The Interaction of Wind Velocity and Air Gap Width on the Thermal Comfort in Naturally Ventilated Buildings with Multiple Skin Facade

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A Multiple (MSF) or Double Skin Facade (DSF) is a building envelope system. It has an external and internal layer that contains buffer space used for controlled windy conditions, ventilation and solar protection. Employing a multiple or double-skin facade for natural ventilation is not an innovative idea, but the background on this mechanism and the impacts of these environmental and designing factors on its performance are still unknown and critically needed. Therefore, with this study, the influences of the Multiple or Double Skin Facade with different width air gaps configurations, alongside the environmental factor on buoyant-driven natural ventilation, are discussed. Naturally ventilated MSFs are often very intriguing in terms of a microclimatic comfort, but an optimum design is crucial to enhance the microclimatic comfort and therefore the proper operation of the entire system. Especially, the development of the system is important when working in a hot climate. There is a significant lack of data within the current literature to demonstrate the complexity and challenges in designing large, naturally ventilated buildings. For these sorts of buildings, it is important to possess the tools to gauge a design's predicted performance to realize successful natural ventilation concepts. However, with the utilization of glass, heat loss during the winter and solar gain during the summer will increase energy loads. At the same time, this will also negatively effect the microclimatic comfort. Through this study, both the effect of the utilization of multiple facades on indoor comfort conditions and thus the effects of distances at different distances from the facade on wind flow and therefore microclimatic comfort at the situation of the Multiple Skin Facades were investigated. This paper demonstrates through a sensitivity analysis, an optimal strategy for completing a CFD simulation of this special building envelope. This study also attempts to research a mechanically ventilated building with DSF configuration—a building in terms of indoor microclimatic thermal comfort. The aim of this study is to work out the effect of wind velocity and wind distribution on naturally ventilated buildings with DSF configuration, to work out if a DSF configuration will provide a far better microclimatic thermal comfort through natural ventilation. This study not only defines and analyzes the dimensional parameters of the air gap to maximize airflows, but also explores the importance of design decisions on system performance, such as the interaction between thermal mass and air gap distances and the building facade.

Keywords: *double skin facade, microclimatic thermal performance, airflow modelling, ındoor microclimatic thermal comfort, wind velocity, wind distribution, CFD, natural ventilation performance simulation*

Introduction

A Multiple (MSF) or Double Skin Facade (DSF) are architectural design elements that have increased in popularity in modern building design. They need to be improved as an alternate technology to enhance the microclimatic thermal

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performance of conventional fully glazed buildings. They also need to be widely used as a solution to scale back the microclimatic thermal instability of inner spaces caused by the growing use of huge glazed areas in buildings. This idea has provided the likelihood of improved sound insulation, pre-heating air for ventilation, and protection from solar shading in urban areas. DSF's can lead to a reduction of winter heating requirements. The building facade plays a crucial role in achieving the microclimatic thermal comfort and energy conservation. A DSF is an envelope system, which has an external and internal layer that contains a buffer space used for controlled ventilation and solar protection.

With the advantages of technological advances, transparency and therefore the use of glass has become a beautiful facade option in architectural design. Building glass facades can provide outdoor views and excellent levels of natural light also because of the potential for natural ventilation. Ventilated facades are already a standard feature of architectural competitions in Europe, but there are still relatively few buildings of which have actually been realized; there is still insufficient experience of their behaviour to be operational. For this reason the CFD analysis might be one among the foremost important tools to predict the behaviour of DSF and help architects make decisions during the planning process (Gratia and De Herde 2007, Ballestini et al. 2007, Zöllner et al. 2002).

The ventilated double skin facade differs from traditional double and triple glazed facades and is characterized by the passage of air through the air gap air space between the inner and outer glass. The movement of air is a crucial departure from more standard glazing systems like double and triple glazed insulating units. Microclimatic thermal mechanisms and its effects on energy and comfort are different. Air flows through it, altering its performance characteristics and dominating from time to time (Lamcour et al. 2012). A ventilated double-skin facade is often defined as a standard single facade that doubles inside or outside with a second, essentially glazed facade. Between these two surfaces there is a ventilated air gap with to a depth of up to about 10 cm from the narrowest place and up to 2 m at the deepest accessible spaces. Air gaps are usually ventilated with natural, mechanical or hybrid ventilation (Waldner et al. 2007). The double skin facade is ventilated with outside air and allows outside air to be ventilated through open windows without causing any disturbance, even in high-rise buildings (Roelofsen, 2002).

In recent years, new building envelope systems are developed so as to enhance microclimatic thermal insulation, to shade solar radiation and to supply appropriate microclimatic thermal and visual comfort conditions. One among these special sorts of envelopes is DSF. DSF are made with two layers of glass separated by a large amount of air space. The space between the glass are often ventilated with three different strategies: mechanical ventilation, natural ventilation or hybrid. The ventilation of the air space between two facade contributes to saving energy both during the summer and therefore the winter time. In fact, in winter, the air between the glass is heated by the sun rays (greenhouse effect) (Gratia and De Herde 2007). Thereby, it provides a reduction in heating costs by improving the microclimatic thermal performance of the facade. In hybrid ventilation systems, fresh air is usually preheated within the

MSF space before entering the HVAC system during the winter months. In summer, air flow from MSF (mechanical or natural) can help lower the temperature inside the cavity. However, when the building is in summer conditions or located in temperate or hot climates, heat gains dominate and thus cooling costs becomes a serious problem.

In the literature there are several examples of using CFD to examine the behavior, characteristics, and energy consumption and comfort status of a DSF (Pappas and Zhai 2008, Safer et al. 2005, Ye et al. 1999). Studies on DSF microclimatic thermal comfort are mostly limited to colder and warmer climatic conditions (Alberto et al. 2017, Chow et al. 2009, Khalvati and Omidvar 2019, Yang et al. 2020, Saroglou et al. 2020, Guardo et al. 2009). However, the use of multiple or double skin facades in hot summer continental climates is not well documented. Additionally, while numerous articles explain how DSFs should improve the microclimatic thermal comfort of a building through principles and ideas, they do not provide calculated or experimental results. Other researchers provided simulation models to specific MSF or DSF typologies, but did not link the facade results level to the microclimatic thermal comfort of the building or link the model to a building energy and comfort model simulation. The significant lack of information that explains the complexity and challenges of designing large, naturally ventilated buildings with MSF or DSF as a means for energy saving with better microclimatic thermal comfort has been addressed in the literature review.

In recent years, the use of multilayer facades has been widely adopted in the design of modern buildings, and the use of more advanced multilayer facades has been investigated, especially for energy savings. However, even if the energy performance side is improved, there is a great need for additional mechanical air conditioners in terms of indoor microclimatic comfort conditions (Gosselin and Chen 2008, Inan et al. 2016, Inan et al. 2017, Ioannidis et al. 2020). Many studies have explored the potential of combining natural ventilation with multiple facades. However, the mechanism behind natural ventilation throughout the facade is still unclear (Inan et al. 2017, Ioannidis et al. 2020). Understanding their optimum designs and the mechanism behind them is critically necessary to broaden relevant studies. In addition, many studies of multiple or double skin facades have ignored the effects of connecting rooms or attached windows, which can lead to overestimation in practical designs (Dama et al. 2017, Wang and Lei 2020). Studying the air flow in the air gap is a major challenge due to the two unique glass facades under combined solar radiation and natural convection in multiple or double skin facades (Souza et al. 2018, Barbosa and Ip 2014, Agathokleous and Kalogirou 2016).

Also, due to some unknown circumstances, previous studies on multiple or double skin facades specifically failed to address the airflow within the inner space (MSF) (DSF) (De Gracia et al. 2013). An accurate CFD study is important to benefit practical applications by allowing the air flow rate to be calculated for natural ventilation in a ventilated air gap, and then unravel the flow details in multiple or dual design (Wang et al. 2019, Nasrollahi and Salehi 2015, Baldinelli 2019). Therefore, an investigation of natural ventilation through different multiple or double skin facades design parameters was administered. This study addressed

the influences of facades and connected rooms configurations alongside the environmental factor of the buoyancy-driven natural ventilation from multiple or double skin facades. The air change rate per hour (ACH) by natural ventilation was addressed over different multiple or double skin facades configuration (Baldinelli 2019).

The Main Objective of this Research

This research presents the foundation of a methodology for modeling natural ventilation airflow in buildings with multiple skin facades to better understand the effect of the shaft air gap and air gap width on the building comfort design and energy performance. This research also investigates the viability of combined shaft-air gap MSF or DSF designs to provide natural ventilation as an energy-efficient solution by means of numerical simulations using CFD coupled with dynamic energy-simulation tools. Actual measured data of the building's energy performance based on a full-scale model is not in the scope of this study.

Therefore, the base case is essentially a simulated base case and is not calibrated with an actual model. The simulated combined shaft-air gap strategy is compared with the simulated base case. In addition, the issue of condensation of the facade system has not been taken into account. As there is no exact method of local comfort measurements, the predicted-mean vote was used to evaluate the comfort performance.

The significant lack of information describing the complexity and challenges of designing large, naturally ventilated buildings with DSF as a means to save energy with better microclimatic thermal comfort is addressed in the literature review. Some of these are:

- To determine the effect of difference in convection coefficient on building surfaces.
- To determine if a DSF configuration will provide a better microclimatic thermal comfort through assisted natural ventilation.
- The building interior boundary conditions will use ASHRAE 62.1 and ASHRAE 90.1 specified conditions.
- A methodology for assessing the performance of naturally ventilated DSF buildings through an airflow model will be developed by three-dimensional analysis using CFD.
- Buoyancy, wind, and combined ventilation strategies for a building with operable openings DSF will be evaluated using the turbulence models in the CFD.

The primary goal of this study is to clarify the state-of-the-art performance of buildings with multiple or double skin facades, so that designers can assess the value of these building concepts in meeting design goals for especially microclimatic comfort conditions, ventilation, productivity, and sustainability. Another aim of this study is to investigate the effect of wind velocity and wind distribution on naturally ventilated buildings with multiple or double skin facade

configuration, to determine if a DSF configuration will provide a better microclimatic comfort through natural ventilation in terms of microclimatic comfort. Also, the influences of the double skin facade with different width air gaps configurations, together with the environmental factor on buoyant-driven natural ventilation, are addressed.

Literature Review

Function of Cavities on Multiple or Double Skin Facades

The double skin facade air gap is a space between the exterior and interior glazing. The air gap of a double-skin facade can be airtight or ventilated. An airtight air gap acts as a buffer zone that is often used to maintain indoor temperature in winter. Ventilated air gaps refer to an air gap with an opening in the lower and upper air gap of a double skin facade. It is generally used in summer, where fresh air from outside is given from the lower air gap and ventilated along the upper air gap. This ventilation system takes advantage of a stack effect that allows the air gap air to flow through the upper air gap. The pressure difference between the lower and upper aisle can be used if the wind speed is sufficient, possibly allowing the air to circulate in the air gap. Both methods' stack effect and pressure difference could beneficially reduce the warmth in a double skin facade. The double skin facade air gap can be naturally, mechanically and hybridly ventilated. The depth of the air gap can vary from 10 cm to more than 2.40 m depending on the concept applied. The depth effects the physical properties of the facade and the way the facade is preserved (Waldner et al. 2012, Streicher 2005).

Multiple or double skin facades are generally designed for different operations in summer and winter conditions. During the summer months, MSFs usually operate in "on" mode. This means that vents are made above and below the facade air gap. The air in the air gap removes the excess heat thanks to the convective flow created by the stack effect. This action prevents excessive heat build-up in spaces in an air gap. If this happens, unwanted heat can pass indoors. This can have a significant impact on microclimatic thermal comfort conditions inside the building which creates a greater need for the use of auxiliary cooling systems, thus causing an increase in energy consumption. When the air in the air gap is cleaned, the temperature of the building facade is lowered and the heat transfer from the interior surface to the occupied area is reduced. Accordingly, less heat is transferred from the outside to the inside and less energy is required to cool the space. The widespread use of DSF in winter is used as a closed air gap with no air circulation. For the winter scenario, the DSF air gap is warmer than the outside temperature. As the air in the air gap is heated by the sun, the temperature of the facade increases and the temperature difference across the facade decreases. Accordingly, given a low temperature difference between the interior conditioned area and the adjacent microclimatic thermal zone, less heat is transferred from the inside of the building to the outside. Therefore, Ssignificantly less energy is required to heat the space (Mulyadi 2012).

The air gap allows the air to be circulated through the double-skin air gap. The lower air gap is the air inlet and the upper air gap is the air outlet. The choice of panel type, shading device, air gap geometry and the type, size and location of the air gap openings and ventilation strategy are crucial to the performance of a double-skin facade system (Yoon et al. 2012). When designing a double-skin facade, it is important to determine the type, size and location of the air gap, as these parameters affect the type of air flow and air velocity and therefore the temperatures in the air gap (more important in tall buildings) (Streicher 2005, Mulyadi 2012).

The Physics of Double-Skin Facades

Some research has been done on the microclimatic thermal performance of the double skin facade. Chan et al. (2009) investigated the performance of a double-skin facade in Hong Kong compared to a traditional single-skin facade with absorbent glass. Additionally, by comparing double-skinned and single-skinned facades in a hot and arid climate, Hamza (2008) found that a double-skin facade with reflective glass could provide better energy savings than a single-skin facade with reflective glass. Xu and Yang (2008) investigated the microclimatic thermal performance of a double-skin facade using natural ventilation and solar control louvers. Hien et al. (2005) discovered that a double-skin facade with natural ventilation can reduce energy consumption and improve microclimatic thermal comfort. Kato et al. (2008) examined the effectiveness of the double-skin facade in reducing the cooling load by combining it with the ground-to-air heat exchanger. Moreover, Yoon et al. (2012) proposed the technique of estimating the performance of the double skin facade during the cooling season. In general, the double-skin facade acts as a microclimatic thermal buffer in front of offices. This has two microclimatic thermal effects for offices (Mulyadi 2012, Barták et al. 2001):

1. The air temperature in the double skin facade will often be higher than outside. This will result in lower conductive heat losses (heating season) and higher conductive heat gains (summer) depending on ambient temperatures and solar radiation levels.
2. The extra outside facade glass of the double skin facade will effectively reduce the amount of solar radiation on the interior, thus reducing the solar radiation load of the offices due to the radiation transmission through the windows (Mulyadi 2012, Barták et al. 2001).

Airflows Around Multiple or Double-Skin Facades

Wind causes variable surface pressures in buildings that alter intake and exhaust system flow rates, natural ventilation, in and exfiltration and internal pressures. The average flow patterns and turbulence of wind passing over a building can recirculate exhaust gases to air intakes. Air flow around buildings consists of natural winds that flow around and possibly through buildings. Air

flow around buildings has two effects on building ventilation (Goodfellow and Tahti 2001):

1. Wind pressures applied to exterior building surfaces can affect indoor air movement.
2. The movement of air pollutants outside, which can reduce indoor air quality if brought indoors with insufficient dilution.

The buildings are immersed in an atmospheric boundary layer where the wind is affected by friction with the earth's surface. In this layer of the building envelope, wind speed tends to increase gradually with height and decreases as turbulence levels rise. The surrounding buildings, terrain, and vegetation strongly affect wind and turbulence at a construction site. Wind and turbulence levels are also affected by the microclimatic thermal stratification of the atmosphere, as are the inversion layers at ground level. The major parameters of the wind at a building site depend on the Reynolds (R_e), Karman (K_a), and Richardson (R_i) dimensionless characteristics (Goodfellow and Tahti 2001):

$$R_e = Vl/v \ K_a = J \ [\ (V7)2/V \ R_i = gl/p \ (dp/dZ) \ / \ (d \ V/dZ) \ 2, \ (7.227) \qquad (1)$$

Where Vl/v = building characteristic dimension (height or width), v = kinematic viscosity, V' = velocity fluctuation, V mean velocity, p = air density, dp/dZ = vertical density gradient, and dV/dZ = vertical velocity gradient. Winds traveling past a building will be greatly modified compared with winds in the absence of the building.

The Physics of Airflows within the Multiple or Double Skin Facade Cavities

The main parameter that promotes air movement within the ventilated spaces is pressure differential. This is due to microclimatic thermal buoyancy, the movement of wind around the building, or mechanical action. Multiple or double skin facades (DSFs) accelerate the air movement in the air gap as a result of the greenhouse effect between the building envelope between the two facades, the heated air density decreases and the buoyancy force creates a clump effect and raises the hot air to the upper part by forcing the cold air to enter from the bottom. However, the temperature difference (ΔT) between the inside and outside of the air gap also causes air movement inside the air gap. In this case, the pressure is high at the bottom of the facade and low at the top, creating a reverse flow towards the inlet. The microclimatic thermal uplift (th Δp) inside the facade air gap is explained by the following equation:

$$\Delta pth = \Delta \rho'. \ g \ .\Delta h \cdot \Delta Tm \ [Pa] \qquad (2)$$
where:
$\Delta \rho'$ = Specific change of air density in relation with temperature change ($kg/m^3 °K$).
 g   = Gravitational acceleration ($9,81 m/s^2$).

Δh   = Effective difference of height of the facade air gap (m).

m ΔT = Mean excess temperature (°K)

The specific change of density ($\Delta\rho'$) is derived from the law of gases to the following formula:

$$\Delta\rho' = \frac{\rho}{T_{ab}} \qquad = [0.004 \text{ kg/m}^3°\text{K}] \qquad (3)$$

And the absolute temperature (ab T) is can be explained by:

$$T_{ab} = T_{zu} + \Delta T_m + 273,15 \qquad [°\text{K}] \quad (4)$$

The wind outside of the facade also has an influence on the airflow inside the air gap of between facade, the pressure created by pressure difference inside the facade and outside is known as "stagnation pressure" (q), which is expressed as:

$$q = \frac{\rho}{2}v^2 \qquad [\text{Pa}] \quad (5)$$

where:

ρ = Density of air (kg/m³)

v = Outside air velocity (m/s)

The pressure of the exterior wind (wind p) is given by the specific wind pressure coefficients (cp) which depend on the facade orientation. The values of these coefficients are positive on the pressure zones facing the wind and negative on the suction zones towards the wind direction. The pressure is expressed by the following formula:

$$p_{wind} = cp \cdot q \qquad [\text{Pa}] \quad (6)$$

According to Osterle et al., "the pressure differences between upper and lower openings are regarded as forces acting on the areas of the openings, whereby the motive force is the product of the pressure difference taken in conjunction with the opening area." This is known as pressure loss (loss Δp), which is formulated as:

$$\Delta p = \zeta \cdot Q \qquad [\text{Pa}] \quad (7)$$

The balance of the volume of air admitted at the inlet (in V) is equivalent to the amount of air leaving the air gap through the outlet (out V), known as the continuity equation, which is expressed basically by:

$$\dot{V}_{in} = \dot{V}_{out} \qquad \text{or} \qquad A_{in} \cdot v_{in} = A_{out} \cdot v_{out} \qquad \begin{matrix}[\text{m}^3] \ (8)\\ \text{where:}\end{matrix}$$

V = Airflow volume (m³)

A = Opening area (m²)

v = Air velocity (m/s)

This relationship determines that when there is a change in the aperture area, the air velocity must be increased in order to maintain stability balance. Pressure balance concept (loss Δp) is explained as:

$$\Delta p_{loss} = \Delta p_{th} + \Delta p_{wind} \qquad [Pa] \quad (9)$$

The previous fundamental equations give a general idea of air flow from inside the facade to the outside. However, the variation of air flows within a DSF is very complex and depends on the interaction of all elements that contribute to the local and total heat transfer coefficients of the facade that determine how the flow behaves. Therefore, CFD analysis is a very useful tool for computing detailed flow models because the momentum, mass, energy, and radiation equations are discretized and calculated to obtain the flow behavior within the inter-facades.

