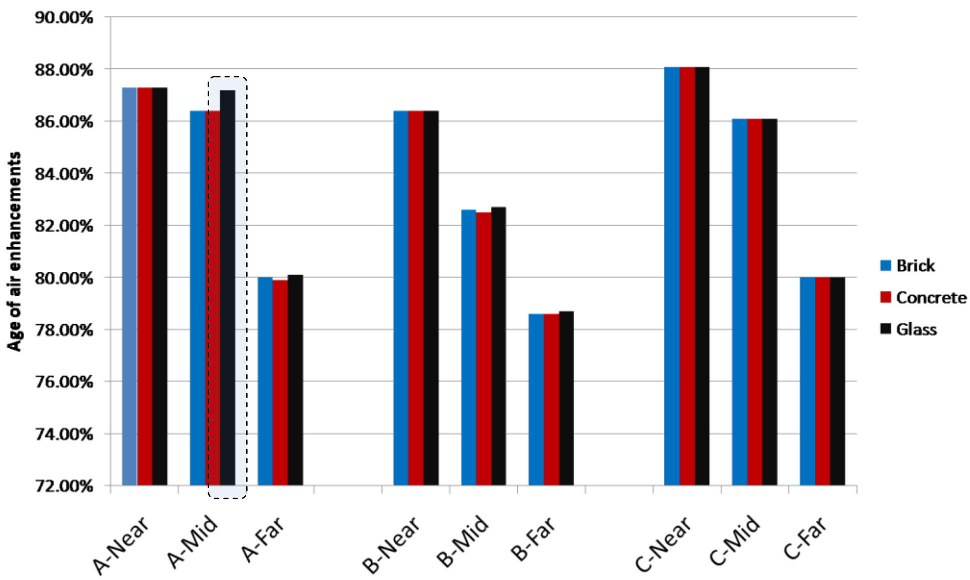


Figure 4.2– Enhancement percentages in ventilation rates for construction materials alternatives when compared with reference case within same time and orientation conditions[1]

Figure 4.2 states that all construction materials show almost similar performance. Glass material shows a little increase in one zone, but referring to the special construction and high cost of glass construction, brick, as a commonly used local construction material, is selected to represent the construction alternative within the best performance case of double wall system.

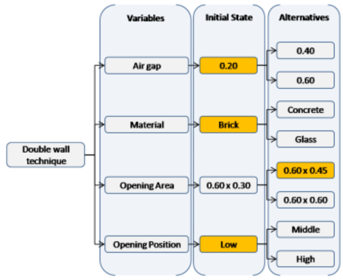
C. Technique opening dimensions

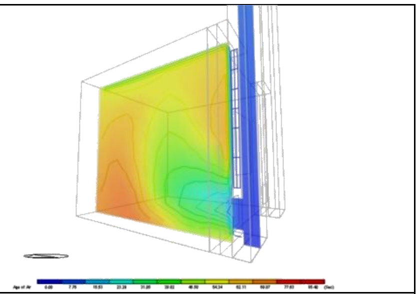
Two different opening dimensions (0.60x0.45 m^2 and 0.60x0.60 m^2) were simulated beside the main dimensions of (0.60x0.30 m^2). While fixed other parameters, a full thermal and CFD simulation was conducted to the double wall technique according to initial state simulation data with the following alternatives:

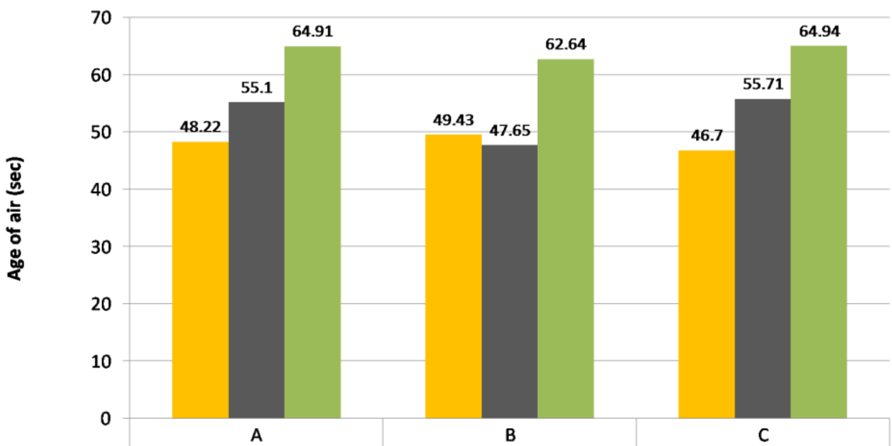
Double wall application results (Opening dimensions of 0.60x0.45 m^2)
Double wall / air gap (0.20) / material (brick) / dimensions (0.60x0.45) / position (low)

[1] The researcher

Age of Air (sec)





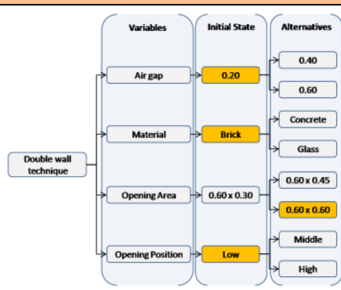


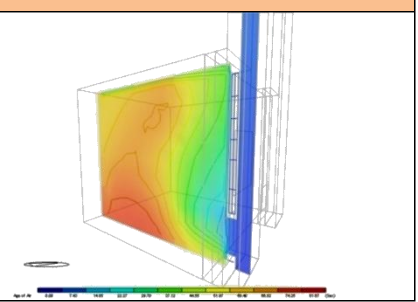
	A	B	C
Near Sector	48.22	49.43	46.7
Mid Sector	55.1	47.65	55.71
Far Sector	64.91	62.64	64.94

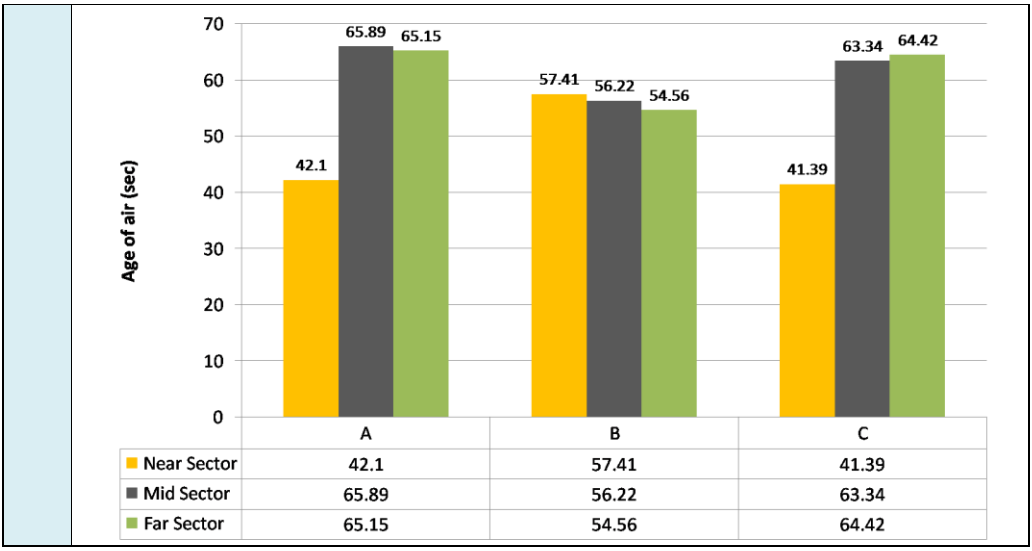
Double wall application results (Opening dimensions of 0.60x0.60 m^2)

Double wall / air gap (0.20) / material (brick) / dimensions (0.60x0.60) / position (low)

Age of Air (sec)







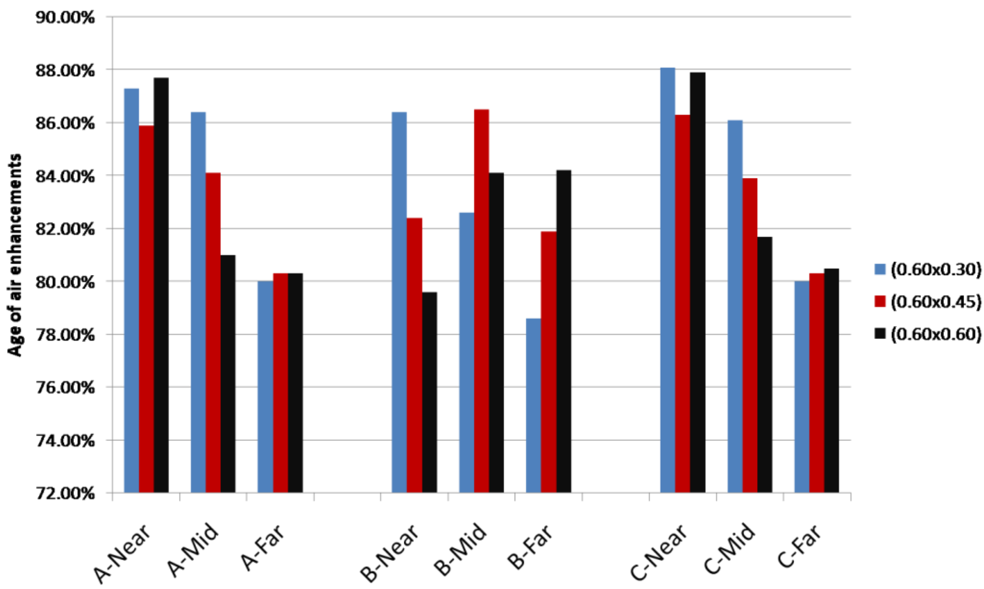


Figure 4.3– Enhancement percentages in ventilation rates for technique opening dimensions alternatives when compared with reference case within same time and orientation conditions[1]

The results show that the overall performances of opening different dimensions (0.60x0.30, 0.60x0.45, and 0.06x0.60) are 83.9%, 83.5%, and 83% respectively; this means that an increase in technique opening area by 0.09 m^2 may reduce the system performance by around 0.5%.

[1] The researcher

Figure 4.3 shows that within sectors A and C, dimensions of 0.60x0.30 achieve better percentage of enhancements within near and mid sectors. Within far sectors, the three different dimensions nearly behave the same.

Thus, dimensions of 0.60x0.30m^2 are selected to represent the technique opening dimensions in the best performance case of passive technique application.

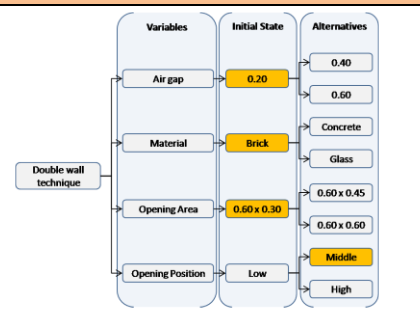
D. Technique opening position

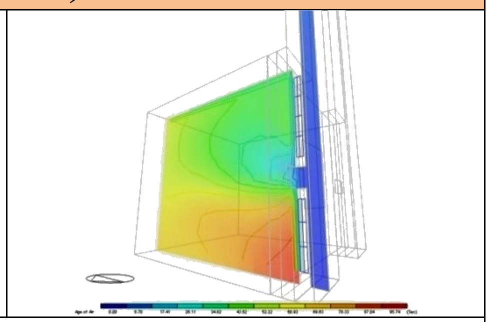
Two different opening positions (middle and high) were simulated beside main low position. While fixed other parameters, a full thermal and CFD simulation was conducted to the double wall technique according to the initial state simulation data with the following alternatives:

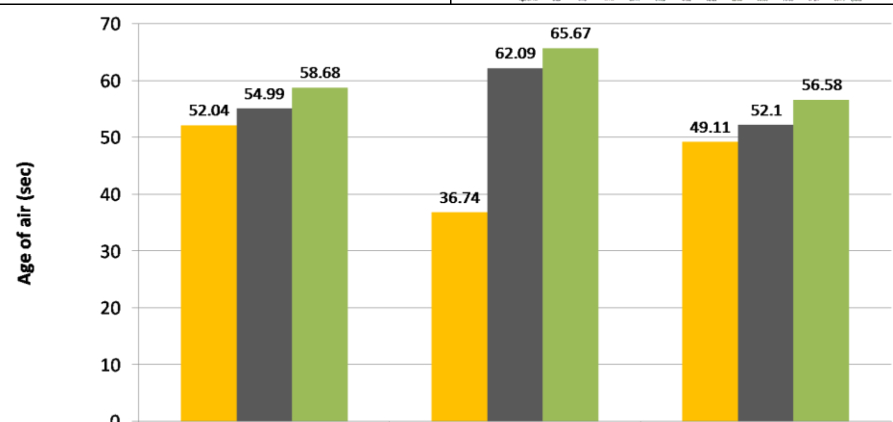
Double wall application results (Opening middle position)

Double wall / air gap (0.20) / material (brick) / dimensions (0.60x0.30) / position (middle)

Age of Air (sec)





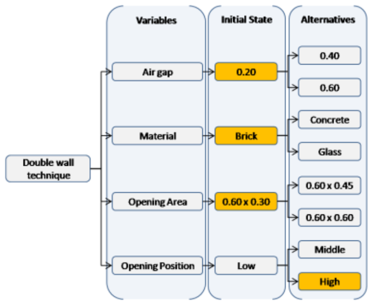


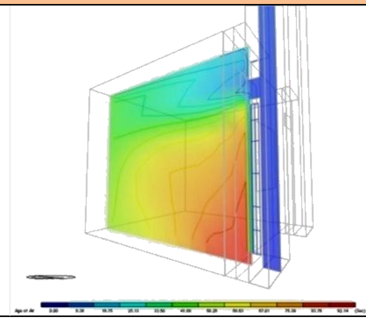
	A	B	C
Near Sector	52.04	36.74	49.11
Mid Sector	54.99	62.09	52.1
Far Sector	58.68	65.67	56.58

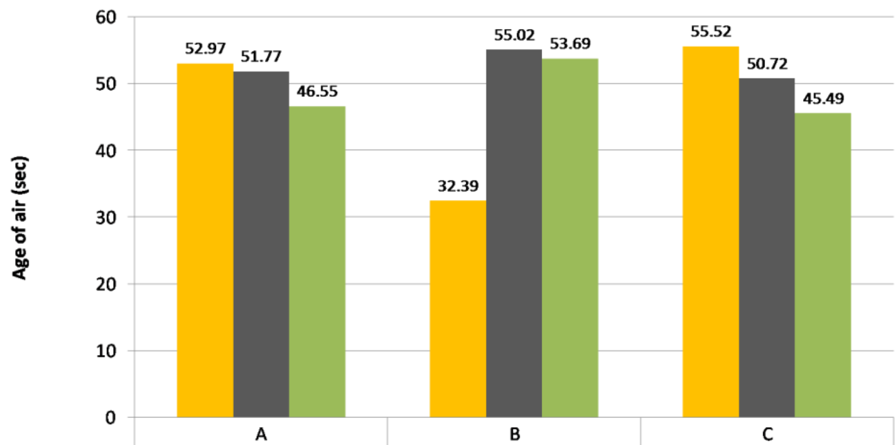
Double wall application results (Opening high position)

Double wall / air gap (0.20) / material (brick) / dimensions (0.60x0.30) / position (high)

Age of Air (sec)







	A	B	C
Near Sector	52.97	32.39	55.52
Mid Sector	51.77	55.02	50.72
Far Sector	46.55	53.69	45.49

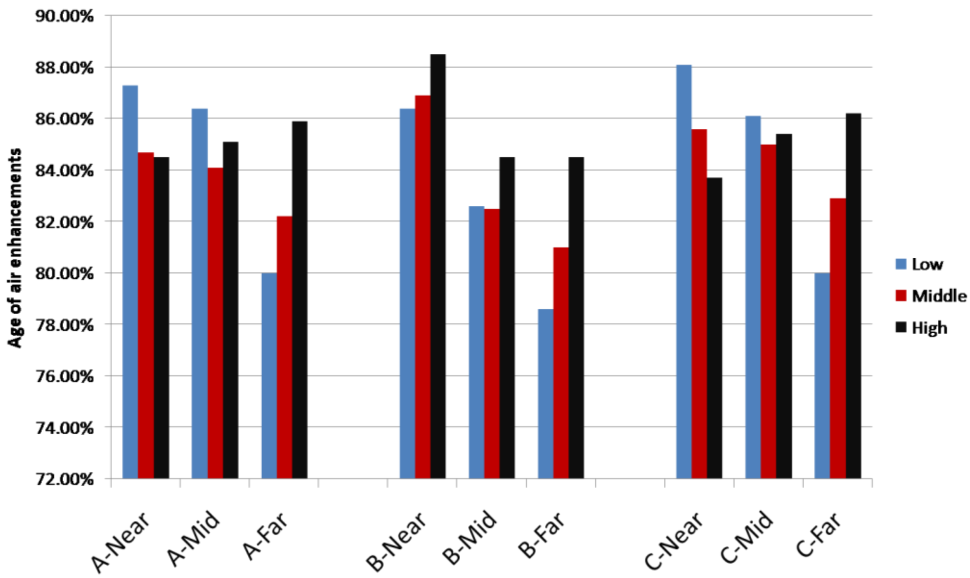


Figure 4.4– Enhancement percentages in ventilation rates for technique opening dimensions alternatives when compared with reference case within same time and orientation conditions[1]

Figure 4.4 shows that high position shows best performance within all far zones and B-sector, and achieves relative highest results not less than 81% at all zones. Within other four zones, low position achieves a better performance but with low performance within far zones.