The two basic types of airflow found in an MSF or DSF are defined as laminar when frictional forces govern over turbulence and inertial forces when high inertia forces are present. Turbulent flows depend on the viscosity of the fluid and the air velocity known as the Reynolds number, which is the relationship between centrifugal force and adhesion. This is explained as:

$$Re = v \cdot \frac{L}{v} \quad (10)$$

where:

v = Air velocity (m/s).

L = Dimension of the change of direction of the air stream (m)

v = Kinematic viscosity of air [~15.5×106m²/s]

There is a critical Reynolds number value when turbulence occurs. According to Osterle, the critical Re in DSFs is from 10.000 to 20.000 (Oesterle et al. 2001). Von Grabe (2002) stated that, "with natural ventilation inside the air gap, the driving force is the reduction of the density due to the increase of air temperature. This increase is greater near the heat sources, thus near the panes and the shading device. Further on it might be non-symmetrical because of different magnitudes of the heat sources." This means that both the streamline flow created at the facade is higher at the inlet and reduces sharply to half the entire height and eventually increases to a smaller magnitude at the outlet, and also means the input/output relationship plays a key role in determining the standard of streamline flow within the air gap. Inside a double skin facade, the air temperature will mainly depend upon the warmth gains and therefore the amount of air flow. However, during a naturally ventilated double skin facade the air flow itself is especially governed by the temperature difference outside and possibly also by the pressure differences caused by the wind; air flow is usually very unsteady (Park et al. 2004).

Natural ventilation is a crucial aspect of double-skin facade performance, which is said to be microclimatic thermal transmittance and solar heat gain.

Several investigations are performed during which an integrated modeling process was used to define the connection between natural ventilation and therefore the microclimatic thermal performance of double-skin facades. They investigate the microclimatic thermal performance and correlations of double-skin facade with buoyancy-driven airflow employing a numerical model (Pappas and Zhai 2008). Ding et al. examined the performance of a solar naturally ventilated double-skin facade (Ding et al. 2005). Manz and Frank (2005) have simulated the microclimatic thermal performance of double skin facade. Most of these reports have focused on the stack effect or the solar chimney concept design.

Research Methodology

This research helps designers to make better selections of multiple or double skin facade MSF or DSF design features in terms of openings, sizes and locations, air gap depth and height of shaft. DSF microclimatic comfort and energy-performance modelling is a complex problem. An accurate assessment of the physics of airflow and temperatures within the air gap requires detailed analyses of solar radiation transmitted through glazed facades, buoyancy, and wind pressure. Annual building simulation programs cannot provide accurate CFD simulations.

Obtaining Meteorological Inputs and the Modeling Process

The first step in the research procedure on microclimatic thermal comfort of the multiple or double skin facade DSF configurations is to collect climatic data and information on the building site. Entry of the Antalya meteorological data and geographic data pertaining o the climatic region of the building are made by the user. Meteorological data entered to FloEFD software is an index pertaining to Republic of Turkey General Directorate of Meteorology for the outdoor weather temperatures, direction and intensity of wind, intensity of the direct and common solar radiation, and sky cloudiness in the region. These weather data include outdoors weather temperatures, direction and intensity of wind, intensity of the direct and common solar radiation, and sky cloudiness in the region.

Boundary Conditions and Limitations and Assumptions

This study is limited to comparative analyses between three different DSF building configurations considered for application in plot centers of "Hot-Humid Climate", a characteristic that is dominant in the southern part of Turkey. In order to observe the effect of the variable DSF with the shaft air gap and air gap width on the building comfort design and energy performance on solar radiation and consequently the necessary energy of the building, different microclimatic thermal factors (except solar heat gain) were fixed throughout the research. The calculated internal loads within one typical day for sizing the total internal gains. The total internal gains during a typical day are 300 kW. This gives an indication that the

internal gains constitute a high amount of energy gain that could be used as a positive in winter times and as negative in summer time.

Each floor height of DSF buildings have been considered 4.00 in average. The indoor comfort limit temperature value for the heating and cooling load within the building has been considered 23°C in all DSF building options.

Entry of the meteorological data and geographical data pertaining to the climatic region of the building are made by the user. Meteorological data entered to FloEFD software is an index pertaining to Republic of Turkey General Directorate of Meteorology for the outdoor weather temperatures, direction and density of wind, density of the direct and common solar radiation, and sky cloudiness in the region.

An important initial concept for CFD analyses is that of boundary conditions. Each of the dependent variable equations requires meaningful values at the boundary of the calculation domain in order for the calculations to generate meaningful values throughout the domain. These values are known as boundary conditions, and can be specified in a number of ways. The specification of boundary conditions for two driving forces of wind and buoyancy effect can be defined as a pressure difference on inlet and outlet. To calculate the stack effect, the energy equation needs to be turned on.

The heat flux coefficient, which is defined as the product of the density, microclimatic thermal conductivity and specific heat capacity quantifies the ability of the material to absorb heat. It has been found to reflect the influence on microclimatic thermal comfort of different surfaces and is therefore used as the basic thermo-physical property defining the materials. The heat flux coefficients for the different layers of each element of the building (walls, roof, floor) are considered as design variables. The thicknesses of the different layers of each building element are also considered as design variables.

The following parameters were taken into account in the analyzed configurations of the double skin facade DSF building; Total volume of room: 7.40 m X 7.60 X 2.85 = 160.2 m^3, thickness: 0.22 m, density: 1,200 kg/m^3, specific heat capacity (Cp): 1,000 J/kg K, microclimatic thermal conductivity: 0.38 W/m K for opaque surfaces; Density: 2,700 kg/m^3, for frame surfaces; specific heat capacity Cp: 953 J/kg K, microclimatic thermal conductivity: 155 W/m K, for transparent surfaces: density: 2,300 kg/m^3, specific heat capacity Cp: 836 J/kg K, microclimatic thermal conductivity: 1.05 W/m K, thickness: 0.05m, turbulence model: (standard model); k-epsilon model, near wall treatment: two-scale wall functions approach, radiation model: discrete transfer method. The materials with different material characteristics used in all DSF; air as fluid, and building envelope, floorings, doors, windows, walls and roofs as building components. The values accepted for fluid air are respectively: Intensity: kg/m^3, Specific heat Cp: J/kg K.

The following parameters given below were analyzed in this research. Building surface temperature values of distribution, building solar heat flux and total surface heat flux (Numerical), temperature, wind flow and wind speed values between DSF and building, building interior surface temperature and wind speed values, wind flow, wind speed and wind direction distribution in interior of building, wind flow changing rate between building temperature zone, heat

transfer rate between building surfaces, total heat flux rate and solar heat flux rate of building, flow temperature in interior of building, perceivable temperature in interior of building, perceivable radiation temperature in interior of building, relative humiditiy in interior of building, PMV and PPD values in building zones.

Creation of the Models and the Analysis Phase in CFD

The geometries of DSF models examined were drawn and the digital mesh networks of the models belonging to each defined DSF option were created, the microclimatic thermal regions of each model were defined and surfaces of the models were created and restricting conditions were decided upon.

Then, geographical and climatic data of different climatic regions were entered into the FloEFD simulation program. Further, data such as permeability and reflectivity of the structure envelope, constructional components and constructional materials were entered. The microclimatic thermal regions, building surfaces and elements thereof previously decided upon during the pre-analys meshing phase were defined. Later, the data comprising the inter-building microclimatic thermal gains were entered and analysis commenced.

As criteria of the case study, for the heating period, average temperature distribution on DSF surface and inner building total temperature gain and loss values, outside air velocity movements, direction of air, layering of air, air change ratio pertaining to DSF buildings zones, for DSF both of building surfaces; overall and average heat transition amount, surface temperatures, pressures, and velocity distributions and wind speed values will be analyzed,

The numerical and visual reports of all such values will be prepared and will rely on such values; evaluations and comments will be made on internal temperature and average temperature distributions on the DSF building surface, overall temperature gain, total temperature loss calculations, investigation of architectural solutions for better cooling and ventilation as well as their effects on cooling and ventilation.

In the CFD FloEFD software where the analysis study is performed, information on the building envelope such the thickness, density, specific heat, microclimatic thermal conductance coefficient, sun radiation absorbency, sun radiation reflectivity, surface roughness and number of layers are defined, whereas layers in the floorings together with (if present) separate stratifications are defined in the ground floor, second floor and roof slab. The thickness, density, specific heat, microclimatic thermal conductance coefficient, sun radiation absorbency, sun radiation reflectivity, surface roughness and number of layers of the material used in the flooring are examined. On the other hand, the data used in the simulation program are defined by entering the values of volume ambient temperatures, boundary conditions for surfaces and microclimatic thermal zones, absorbency of surfaces, reflectivity, density, specific heat and microclimatic thermal conductance. The correct type of fluid flow is a very important aspect of the CFD simulation as well.

There are two radically different states of flows that are easily identified and distinguished: laminar flow and turbulent flow. Laminar flows are characterized

by smoothly varying velocity fields in space and time in which individual ─laminar─move past one another without generating cross currents. These flows arise when the fluid viscosity is sufficiently large to dampen out any perturbations to the flow that may occur due to boundary imperfections or other irregularities. These flows occur at low-to-moderate values of the Reynolds number 5. In contrast, turbulent flows are characterized by large, nearly random fluctuations in velocity and pressure in both space and time.

These fluctuations arise from instabilities that grow until nonlinear interactions cause them to break down into finer and finer whirls that eventually are dissipated (into heat) by the action of viscosity. Turbulent flows occur in the opposite limit of high Reynolds numbers. The solver needs for this study are more likely to be turbulent due to irregularities of the surface. There are usually regions with and without turbulence in the same space. The turbulence model must be able to deal with laminar and transitional flow at the same time and the RNG k-e model of turbulence appears to be the most suitable choice among other models in CFD.

HVAC System and Components for Case Study

The building is equipped with a typical HVAC system that follows the following process. The outdoor air flows into the air handling unit through a filter to dilute and remove air contaminants. However, the energy required to condition this outdoor air could be of significant effect on the total-consumed load. The floor heating system is used in winter. Following this process, the air is heated or cooled with respect to the difference between the ambient temperature and the required room temperature. The assumptions are made according to the following:

Infiltration
The infiltration rate is assumed because the accurate air change rate through infiltration usually depends on many factors such as the outside air velocity, the pressure distribution around the building, the tightness of the windows, etc. So, it cannot be precisely predicted. The assumption is based on a referred office building example in the ASHRAE Handbook 2009. This example assigned an infiltration rate of 0.1 h^{-1} depending on the building tightenness and insulation. Likewise, the example in the studied building has the same degree of tightens and is well insulated. Thus, the infiltration rate is assigned as 0.1 h^{-1} in the winter period. In summer the infiltration rate should be higher, due to the uncertainty of the occupants' behaviours for opening the windows.

Interior Gains
The heat gains from office appliances are assigned according to ASHRAE Research 1482-RP (ASHRAE 1999). It mentioned that flat panel monitors of 30-inches in size has an average power consumption of 80W. Printer's power consumption during a printing cycle varies from 80 to 150 W depending on the model, print capacity, and speed. An average heat gain of 90 W was assumed for each monitor; that is in total 90 monitors with total gains of 7860 W. Also, an

average heat gain of 110 W was assumed for each printer which is in total 10 printers with total gains of 860 W.

Ventilation Rate

The minimum required fresh air is calculated according to ASHRAE Standard 62-1999. Based on one person's needs, the quantity of fresh air inside an office is 20 CFM, which is equal to 35m3/hr. Since the first floor zone is occupied by 85 employees, the minimum required fresh air is 3000 m^3/hr (ASHRAE 1999).

Wind Speed, Wind Direction, and Mean Wind Speed Profile

The natural wind speed varies in time and space; the character of its variation is highly random and the wind flow is highly turbulent. All CFD analysis had conducted 16 different configurations under different radiations and velocities. But in this study, it is used two different exterior flow velocity 5 m/s, 15 m/s.

Geometry Model of Validation for CFD Validation

For achieving model validation, an iterative process of calibrating the model took place; comparing the model to actual system behaviour. This process was repeated until sufficient model accuracy was reached. The calibration process is performed manually by making small changes to the values of the parameters and re-running the simulation to see the results. The calibration methodology with the parameters that were checked iteratively. After 45 simulation trials, satisfying results were obtained for the model (Figure 1).

Figure 1. *Convergence of Residuals of the Model*
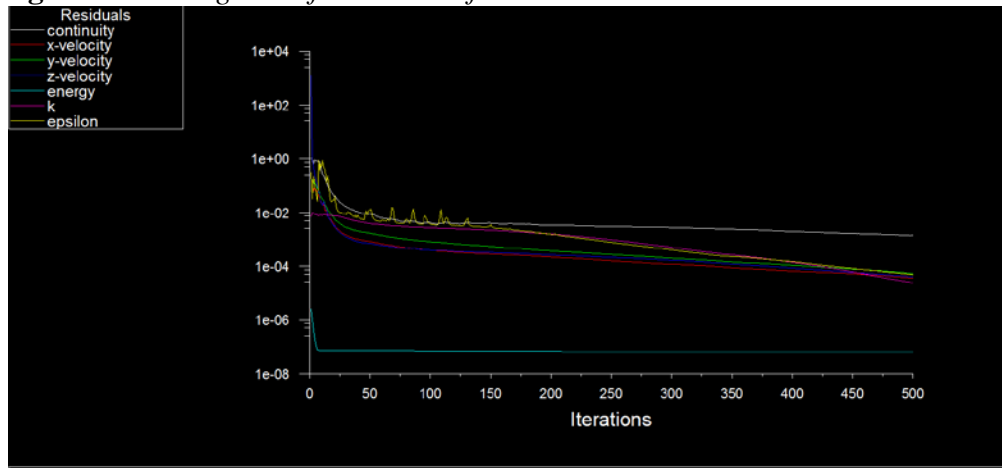
The CFD simulations provides a good prediction with an average absolute error of 2.85% for the 80 cm air gap and 3.95% for the 100 cm air gap distance. The maximum errors for each case are found at 3.2 m in the air gap. Errors are generally higher at the bottom (1.2 m) and top (3.2 m) locations than in the middle.

This research of the CFD model was validated in a laboratory test conducted by Inan and Basaran (2019). The geometry model was conducted according to the experiment (Figure 3). The building chosen as the reference in the study model is

considered as having 2 storeys, with a floor height of 4.00 m, with exterior building dimensions of 7.80 m x 7.80 x 7.80 m and model dimensions of 7.40m x 7.60 x 2.85m (Figures 2-3).

Figure 2. *Model of Building with DSF*
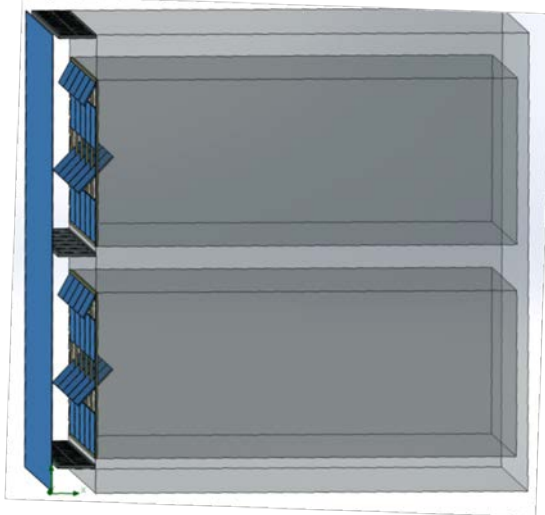
Figure 3. *Model of Double-Skin Facade*
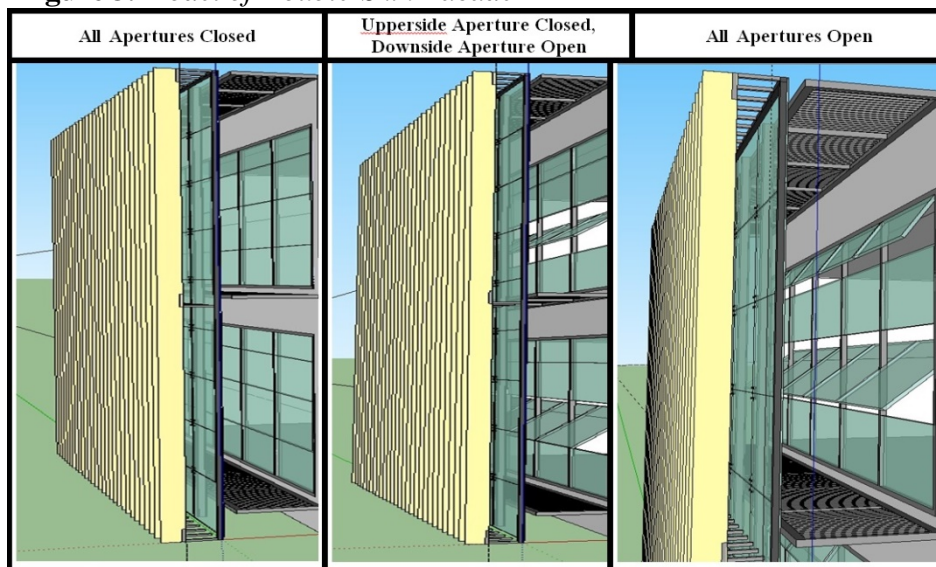
The performed configurations in this research are the following: DSF-1 (air gap width 80 cm with all operable windows are closed); DSF-1 (air gap width 80 cm with all operable windows are open); DSF-1 (air gap width 80 cm with bottomside operable window open, upperside closed); DSF-1 (air gap width 80 cm with bottomside operable window closed, upperside open); DSF-2 aAir gap width 160 cm with all operable windows are closed); DSF-2 (air gap width 160 cm with all operable windows are open); DSF-2 (air gap width 160 cm with bottomside operable window open, upperside closed); DSF-2 (air gap width 160 cm with

bottomside operable window closed, upperside open); DSF-3 (air gap width 240 cm with all operable windows are closed); DSF-3 (air gap width 240 cm with all operable windows are open); DSF-3 (air gap width 240 cm with bottomside operable window open, upperside closed); DSF-3 (air gap width 240 cm with bottomside operable window closed, upperside open); DSF-4 with shaft (air gap width 240 cm with all operable windows are closed); DSF-2 with shaft (air gap width 160 cm with all operable windows are open); DSF-2 with shaft (air gap width 160 cm with bottomside operable window open, upperside closed); DSF-2 with shaft (air gap width 160 cm with bottomside operable window closed, upperside open) (Figure 3).

Mesh Modelling

The relative number of cells of the mesh is a vital parameter that strongly influences the computational time. Increasing the number of cells can often increase computational time by an order of magnitude. Also the grid dimensions influence the accuracy of CFD results and the value of y+. The parameter y+ is critical to the correct use of turbulence models. Before conducting the simulations, different meshes were analysed, for 2D and 3D models, in order to find the minimum amount of cells that can guarantee the invariability of the results. A vital of mesh feature is that the y+ value must be less than, or close to, 1 for the first grid close to the walls. This permitted the use of k-ε with enhanced wall treatment, and k-ω models as turbulent models. The ventilation of the building is purely driven by buoyancy force in the air gap. That is why it is important to have sufficient fine mesh to resolve the microclimatic thermal comfort boundary layer on both facades. The better mesh sizes with y+ < 1 was determined for the glazing facades. The grid sensitivity is examined over five mesh sizes which were consecutively refined by around 1.8 at each dimension.

Figure 4. *Computational Domain Mesh System of the Building with Double-Skin Facade*
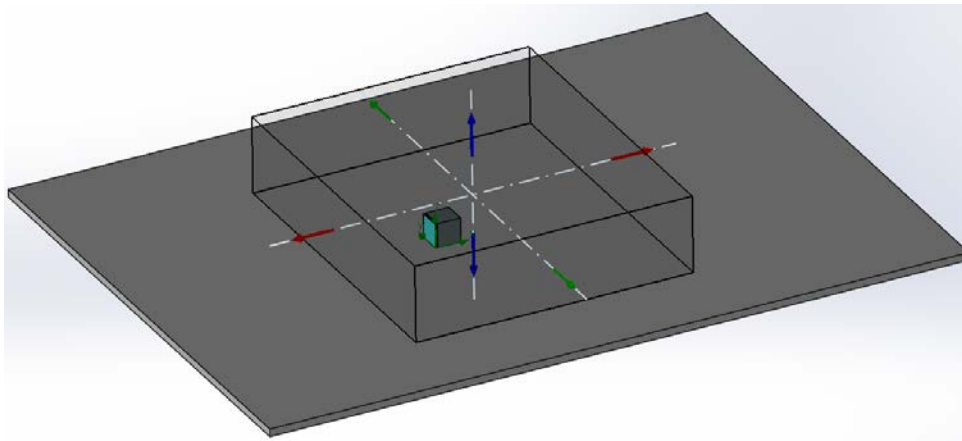
The computational domain mesh consisted of about 13 million polyhedral cells. The computational time was 45 s per iteration. The *y*+ value was close to 1;

The calibration methodology with the parameters that were checked iteratively. After 45 simulation trials, satisfying results were obtained for the model (Figure 4).

Governing Equations for CFD

Numerical simulations were carried out using the commercial CFD software FloEFD. A finite-volume based fluid dynamics solver. The general form of transport equations for incompressible flow can be expressed as:

Momentum equation,

$$\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla \right) \vec{V} = \Gamma \nabla^2 \vec{V} - \frac{1}{\rho} \nabla p \qquad (11)$$

The equations for viscous flow that have been derived in the preceding sections apply to a viscous flow, i.e., a flow which includes the dissipative, transport phenomena of viscosity and microclimatic thermal conduction.

$$x\text{-component}: \quad \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \qquad (12)$$

$$y\text{-component}: \quad \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \qquad (13)$$

$$z\text{-component}: \quad \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \qquad (14)$$

The equations for inviscid flow inviscid flow is, by definition, a flow where the dissipative, transport phenomena of viscosity, mass diffusion and microclimatic thermal conductivity are neglected. The governing equations for an unsteady, three-dimensional, compressible inviscid flow are obtained by dropping the viscous terms in the above equations.

Continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V} \right) = 0 \qquad (15)$$

Energy conservation equation,

$$\frac{\partial T}{\partial t} + \left(\vec{V} \cdot \nabla \right) T = \Gamma \nabla^2 T + S_T \qquad (16)$$

Where fluid velocity $\vec{V}$ at any point in the flow field is described by the local velocity components u, v, and w. Γ is a general diffusion coefficient, t represents time, and S_T is the energy source term (Pasut and De Carli 2012).

Results and Discussion

Evaluation of Air Gap Effects for Double Skin Facade on Building Regarding Post-Process Analysis of Visual Data

In this study, only air gap width 80 cm—all openings-open and closed configurations will be considered as post analysis visual data.

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Air Flow Temperature in İnterior of Building (°C)

Figure 5. *Air Flow Temperature in Interior of Building (°C) for Wind Velocity 5 m/s*
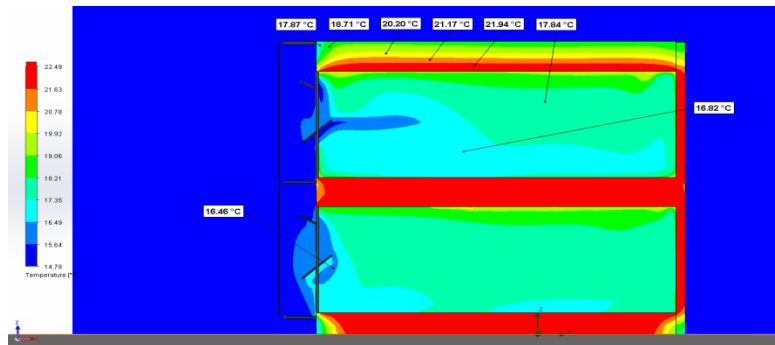
In the configuration where both openings on the interior facade of the building are open, interior temperature values are between 17 °C - 20 °C on entry of the flow between two facades toward the interior space from the openings on the building while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C. It has been observed that when both openings on the building are open, the flow from both openings reduces the indoor temperature value of the building by between 3 °C and 6 °C (Figure 5).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Interior Facade Temperature Distribution Vertical (Between Two Facades) (°C)

Figure 6. *Interior Facade Temperature Distribution-Vertical (Between Two Facades) (°c) for Wind Velocity 5 m/s*
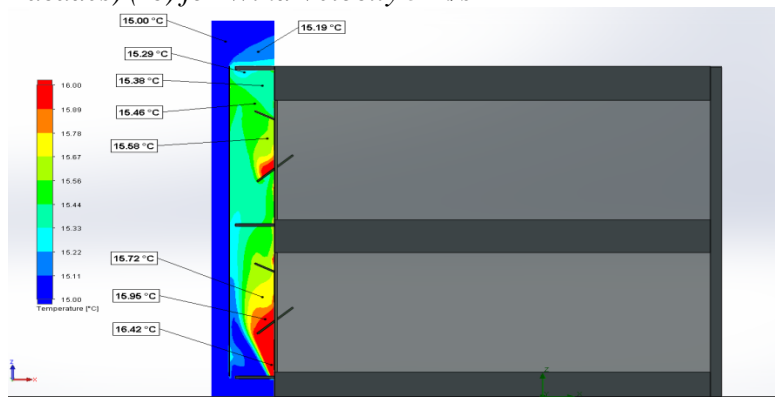
In the configuration where both openings on the interior facade of the building are open, as a result of the examination of the temperature values between two facades, the flow temperature from the opening toward the interior space has been observed 16 °C, and about 15 °C at the upper spaces while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C (Figure 6).

<u>Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Interior Facade Temperature Distribution-Horizontal (Between two Facades) (°C)</u>
] *(°c) for Wind Velocity 5 m/s*
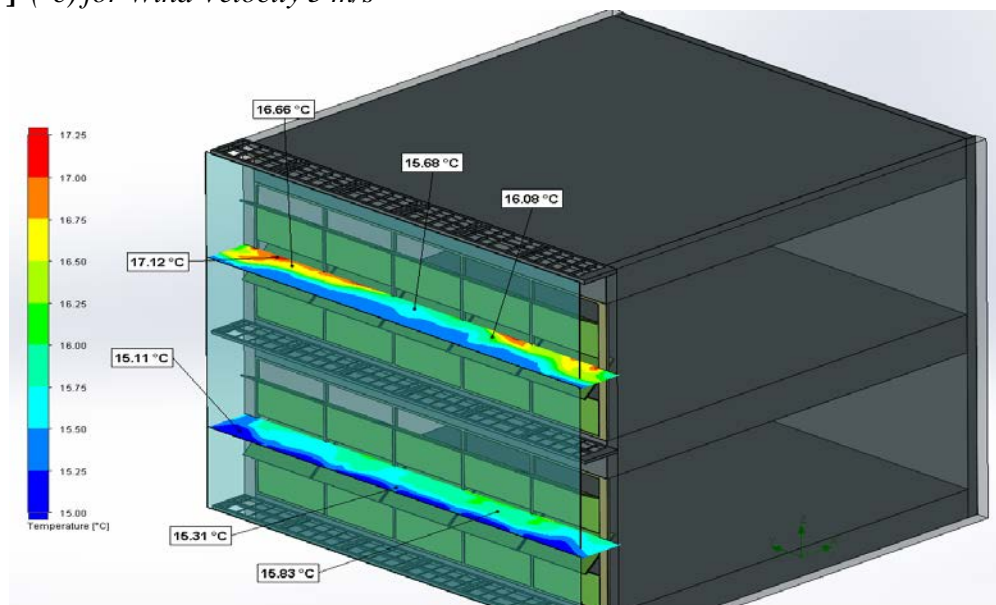
In the configuration where both openings on the interior Ffcade of the building are open, as a result of the examination of the temperature values between two facades, the flow temperature from the opening toward the interior space has been observed 15 °C on the ground floor, and about 17 °C at the upper spaces of the ground floor while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C (Figure 7).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Wind Velocity-Wind Distribution in DSF and Around Building (°C)

Figure 8. *Wind Velocity - Wind Distribution in DSF and Around Building for Wind Velocity 5 m/s*
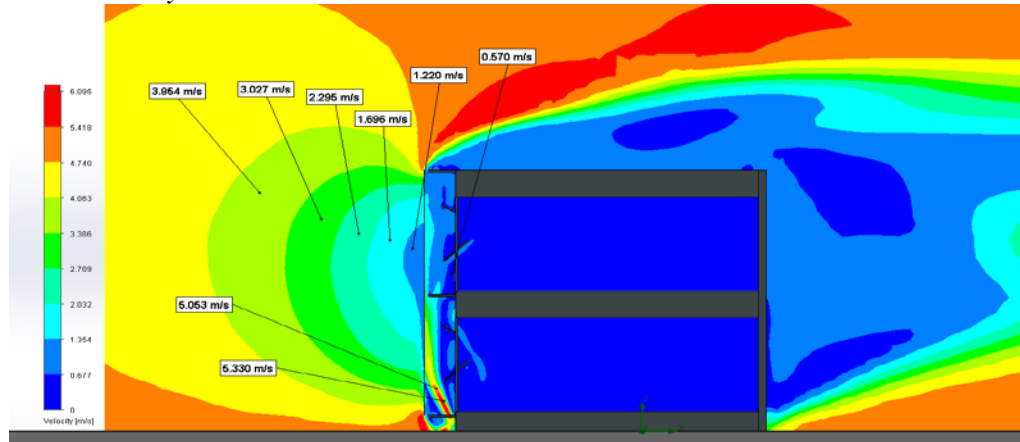
In the configuration where both openings on the interior facade of the building are open, examining the exterior flow velocity values it has been observed that the exterior flow velocity fell toward the exterior surface of the building, and the flow velocity increased due to the chimney effect between the two facades while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It has been seen that the velocity between two facades increased to values of 5 m/s on the ground floor space while the exterior flow velocity is 2-3 m/s (Figure 8).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Interior Facade Wind Velocity-Wind Distribution in Interior of Building

Figure 9. *Interior Facade Wind Velocity-Wind Distribution (Between two Facades) m/s for Wind Velocity 5 m/s*
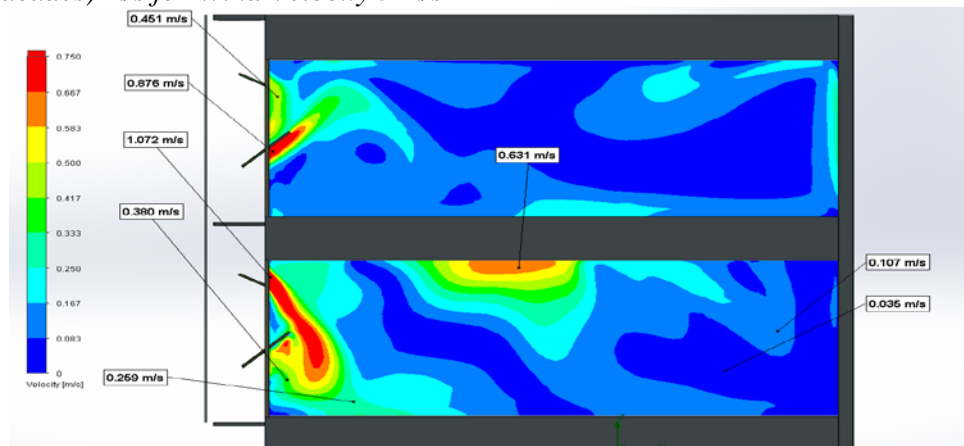
In the configuration where both openings on the interior facade of the building are open, the building interior flow velocity has been observed that the flow toward the interior from the openings on the building change the building

flow and temperature values when the exterior flow velocity is 5 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It has been observed that while the ground floor indoor flow values are about 0.75 m/s close to the openings, the flow velocity values inward at the vicinity of the opening are about 0.2-0.3 m/s (Figure 9).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Outside Facade Temperature Values of Distribution (°C)

Figure 9. *Outside in Front of Facade Building Temperature Values of Distribution (°C) for Wind Velocity 5 m/s*
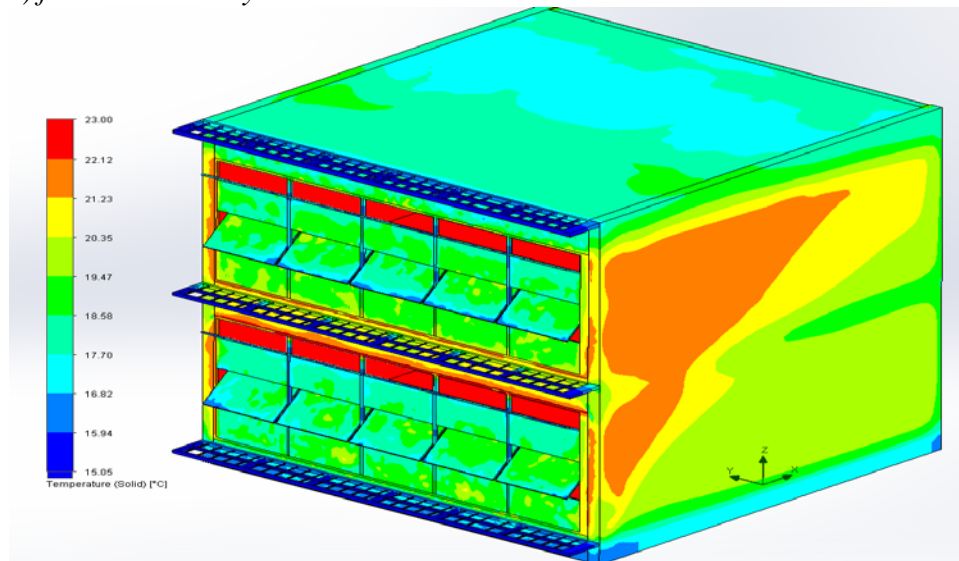
In the configuration where both openings on the building interior facade are open, it has been seen that the temperature values of transparent surfaces with openings, particularly to the bottom rose to 18 °C, and that the transparent surface temperature value of the transparent surface of the opening to the top rose to 23 °C while the exterior temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C. Besides, the building side surface temperature distribution average has been observed between 20 -21 °C (Figure 9).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5
m/s - PMV and PPD Values in Building Zones