The results show that the overall performances of opening different positions (low, middle, and high) are 83.9%, 83.9%, and 85.4% respectively. Thus, high position alternative will be chosen for better performance condition.

4.2.3.2. Second stage results *(orientation parameter)*

By the previous phase, the variables that achieved better performance have been selected to form the double wall system parameters. Figure 4.5 shows the complete technique variables that achieved better performance.

[1] The researcher

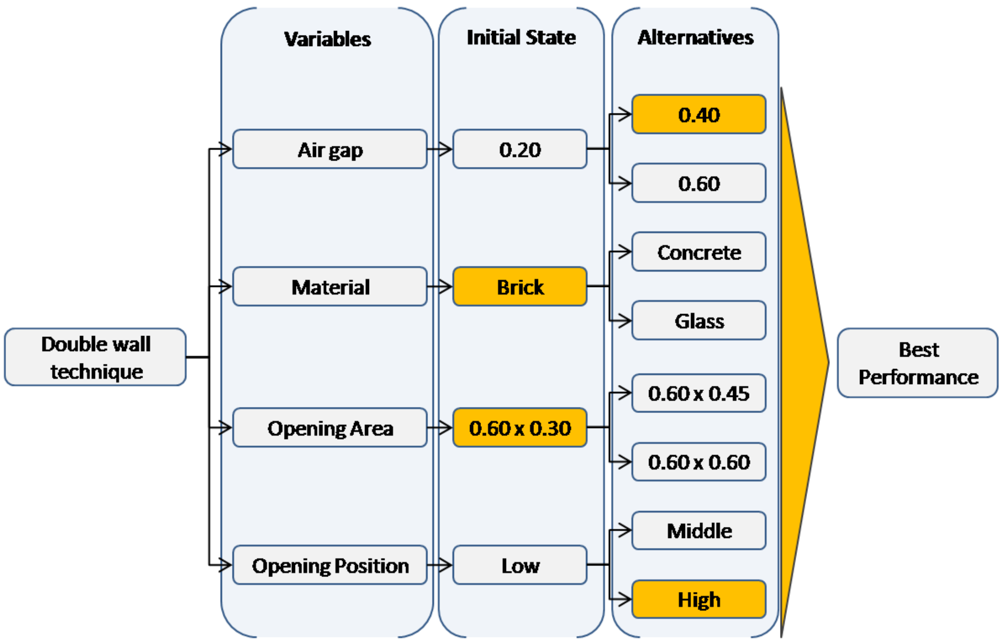


Figure 4.5– Double wall application alternatives that achieve best performance

Within this stage of simulation, best performance case was simulated with the three different space orientations and two different day and night conditions as similar as reference case simulation and then compared with reference case conditions.

The results were compared to reference case results to state the performance of technique by monitoring the percentage of increase and enhancement in results values. The following data directly show the changes in space behavior due to technique application. Complete comparison between reference case and double wall technique results is shown in table 4.3.

Time	Day																		Night																	
Orientation	South						East						West						South						East						West					
	Reference case			Double wall technique			Reference case			Double wall technique			Reference case			Double wall technique			Reference case			Double wall technique			Reference case			Double wall technique			Reference case			Double wall technique		
Sectors	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far	Near	Mid	Far
Space Temp.	32.35			31.59			28.15			26.46			34.25			32.46			30.41			28.85			30.50			28.95			31.27			28.55		
Air Velocity	0.07	0.04	0.05	0.13	0.14	0.13	0.06	0.04	0.05	0.06	0.05	0.06	0.07	0.05	0.06	0.15	0.16	0.17	0.07	0.04	0.05	0.15	0.13	0.10	0.06	0.05	0.06	0.24	0.21	0.23	0.07	0.05	0.05	0.15	0.12	0.10
AVG	0.05			0.13			0.05			0.06			0.06			0.16			0.05			0.13			0.06			0.23			0.06			0.12		
Age of Air	321.06	349.22	335.43	47.97	46.77	47.03	300.23	367.29	360.50	114.00	104.98	100.43	295.13	324.89	313.16	50.85	49.08	40.38	311.61	354.20	342.85	47.23	44.69	56.73	165.26	184.67	174.26	49.10	52.67	46.12	289.51	334.80	324.73	45.85	49.60	44.52
AVG	335.24			47.26			342.68			106.47			311.06			46.77			336.22			49.55			174.73			49.30			316.35			46.66		
Operative Temperature	29.06	29.29	29.08	30.34	30.68	30.60	28.52	28.82	28.61	27.80	28.17	28.07	31.03	31.20	30.87	31.02	31.53	31.68	28.95	29.15	28.85	29.49	29.97	30.27	31.85	32.00	31.97	27.98	28.49	28.39	30.15	30.28	29.96	29.96	30.43	30.51
AVG	29.14			30.54			28.65			28.02			31.04			31.41			28.98			29.91			31.94			28.29			30.13			30.30		

Table 4.3 - Complete comparison between reference case and double wall technique results

A. South orientation

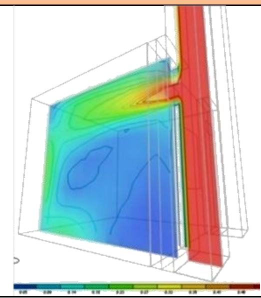
South case is the initial simulation condition of double wall technique with which the previous stage of simulation conducted with the same simulation data of south reference case condition. Within day conditions, the space average temperature while applying double wall is 31.59°C, in return, the reference space temperature is 32.35°C. This reduction of 0.76°C is due to thermal isolation and shading effect of double wall.

Double wall technique (South Day condition) results

Double wall / best performance / South / Day

Air Velocity Performance (m/s)

A	B	C	
0.14	0.12	0.14	**Far Sector**
0.12	0.17	0.12	**Mid Sector**
0.12	0.16	0.12	**Near Sector**



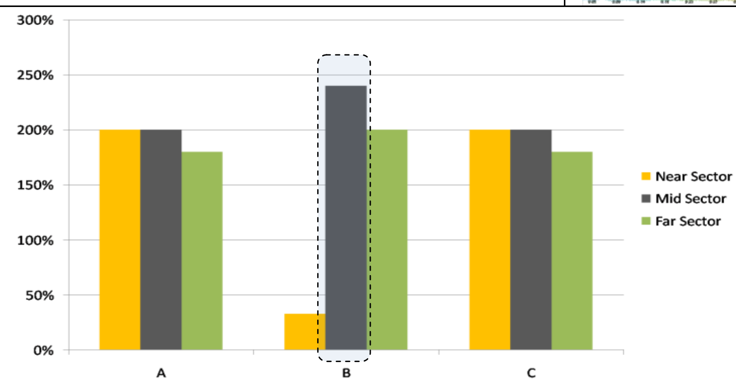


Figure 4.6– Percentage of increase in indoor air velocity comparing to reference case performance[1]

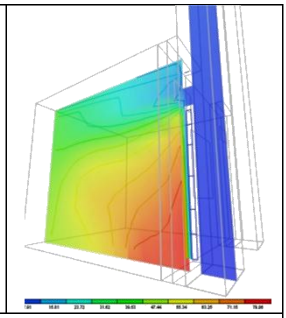
Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.17 m/s at B-Mid zone.
- Overall air velocity values vary from 0.12 to 0.17 m/s, with a minimum percentage of increase in B-Near zone due to high zone performance in reference case.
- The average value of air velocity inside space is 0.13 m/s.

[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)

Age of Air Performance (sec)

A	B	C	
43.6	52.43	45.07	**Far Sector**
47.65	44.04	48.62	**Mid Sector**
53.45	36.37	54.1	**Near Sector**



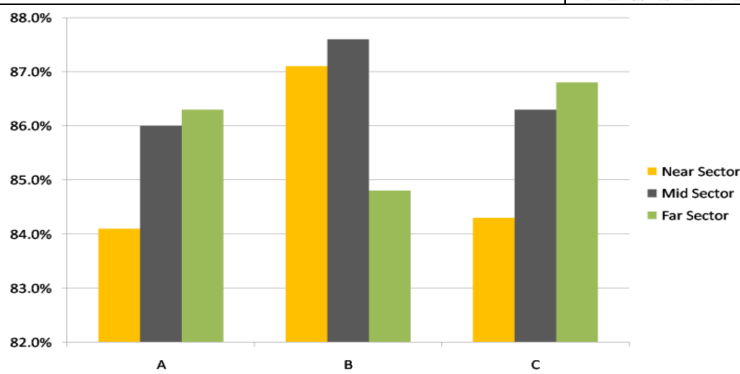


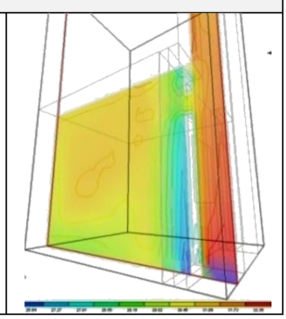
Figure 4.7– Percentage of enhancements in indoor age of air comparing to reference case performance[1]

Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 43.6 sec at A-Far zone.
- Overall age of air values vary from 43.6 to 53.45 sec, with an average value of 47.25 sec.

Operative Temperature (°C)

A	B	C	
30.57	30.67	30.55	**Far Sector**
30.69	30.68	30.67	**Mid Sector**
30.31	30.44	30.28	**Near Sector**



[1] *Ibid.*

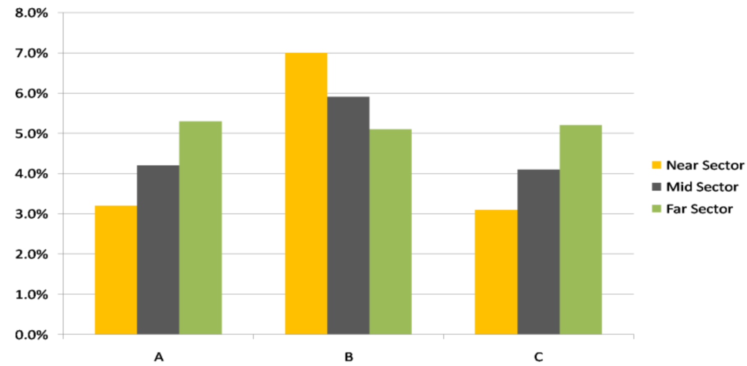


Figure 4.8– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the operative temperature by a maximum value of 1.7°C at B-Mid zone.
- Overall increases in operative temperature values vary from 0.9 to 1.7°C , with an average value of operative temperature increase inside space of 1.4°C.
- Although application of double wall decreases space temperature by 0.76°C, operative temperature rises by an average of 1.4°C (4.8%) due to high temperature of incoming air when ventialtion rates increase by technique application.

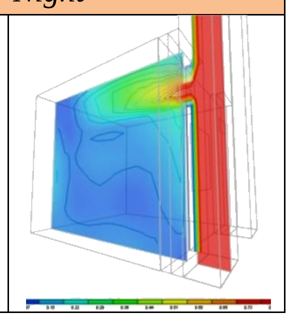
Within night conditions, the space average temperature while applying double wall is 28.85°C, in return, the reference space temperature is 30.41°C. This reduction of 1.56°C is due to thermal isolation of double wall.

Double wall technique (South Night condition) results

Double wall / best performance / South / Night

Air Velocity Performance (m/s)

A	B	C	
0.07	0.08	0.14	**Far Sector**
0.12	0.11	0.16	**Mid Sector**
0.17	0.1	0.18	**Near Sector**



[1] *Ibid.*

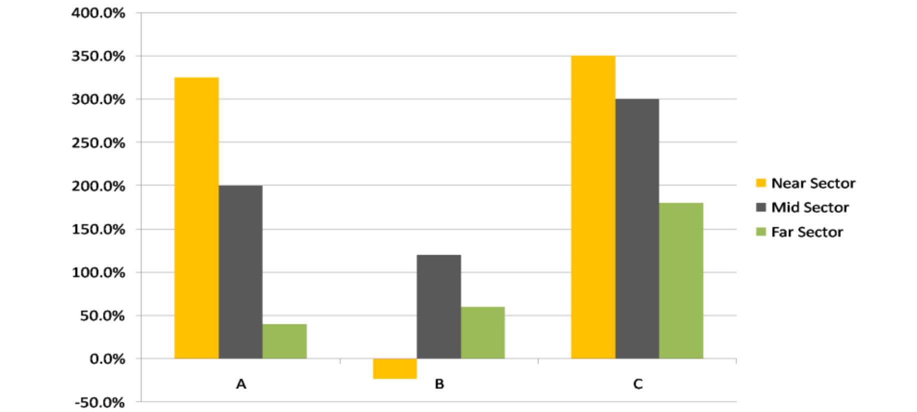


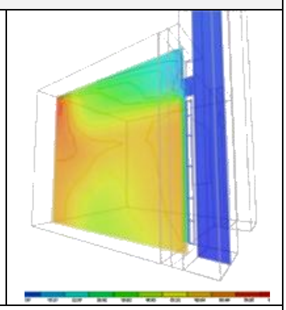
Figure 4.9– Percentage of changes in indoor air velocity comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.18 m/s at C-Near zone, with a single decrease in air velocity at B-Near zone by 0.03 m/s.
- Overall air velocity values vary from 0.1 to 0.18 m/s, with an average value of 0.13 m/s.