Figure 10. *PMV and PPD Values in Building Zones of Bottom Side Openings
Level for Wind Velocity 5 m/s*
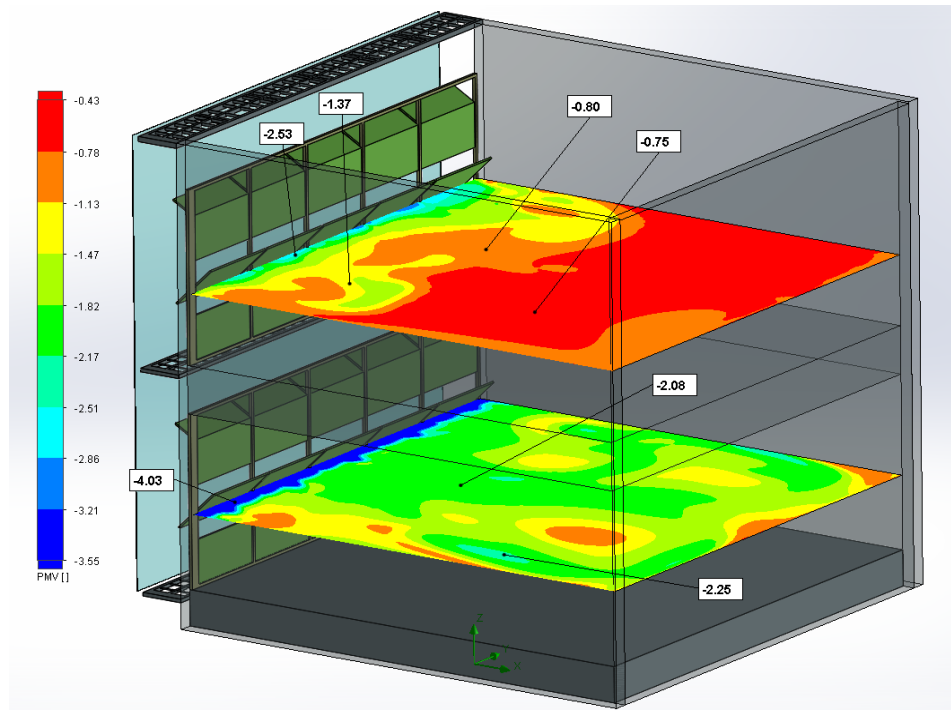
Figure 11. *PMV and PPD Values in Building Zones of Upper Side Openings Level
for Wind Velocity 5 m/s*
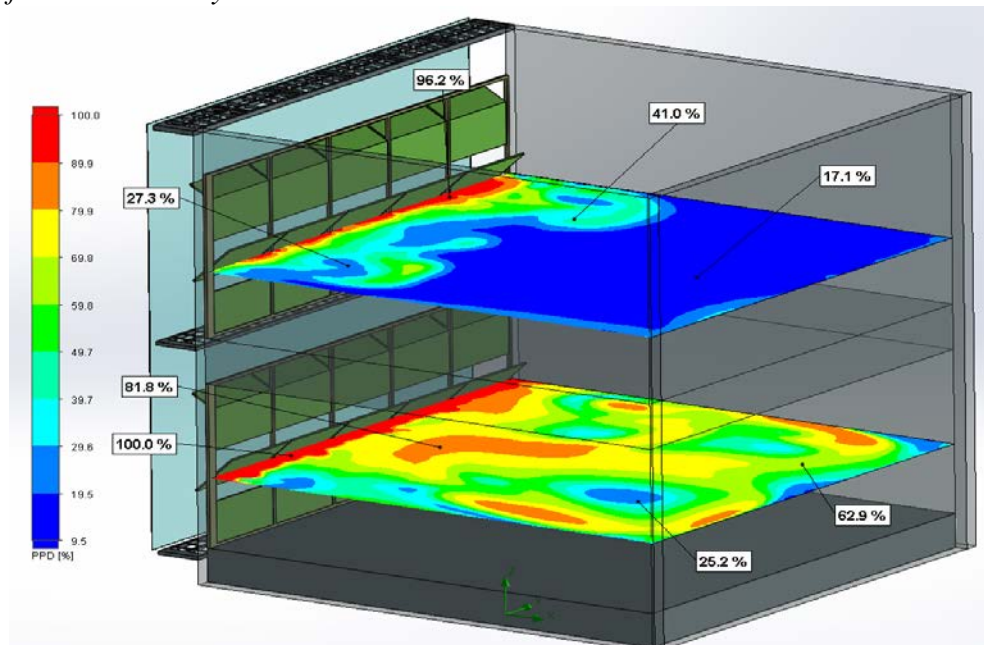
In the configuration where both openings on the interior facade of the building are open, the PMV values were observed between -1.15 and -2.55 at ground floor 1.8 m level while the peripheral temperature is 15 °C, exterior flow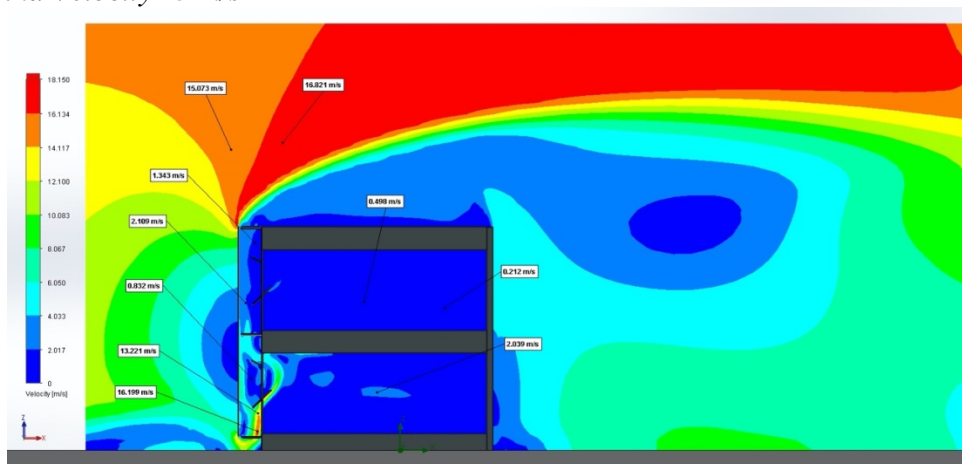 velocity is 5 m/s, and fixed indoor temperature is 23 °C. It was observed between values -0.40 and -1.80 at 1.8 m elevation upstairs.

Examining PPD values in the same configuration and levels, values between 30% and 60% have been observed at 1.8 m level of the ground floor, values between 10% and 20% at spaces mostly behind the opening area of the interior space, and values between 40-50% at locations close to the opening space (Figures 10-11).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 5 m/s - Relative Humiditiy in Interior of Building (%)

Figure 12. *Relative Humiditiy in Interior of Building (%) for Wind Velocity 5 m/s*
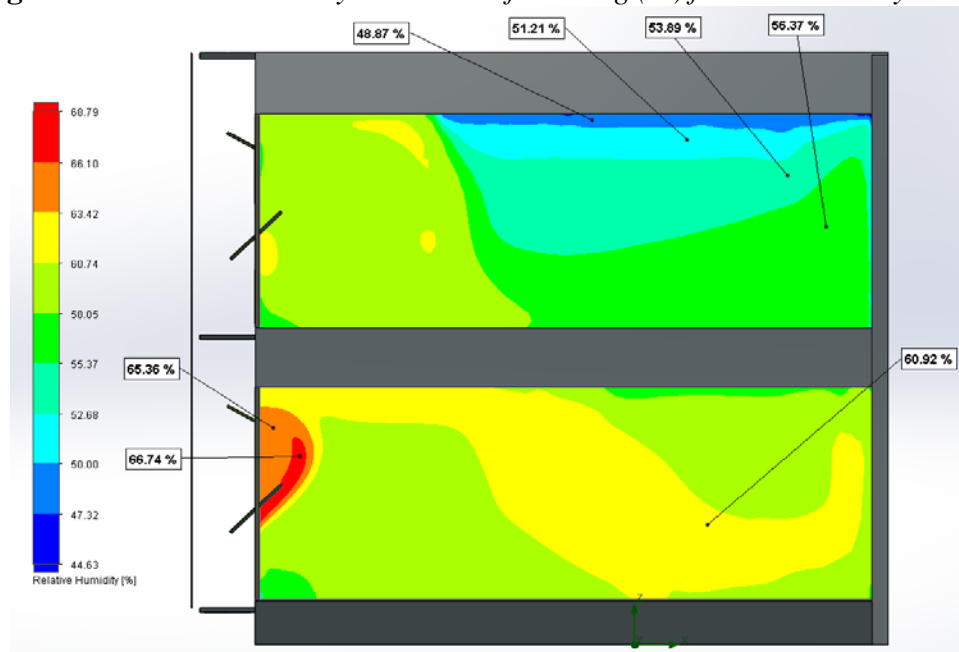
In the configuration where both openings on the interior facade of the building are open, the building ground floor relative humidity values average has been observed about 62% at locations close to the openings and about 50% in further inside areas while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C and while the average ground floor inner space relative humidity values are about 60% (Figure 12).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - Air Flow Temperature in Interior of Building (°C)

Figure 13. *Air Flow Temperature in Interior of Building (°C) for Wind Velocity 15 m/s*
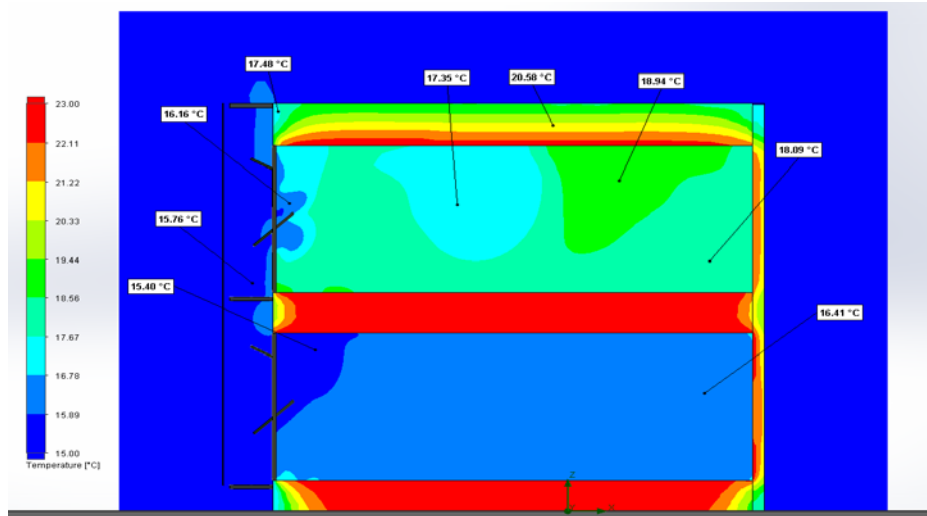
In the configuration where both openings on the interior facade of the building are open, ground floor average interior space flow temperature values have been observed between 15 °C - 16 °C on entry of the flow between two facades toward the interior space from the openings on the building while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C. The upstairs interior space average temperature values are between 17 °C - 19 °C (Figure 13).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - Interior Facade Temperature Distribution (Between Two Facades) (°C)

Figure 14. *Interior Facade Temperature Distribution-Vertical (Between two Facades) (°C) for Wind Velocity 15 m/s*
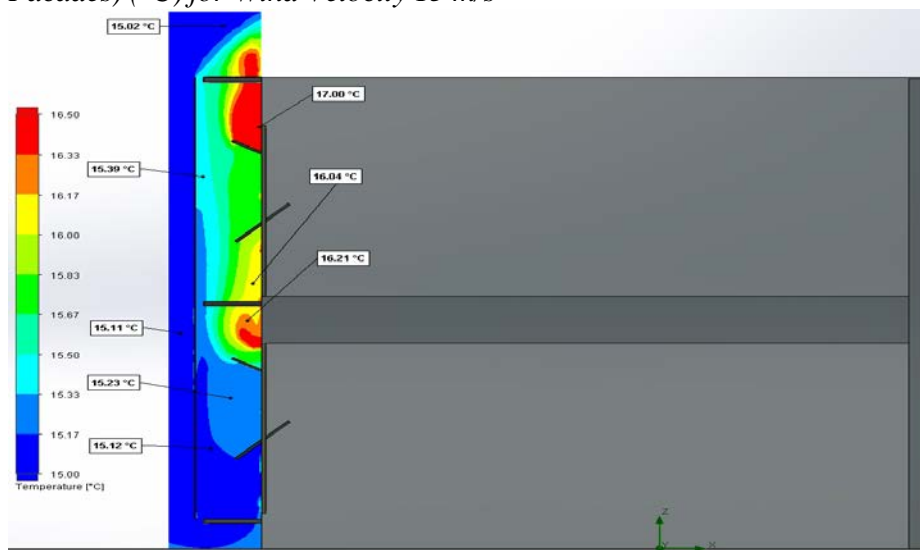
In the configuration where both openings on the interior facade of the building are open, it has been observed that the flow temperature values between the two facades at ground level was 15-16 °C and that it increased to 17 °C at upper floors while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, and fixed indoor temperature is 23 °C (Figure 14).

Figure 15. *Interior Facade Temperature Distribution-Horizontal (Between two Facades) (°C) for Wind Velocity 15 m/s*
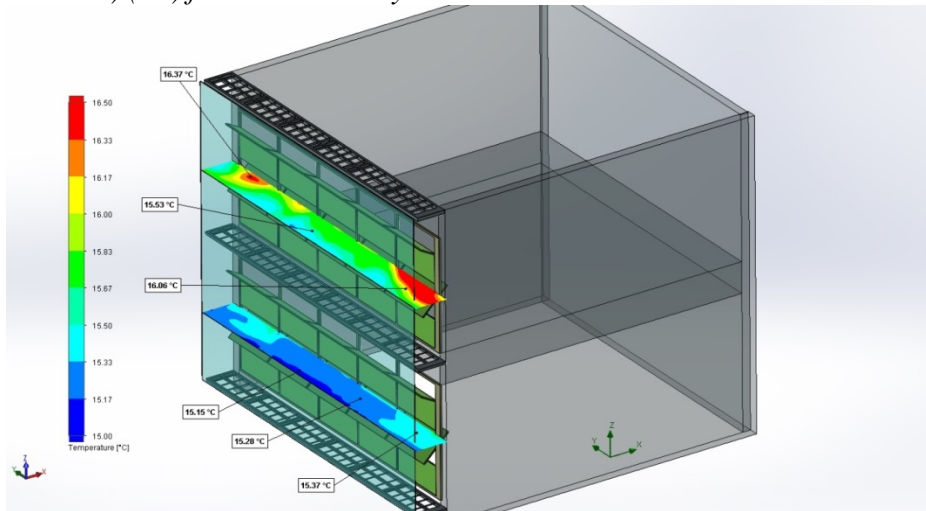
In the configuration where both openings on the interior facade of the building are open, as a result of the examination of the temperature values between two facades, the flow temperature both on the ground floor and on the opening toward the interior space have been observed 15 °C, and about 17 °C at the upper spaces of the ground floor, while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C (Figure 15).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - Wind Velocity-Wind Distribution in DSF and Around Building (°C)
Figure 16. *Wind Velocity-Wind Distribution in DSF and Around Building for Wind Velocity 15 m/s*

In the configuration where both openings on the interior facade of the building are open, the wind velocity values between two facades have been observed to fall down to 2-4 m/s while the exterior velocity values are about 8-10 m/s at building level while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C.

While it has been observed that the building exterior flow velocity value is 5 m/s, the flow velocity value approached the exterior flow level; and it has been observed in the 15 m/s exterior flow fixed value analysis that the instant flow velocity values between two facades fell down from about 15 m/s to 2-4 m/s. In this case, it has been observed that the wall effect of the exterior Facade reduced velocity values quite high in transition to between interior facade.

Besides, where exterior flow velocity is 15 m/s, it has been observed that the flow amount passing from the openings at the upper floor interior space was less compared to the 5 m/s velocity value (Figure 16).

Figure 17. *Wind Velocity-Wind Distribution of Interior Building for Wind Velocity 5 m/s*
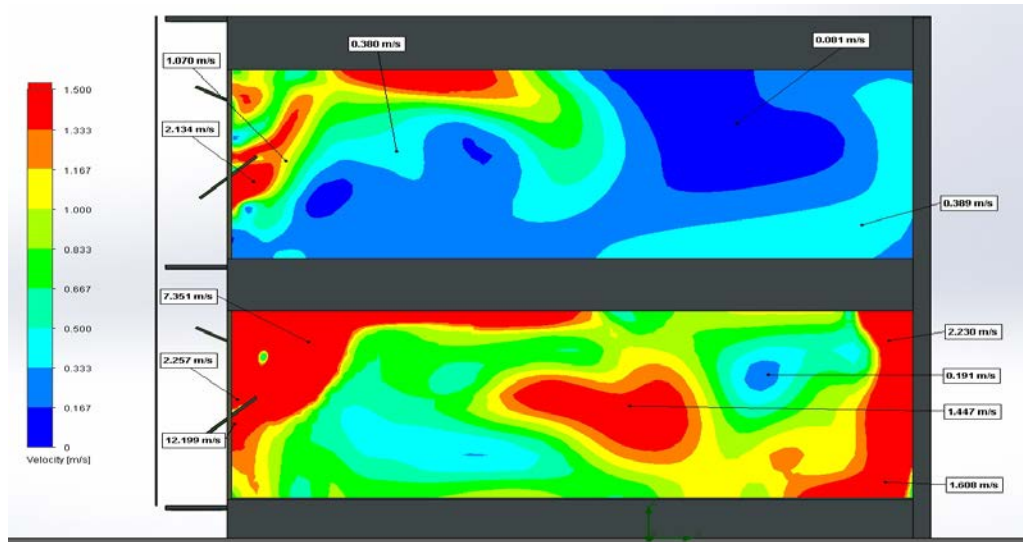
In the configuration where both openings on the interior facade of the building are open, the building interior flow velocity has been observed that the flow toward the interior from the openings on the building change the building flow and temperature values when the exterior flow velocity is 5 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It has been observed that while the ground floor indoor flow values are about 1.5 m/s close to the openings, the flow velocity values inward at the vicinity of the opening are about 0.4-0.7 m/s (Figure 17).

<u>Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - Outside Facade Temperature Values of Distribution (°C)</u>

Figure 18. *Outside in Front of Facade Building Temperature Values of Distribution (°C) for Wind Velocity 15 m/s*
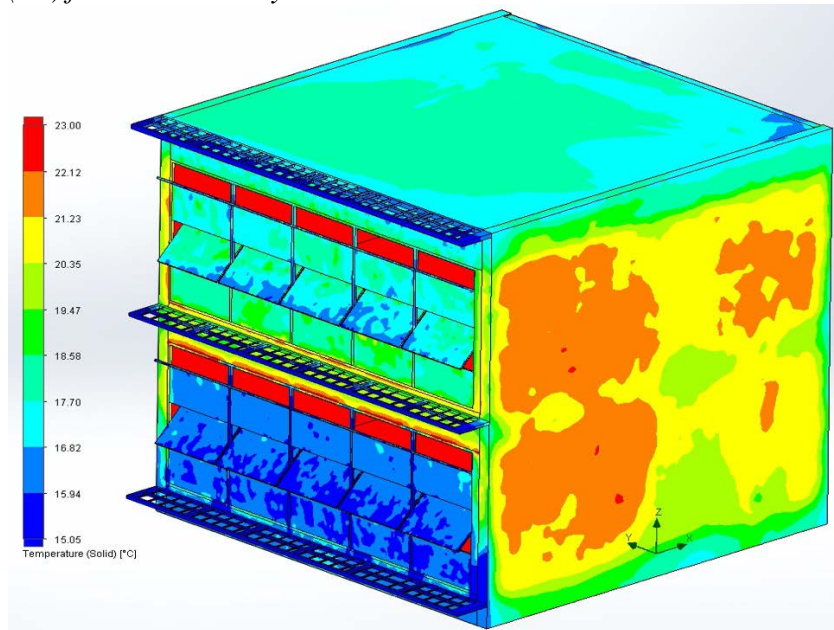
In the configuration where both openings on the interior facade of the building are open, the building exterior surface temperature distribution values, particularly ground floor building facade and indoor facade transparent surface temperature values have been observed 15 °C and upper floor level opening area transparent surface temperature value about 17-18 °C, while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C. Besides, the building side surface temperature distribution average has been observed between 20-21 °C (Figure 18). As to the exterior flow fixed value analysis with exterior flow velocity value 15 m/s while building interior facade transparent surface temperature distribution average values are 19-20 °C while building exterior flow velocity value is 5 m/s, it has been observed that the average values of building interior Facade transparent surface temperature distribution fell down to 15 m/s. It has been observed that the increase in the exterior flow velocity caused a fall on the average double skin facade interior facade temperature values (Figure 18).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - PMV and PPD Values in Building Zones

Figure 19. *PMV and PPD Values in Building Zones of Bottom Side Openings Level for Wind Velocity 15 m/s*
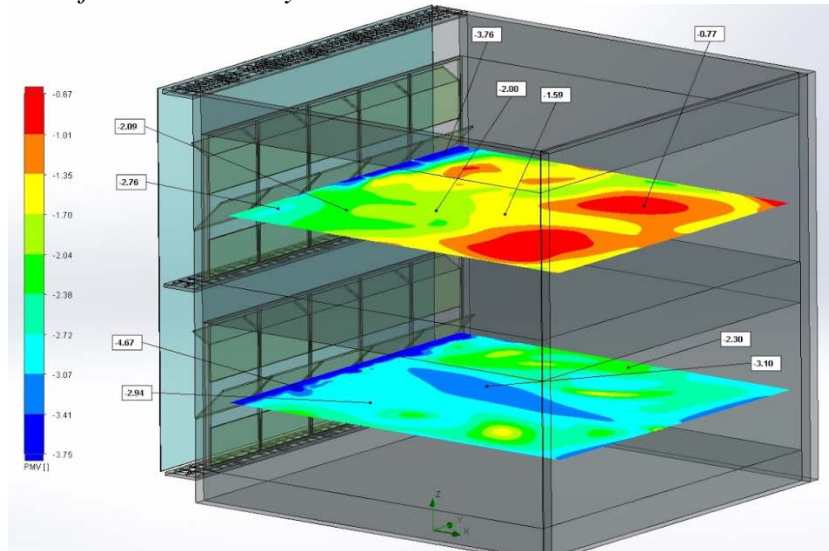
Figure 20. *PMV and PPD Values in Building Zones of Upper Side Openings Level for Wind Velocity 15 m/s*
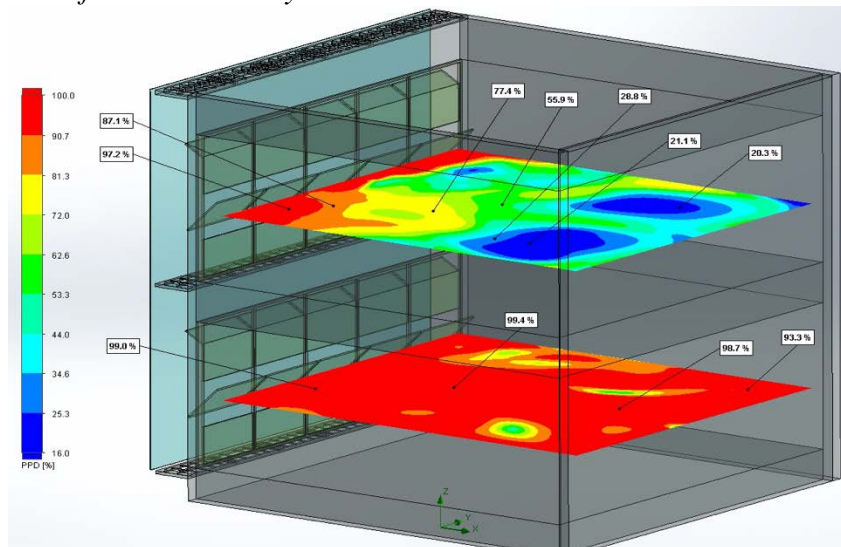
In the configuration where both openings on the interior facade of the building are open, the PMV values were observed between -2.30 and -2.90 at ground floor 1.8 m level while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It was observed between values -0.90 and -2.00 at 1.8 m elevation upstairs.

Examining PPD values in the same configuration and levels, values of 90% have been observed at 1.8 m level of the ground floor, values between 70% and 80% at spaces mostly behind the opening area of the interior space, and values between 40-50% at locations close to the opening space (Figures 19-20).

Air Gap Width 80 cm - All Openings-Open Configurations for Wind Velocity 15 m/s - Relative Humiditiy in Interior of Building (%)
Figure 21. *Relative Humiditiy in İnterior of Building (%) for Wind Velocity 15 m/s*
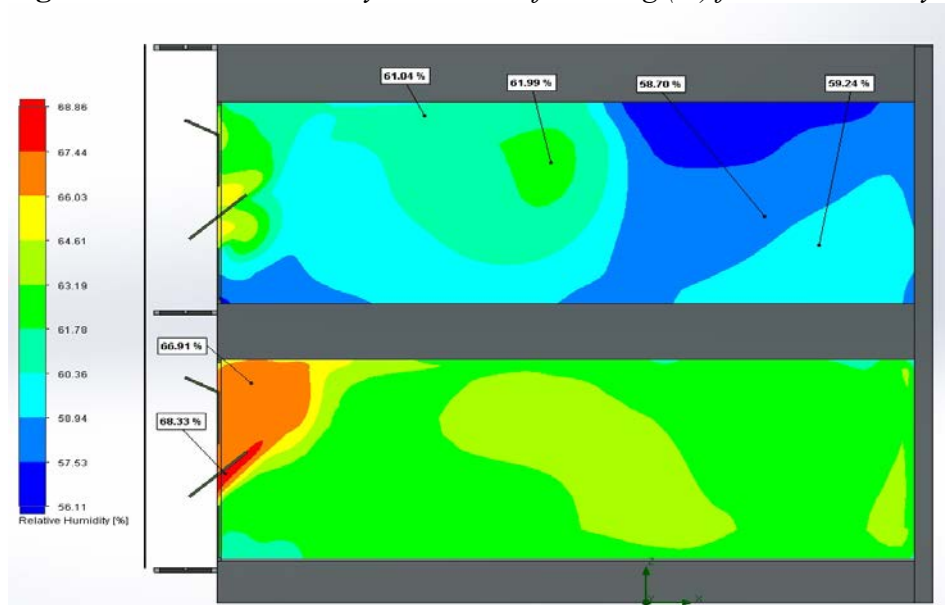
In the configuration where both openings on the interior facade of the building are open, the building ground floor relative humidity values average has been observed about 60% at locations close to the openings and about 50% in further inside areas while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C, and average ground floor interior relative humidity values are about 65% (Figure 21).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - Air Flow Temperature in Interior of Building (°C)
Figure 22. *Air Flow Temperature in Interior of Building (°C) for Wind Velocity 5 m/s*
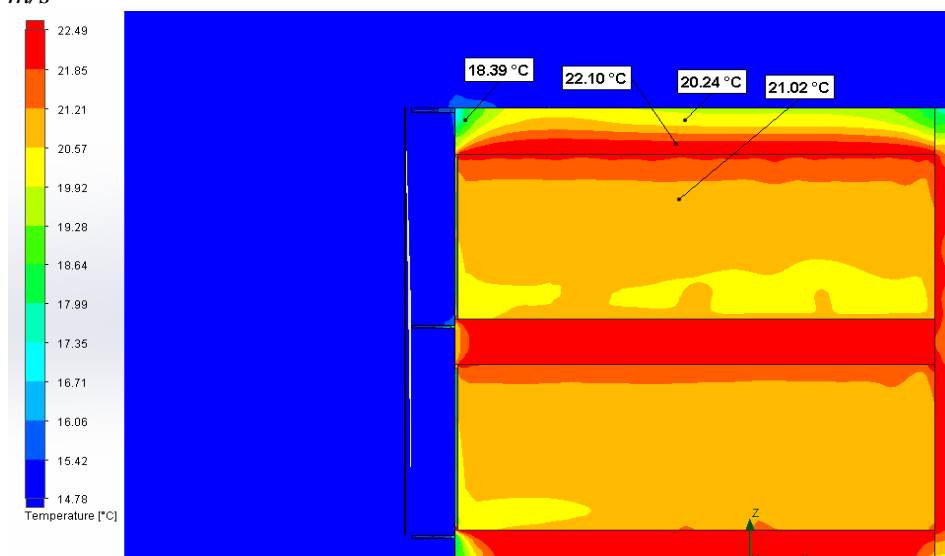
In the configuration where both openings on the interiorfFacade of the building are totally closed, interior temperature values are between 18 °C - 22 °C while the peripheral temperature is 15 ^{0}C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C (Figure 22).
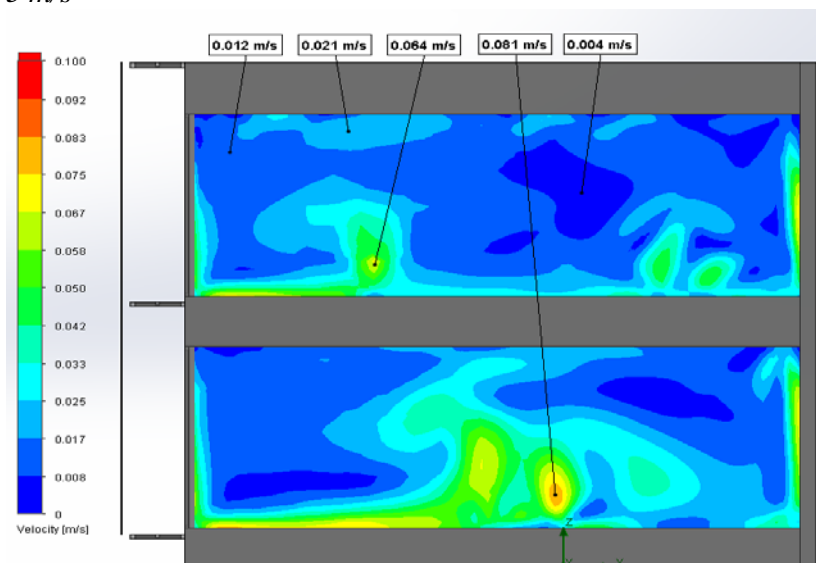
Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - Interior Facade Temperature Distribution (Between Two Facades) (°C)

Figure 23. *Interior Facade Temperature Distribution-Vertical (Between Two Facades) (°C) for Wind Velocity 5 m/s*
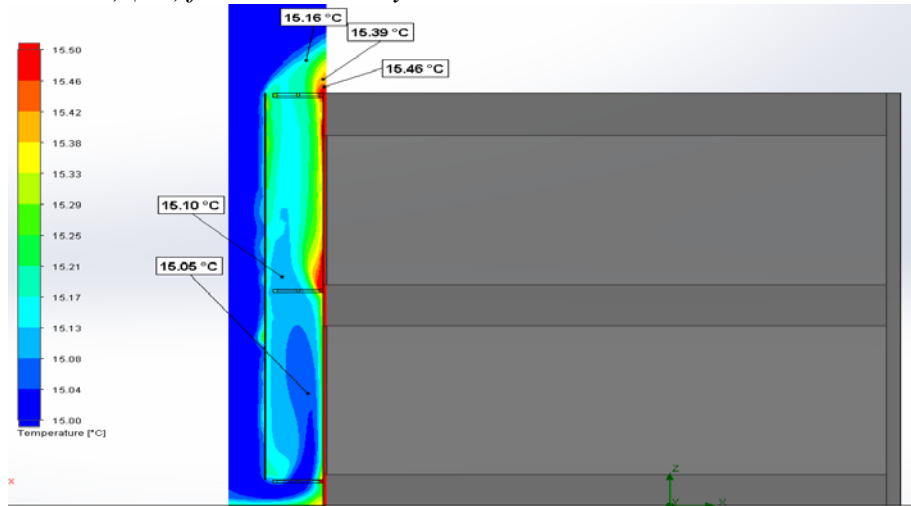
Figure 24. *Interior Facade Temperature Distribution-Horizontal (Between Two Facades) (°C) for Wind Velocity 5 m/s*
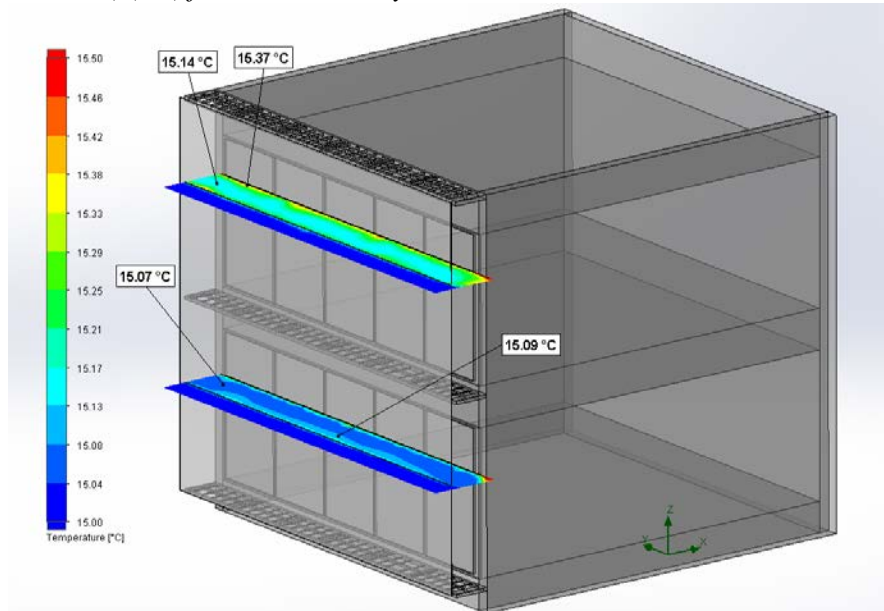
In the configuration where both openings on the interior facade of the building are totally closed, the flow temperature from the opening toward the interior space has been observed 15 °C, and about 15 °C at the upper spaces while the peripheral

temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C (Figures 23-24).

Air gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - Interior Facade Wind Velocity-Wind Distribution (Between Two Facades) m/s
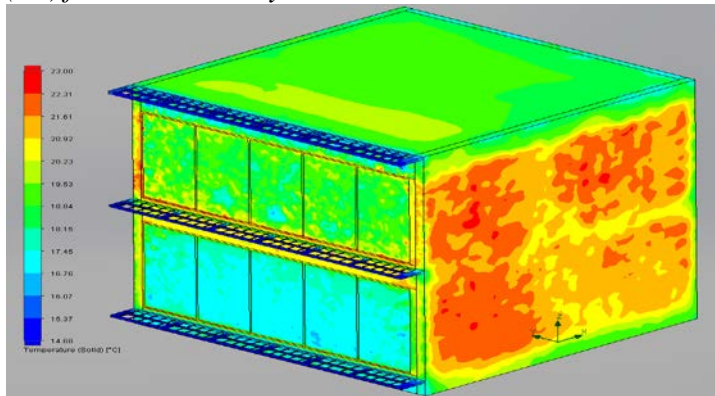
Figure 25. *Wind Velocity-Wind Distribution in DSF and Around Building for Wind Velocity 5 m/s*
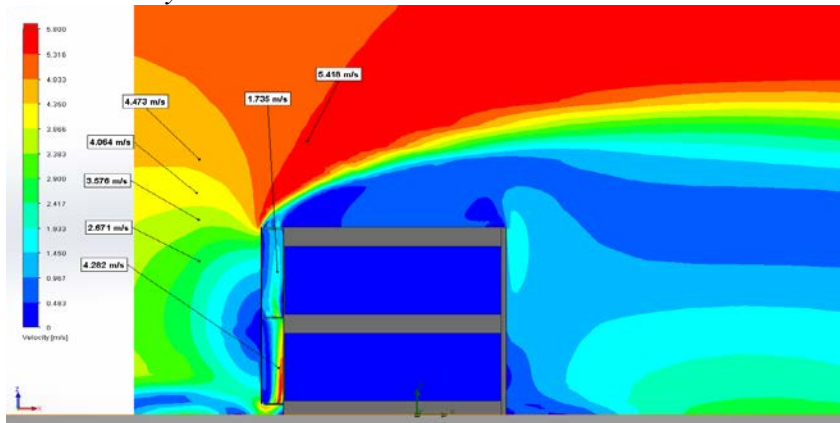
In the configuration where both openings on the interior facade of the building are totally closed, the wind velocity values between two facades particularly at the entry spaces with openings on the building have been observed up to 5 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C, and exterior windward flow speed is 2m/s-2.5 m/s at levels with openings on building. Flow speed increases at once due to the chimney effect between two facades. At the downwind space of the building, flow velocity values were observed about 1.8 m/s (Figure 25).

Figure 26. *Wind Velocity-Wind Distribution of Interior Building for Wind Velocity 5 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the building interior flow velocity has been observed at levels of 0.02-0.05 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C, and exterior flow speed is 5 m/s because the building openings are totally closed and since there is no incoming flow in the volume (Figure 26).

Air gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - Outside Facade Temperature Values of Distribution (°C)

Figure 27. *Outside in Front of Facade Building Temperature Values of Distribution (°C) for Wind Velocity 5 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the building exterior surface temperature values, particularly ground floor and upstairs region side facade surface temperature values, are about 21 °C - 22 °C, while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C (Figure 27).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - PMV and PPD Values in Building Zones

Figure 28. *PMV and PPD Values in Building Zones of Bottom Side Openings Level for Wind Velocity 5 m/s*
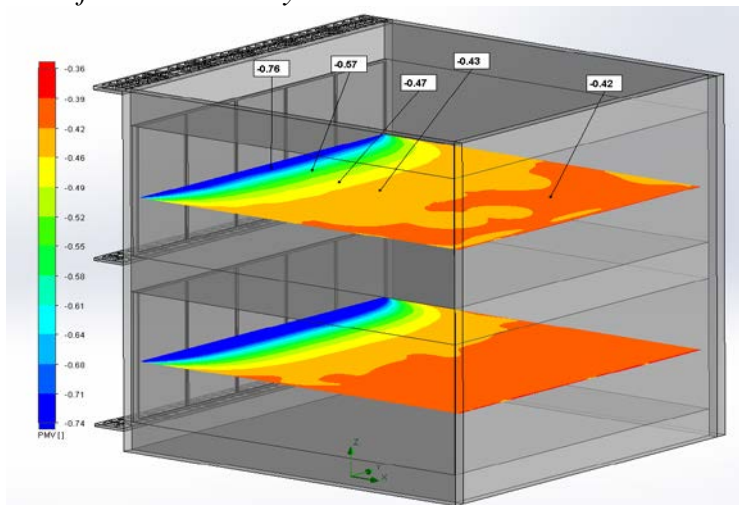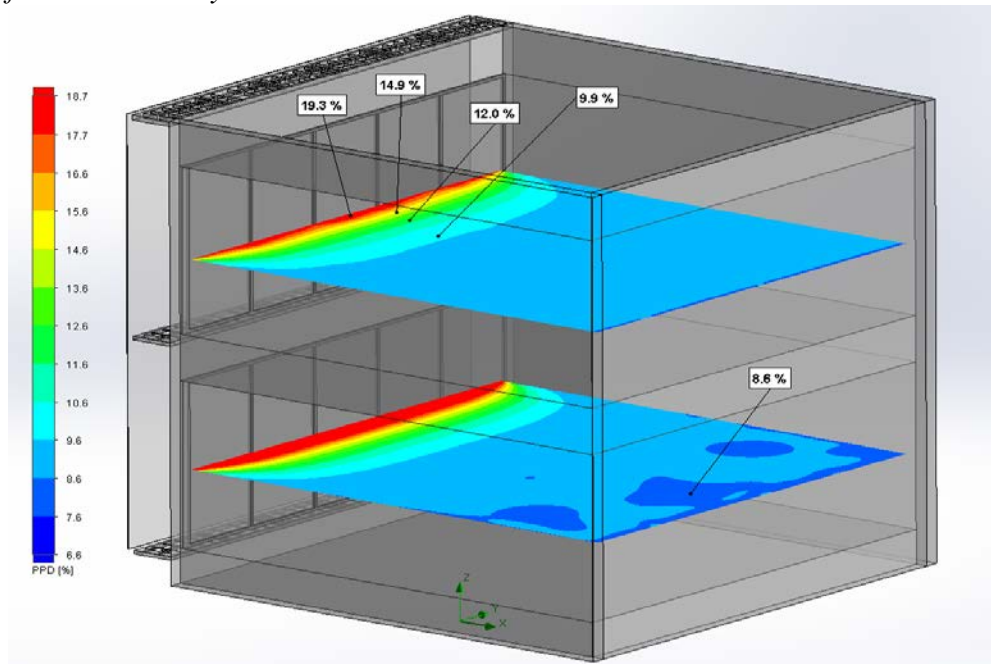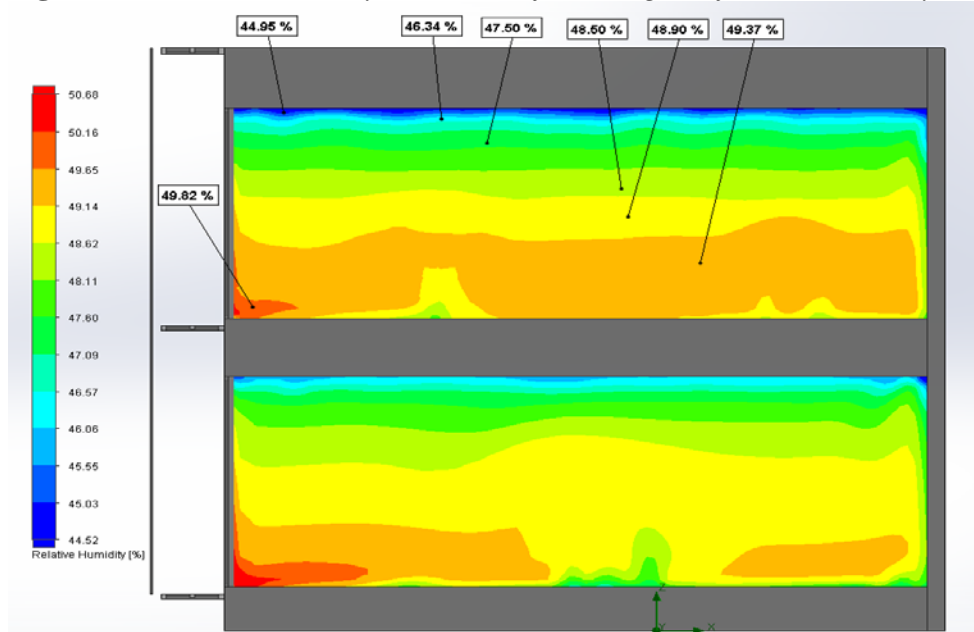
Figure 29. *PMV and PPD Values in Building Zones of Upper Side Openings Level for Wind Velocity 5 m/s*