Age of Air Performance (sec)

A	B	C	
63.54	60.16	46.48	**Far Sector**
50.37	41.22	42.47	**Mid Sector**
50.99	44.96	45.73	**Near Sector**



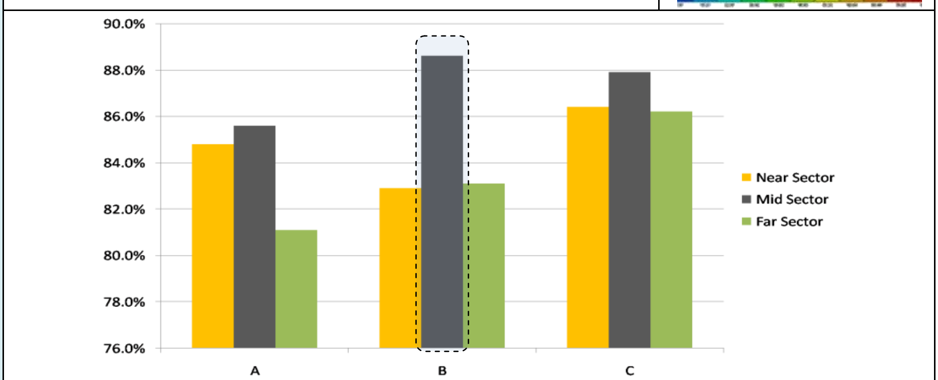


Figure 4.10– Percentage of enhancements in indoor age of air comparing to reference case performance[2]

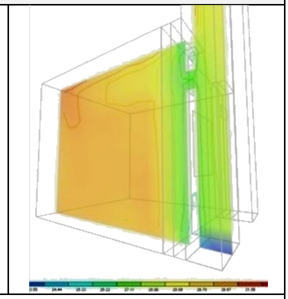
[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)
[2] *Ibid.*

Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 41.22 sec at B-Mid zone.
- Overall age of air values vary from 41.22 to 63.54 sec, with an average value of 49.55 sec.

Operative Temperature (°C)

A	B	C	
30.42	30.4	29.98	**Far Sector**
30.06	30.05	29.79	**Mid Sector**
29.46	29.72	29.29	**Near Sector**



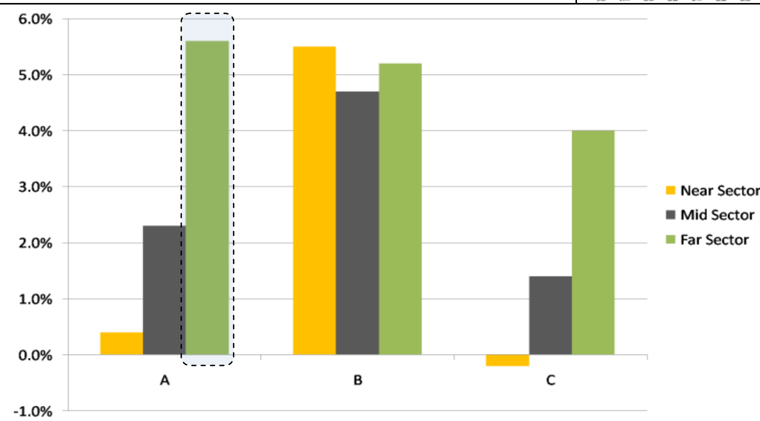


Figure 4.11– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the operative temperature by a maximum value of 1.6°C at A-Far zone.
- Overall increases in operative temperature values vary from 0.1 to 1.6°C , with a single decrease of 0.1°C at C-Near zone.
- Although application of double wall decreases space temperature by 1.56°C, operative temperature rises by an average of 0.9°C (3.2%) due to thermal storage of space.

[1] *Ibid.*

B. East orientation

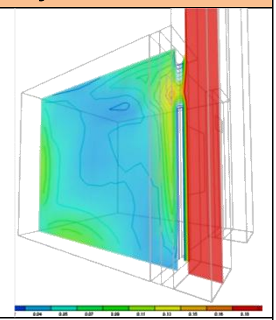
East simulation case was conducted within the same simulation data of east reference case condition. Within day conditions, the space average temperature while applying double wall is 26.46°C, in return, the reference space temperature is 28.15°C. This reduction of 1.69°C is due to thermal isolation and shading effect of double wall.

Double wall technique (East Day condition) results

Double wall / best performance / East / Day

Air Velocity Performance (m/s)

A	B	C	
0.06	0.06	0.06	**Far Sector**
0.04	0.08	0.04	**Mid Sector**
0.04	0.07	0.06	**Near Sector**



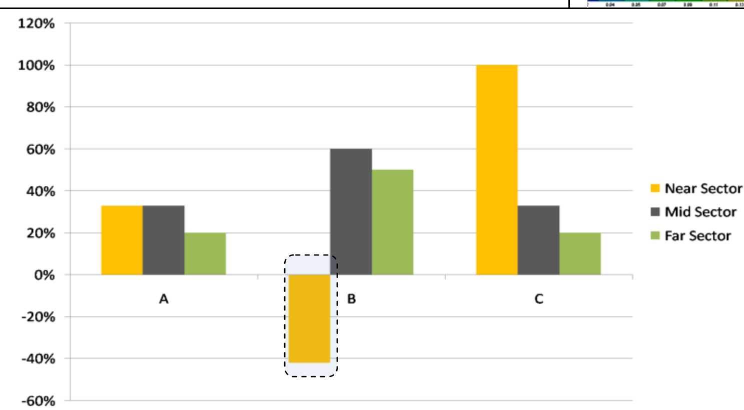


Figure 4.12– Percentage of changes in indoor air velocity comparing to reference case performance[1]

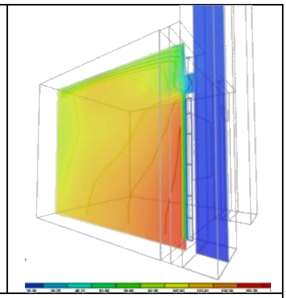
Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.08 m/s at B-Mid zone.
- Overall air velocity values vary from 0.04 to 0.08 m/s.
- Air velocity at B-Near zone (0.07 m/s) is less than reference case (0.12 m/s) by 42%.

[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)

Age of Air Performance (sec)

A	B	C	
108.87	88.3	104.12	**Far Sector**
122.09	88.1	104.76	**Mid Sector**
129.98	101.17	110.86	**Near Sector**



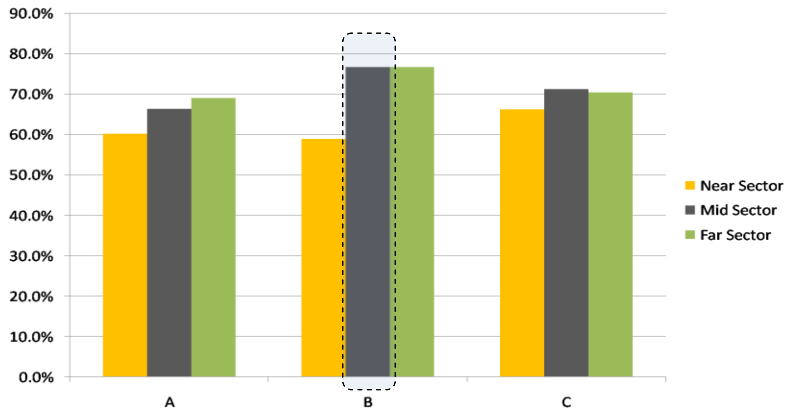


Figure 4.13– Percentage of enhancements in indoor age of air comparing to reference case performance[1]

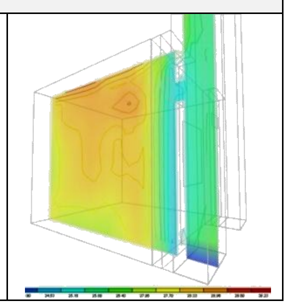
Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 88.1 sec at B-Mid zone.

- Overall age of air values vary from 88.1 to 129.98 sec, with an average value of 106.49 sec.

Operative Temperature (°C)

A	B	C	
27.95	28.24	28.02	**Far Sector**
28.23	28.03	28.26	**Mid Sector**
27.9	27.95	27.64	**Near Sector**



[1] *Ibid.*

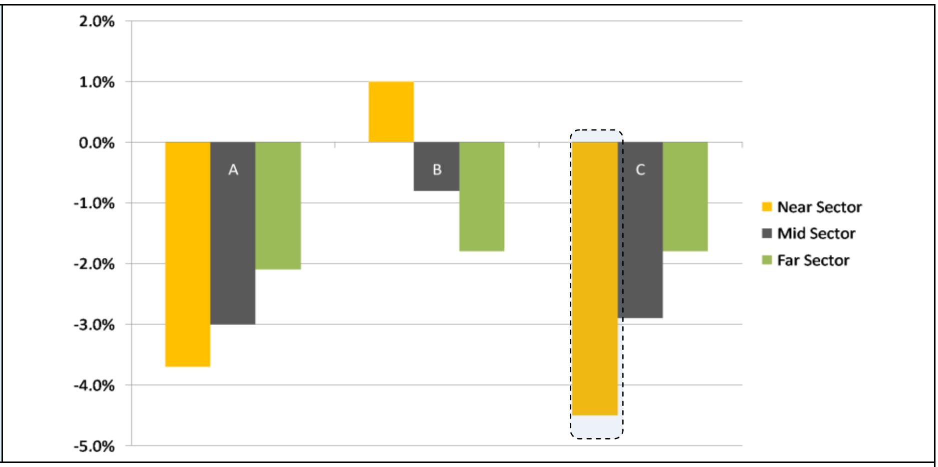


Figure 4.14– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique decreses the operative temperature by a maximum value of 1.3°C at C-Near zone.
- Overall decreases in operative temperature values vary from 0.3 to 1.3°C , with a single increase of 0.3°C at B-Near zone.
- In addition to the decreasing of space temperature at day East conditions by 1.69°C, the operative temperature also decreases by an average value of 0.63°C due to the less values of air velocities and age of air inside space.

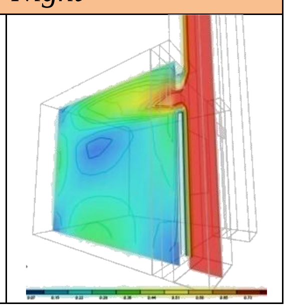
Within night conditions, the space average temperature while applying double wall is 28.95°C, in return, the reference space temperature is 30.50°C. This reduction of 1.55°C is due to thermal isolation of double wall.

Double wall technique (East Night condition) results

Double wall / best performance / East / Night

Air Velocity Performance (m/s)

A	B	C	
0.21	0.23	0.26	**Far Sector**
0.23	0.16	0.25	**Mid Sector**
0.27	0.16	0.3	**Near Sector**



[1] *Ibid.*

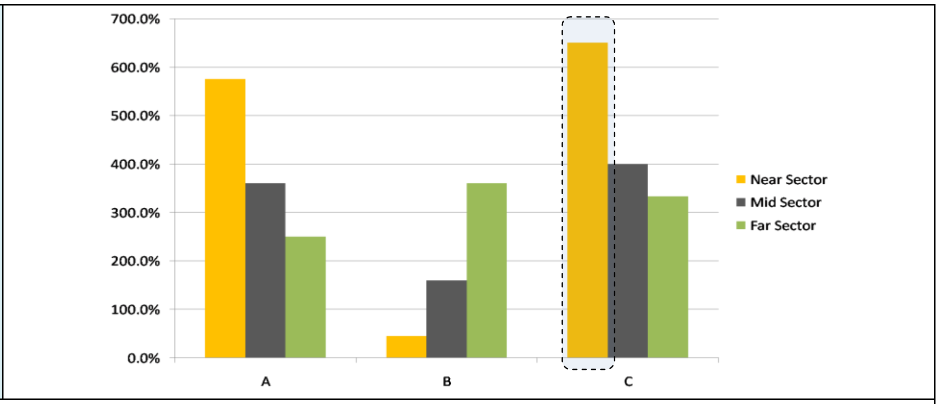


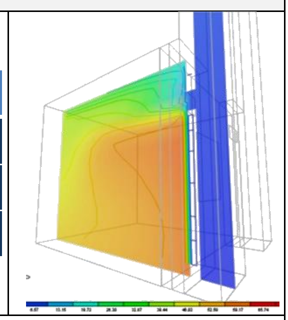
Figure 4.15– Percentage of changes in indoor air velocity comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.30 m/s at C-Near zone.
- Overall air velocity values vary from 0.16 to 0.30 m/s, with an average value of 0.23 m/s.

Age of Air Performance (sec)

A	B	C	
46.77	45.32	46.28	**Far Sector**
51.67	52.78	53.55	**Mid Sector**
52.18	42.44	52.67	**Near Sector**



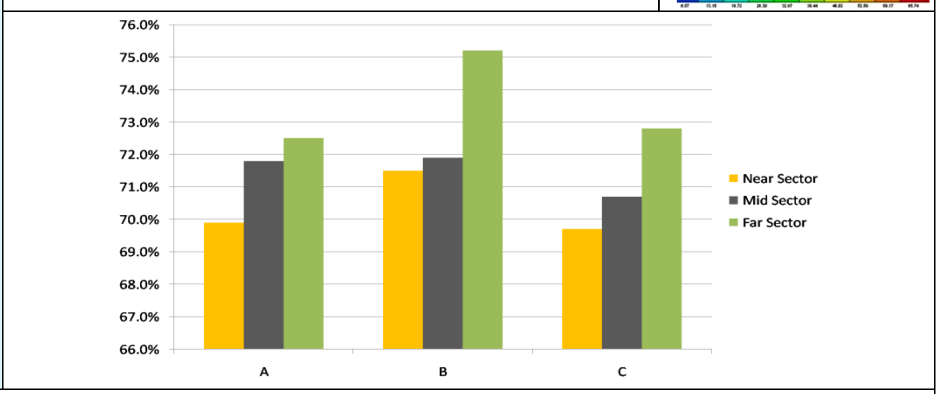


Figure 4.16– Percentage of enhancements in indoor age of air comparing to reference case performance[2]

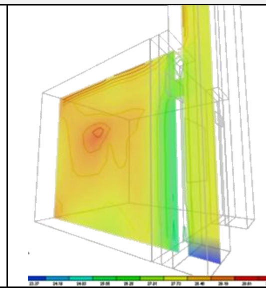
[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)
[2] *Ibid.*

Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 42.44 sec at B-Near zone.
- Overall age of air values vary from 42.44 to 53.55 sec, with an average value of 49.30 sec.

Operative Temperature (°C)

A	B	C	
28.4	28.46	28.31	**Far Sector**
28.34	28.72	28.42	**Mid Sector**
27.81	28.28	27.85	**Near Sector**



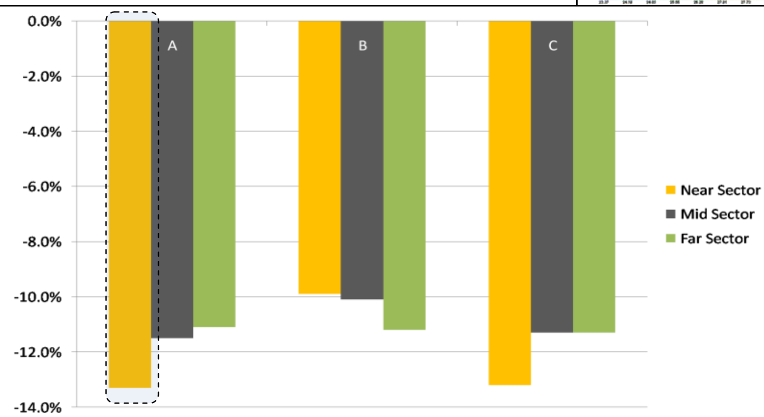


Figure 4.17– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique decreases the operative temperature by a maximum value of 4.3°C at A-Near zone.
- Overall decreases in operative temperature values vary from 3.1 to 4.3°C.
- In addition to the reduction of space temperature at night East conditions. by 1.55°C, the operative temperature also decreases by an average value of 3.6°C (11.3%).

C. West orientation

West simulation case is the same simulation data of west reference case condition. Within day conditions, the space average temperature while

[1] *Ibid.*

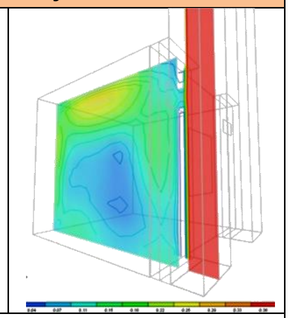
applying double wall is 32.46°C, in return, the reference space temperature is 34.25°C. This reduction of 1.79°C is due to thermal isolation and shading effect of double wall.

Double wall technique (West Day condition) results

Double wall / best performance / West / Day

Air Velocity Performance (m/s)

A	B	C	
0.14	0.22	0.14	**Far Sector**
0.12	0.24	0.12	**Mid Sector**
0.13	0.19	0.14	**Near Sector**



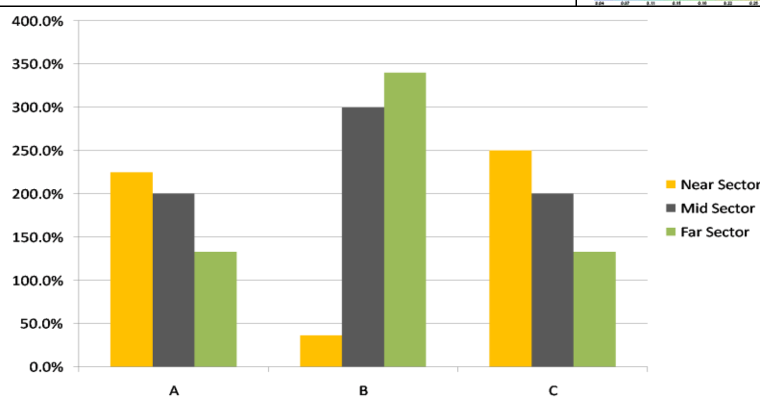


Figure 4.18– Percentage of changes in indoor air velocity comparing to reference case performance[1]

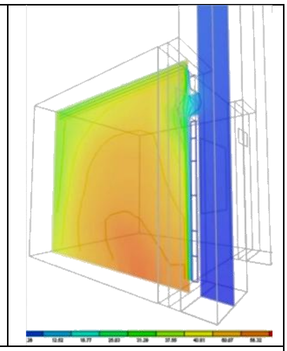
Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.24 m/s at B-Mid zone.
- Overall air velocity values vary from 0.12 to 0.24 m/s, with an average value of 0.16 m/s.

[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)

Age of Air Performance (sec)

A	B	C	
42.46	37.44	41.23	**Far Sector**
51.51	45.5	50.23	**Mid Sector**
51.73	46.96	53.85	**Near Sector**



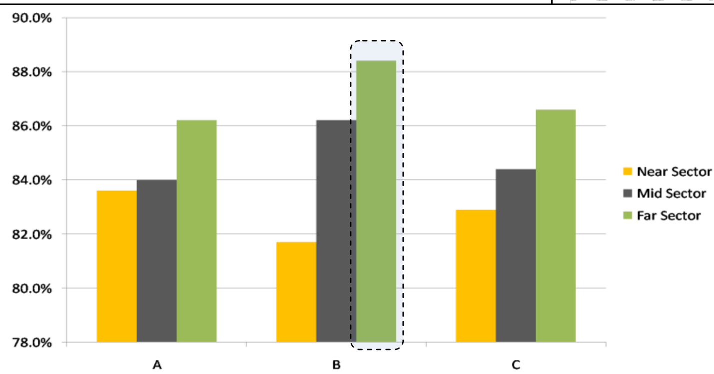


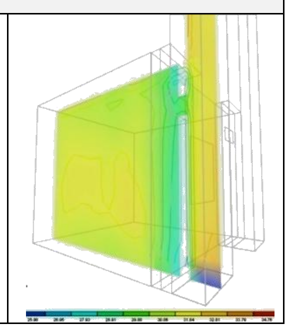
Figure 4.19– Percentage of enhancements in indoor age of air comparing to reference case performance[1]

Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 37.44 sec at B-Far zone.
- Overall age of air values vary from 37.44 to 53.85 sec, with an average value of 46.77 sec.
- Far sector records the highest percentage of enhancement within all zones.

Operative Temperature (°C)

A	B	C	
31.63	31.76	31.66	**Far Sector**
31.5	31.6	31.49	**Mid Sector**
30.98	31.18	30.9	**Near Sector**



[1] *Ibid.*

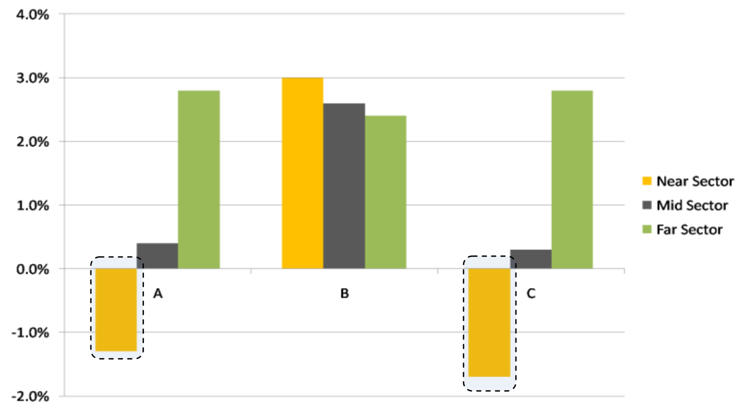


Figure 4.20– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique increses the operative temperature by a maximum value of 0.9°C at C-Far and A-Far zones.
- Overall increses in operative temperature values vary from 0.1 to 0.9°C , with decreases of 0.4°C at A-Near and C-Near zone.
- Although application of double wall decreases space temperature by 1.79°C, operative temperature rises by an average of 0.4°C (1.3%) due to high temperature of incoming air when ventialtion rates increase by technique application.

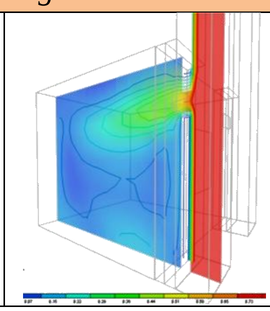
Within night conditions, the space average temperature while applying double wall is 28.55°C, in return, the reference space temperature is 31.27°C. This reduction of 2.72°C is due to thermal isolation of double wall.

Double wall technique (West Night condition) results

Double wall / best performance / West / Night

Air Velocity Performance (m/s)

A	B	C	
0.07	0.13	0.09	**Far Sector**
0.13	0.15	0.09	**Mid Sector**
0.17	0.18	0.1	**Near Sector**



[1] *Ibid.*

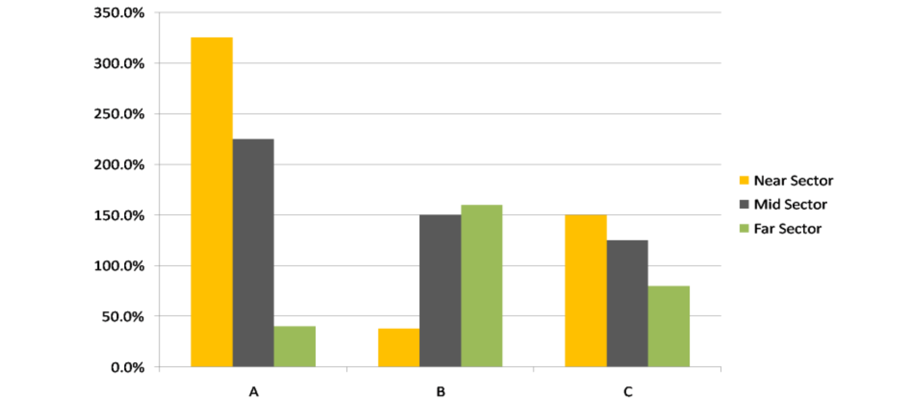


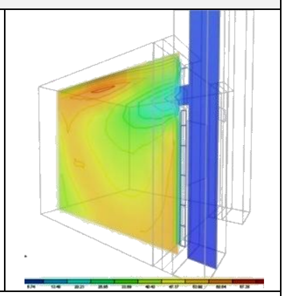
Figure 4.21– Percentage of changes in indoor air velocity comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the air velocity by a maximum value of 0.18 m/s at B-Near zone.
- Overall air velocity values vary from 0.07 to 0.18 m/s, with an average value of 0.12 m/s.

Age of Air Performance (sec)

A	B	C	
49.94	39.63	44	**Far Sector**
48.5	46.9	53.41	**Mid Sector**
41.92	42.67	52.96	**Near Sector**



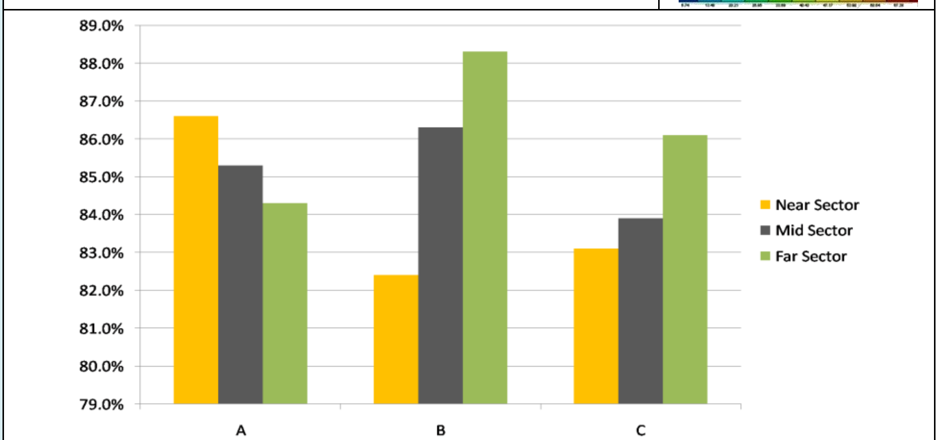


Figure 4.22– Percentage of enhancements in indoor age of air comparing to reference case performance[2]

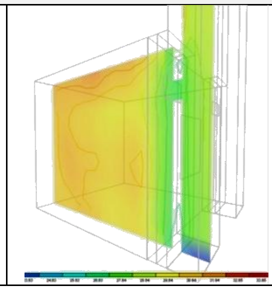
[1] The researcher, (DesignBuilder-Software, Energy plus weather data file, 2009)
[2] *Ibid.*

Discussion:

- Application of double wall technique reduces the age of air by a minimum value of 39.63 sec at B-Far zone.
- Overall age of air values vary from 39.63 to 53.41 sec, with an average value of 46.66 sec.

Operative Temperature (°C)

A	B	C	
30.75	30.25	30.52	**Far Sector**
30.38	30.41	30.51	**Mid Sector**
29.81	29.92	30.14	**Near Sector**



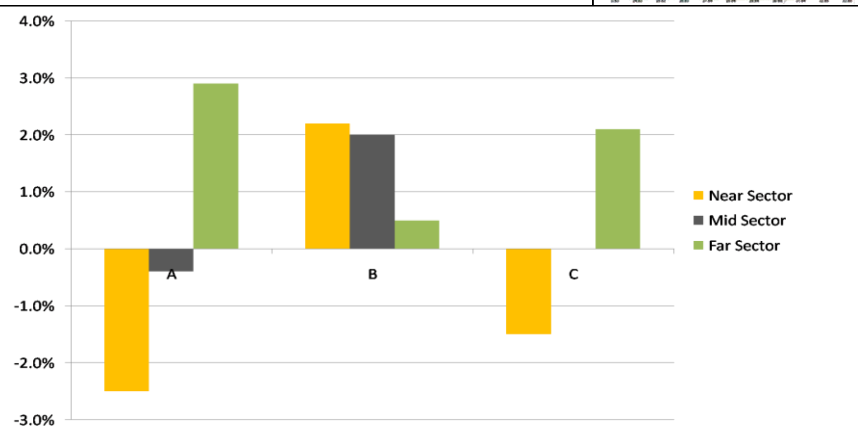


Figure 4.23– Percentage of changes in indoor operative temperature comparing to reference case performance[1]

Discussion:

- Application of double wall technique increases the operative temperature by a maximum value of 0.9°C at A-Far zone.
- Overall increases in operative temperature values vary from 0.2 to 0.9°C, with decreases within three zones vary from 0.1 to 0.8°C.
- Although application of double wall decreases space temperature by 2.72°C, average operative temperature inside space records an increase in the average operative temperature of 0.17°C due to thermal storage of space.

[1] *Ibid.*

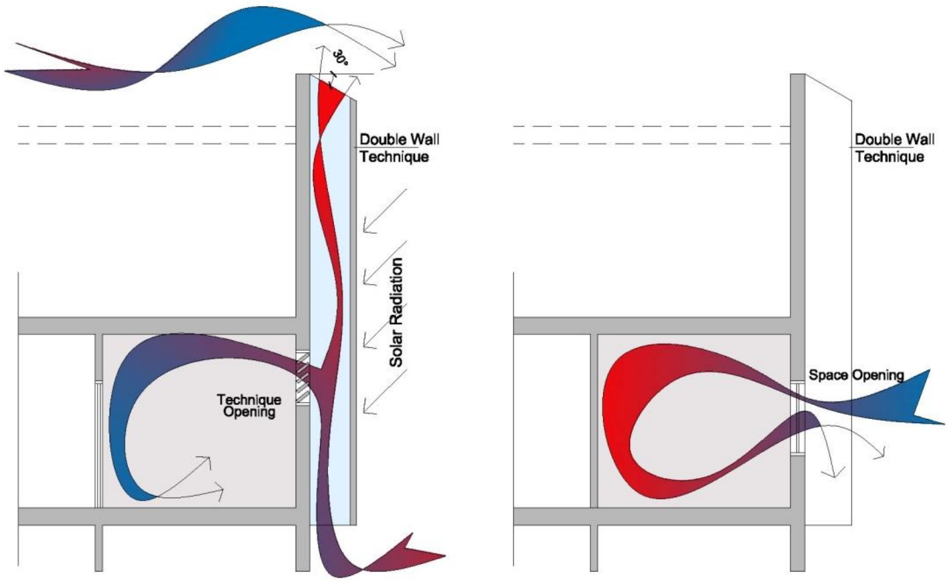


Figure 4.24– Air flow directions inside space due to double wall application[1]

4.2.3.3. Air flow within space

Through analysis of air velocity vectors within space due to applying of double wall technique, the deduced indoor air flow directions resulted from technique application are available. Figure 4.24 shows that technique openings act as air suppliers of incoming air from double wall cavity. The air then circulates inside space and drawn out of space through space opening due to pressure differences on space opening.