In the configuration where openings on the interior facade of the building are totally closed, the PMV values were observed about -0.75 at the space close to the building interior facade transparent surface, and about -0.35 at farther internal spaces at ground floor 1.8 m level while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It was observed between values 0.75 and -0.45 at 1.8 m elevation upstairs. In the same configuration and levels, the PPD values were observed 18% close to the transparent surface of the building interior facade surface, about 10% further into the interior space, is occasionally 8% at ground floor 1.8 m level. At 1.8 m level of the upper floor, 10% and 18% values were observed at this time respectively at the spaces of the interior space behind the opening and spaces close to the opening (Figures 28-29).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 5 m/s - Relative Humiditiy in Interior of Building (%)
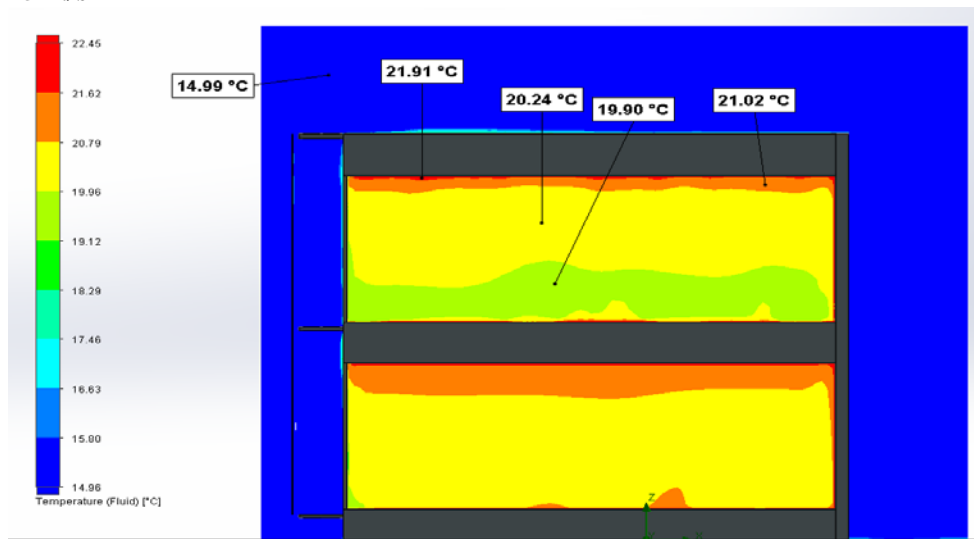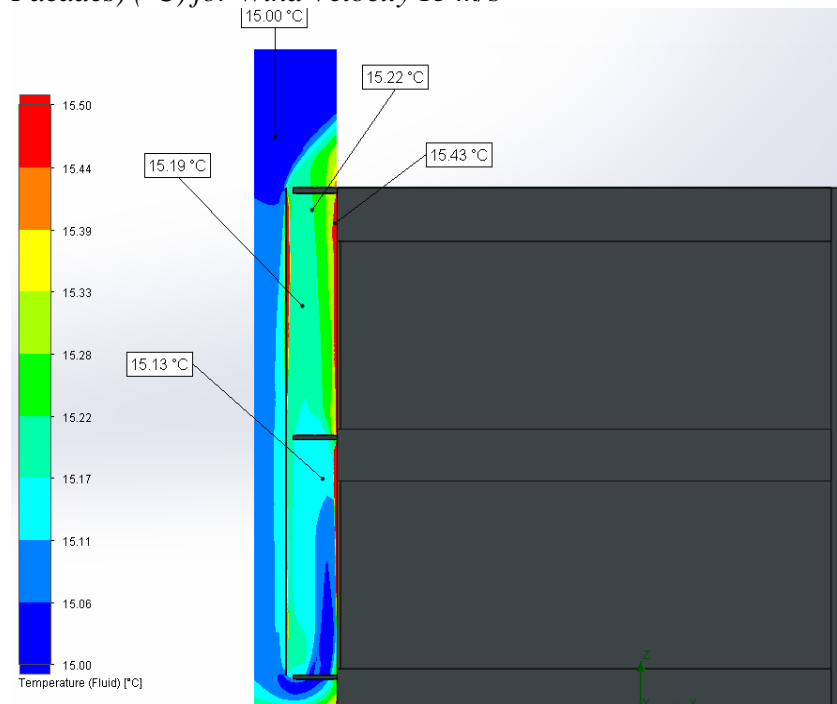
Figure 30. *Relative Humiditiy in Interior of Building (%) for Wind Velocity 5 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the building ground floor and upper floor interior space relative humidity values average has been observed about 48% while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. (Figure 30).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - Air Flow Temperature in Interior of Building (°C)

Figure 31. *Air Flow Temperature in Interior of Building (°C) for Wind Velocity 15 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the interior space temperature values of ground floor interior space flow temperature average has been observed between 20 °C - 21 °C while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C, and exterior flow speed is 5 m/s because the building openings are totally closed and there is no incoming flow. The upstairs interior space average temperature values are about 20 °C (Figure 31).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - Interior Facade Temperature Distribution (Between two Facades) (°C)

Figure 32. *Interior Facade Temperature Distribution-Vertical (Between Two Facades) (°C) for Wind Velocity 15 m/*s

In the configuration where both openings on the interior facade of the building are totally closed, it has been observed that flow temperature value increases in proportion with upward flow from the double facade to the exterior facade surface toward between the two facades at ground level while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, and fixed indoor temperature is 23 °C (Figure 32).

Figure 33. *Interior Facade Temperature Distribution-Horizontal (Between Two Facades) (°C) for Wind Velocity 15 m/s*
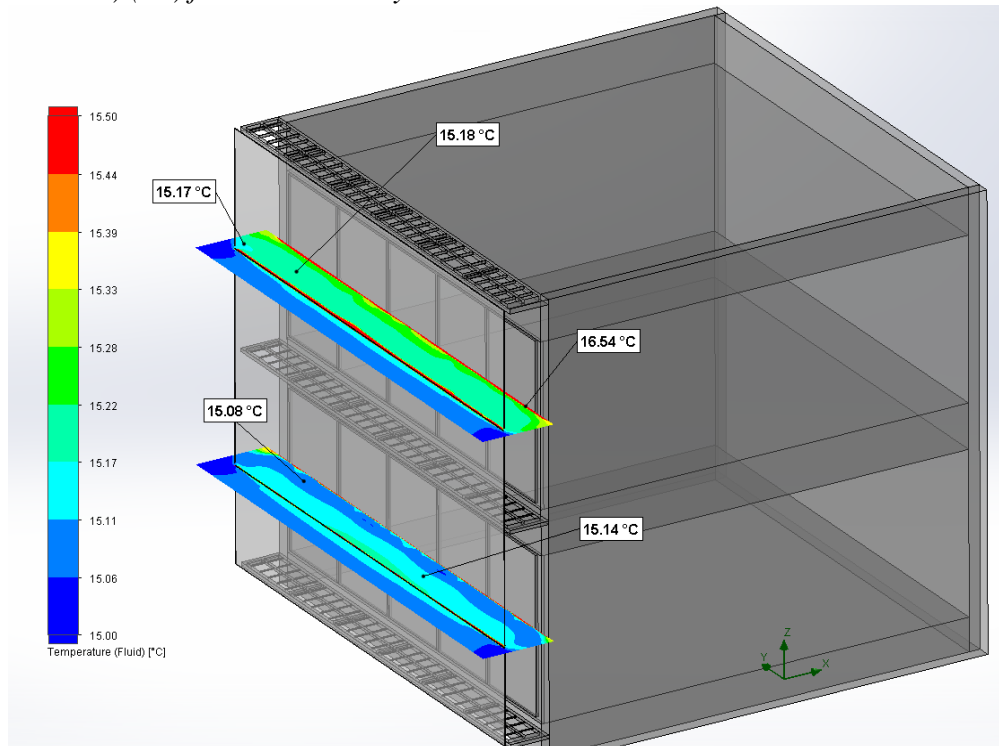
In the configuration where both openings on the interior facade of the building are totally closed, it has been observed that the flow temperature value of flow from double facade exterior facade surface toward between the two facades at ground level was 15 °C, and the upper space ground floor level was about 17 °C while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, and fixed indoor temperature is 23 °C (Figure 33).

<u>Air Gap Width80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - Interior Facade Wind Velocity-Wind Distribution (°C)</u>
Figure 34. *Wind Velocity-Wind Distribution in DSF and Around Building for Wind Velocity 15 m/s*
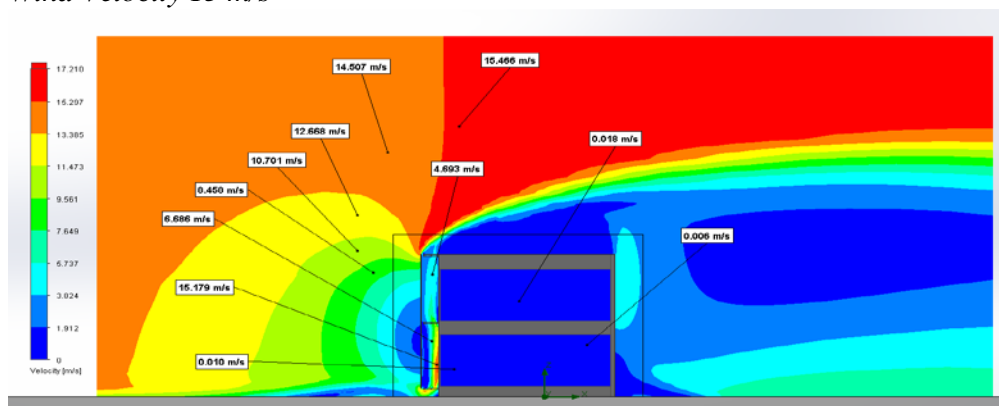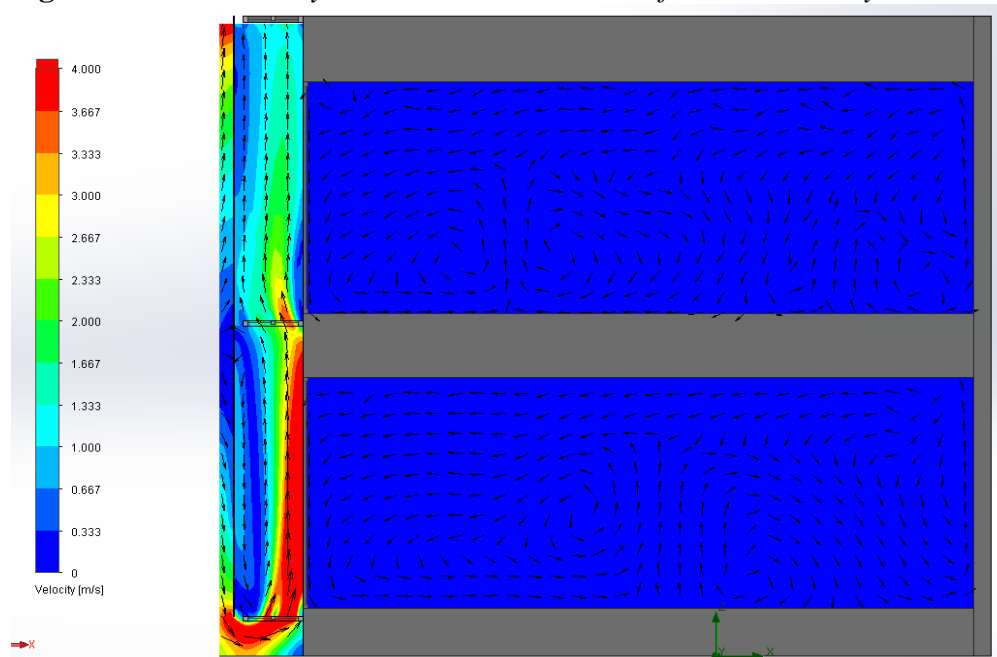
Figure 35. *Wind Velocity-Wind Distribution in DSF for Wind Velocity 15 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the wind velocity values between two facades have been observed to increase up to 17 m/s instantly at ground level, and reduce down to 4-5 m/s at the upper floor level, while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C, and exterior flow speed is 10-12m/s at building level (Figures 34-35).
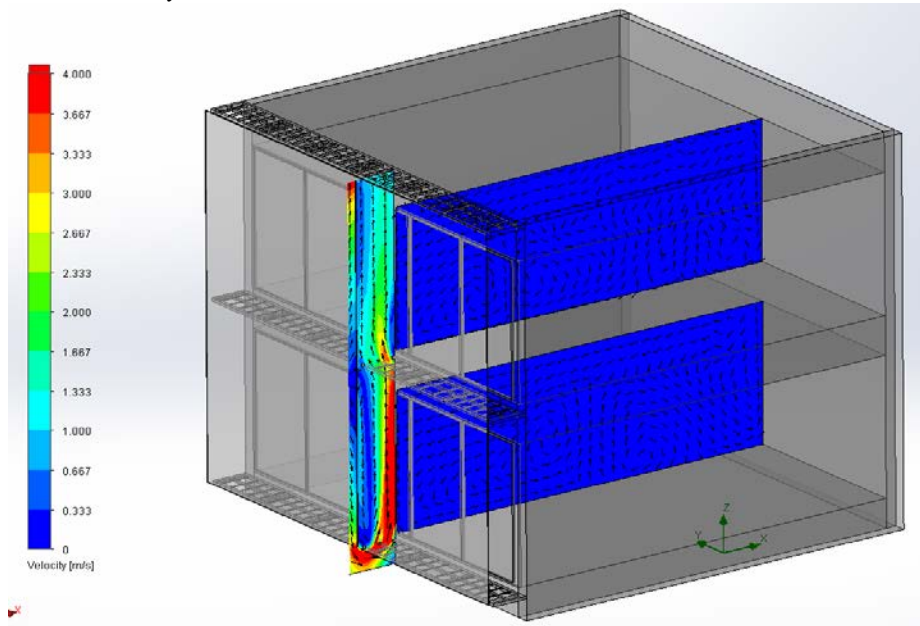
Figure 36. *Wind Velocity-Wind Distribution Interior of Building for Wind Velocity 15 m/s*
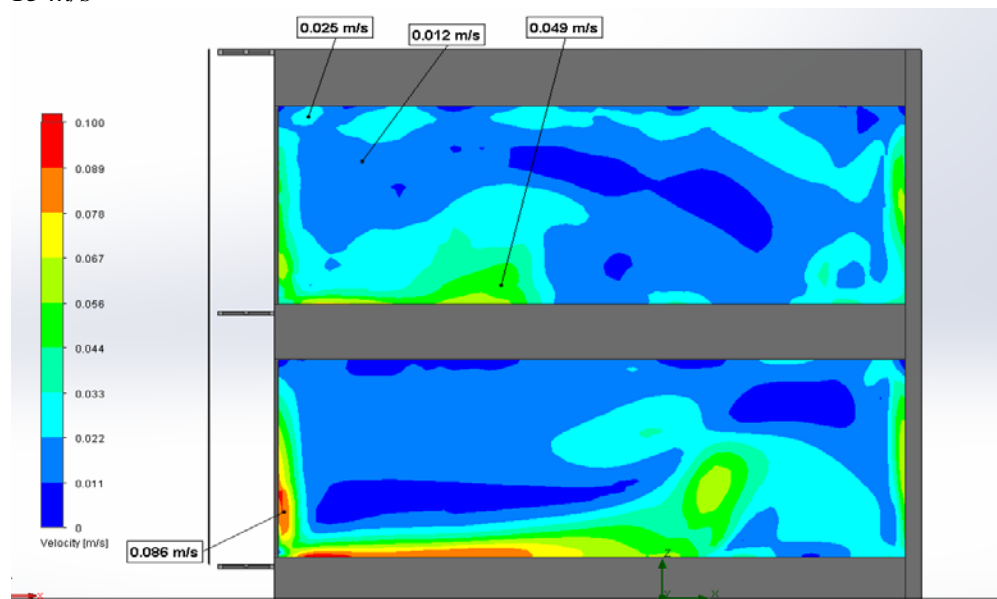
Figure 37. *Section of Wind Velocity-Wind Distribution of Interior of Building for Wind Velocity 15 m/s*

In the configuration where all openings are totally closed, it has been observed that while the building exterior flow velocity value is 15 m/s , the interior space flow velocity values were about 0.02-0.03 m/s on average (Figures 36-37).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - Outside Facade Temperature Values of Distribution (°C)

Figure 38. *Outside in Front of Facade Building Temperature Values of Distribution (°C) for Wind Velocity 15 m/s*
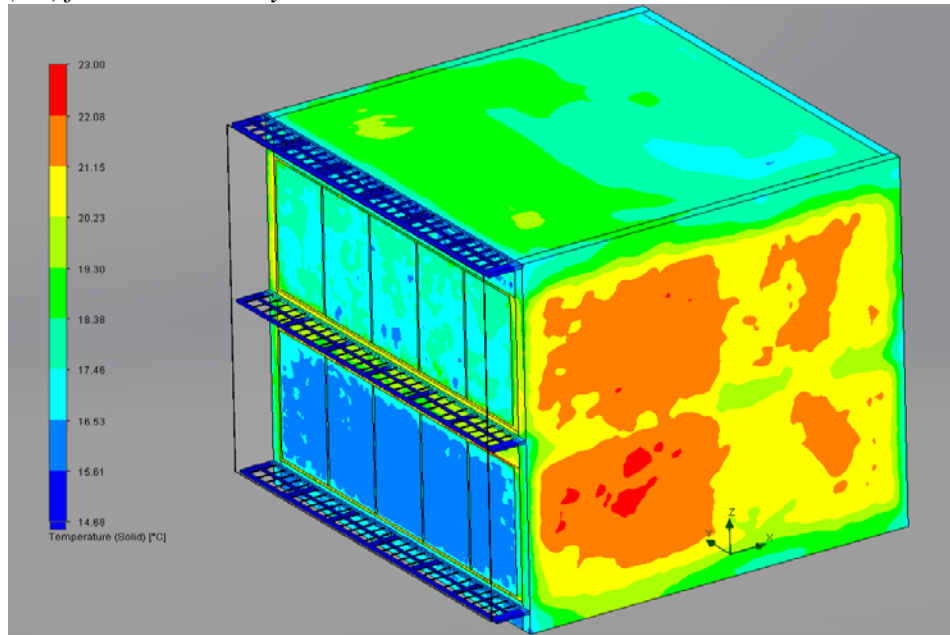
In the configuration where both openings on the interior facade of the building are totally closed, the building's exterior surface temperature distribution values, particularly ground floor building facade and indoor facade, have transparent surface temperature values that have been observed at 14-15 °C and upper floor level opening area transparent surface temperature value about 19 °C while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C. Besides, the building side surface temperature distribution average has been observed between 20-21 °C (Figure 38). As to the exterior flow fixed value analysis with exterior flow velocity value 15 m/s while building interior facade transparent surface temperature distribution average values are 19-20 °C while building exterior flow velocity value is 5 m/s, it has been observed that the average values of building interior facade transparent surface temperature distribution rise up to 22 m/s. It has been observed that the increase in the exterior flow velocity caused a fall on the average double skin Facade interior Facade temperature values (Figure 39).