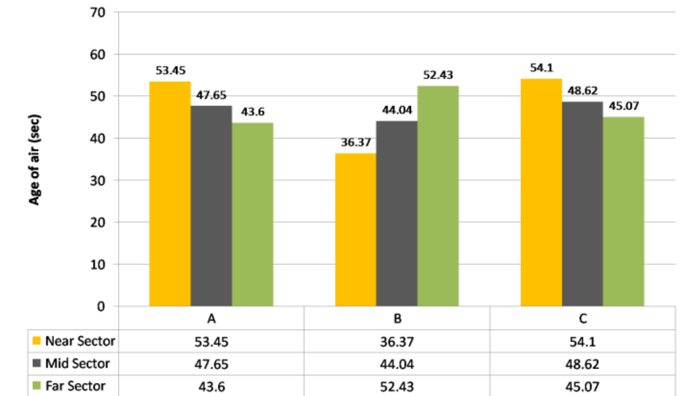
4.2.3.4. Chimney height variable

An additional variable was added to test the effect of chimney height on indoor ventilation rates. This variable is the height of the double wall. The study unit is located at the 3rd floor with a chimney begins at the same floor (one floor in height). Two other cases were tested: 1- chimney begins at the 2nd floor (2 floors in height) 2- chimney begins at the 1st floor (3 floors in height).The study was conducted within day conditions and south direction, with variables alternatives that achieve best technique performance.

[1] *Ibid.*

One Floor in Height

Age of Air (sec)

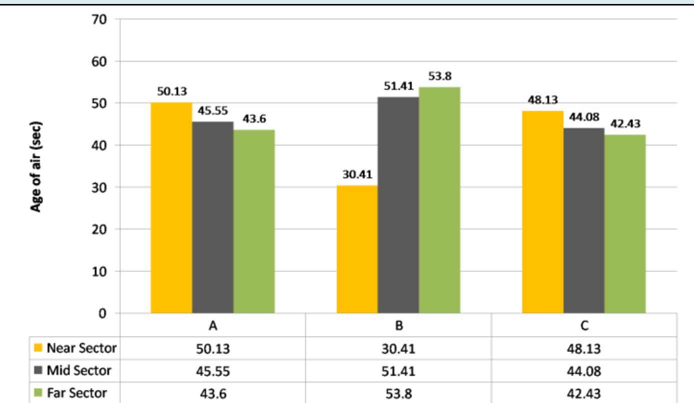


Average value of age of air inside space

47.26 sec

Two Floors in Height

Age of Air (sec)

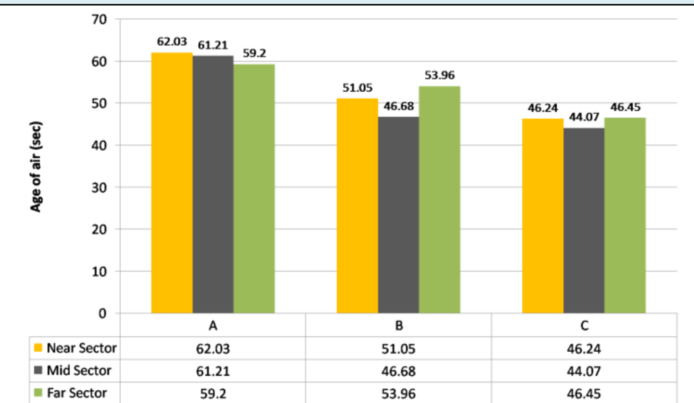


Average value of age of air inside space

45.50 sec

Three Floors in Height

Age of Air (sec)



Average value of age of air inside space

52.32 sec

The results show that chimney height does not heavily affect the ventilation rates inside the space, with a maximum total average difference in age of air values of around 7 seconds. This means that double wall system is applicable for applying in multi-storey buildings that fit the local contemporary residential typology.

4.3. Conclusion

The results conclusion can be divided into two stages. The first stage is to select double wall variables alternatives that achieve the best performance. The second stage is to compare the simulation results of reference case with those of double wall technique with alternatives that achieve best performance.

4.3.1. First stage conclusions *(technique variables)*

1- Air gap width (0.20, 0.40, and 0.60 m): the results showed that air gap of 0.40m showed the best ventilation rates values within space. Air gap of 0.20m performance decreased rapidly towards far zones achieving the worst enhancement values of ventilation rates. While air gap of 0.60m showed the lowest values in enhancement percentage of ventilation rates within near zones, with bad indoor air distribution. Air gap of 0.40m achieved an overall enhancement percentage of 84.8%, while air gaps of 0.20m and 0.60m achieve an overall enhancement percentage of 83.9% and 83% respectively. Architecturally, air gap of 0.60m does the more waste of floor area, while it achieves the worst overall performance.

2- Construction material (brick, glass, and concrete): the results revealed that all construction materials showed almost similar performance. Glass material showed a little increase in one zone. But referring to the special construction and high cost of glass construction, brick, as a commonly used local construction material, is considered the best alternative.

3- Opening dimensions (0.60x0.30, 0.60x0.45, and 0.06x0.60 m^2): the results showed that the overall performances of opening different dimensions (0.60x0.30, 0.60x0.45, and 0.06x0.60) were 83.9%, 83.5%, and 83% respectively. This means that an increase in technique opening area by 0.09 m^2 may reduce the system performance by around 0.5%. The results also monitored that dimensions of 0.60x0.30 achieve better percentage of enhancements within near and mid sectors. Within far sectors, the three different dimensions nearly behave the same.

4- Opening position (low, middle, and high): the results revealed that high position showed best performance within all far zones and B-sector, and achieved relative highest results not less than 81% at all zones, with an overall enhancement percentage of ventilation rates of 85.4%. Within other four zones, low position achieves a better performance but with low performance within far zones.

Due to the high position of the opening, far zone recorded significant flow rates within the study room of 3.35m in depth. Within reference case, it showed worse behavior. It means that applying double wall system positively induces the flow rates within all space depth not only close to exterior wall.

The results revealed that a combination of the following parameters: air gap of 0.40m, brick construction material, opening dimensions of (0.60mx0.30m), and opening high position results in best performance of ventilation rates inside space.

Chimney height

In a separate simulation analysis, study showed that chimney height does not heavily affect the ventilation rates inside space. This means that double wall system is applicable for applying within multi-storey buildings that fit the local contemporary residential typology.

4.3.2. Second stage conclusions *(orientation parameter)*

The second stage of simulation analysis is to compare the simulation results of reference case with those of double wall technique with alternatives that achieve best performance within daytime and nighttime conditions for each orientation:

1- South orientation:

Applying the double wall system within daytime conditions at the southern facade can enhance natural ventilation rates inside the space by mean value of 85.9% (reduction in mean age of air from 335.24 sec to 47.26 sec). System achieves an increase in indoor mean air velocity from 0.05 m/s to 0.13 m/s. System also reduces the indoor air temperature by 0.76°C (from 32.35°C to 31.59°C). Despite this, supplying space with high temperature ambient air affects negatively the comfort levels inside space and raises mean operative temperature by 1.4°C (from 29.14°C to 30.54°C).

Within nighttime conditions system can enhance ventilation rates by mean value of 85.3% (reduction in mean age of air from 336.22 sec to 49.55 sec). System achieves an increase in indoor mean air velocity from 0.05 m/s to 0.13 m/s. System also reduces the indoor air temperature by 1.56°C (from 30.41°C to 28.85°C), but with a raise in mean operative temperature by 0.93°C (from 28.98°C to 29.91°C).

It is concluded that application of double wall technique at southern facade enhances ventilation rates values, but caused decline to the thermal comfort levels.

2- East orientation:

Applying the double wall system within daytime conditions at the eastern facade can enhance natural ventilation rates inside the space by mean value of 68.9% (reduction in mean age of air from 342.68 sec to 106.47 sec). The system also reduces the indoor air temperature by 1.69°C (from 28.15°C to 26.46°C). In addition, system showed positive performance within comfort levels inside space with a reduction in mean operative temperature of 0.63°C (from 28.65°C to 28.02°C).

Within nighttime conditions system can enhance ventilation rates by mean value of 71.8% (reduction in mean age of air from 174.73 sec to 49.30 sec). System achieves an increase in mean air velocity from 0.06 m/s to 0.23 m/s. System also reduces the indoor air temperature by 1.55°C (from 30.50°C to 28.95°C), with reduction in mean operative temperature of 3.65°C (from 31.94°C to 28.29°C).

It is concluded that application of double wall technique at eastern facade enhances both ventilation rates values and thermal comfort levels.

3- West orientation:

Applying the double wall system within daytime conditions at the western facade can enhance natural ventilation rates inside the space by mean value of 85% (reduction in mean age of air from 311.06 sec to 46.77 sec). System achieves an increase in mean air velocity from 0.06 m/s to 0.16 m/s. System also reduces the indoor air temperature by 1.79°C (from 34.25°C to 32.46°C). Despite this, supplying space with high temperature ambient air affects negatively the comfort levels inside space and rises mean operative temperature by 0.37°C (from 31.04°C to 31.41°C).

Within nighttime conditions system can enhance ventilation rates by mean value of 85.3% (reduction in mean age of air from 316.35 sec to 46.66 sec). System achieves an increase in mean air velocity from 0.06 m/s to 0.12 m/s. System also reduces the indoor air temperature by 2.72 °C (from 31.27°C to 28.55°C), but with raise in mean operative temperature by 0.17°C (from 30.13°C to 30.30°C).

It is concluded that application of double wall technique at western facade within night conditions enhances ventilation rates values, but caused decline to the thermal comfort levels.

4.3.3. Double wall technique and tri-directional flow performances

The investigation has proved that applying double wall technique through single flow strategy can enhance the ventilation rates more than the tri-directional flow strategy, within similar conditions of time and orientation, by 77% (double wall technique average age of air is 47.26 sec, and tri-directional flow average age of air is 203.5 sec). The system can also reduce the space temperature by 0.12°C (from 31.71°C to 31.59°C) and the operative temperature by 1.17°C (from 31.71°C to 30.54°C), with no substantial increase in air velocity in the space. The increase in mean air speed is by only 0.01 m/s (from 0.12 m/s to 0.13 m/s).

4.3.4. Incoming air temperature parameter

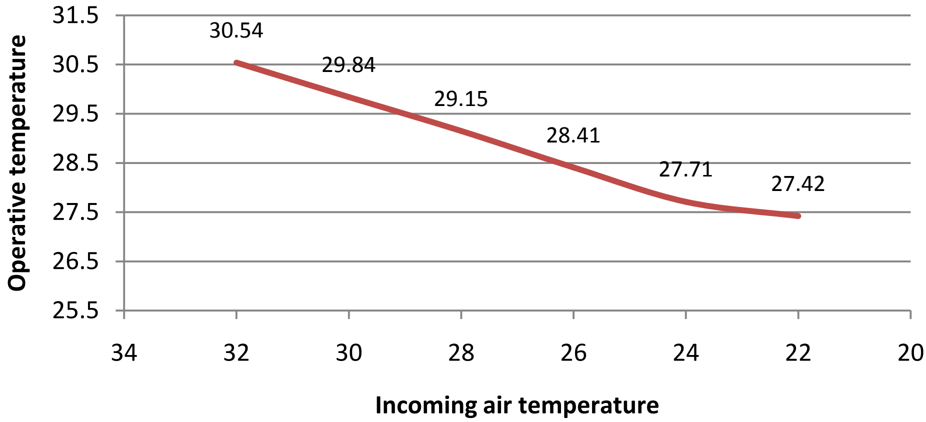


Figure 4.25. Effect of reducing incoming air temperature on indoor operative temperatures at southern façade at daytime simulation conditions

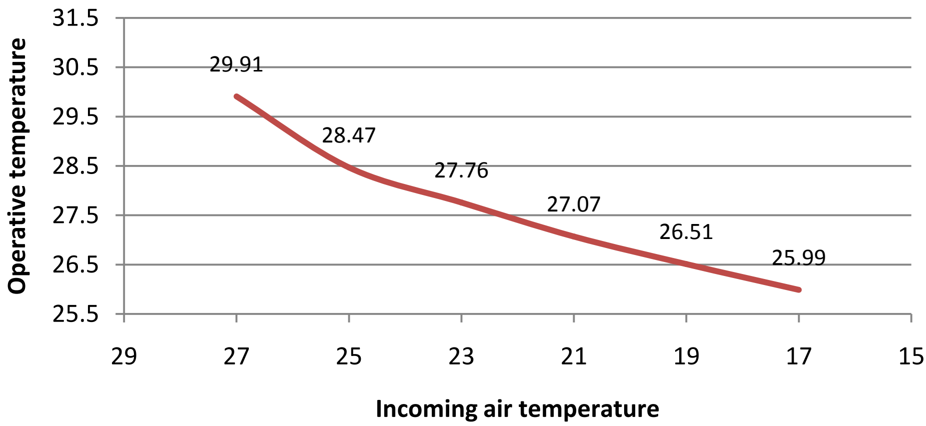


Figure 4. 26. Effect of reducing incoming air temperature on indoor operative temperatures at southern façade at nighttime simulation conditions

Based on the previous conclusions, a supplementary simulation study is conducted on application of double wall technique at southern facade with daytime and nighttime conditions. This study, shown in figures 4.25 and 4.26, revealed that reducing incoming air temperature while applying double wall technique can reduce the indoor mean operative temperature by around 0.3°C to 0.4°C for each reduction in incoming air temperature of 1.0°C. This gives promising indicators that applying double wall technique during warm season may enhance the thermal comfort conditions through high levels of ventilation rates.

Also it indicates that using any other radiative or evaporative technique in combination with double wall to reduce the incoming air temperature may raise the double wall performance in enhancing thermal comfort levels inside space, which ensures the conclusion mentioned before that to achieve better thermal indoor conditions with techniques that depend on thermal buoyancy, they should combined with another passive cooling strategy, like evaporative or radiative techniques.

Conclusion and Recommendations

Conclusion

According to main goal, the present research aimed to define natural ventilation passive techniques that are suitable and appropriate to be applied into the local climate of Cairo. The research methodology was to evaluate the efficiency of applying the natural ventilation passive techniques within a residential space on the indoor ventilation rates and thermal comfort within local hot summer climate. The research revealed that the techniques that depend on thermal buoyancy effect, as a working principle, could achieve significant high ventilation rates within local hot climate of high temperatures and solar radiation. The study also revealed that to achieve better thermal indoor conditions with these techniques, they should be combined with another passive cooling strategy, like evaporative or radiative techniques.

Double wall technique, with variables of air gap, construction material, opening dimensions, and opening position, was investigated within local summer conditions using EnergyPlus as a CFD simulation engine to study the system efficiency on flow rate and thermal comfort using only passive convective strategy within both day and night conditions and all orientations of solar exposure (east, south, and west orientations).

The research got some conclusions which can be shown within the following points:

1- Air velocity may not truly indicate the ventilation rates and so indoor air quality. This is due to the pressure differences that result a chaotic or semi-static air movement conditions that affect indoor air quality.

2- Space temperatures do not necessarily reflect thermal comfort levels where there is no obvious relation between reduction in space temperature and enhancements of thermal comfort levels. The results recorded maximum reduction in space temperature of 2.72°C, with an increase in operative temperature of 0.17°C within night west conditions. While with a reduction in space temperature of only 1.55°C, results recorded a reduction in operative temperature of 3.65°C within night east conditions.

3- High ventilation rates do not necessarily provide better thermal comfort conditions. As the factor of incoming ambient air temperature is a critical concern. At high ambient air temperatures, high ventilation rates may raise the operative temperature, and the feeling of discomfort and dissatisfaction.

4- Double wall height does not negatively affect the ventilation rates inside space. This means that double wall system is applicable for application in multi-storey buildings that fit the local contemporary residential typology.

The effect of applying the passive technique on ventilation rates:

It can be concluded that, by applying double wall technique with the given configurations, ventilation rates can be enhanced at all orientations by mean values vary from 68.9% to 85.9%, with minimum mean age of air value of 129.98 sec (260 L/s). This means that, in case of high outdoor air quality, applying double wall system can provide high levels of indoor air quality. The maximum recorded mean air velocity was 0.3 m/s. This is still in range of acceptable indoor air speeds.

The effect of applying the passive technique on thermal comfort:

It can be concluded from results that applying technique within eastern façade can enhance thermal comfort levels inside space by a maximum mean operative temperature value of 3.65°C at night. Referring to figure 1.2 (acceptable operative temperatures for naturally ventilated spaces), eastern façade technique application can provide mean operative temperatures inside space that achieve the 80% acceptability limits at day, and 90% acceptability levels at night.

About southern and western orientations, applying system did not enhance the thermal comfort levels at day or night conditions. So, supplementary simulations were conducted on southern façade within day and night conditions to study the effect of reducing incoming air temperature on indoor operative temperatures.

The effect of reducing incoming air temperature:

The supplementary study revealed that reducing incoming air temperature while applying double wall technique can reduce the indoor mean operative temperature by around 0.3°C to 0.4°C for each reduction in an incoming air temperature of 1.0°C. This gives promising indicators that applying double wall technique during warm season, or combining the system with another passive cooling strategy, may enhance the thermal comfort conditions through high levels of ventilation rates.

Recommendations

For future investigations on the techniques that depend on thermal buoyancy within hot arid local climate, the research introduces some recommendations:

1- The importance of simulation performance analysis for such type of study.

2- The conduction of a validation case and field measurements for the reference case to evaluate research comparative simulation results, and validate the technique for actual applications.

3- Completing the set of results by CFD simulations for double wall application within warm seasons to study system efficiency with lower ambient air temperatures.

4- The investigation of the study unit with different building levels to support the concept of system applicability within multi-storey residential building.

5- Studying the integration of another passive strategy to the convective strategy, like evaporative or radiative strategy or both, to study the effect of merging a supplementary technique on the thermal behavior of the residential space.

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Appendices

Appendix -A- Definitions and explanations

***Clo**:* A unit used to express the thermal insulation provided by garments and clothing ensembles, where 1 clo = 0.155 m^2 °C/W[1].

Humidity ratio: the ratio of the mass of water vapor to the mass of dry air in a given volume.

Indoor Air Quality: Air; toward which; a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation , and in which there are not likely to be contaminants at concentrations that are known to pose a health risk[2].

The changes in life style were the main reason in the existing of what is called “sick building syndrome”. Low indoor air quality is one of the most factors that can define the sick building, as pollutants within our homes have been recognized as threats to our health. Therefore, the removal of contaminants generated within inner volume is a vital process, and can be achieved by keeping the air quality within an acceptable level with comfortable levels of temperature and humidity. One of the main purposes of ventilation is to provide acceptable indoor air quality[3].

***Mean monthly outdoor air temperature**:* temperature that is based on the arithmetic average of the mean daily minimum and mean daily maximum outdoor dry-bulb temperatures for the month in question.

***Mean Radiant Temperature**:* The uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

***Met**:* A unit is used to describe the energy generated inside the body due to metabolic activity, and defined as 58.2 W/m^2, which is equal to the energy

[1] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 2)

[2] (ASHRAE-Standard, ASHRAE Standard 62-2-2007 (Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, 2007, p. 3)

[3] *Ibid*. p.3

produced per unit surface area of an average person seated at rest (the surface area of an average person is 1.8 m^2)

Natural Ventilation: Ventilation is, essentially, the flow of air between the inner space and the outer environment through the ventilation vents[1] within a well-known time, for the following purposes:

- Air Quality Control: By replacing internal air with cleaner outdoor air.
- Direct Cooling: By replacing inner warm indoor air with cooler outdoor air with sufficient velocity to enhance convective transport of heat and moisture.
- Indirect Cooling: By pre-cooling thermally massive components of the building fabric, or a thermal storage system by thermal conduction[2].

Operative Temperature*:* The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

Predicted Mean Vote (PMV): An index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale.

Predicted Percentage of Dissatisfied (PPD)*:* An index establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV[3].

Thermal comfort*:* that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Thermal comfort index in naturally ventilated buildings: Latest studies show that individuals are more likely to adapt to seasonal variations when they are given the choice to control solar shading and air velocity, and thus larger variation range might be allowed for indoor air temperature. This range is increased when natural or hybrid ventilation is used for night cooling of building thermal mass, while mean radiant temperature of wall surface would decrease indoor air temperature.

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[1] (Linden, The Fluid Mechanics of Natural Ventilation, 1999, p. 203)
[2] (Steven J. Emmerich, Natural Ventilation Review and Plan for design and Analysis Tools, 2001, p. 3)
[3] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 3)

According to CIBSE (Chartered Institution of Building Services Engineers, UK), the benefits of air velocity and radiant temperature may be estimated using a thermal comfort index equals to the average of mean radiant temperature, and room air temperature, as follows:

$Tc = (Tmr + Ta\sqrt{10u}) / (1 + \sqrt{10u})$

Where,

Tc (°C) is the comfort temperature,

Tmr (°C) is the mean radiant temperature,

Ta (°C) is the room air temperature, and

U (m/s) is the air velocity

For low air velocities, $u \approx 0.1$ m/s, the resultant comfort temperature can be estimated as the simple average of the mean radiant temperature and room air temperature, Tc = 0.5Tmr + 0.5Ta. At relatively high air velocities, $u \approx 2$ m/s, the average is dominated by the room air temperature, Tc = 0.2Tmr + 0.8Ta, reducing the impact of radiant exchange[1].

Ventilation Rate: Ventilation rate can be clarified as follows:

- Total amount of air passing into or out of the room per unit time (litters/second)
- The amount of air supplied per occupant / unit time.
- The number of air changes in the space per hour. The changes here do not mean that all the air inside the room is totally replaced a given number of times per hour, but they indicate to the number of times that an air volume equals the volume of space moving through the space.

Alterations to the natural compositions of dry air by human activities are to reduce the oxygen content, increase the carbon dioxide content, and add water vapor and odors. A little decrease in Oxygen concentration (1-2%) has a little effect on human health, but the increase in Carbon Dioxide levels would cause health problems and discomfort. The minimum ventilation rate

[1] (Santamouris M. , Solar Thermal Technologies for Buildings (The State of The Art), 2003, p. 117)

required to hold the CO2 level in 0.25%1; is 2.5 L/s per person for sedentary activity. This rate provides safety factors for increased activity or reduced ventilation2.

Whole-Building Ventilation: There are three primary sets of requirements to achieve indoor ventilation strategy; those sets involve *Whole-Building Ventilation, Local Exhaust, and Source Control. Whole-building ventilation* is intended to bring fresh air into the general environment to clear unavoidable contaminants emitted from people, materials, and background processes. *Local ventilation* is intended to remove pollutants from specific rooms in which 'sources' are expected due to their functions; before they spread throughout the house (e.g. Kitchens and bathrooms). While the most effective strategy to reduce the exposure to pollutants; is usually to prevent pollutants from being released into the indoor environment, and this strategy is called 'source control', as source is defined as 'an indoor object, person, or activity from which indoor air contaminants are released', while any contaminants from outdoor sources or from high-polluting events like smoking cannot be taken into consideration with previous definition[3].

In whole-building ventilation, ventilation system should provide whole the building with outdoor air each hour by no less than the rates specified in table 1, or equation 1, based on the floor area of the ventilated space and number of bedrooms.

$Q = 0.05\ A_{floor} + 3.5\ (N_{br} + 1)$..Equation A.1

Where,

Q = flow rate (ventilation rate required), L/s

A_{floor} = floor area, m^2

N_{br} = number of bedrooms

[1] The normal percentage of Carbon Dioxide in Dry air in 0.03%, normal healthy people can tolerate concentrations of Carbon Dioxide until 0.5% without undesirable symptoms.

[2] (ASHRAE-Standard, ASHRAE Standard 62.1.2007 (Ventilation for Acceptable Indoor Air Quality), 2007, p. 14)

[3] (ASHRAE-Standard, ASHRAE Standard 62-2-2007 (Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, 2007, pp. 2,3)

Table A.1 and equation A.1 assume two persons in a one-bedroom dwelling unit and an additional person for each additional bedroom. When higher occupant densities are known, the rate shall be increased by 3.5 L/s for each additional person[1].

In local ventilation strategy, the minimum required delivered ventilation rate during each hour of operation shall be at least 50 L/s for kitchens, and 25 L/s for bathrooms[2].

Ventilation Air Requirements, L/s

Floor Area (m^2)	Bedrooms				
	0–1	2–3	4–5	6–7	>7
<139	14	21	28	35	42
139.1–279	21	28	35	42	50
279.1–418	28	35	42	50	57
418.1–557	35	42	50	57	64
557.1–697	42	50	57	64	71
>697	50	57	64	71	78

Table A.1 – Whole-Building required ventilation rates[3]

1 (*Ibid.*, p.4)
2 (*Ibid.*, p.6)
3 (*Ibid.*, p.4)

Appendix -B- Acceptable Thermal Conditions

This appendix specifies the conditions in which a well-known percentage of occupants will find the indoor environment thermally acceptable. Information herein is ready for applying on indoor spaces at normal atmospheric pressure (up to 3000 m above sea level) designed for human occupancy for periods not less than 15 minutes. These thermal conditions are considered regarding the environmental factors of temperature, thermal radiation, humidity, and air speed, and the personal factors of activity, and clothing within a steady state, and regardless non-thermal environmental factors like air quality, acoustics, and illumination, or other physical, chemical, or biological space contaminants that may affect comfort or health[1].

The environmental conditions required for comfort are not the same for everyone because there are large variations, both physically and psychologically, from person to another. However, environmental thermal conditions determined here are necessary to achieve acceptance by a specified percentage of occupants of space.

There are six primary factors that must be addressed when defining conditions for thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. All of these factors may vary with time, so the information here only addresses thermal conditions in a steady state.

As a result, people entering a space that meets the conditions stated here may not immediately find the conditions comfortable if they have experienced different environmental conditions just before entering the space. The effect of previous exposure or activity may affect comfort perceptions for approximately one hour[2].

[1] (Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 2)
[2] (*Ibid.*, p.4)

1. Operative Temperature

For given values of humidity, air speed, metabolic rate, and clothing insulation, a comfort zone may be determined. The comfort zone is defined in terms of a range of operative temperatures that provide acceptable thermal environmental conditions or in terms of the combinations of air temperature and mean radiant temperature that people find thermally acceptable.

The following two sections describe methods that are used to determine temperature limits for the comfort zone. The graphical method is used for determining the comfort zone that may be used for many typical applications. The computer program method that based on a heat balance model is used to determine the comfort zone for a wider range of applications[1].

1.1. Graphical Method

This method is applied to spaces where the occupants have activity levels that result in metabolic rates between 1.0 and 1.3 met, and where clothing is worn that provides between 0.5 and 1.0 clo of thermal insulation.

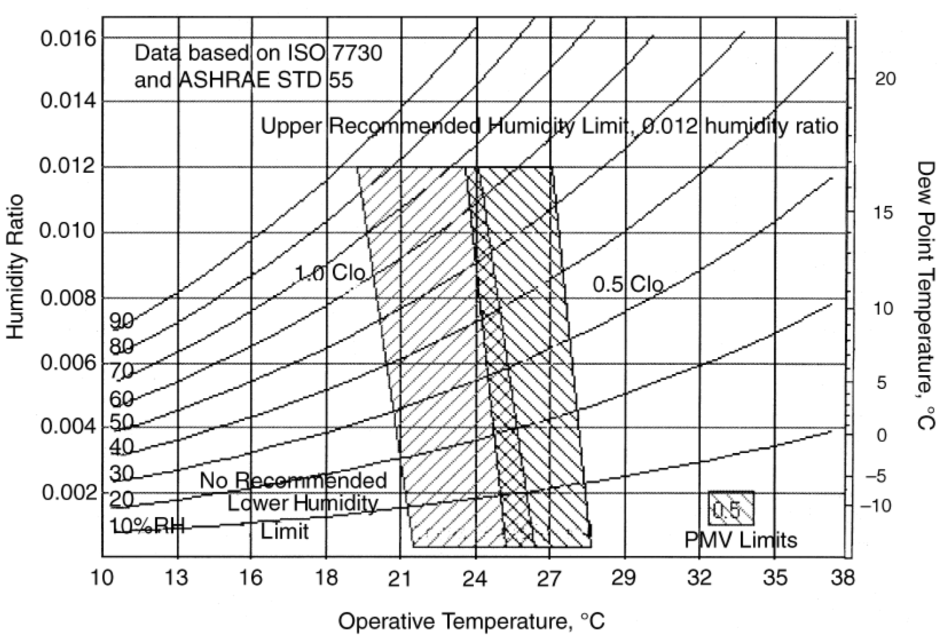

Figure B.1 - Acceptable range of operative temperature and humidity[2]

[1] (*Ibid.*, p.4)
[2] (*Ibid.*, p.4)

Appendix C is assigned for viewing estimation of metabolic rates, and appendix D is assigned for viewing estimation of clothing insulation.

The range of operative temperatures presented in Figure B.1 is for 80% occupant acceptability. This is based on a 10% dissatisfaction criteria for general (whole body) thermal comfort based on the PMV-PPD index, plus an additional 10% dissatisfaction that may occur from local (partial body) thermal discomfort.

Figure B.1 specifies the comfort zone for environments that meet the above criteria and where the air speeds are not greater than 0.20 m/s. Two zones are shown: one for 0.5 clo of clothing insulation and the other for 1.0 clo of insulation. These levels are typical clothing insulation levels when the outdoor environment is warm and cool, respectively.

The operative temperature range allowed for intermediate values of clothing insulation may be determined by linear interpolation between the limits for 0.5 clo and 1.0 clo, using the following relationships:

$$T_{min,\,Icl} = [(I_{cl} - 0.5\ clo)\ T_{min,\ 1.0\ clo} + (1.0\ clo - I_{cl})\ T_{min,\ 0.5clo}]\ /\ 0.5\ clo$$

$$T_{max,\,Icl} = [(I_{cl} - 0.5\ clo)\ T_{max,\ 1.0\ clo} + (1.0\ clo - I_{cl})\ T_{max,\ 0.5clo}]\ /\ 0.5\ clo$$

Where,

$T_{max,\,Icl}$ = upper operative temperature limit for clothing insulation I_{cl}.