Air Gap Width 80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - PMV and PPD Values in Building Zones

Figure 40. *PMV and PPD Values in Building Zones of Bottom Side Openings Level for Wind Velocity 15 m/s*
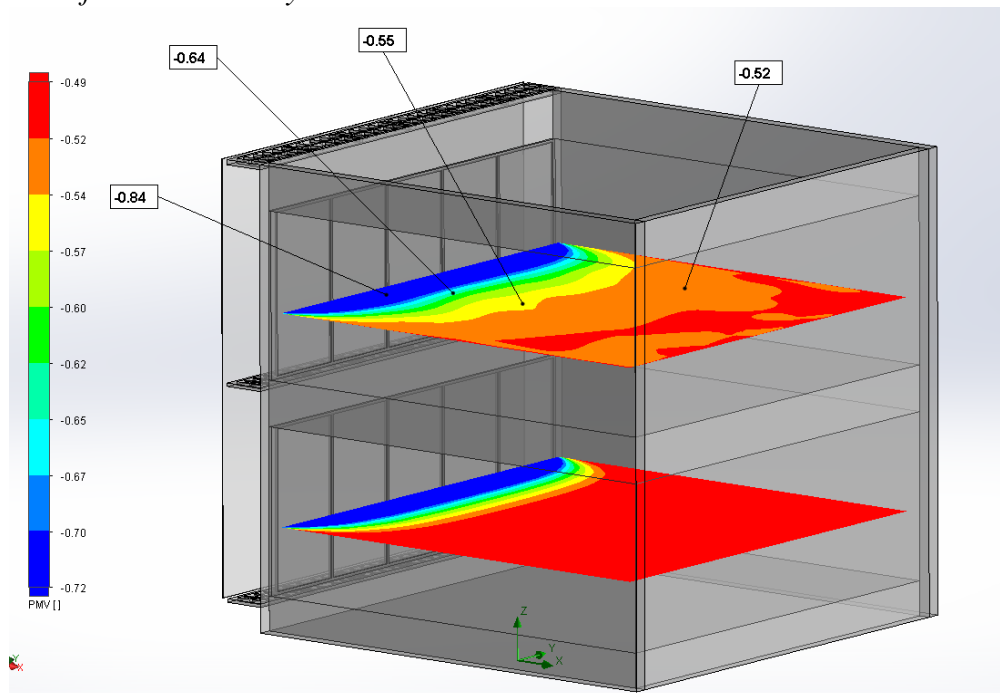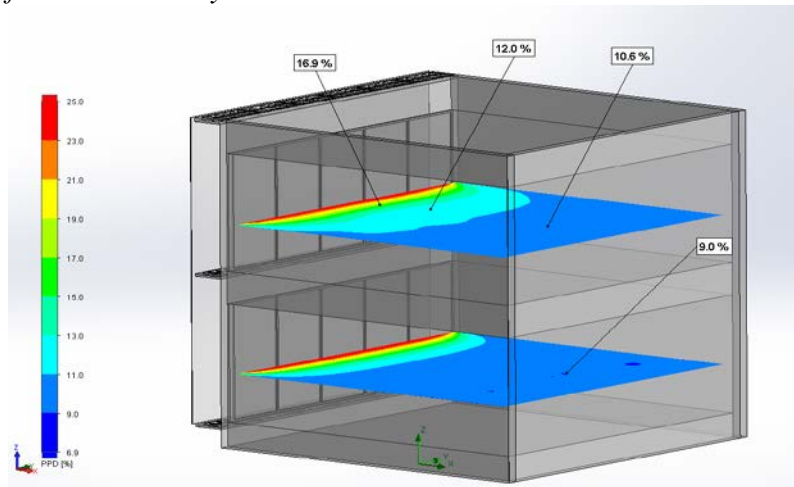
Figure 41. *PMV and PPD Values in Building Zones of Upper Side Openings Level for Wind Velocity 15 m/s*
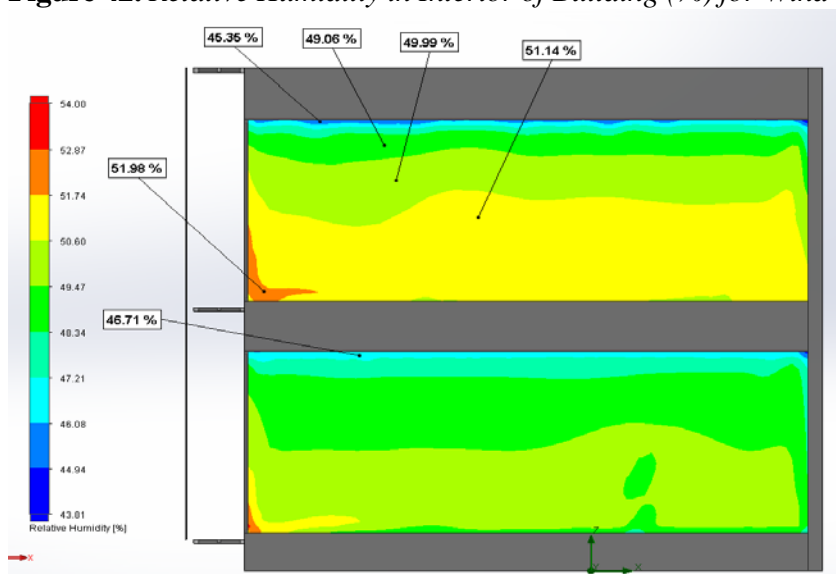

In the configuration where both openings on the interior facade of the building are totally closed, the PMV values were observed between -0.75 and -0.60 at the space close to the building interior facade transparent surface, and about 0.35 backwards at ground floor 1.8 m level while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, and fixed indoor temperature is 23 °C. It was observed that the internal space average PMV value is about -0.52 at 1.8 m elevation upstairs.

Examining PPD values in the same configuration and levels, values of 10% have been observed at 1.8 m level of the ground floor, values between 11% and 13% at spaces mostly behind the opening area of the interior space, and values between 20-25% at locations close to the opening space (Figures 39-41).

Air Gap Width80 cm - All Openings-Closed Configurations for Wind Velocity 15 m/s - Relative Humiditiy in Interior of Building (%)
Figure 42. *Relative Humiditiy in Interior of Building (%) for Wind Velocity 15 m/s*

In the configuration where both openings on the interior facade of the building are totally closed, the building's ground floor relative humidity values average has been observed about 48% and upper floor interior space relative humidity values average about 52% at spaces close to the openings while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, and fixed indoor temperature is 23 °C (Figure 42).

Evaluation of the Effects of Wind Speed Between Multiple Facades for 5 m/s Wind Flow Speed Conditions, Building Interior Operative Temperature, Mean Relative Humidity, Air Diffusion Performance Index Values on Microclimatic Comfort

An examination of the building's wind flow values on the ground floor in analysis studies with an exterior wind flow speed of 5 m/s has shown that in configurations where all cavities are open, there are configurations with highest flow amounts and flow rates within the space. However, in the case where all cavities are open in the three configurations, it is seen that the configuration with the highest flow and flow rate into the space is DSF 1 where the width between two facade is 80 cm (Figure 43).

Figure 43. *Ground Floor Interior Wind Velocity - For Wind Speed 5 m/s*
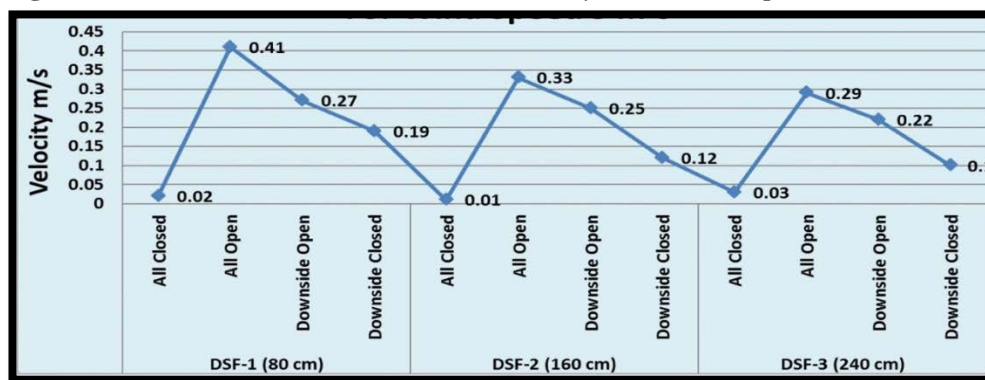
In analyses with exterior wind flow rate 5 m/s on the ground floor plane in DSF-1 configuration, the flow into the space increased the indoor fixed flow rate value to 0.4 m/s value, and it was observed that the increase reduced the fixed indoor temperature value, which was 23 °C at the same time, to 19.27 °C (Figure 44). Furthermore, an examination of other analysis results regarding the cavities on the inner facade showed that the case where the downside open case on the facade ensured increased flow and speed indoor compared to the alternative case in terms of indoor flow rate and amount values (Figure 43).

Figure 44. *Ground floor Interior Operative Temperature (t0) - For Wind Speed 5 m/s*
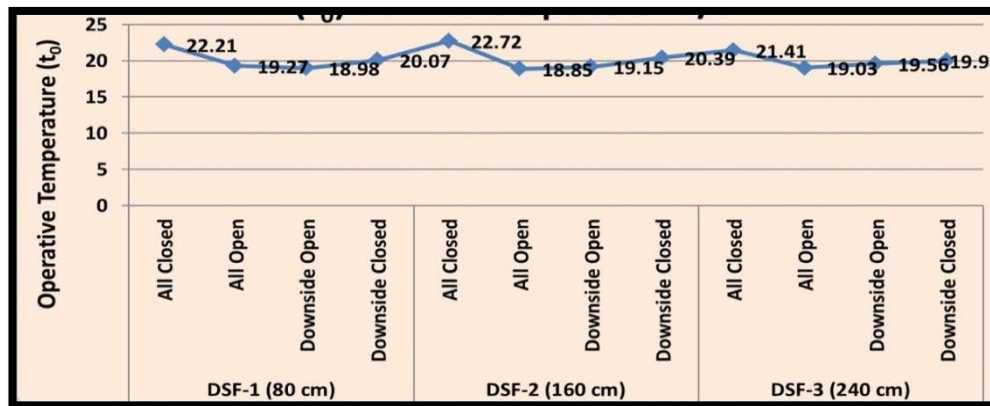
An examination of the indoor relative humidity values on the ground floor plane in analysis studies with an exterior wind flow rate of 5 m/s has shown that the case with the lowest relative humidity comfort value (48%) is seen in configurations where all cavities are closed on the Facade (Figure 44).

Figure 45. *Ground Floor Mean Relative Humidity (%) - For Wind Speed 5 m/s*
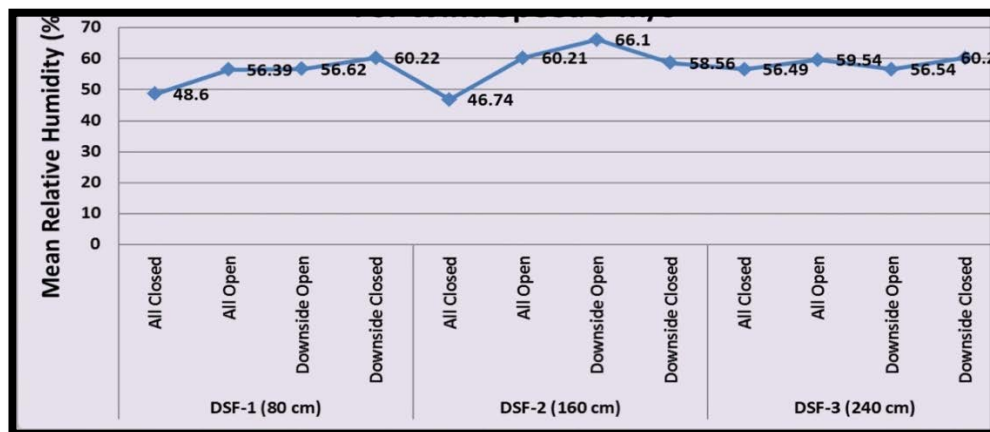
ADPI (Air Diffusion Performance Index) is defined as the percentage of locations in the occupied space which meet the comfort criteria based on velocity and temperature measurements taken at a given number of uniformly distributed points. This ADPI value has proven to be a valid measure of an air diffusion system. The higher the ADPI rating, the higher the quality of room air diffusion within the space, Generally an ADPI of 80 is considered acceptable.

In examination of the acceptable comfort level of the flow to indoor of all ground floor indoor configurations in analysis studies where exterior wind flow rate is 5 m/s, it was seen that ASHRAE acceptable indoor comfort flow percentage according to standard 55 is 80% and above, ADPI percentage is 33% in DSF-1, 46% in DSF-2 and 70% in DSF-3 according to acceptable reference where cavities on the building inner facade are completely open, while ADPI percentage rose to

90% and above in downside closed upside open, or upside open configurations (Figure 46).

Figure 46. *Ground floor Air Diffusion Performance Index (%) - For Wind Speed 5 m/s*
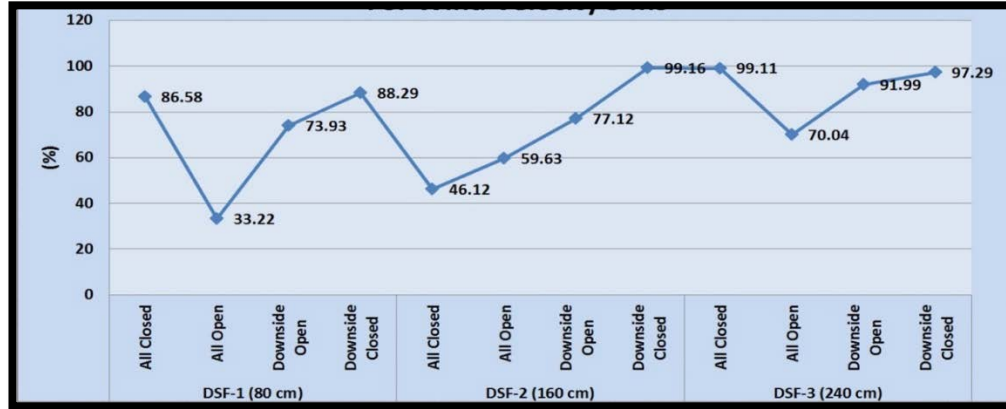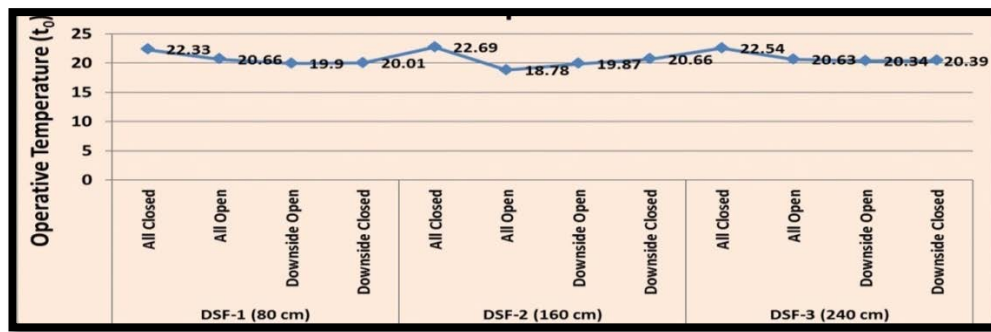

An examination of the building wind flow values on the first floor plane in analysis studies with an exterior wind flow rate of 5 m/s has shown that in configurations where all cavities are open, there are configurations with highest flow amounts and flow rates within the space. However, in the case where all cavities are open in the three configurations, it is seen that the configuration with the highest flow and flow rate into the space is DSF 2 where the widthbetween two facades is 160 cm (Figure 47).

**Figure 47.** *First floor İnterior Wind Velocity - For Wind Speed 5 m/s*
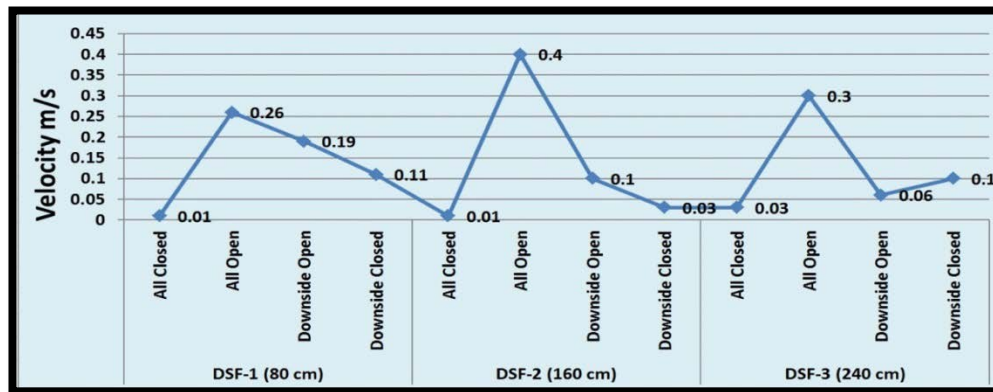
In analyses with exterior wind flow rate 5 m/s on the first floor plane in DSF-1 configuration, the flow into the space increased the indoor fixed flow rate value to 0.3 m/s value, and it was observed that the increase reduced the fixed indoor temperature value, which was 23 °C at the same time, to 18.78 °C (Figure 48).