$T_{min,\,Icl}$ = lower operative temperature limit for clothing insulation I_{cl}.

I_{cl} = thermal insulation of the clothing in question (clo).

Figure B.1 specifies the upper recommended humidity limit by 0.012 humidity ratio, with no recommended lower humidity limit. Air speeds greater than 0.20 m/s may be used to increase the upper operative temperature limit for the comfort zone in certain circumstances[1].

1.2. Computer Model Method

This method may be applied to spaces where the occupants have activity levels of metabolic rates between 1.0 met and 2.0 met, clothing is worn that

[1] (Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, pp. 4, 5)

provides 1.5 clo or less of thermal insulation, and where air speeds are not greater than 0.20 m/s.

The ASHRAE thermal sensation scale, which was developed for use in quantifying people's thermal sensation, is defined as follows:

+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

Table B.2. Thermal sensation scale[1]

The predicted mean vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort to the average response of people on the above scale. The PPD (predicted percentage of dissatisfied) index is related to the PMV as defined in Figure B.2. It is based on the assumption that people voting +2, +3, –2, or –3 on the thermal sensation scale are dissatisfied, and the simplification that PPD is symmetric around a neutral PMV.

Table B.3 defines the recommended PPD and PMV range for typical applications. The comfort zone is defined by the combinations of air temperature and mean radiant temperature for which the PMV is within the recommended limits specified in Table B.3.

The PMV model is calculated with the air temperature and mean radiant temperature in question along with the applicable metabolic rate, clothing insulation, air speed, and humidity. If the resulting PMV value generated by the model is within the recommended range, the conditions are within the comfort zone.

[1] (*Ibid.*, p.5)

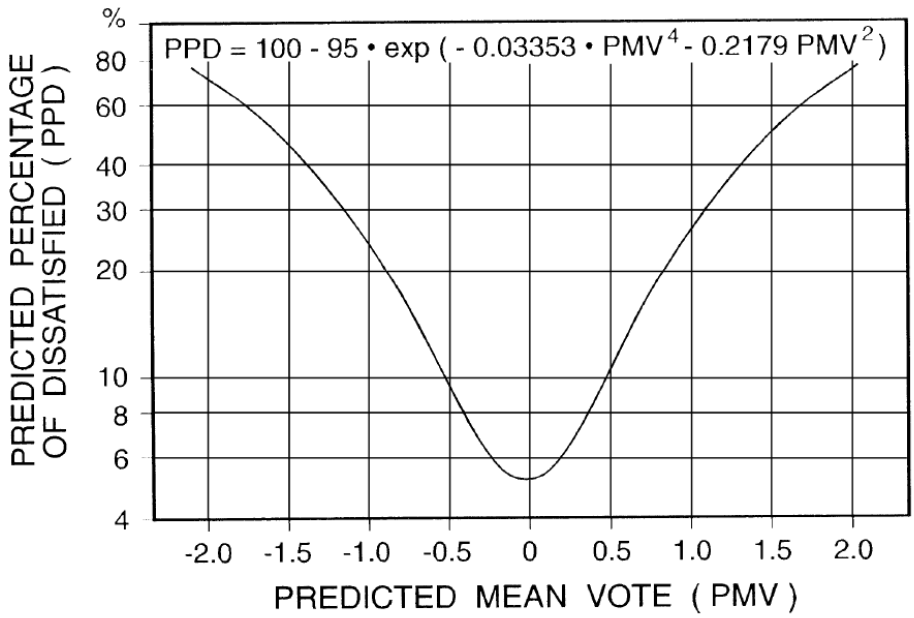

Figure B.2- Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV)[1]

PPD	PMV range
< 10	-0.5 < PMV < +0.5

Table B.3. Acceptable Thermal Environment for General Comfort[2]

2. Humidity Limits

The recommended humidity ratio is at or below 0.012, which corresponds to a water vapor pressure of 1.910 kPa at standard pressure or a dew-point temperature of 16.8°C.

3. Elevated Air Speed

Precise relationships between increased air speed and improved comfort have not been established. Generally, elevated air speed can be used to increase the maximum temperature for acceptability if the affected occupants are able to control the air speed. The amount that the temperature may be increased is shown in Figure B.3. This figure applies to a lightly clothed person (with clothing insulation between 0.5 clo and 0.7 clo) who is engaged in near

[1] (*Ibid.*, p.5)
[2] (*Ibid.*, p.6)

sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met).

The indicated increase in temperature depends on both the mean radiant temperature (Tr) and the air temperature (Ta). Both temperatures increase by the same amount with respect to the starting point. When the mean radiant temperature is low and the air temperature is high, as in -10° C and -5° C curves, elevated air speed is less effective at increasing heat loss. Conversely, elevated air speed is more effective at increasing heat loss when the mean radiant temperature is high and the air temperature is low.

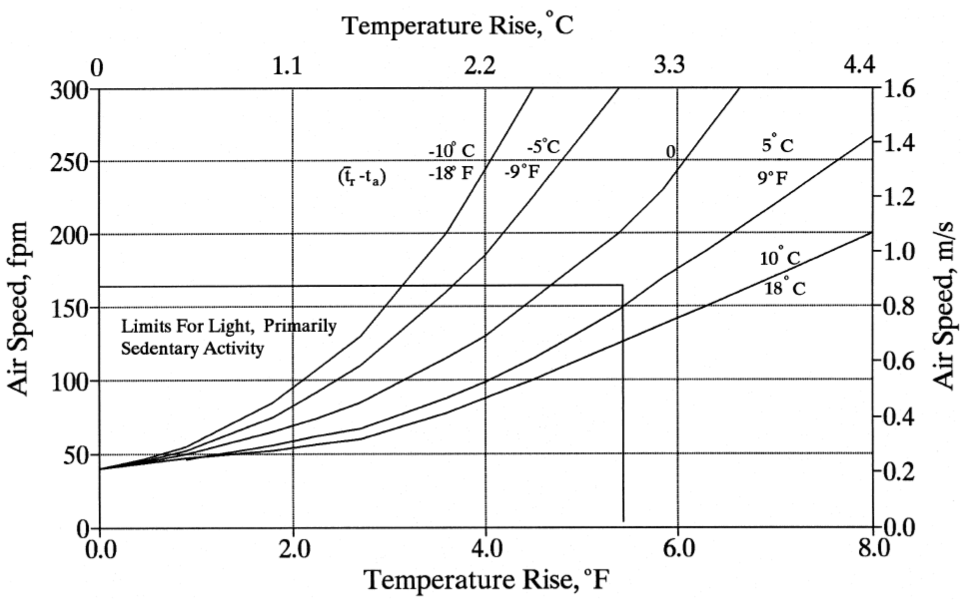

Figure B.3 - Air speed required for offsetting increased temperature[1]

Elevated air speed may be used to offset an increase in the air temperature and the mean radiant temperature, but not by more than 3.0°C (5.4°F) above the values for the comfort zone without elevated air speed. The required air speed may not be higher than 0.8 m/s. As, with higher air speeds, large individual differences exist between people with regard to the preferred air speed.

Therefore, the elevated air speed must be under the direct control of the affected occupants. The benefits that can be gained by increasing air speed

[1] (*Ibid.*, p.6)

depend on clothing and activity. Due to increases in skin wetness at heavy activities, the effect of increased speed is greater with elevated activity than with sedentary activity. Due to increased amounts of exposed skin, the effect of increased air speed is greater with lighter clothing.
Thus, Figure B.3 is conservative for activity levels above 1.3 met and/or for clothing insulation less than 0.5 clo and may be applied in these circumstances[1].

[1] (*Ibid.*, p.6)

Appendix -C- Metabolic Rates for Typical Activities

Activity	Met Units	Metabolic Rate W/m²	(Btu/h·ft²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0-2.4	115-140	(37-44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

Table C. 4 – Metabolic rates for typical activities[1]

[1] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 15)

The values in table C.4 represent typical metabolic rates per unit of skin surface area for an average adult (The surface area of an average person = 1.8 m^2). This appendix provides additional information for estimating and measuring activity levels, and general guidelines for the use of these data.

Every activity that may be of interest and not included in this table, one should use his judgment to match the activities being considered to comparable activities in the table. Some of the data in this table are reported as a range, and some as a single value. For all activities except sedentary activities, the metabolic rate for a given activity is likely to have a substantial range of variation that depends on the individual performing the task and the circumstances under which the task is performed.

A time-weighted average metabolic rate may be used for individuals with activities that vary over a period of one hour or less. For example, a person who typically spends 30 minutes out of each hour “lifting/packing,” 15 minutes “filing, standing,” and 15 minutes “walking about” has an average metabolic rate of $0.50 \times 2.1 + 0.25 \times 1.4 + 0.25 \times 1.7 = 1.8$ met. Such averaging should not be applied when the period of variation is greater than one hour. For example, a person who is engaged in “lifting/packing” for one hour and then “filing, standing” the next hour should be treated as having two distinct metabolic rates.

As metabolic rates increase above 1.0 met, the evaporation of sweat becomes an increasingly important factor for thermal comfort. The PMV method does not fully account for this factor, and these data should not be applied to situations where the time-averaged metabolic rate is above 2.0 met. Typically, rest breaks (scheduled or hidden) or other operational factors (get parts, move products, etc.) combine to limit time-weighted metabolic rates to about 2.0 met in most applications.

Time averaging of metabolic rates only applies to an individual. The metabolic rates associated with the activities of various individuals in a space may not be averaged to find a single average metabolic rate to be applied to that space. The range of activities of different individuals in the space, and the environmental conditions required for those activities, should be considered in applying data stated at this appendix. For example, the customers in a restaurant may have a metabolic rate near 1.0 met, while the servers may have metabolic rate closer to 2.0 met. Each of these groups of occupants should be considered separately in determining the conditions required for comfort. In some situations, it will not be possible to provide an acceptable level or the same level of comfort to all disparate groups of occupants (e.g., restaurant customers and servers)[1].

[1] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 16)

Appendix -D- Clothing Insulation

The amount of thermal insulation worn by a person has a substantial impact on thermal comfort and is an important variable in applying the requirements mentioned at this appendix. Clothing insulation is expressed in a number of ways. In this appendix, the clothing insulation expressed as a clo-value (I_{cl}) is used.

The insulation provided by clothing can be determined by a variety of means. The tables in this appendix may be used to estimate clothing insulation using one of the methods described below.

Regardless of the source of the clothing insulation value, these requirements shall not be used with clothing ensembles with more than 1.5 clo of insulation. Also, these requirements should not be used with clothing that is highly impermeable to moisture transport (e.g., chemical protective clothing or rain gear).

Three methods for estimating clothing insulation are presented. These methods are listed in order of accuracy and should be used in this order of preference.

Method 1: Table D.5 lists the insulation provided by a variety of common clothing ensembles. If the ensemble in question matches reasonably well with one of the ensembles in this table, then the indicated value of I_{cl} should be used.

Method 2: Table D.6 presents the thermal insulation of a variety of individual garments. These garments may be added to or subtracted from the ensembles in Table D.5 to estimate the insulation of ensembles that differ in garment composition from those in Table D.5. For example, if long underwear bottoms are added to Ensemble 5 in Table D.5, the insulation of the resulting ensemble is estimated as I_{cl} = 1.01 clo + 0.15 clo = 1.16 clo.

Method 3: A complete clothing ensemble may be defined using a combination of the garments listed in Table D.6. The insulation of the ensemble is estimated as the sum of the individual values listed in Table D.6.

For example, the estimated insulation of an ensemble consisting of overalls worn with a flannel shirt, T-shirt, briefs, boots, and calf-length socks is I_{cl} = 0.30 + 0.34 + 0.08 + 0.04 + 0.10 + 0.03 = 0.89 clo.

Tables D.5 and D.6 are for a standing person. A sitting posture results in a decreased thermal insulation due to compression of air layers in the clothing. This decrease may be offset by insulation provided by the chair. Table D.7 shows the net effect on clothing insulation for typical indoor clothing ensembles that results from sitting in a chair.

Clothing Insulation Values for Typical Ensembles[a]

Clothing Description	Garments Included[b]	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

a Data are from Chapter 8 in the *2001 ASHRAE Handbook—Fundamentals*.
b All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Table D.5 – Clothing insulation values for typical ensembles[1]

These data may be used to adjust clothing insulation calculated using any of the above methods. For example, the clothing insulation for a person wearing ensemble 3 from Table D.5 and sitting in an executive chair is 0.96 clo + 0.15 clo = 1.11 clo. For many chairs, the net effect of sitting is a minimal change in clothing insulation. For this reason, it is recommended that no adjustment

[1] (ASHRAE-Standard, ASHRAE Standard 55-2004 (Thermal Environmental Conditions for Human Occupancy), 2004, p. 18)

be made to clothing insulation if there is uncertainty as to the type of chair and/or if the activity for an individual includes both sitting and standing.

Tables D.5 and D.6 are for a person that is not moving. Body motion decreases the insulation of a clothing ensemble by pumping air through clothing openings and/or causing air motion within the clothing. This effect varies considerably depending on the nature of the motion (e.g., walking versus lifting) and the nature of the clothing (stretchable and snug fitting versus stiff and loose fitting). Because of this variability, accurate estimates of clothing insulation for an active person are not available unless measurements are made for the specific clothing under the conditions in question (e.g., with a walking manikin). A rough estimate of the clothing insulation for an active person is:

$I_{cl,\ active} = I_{cl} \times (0.6 + 0.4 / M)$ 1.2 met $< M <$ 2.0 met

Where M is the metabolic rate in met units, and I_{cl} is the insulation without activity.

For metabolic rates less than or equal to 1.2 met, no adjustment is recommended. When a person is sleeping or resting in a reclining posture, the bed and bedding may provide considerable thermal insulation. It is not possible to determine the thermal insulation for most sleeping or resting situations unless the individual is immobile. Individuals will adjust the bedding to suit individual preferences. Provided adequate bedding materials are available, the thermal environmental conditions desired for sleeping and resting vary considerably from person to person and cannot be determined by the methods included here.

Clothing variability among occupants in a space is an important consideration. This variability takes two forms. In the first form, different individuals wear different clothing due to factors unrelated to the thermal conditions. Examples include different clothing style preferences for men and women and offices where managers are expected to wear suits while other staff members may work in shirtsleeves. In the second form, the variability results from adaptation to individual differences in response to the thermal environment. For example, some individuals may wear sweaters, while others wear short-sleeve shirts in the same environment if there are no constraints limiting what is worn.

The first form of variability may result in differences in the requirements for thermal comfort between the different occupants. In this situation, it is not acceptable to determine the average clothing insulation of various groups of occupants to determine the thermal environmental conditions needed for all occupants. Each group must be considered separately. Where the variability within a group of occupants is of the second form and is a result only of individuals freely making adjustments in clothing to suit their individual thermal preferences, it is acceptable to use a single representative average clothing insulation value for everyone in that group.

For near sedentary activities where the metabolic rate is approximately 1.2 met, the effect of changing clothing insulation on the optimum operative temperature is approximately 6.0°C per clo. For example, Table D.6 indicates that adding a thin, long-sleeve sweater to a clothing ensemble increases clothing insulation by approximately 0.25 clo. Adding this insulation would lower the optimum operative temperature by approximately 6.0°C/clo × 0.25 clo = 1.5°C. The effect is greater with higher metabolic rates[1].

[1] (*Ibid.*, pp.16, 17)

Garment Insulation[a]

Garment Description[b]	I_{clu} (clo)	Garment Description[b]	I_{clu} (clo)
Underwear		**Dress and Skirts**[c]	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	**Sweaters**	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Pantyhose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	**Suit Jackets and Vests**[d]	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10
Calf-length socks	0.03	Sleeveless vest (thick)	0.17
Knee socks (thick)	0.06	Single-breasted (thin)	0.36
Boots	0.10	Single-breasted (thick)	0.42
Shirts and Blouses		Double-breasted (thin)	0.44
Sleeveless/scoop-neck blouse	0.13	Double-breasted (thick)	0.48
Short-sleeve knit sport shirt	0.17	**Sleepwear and Robes**	
Short-sleeve dress shirt	0.19	Sleeveless short gown (thin)	0.18
Long-sleeve dress shirt	0.25	Sleeveless long gown (thin)	0.20
Long-sleeve flannel shirt	0.34	Short-sleeve hospital gown	0.31
Long-sleeve sweatshirt	0.34	Short-sleeve short robe (thin)	0.34
Trousers and Coveralls		Short-sleeve pajamas (thin)	0.42
Short shorts	0.06	Long-sleeve long gown (thick)	0.46
Walking shorts	0.08	Long-sleeve short wrap robe (thick)	0.48
Straight trousers (thin)	0.15	Long-sleeve pajamas (thick)	0.57
Straight trousers (thick)	0.24	Long-sleeve long wrap robe (thick)	0.69
Sweatpants	0.28		
Overalls	0.30		
Coveralls	0.49		

a Data are from Chapter 8 in the *2001 ASHRAE Handbook—Fundamentals*.
b "Thin" refers to garments made of lightweight, thin fabrics often worn in the summer; "thick" refers to garments made of heavyweight, thick fabrics often worn in the winter.
c Knee-length dresses and skirts.
d Lined vests.

Table D.6 – Garment insulation[1]

Typical Added Insulation when Sitting on a Chair

(Valid for Clothing Ensembles with Standing Insulation Values of 0.5 clo < I_{cl} < 1.2 clo)

Net chair[a]	0.00 clo
Metal chair	0.00 clo
Wooden side arm chair[b]	0.00 clo
Wooden stool	+0.01 clo
Standard office chair	+0.10 clo
Executive chair	+0.15 clo

a A chair constructed from thin, widely spaced cords that provide no thermal insulation. Included for comparison purposes only.
b Chair used in most of the basic studies of thermal comfort that were used to establish the PMV-PPD index.

Table D.7 – Typical added insulation when sitting on a chair[2]

[1] (*Ibid.*, p.19)
[2] (*Ibid.*, p.20)

Arabic Summary

جامعة عين شمس
كلية الهندسة
قسم الهندسة المعمارية

أساليب التهوية الطبيعية كأساس للعمارة البيئية السالبة

دراسة تطبيقية للمنشآت السكنية بإقليم القاهرة الكبرى

رسالة مقدمة من

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يونيو 2012

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إعداد

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بكالوريوس الهندسة المعمارية ٢٠٠٦ – جامعة عين شمس

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\ \ ٢٠١ \ \ ٢٠١

ملخص البحث

يهدف البحث لدراسة تأثير تطبيق التقنيات السالبة للتهوية الطبيعية على معدلات تدفق الهواء ومعدلات الراحة الحرارية للوحدات السكنية بالمناخ المحلي الحار الجاف. تم اختيار التقنيات السالبة التي تعتمد في فكرة عملها على نظريات الطفو الحراري لتمثيل المعالجات السالبة ودراسة مدي فاعلية تطبيقها ، ويرجع ذلك الاختيار إلى كثافة الإشعاع الشمسي بالمناخ المحلي مما يمنح هذه التقنيات كفاءة التشغيل نظريا. تم اختبار تقنية الحائط المزدوج باستخدام برنامج رقمي لمحاكاة حركة الموائع لدراسة مدى فاعلية تقنية التهوية الطبيعية على معدلات التدفق والراحة الحرارية خلال فترات النهار والليل ، وقد شملت متغيرات الدراسة سمك الحائط المزدوج ومواد البناء للتقنية وأبعاد فتحة التقنية ومكان الفتحة داخل الفراغ. وقد شملت المحاكاة أيضا العناصر الأخرى للتهوية الطبيعية الموجودة أصلا في الوحدة المختارة لإجراء هذا الاختبار.

يهدف هذا الاختبار لتحديد تقنيات التهوية الطبيعية الملائمة للتطبيق بالبيئة المناخية المحلية لإقليم القاهرة الكبرى. جاءت نتائج الاختبار موضحة أن استخدام الحائط المزدوج للتهوية بجميع الواجهات المعرضة للإشعاع الشمسي يحقق تحسن لمعدلات تدفق الهواء داخل الفراغ بمتوسط قيم يتراوح بين 68.9% و 85.9% ، وسرعة هواء داخلية بحد أقصى 0.3 م/ث.

وقد أثبت تطبيق أسلوب التهوية على الواجهة الشرقية انخفاضا في درجة الحرارة المحسوسة داخل الفراغ بقيمة وصلت إلى 3.65 درجات سليزية أثناء فترات الليل ،وعلى العكس من ذلك، أظهرت النتائج تأثيرا سلبيا لمعدلات الراحة الحرارية عندما تم تطبيق التقنية على الواجهات الجنوبية والغربية. وقد أظهرت دراسة تكميلية بالبحث أن كل تقليل لدرجة حرارة الهواء المتدفق داخل الفراغ تحت نفس ظروف التجربة بقيمة 1 درجة سليزية يؤدي إلى تخفيض درجة الحرارة المحسوسة بقيم تتراوح بين 0.3 و 0.4 درجة سليزية ، مما يعطي مؤشرات إيجابية لتطبيق التقنية خلال الموسم الدافئ في تحسين معدلات الراحة الحرارية بكل التوجيهات داخل الفراغ.

يثبت البحث أن نظام الحائط المزدوج له تأثير إيجابي على معدلات تدفق الهواء الداخلي والتي بدورها تؤثر إيجابيا على جودة الهواء داخل الفراغ ، ومعدلات الراحة الحرارية بالتطبيق على الواجهة الشرقية.

1. تمهيد

يهدف التصميم السالب لتحقيق الاتزان الفطري بين الإنسان ومعطيات البيئة المحيطة ، وذلك باستخدام عناصر التصميم الأولية ودون التكلف والمغالاة في استغلال المزيد من طاقات البيئة لتحقيق الظروف البيئية الملائمة للإنسان. يبحث التصميم السلبي لتحقيق أفضل النتائج باستخدام أبسط الوسائل وأكثرها ميلا للفطرة.

وقد عبرت العمارة المحلية التقليدية عن هذا المفهوم ، فجاءت انعكاسا واضحا لملامح المجتمع والحياة اليومية الاجتماعية والاقتصادية والمناخية. أما حديثا ، فبين تيارات التغريب الشديدة وبين القصور الثقافي المحلي المعاصر ، جاءت العمارة المحلية المعاصرة لتفتقد معايير التصميم البيئي التلقائي وتفتقد الانسجام مع المحيط. وعلى عكس كل ما يتم النداء له من أهمية الحفاظ على موارد الطاقة ، تأتي الدراسات لتؤكد أن متوسط الاستهلاك السنوي للطاقة في ازدياد مستمر ، فنتيجة لهذا النتاج المعماري المشوه بيئيا ، اضطر مستخدم الفراغ إلى اللجوء إلى أساليب التكيف البيئي المستهلك للطاقة لتوفير ظروف معيشية ملائمة. من هنا تأتي مسئولية المعماريين والباحثين لبحث تعويض هذا القصور في الظروف الملائمة للبيئة المعيشية.

انتهاجا لهذا المبدأ ، يأتي هذا العمل البحثي مناشدا خطوة في طريق تصحيح المسار عن طريق دراسة جانب هام من جوانب التصميم السالب ، يؤثر في معدلات الراحة الحرارية ومعدلات جودة الهواء الداخلية للفراغات ، ألا وهو التهوية الطبيعية.

ويتم البحث من خلال تحليل وتقييم تقنيات التهوية الطبيعية ، إلى جانب دراسة مدي فاعلية تطبيق هذه التقنيات بالفراغات المعيشية بالمناخ المحلي.

2. مشكلة البحث

انتشر استخدام أساليب التهوية الميكانيكية للتبريد للوصول إلى معدلات معيشية ملائمة داخل الفراغات ، خاصة في فصل الصيف ، والذي تتضاعف خلاله ساعات التشغيل ، التي قد تمتد إلى فصلي الربيع والخريف في بعض الحالات. الاعتماد المتزايد على الوسائل الميكانيكية لتوفير الراحة الحرارية داخل الفراغات يؤثر بشدة على جودة الهواء الداخلي وعلى معدلات استهلاك الطاقة.

يهدف التصميم السالب إلى تقليص عدد ساعات التشغيل الميكانيكي بقدر الإمكان ، ففي المناخ شديد الحرارة كالمناخ المحلي ، يكون الاستغناء الكامل عن التبريد الميكانيكي غير وارد. وبالتالي تقاس فاعلية النظام السالب بمدي إمكانية استبداله بالنظام الميكانيكي للوصول إلى بيئة معيشية مناسبة.

تتعدد الأنظمة السالبة في فكرة عملها ، وتظهر إمكانياتها القصوى عندما تتحد هذه الأنظمة معا ، من بين تلك الأنظمة يركز البحث في دراسته على تلك التي تعتمد على تيارات الحمل الحراري والتهوية الطبيعية ، ويدرس مدى فاعلية هذه الأنظمة في المناخ المحلي.

يفتقد كثير من المباني السكنية المحلية نظام التهوية السلبي الملائم والذي يحقق معدلات تدفق مناسبة ، وهذا ما يؤدي إلى التأثير السلبي على معدلات الراحة الحرارية وجودة الهواء داخل الفراغات.
اعتبار مثل هذه الأنظمة السلبية منذ مراحل التصميم الأولية يكون له بالغ الأثر الإيجابي في سلوك المباني حراريا وصحيا ، أما بالنسبة للمباني القائمة فإن تطبيق هذه الأنظمة يكون بالغ الحساسية لأنه يتعامل في هذه الحالة مع ظروف بيئية وبنائية قائمة ، وهذا هو نطاق العمل بالبحث.

3. فرضية البحث

تطبيق تقنيات التهوية الطبيعية بالمباني السكنية بالمناخ الحار المحلي يؤثر بالإيجاب على معدلات الراحة الحرارية ومعدلات جودة الهواء الداخلي من خلال تحسين معدلات تدفق الهواء داخل الفراغ.

4. أهداف البحث

يتلخص الهدف الرئيسي للبحث في تحديد نوعيات تقنيات التهوية الطبيعية الأنسب للتطبيق بالمناخ المحلي لإقليم القاهرة الكبرى ، ولتحقيق هذا الهدف يمر البحث بعدة أهداف جزئية:

- دراسة تقنيات التهوية الطبيعية من حيث كيفية عمل كل منها وتطبيقاتها المختلفة.
- دراسة التطبيقات السكنية العالمية لتقنيات التهوية الطبيعية في بيئات حرارية مشابهة للمناخ المحلي.
- تقييم خصائص وأداء الحالة المرجعية.
- تقييم مدى فاعلية تطبيق تقنية التهوية الطبيعية على معدلات تدفق الهواء ومعدلات الراحة الحرارية ومقارنة النتائج بالحالة المرجعية.

5. نطاق البحث

تتم الدراسة خلال فصل الصيف فقط في ظروف النهار والليل

6. منهج البحث

يمر البحث بعدة خطوات متعاقبة في الدراسة:

<u>أ. دراسة نظرية</u>

- دراسة نظرية لمفهوم التهوية الطبيعية.
- دراسة نظرية لأكثر التقنيات السالبة للتهوية الطبيعية انتشارا وشيوعا من خلال دراسة كيفية عملها وتطبيقاتها المختلفة.

<u>ب. مرحلة تحليلية</u>

- دراسة تحليلية لتطبيقات تقنيات التهوية الطبيعية بالمباني السكنية في بيئات حرارية مشابهة للمناخ المحلي محل الدراسة.

<u>ج. دراسة تطبيقية مقارنة</u>

- اختيار الحالة المرجعية وتقنية التهوية الطبيعية الأنسب لإجراء الاختبار

- دراسة فاعلية التقنية المختارة عن طريق المحاكاة الحرارية ومحاكاة حركة الموائع ، مع تقييم ومقارنة نتائج الاختبار مع الحالة المرجعية.

7. هيكل البحث

يرتبط هيكل البحث بمنهجه في توزيع أبوابه:

الباب الأول: التقنيات السالبة للتهوية الطبيعية

يشرح الباب الأول خلفية نظرية موجزة لأنظمة التبريد السالب ومدخل نظري لمبادئ التهوية الطبيعية. كما يعمل الباب الأول من خلال دراسة فكرة العمل والتطبيق على تحليل تقنيات التهوية الطبيعية من خلال تصنيف مقترح للدراسة.

الباب الثاني: تطبيقات سكنية معاصرة للتقنيات السالبة للتهوية الطبيعية

أفرد الباب الثاني لتحليل أربع حالات دراسة لتطبيق تقنيات التهوية الطبيعية السالبة بالوحدات السكنية ، ودراسة أداء التطبيق ، وتقييم النتائج، بحيث يتم اختيار حالات الدراسة في بيئات مناخية مشابهة للإقليم المناخي للقاهرة الكبرى.

الباب الثالث: المحاكاة الرقمية لحركة الموائع

يناقش الباب الثالث الظروف المناخية المحلية التي على أساسها يتم اختيار الحالة المرجعية المحلية واختيار تقنية التهوية الطبيعية لإجراء الاختبار. ومن خلال تحديد نطاق ومعطيات الاختبار ، يضع الباب الثالث أسلوب تحليل الحالة المرجعية وتطبيق التقنية بواسطة البرنامج الرقمي لمحاكاة حركة الموائع.

الباب الرابع: نتائج اختبار المحاكاة الرقمية

خصص الباب الرابع لعرض ومقارنة وتقييم نتائج اختبار المحاكاة الرقمية لكل من الحالة المرجعية وتقنية التهوية الطبيعية المطبقة. يتم في هذا الباب اختيار بدائل متغيرات التقنية والتي تحقق أفضل نتائج لمعدلات تدفق الهواء داخل الفراغ. كما يتم اختبار التقنية بثلاثة توجيهات مختلفة (الواجهات الجنوبية والغربية والشرقية) لدراسة تأثير تطبيق التقنية على معدلات التدفق والراحة الحرارية داخل الفراغ.

النتائج والتوصيات

من نتائج ومقارنات الأبواب الأربعة يتوصل البحث إلى النتائج والتوصيات والتي تحقق هدف البحث الرئيسي بتحديد تقنيات التهوية الطبيعية الملائمة للتطبيق بالبيئة المناخية المحلية لإقليم القاهرة الكبرى ، وترصد تأثير تطبيق التقنية على معدلات تدفق الهواء والراحة الحرارية داخل فراغ الدراسة.