Figure 48. *First floor Interior Operative Temperature (t0) - For Wind Speed 5 m/s*

An examination of the indoor relative humidity values on the ground floor plane in analysis studies with an exterior wind flow rate of 5 m/s has shown that the case with the lowest relative humidity comfort value (48%) is seen in configurations where all cavities are closed on the facade (Figures 48-49).

Figure 49. *First Floor Mean Relative Humidity (%)- For Wind Speed 5 m/s*
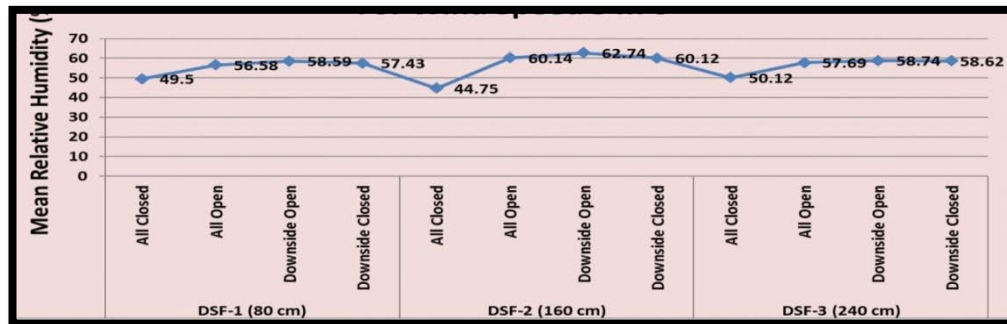
On examination of the acceptable comfort level of the flow to indoor of all first floor indoor configurations in analysis studies where exterior wind flow rate is 5 m/s, it was seen that according to acceptable reference of standard 55 of ASHRAE acceptable indoor comfort flow percentage of 80% and above; 80% and above ADPI levels of performance was observed in configurations other than all closed ones (Figure 50).

Figure 50. *First Floor Air Diffusion Performance Index (%)-For Wind Speed 5 m/s*
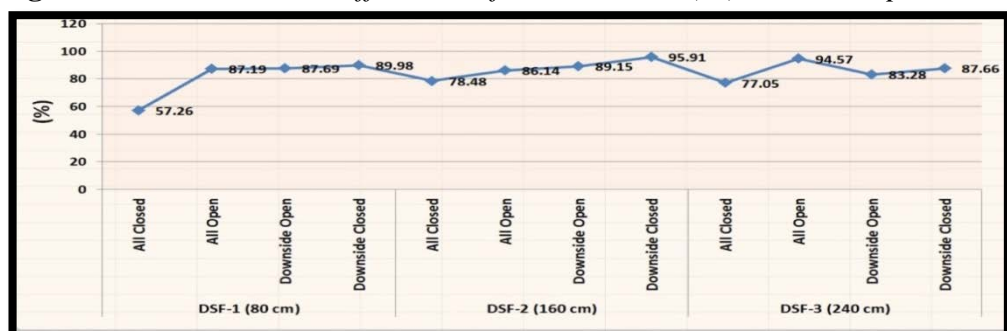
An examination of the building's wind flow values on the ground floor plane in analysis studies with an exterior wind flow rate of 15 m/s has shown that the option downside open on the facade is the configuration with highest flow amount and flow rate into the space. However, in DSF-2 configuration, the highest flow and highest speed (0.88 m/s) to indoor in DSF-2 configuration was seen in all open option. An examination of the DSF-3 configuration analysis results shows that the option downside open is the configuration with highest flow amount and flow rate (0.79 m/s) into the space (Figures 50-51). Nevertheless, the case whereby the flow rate is highest to the interior space has been seen in the all open configuration where exterior wind speed is 5 m/s.

Evaluation of the Effects of Wind Speed Between Multiple Facades for 15 m/s Wind Flow Speed Conditions, Building Interior Operative Temperature, Mean Relative Humidity, Air Diffusion Performance Index Values on Microclimatic Comfort

Figure 51. *Ground Floor Interior Wind Velocity - For Wind Speed 15 m/s*
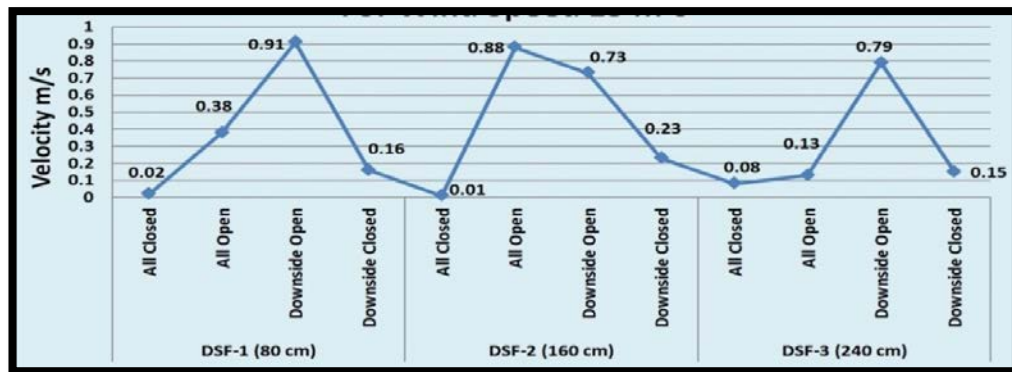
In analyses with exterior wind flow rate 15 m/s on the ground floor plane in the downside open option with the highest indoor flow amount and flow rate in DSF-1 configuration, the fixed flow indoor increased the flow rate to 0.9 m/s, and it was observed that the increase reduced the fixed indoor temperature value, which was 23 °C at the same time, to 17.74 °C (Figure 52).

Figure 52. *Ground floor Interior Operative Temperature (t0) - For Wind Speed 15 m/s*

In the analysis works where exterior wind speed is 15 m/s, examination of the indoor relative humidity values on the ground floor plane showed that the case whereby the relative humidity comfort values are the lowest (46%) is the configurations whereby all cavities on the facade are closed (Figure 53).

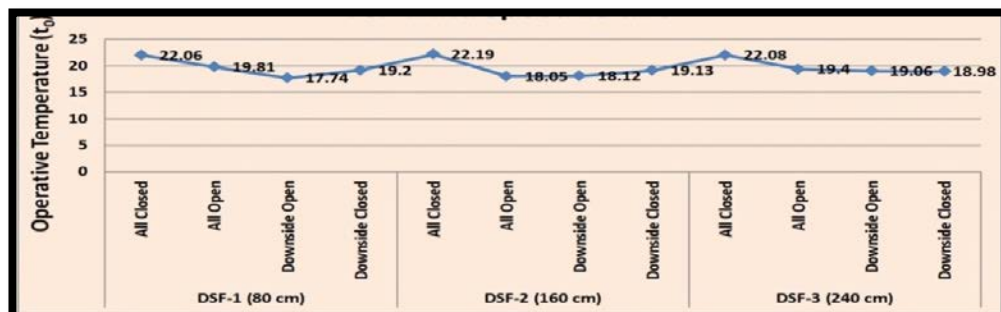**Figure 53.** *Ground Floor Mean Relative Humidity (%) - For Wind Speed 15 m/s*
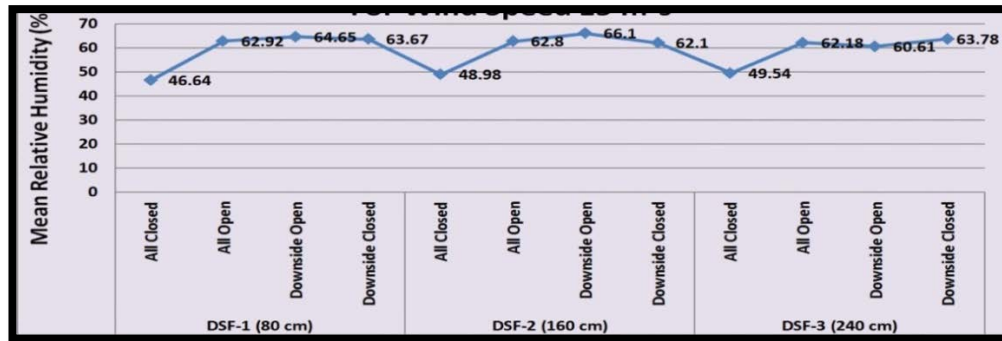
On examination of the acceptable comfort level of the flow to indoor of all ground floor indoor configurations in analysis studies with an exterior wind speed of 15 m/s, it was seen that according to ASHRAE standard 55 reference stipulating acceptable indoor comfort flow percentage of 80% and above, ADPI percentage is 89% in DSF-1 in downside closed case, ADPI percentage is 89% in DSF-2 in downside open case and of 89% and above in DSF-3 in both downside open and downside closed configurations (Figure 54).

Figure 54. *Ground floor Air Diffusion Performance Index (%)-For Wind Speed 15 m/s*
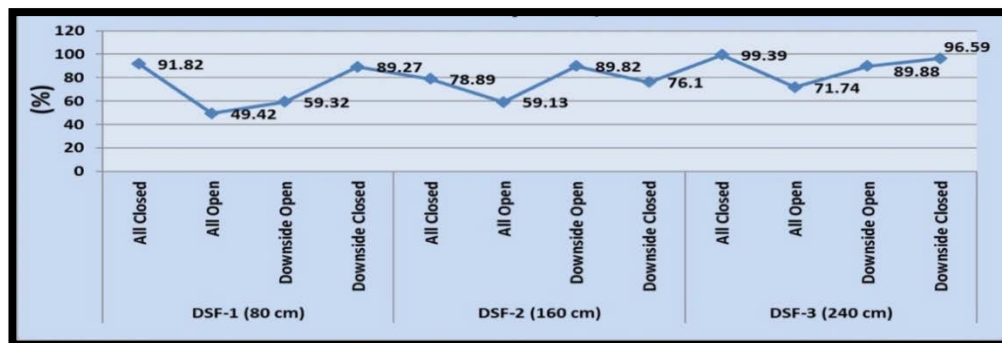

An examination of the building wind flow values on the first floor in analysis studies with an exterior wind flow rate of 15 m/s has shown that the configurations with the highest flow amount and flow speed (0.63 m/s) into the space is DSF-3, the downside open configuration of the cavities on the facade. Nevertheless, an examination of the analysis study results where exterior wind flow speed is 5 m/s, it was observed that the configuration with highest flow reaching highest speeds is the all open configurations of the facade. In analysis studies with an exterior wind

flow speed of 15 m/s, it has been seen that the highest flow speed and flow amount (0.39 m/s) is in DSF-2 all open configurations on the first floor (Figure 55).

Figure 55. *First Floor Interior Wind Velocity - For Wind Speed 15 m/s*
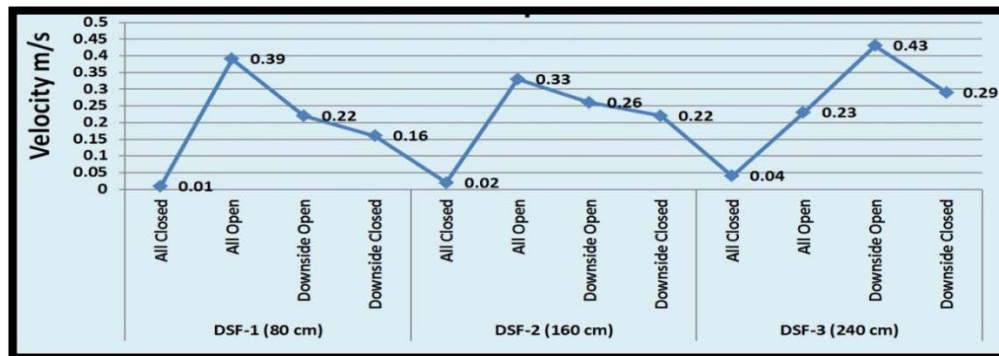
In analyses with exterior wind flow speed 15 m/s, it has been observed that the flow into the space on the first floor plane in DSF-3 configuration increased the in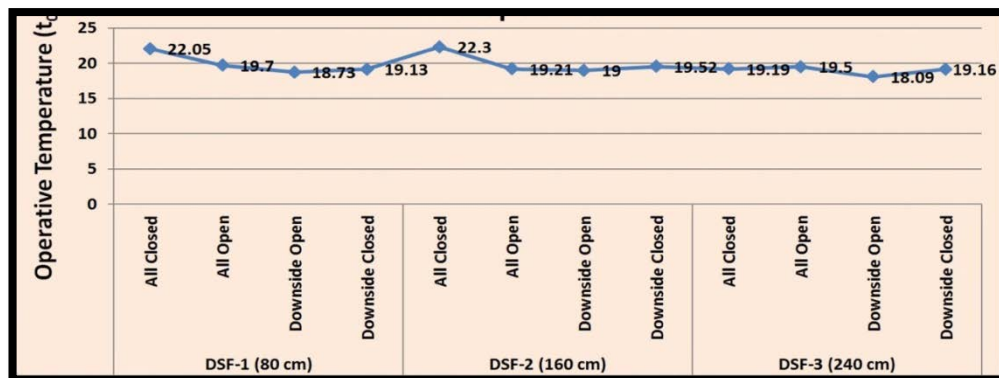door fixed flow rate value of the downside open configuration to 0.63 m/s value, and that the increase reduced the fixed indoor temperature value, which was 23 °C at the same time, to 18.09 °C (Figure 56).

Figure 56. *First floor Interior Operative Temperature (t0) - For Wind Speed 15 m/s*

In the analysis works where exterior wind speed is 15 m/s, examination of the indoor relative humidity values on the ground floor plane showed that the case whereby the relative humidity comfort values are the lowest (48%) is the configurations whereby all cavities on the facade are closed (Figure 45). As to the examination of the relative humidity values in configurations where there is inward flow, the lowest values are observed approximately at 57% level in all open case (Figure 57).

Figure 58. *First Floor Mean Relative Humidity (%)- For Wind Speed 15 m/s*
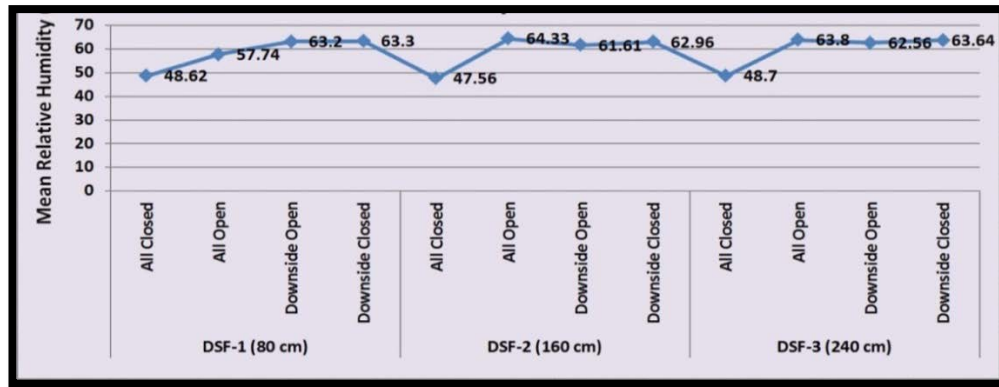
On examination of the acceptable comfort level of the flow to indoor of all first floor indoor configurations in analysis studies where exterior wind flow rate is 15 m/s, it was seen that according to acceptable reference of standard 55 of ASHRAE acceptable indoor comfort flow percentage of 80% and above; 80% and above ADPI levels of performance were observed in all configurations other than all closed and all opened ones (Figure 52). Nevertheless, on examination of the first floor indoor ADPI percentages where exterior wind flow rate is 15 m/s, it was seen that 80% and above values were obtained in configurations other than all closed ones (Figure 59).

Figure 59. *First Floor Air Diffusion Performance Index (%) - For Wind Speed 15 m/s*
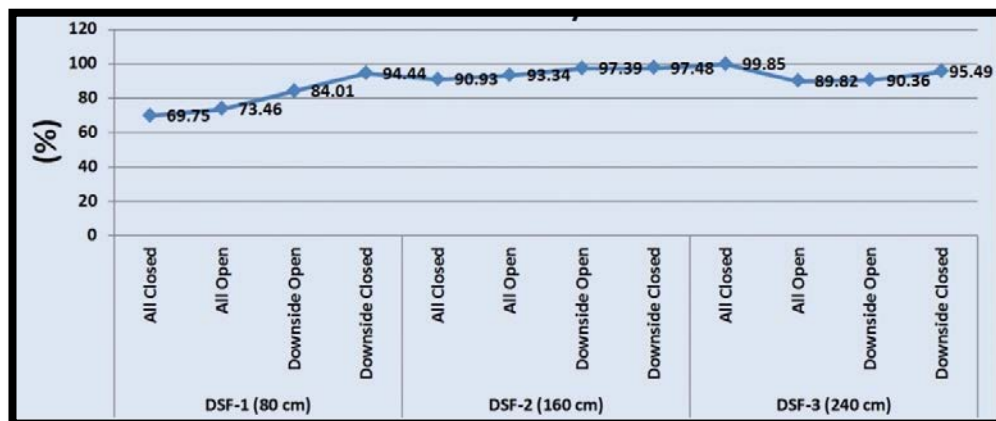
Solar Heat Flux and Total Heat Transfer Rate Values from the Interior Facade for Air Gap Width 80 cm Configurations

In building configuration where DSF Widthbetween two facade is 80 cm and all building surface openings are closed, the building surface area is 320 m^2, and the surface area between two facades is 58.4 m^2.

In the configuration where both openings on the interior facade of the building are totally closed, the solar heat flux value was 0.315 W/m^2 over the 320

m^2 interior surface of the building while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s and fixed indoor temperature is 23 °C, and the solar heat flux value over the interior surface of the building was 0.625 W/m^2 over the building interior surface while the total heat transfer rate value is 101 W/m^2 and exterior wind velocity speed was 15 m/s.

In the configuration where the openings on the interior facade of the DSF building are totally closed, the wind flow velocity average between two facades has been 1.8 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C, and the average wind flow velocity value between two facades has been observed 4.9 m/s where the exterior wind flow is 15 m/s.

ACH Value for Air Gap Width 80 cm Configurations

ACH (Air Change Per Hour) Value is (1 ACH = 46 m^3/h; Total volume 46 m^3). In the configuration where both openings on the interior facade of the building are totally closed, ACH ratio at 58.4 m^2 between two facades is 1.996, and the total flow rate value is 91.80 while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, fixed indoor temperature is 23 °C. ACH ratio at 58.4 m^2 between two facades is 5.872 and the total flow rate value is 270 while the exterior flow velocity is 15 m/s.

In the configuration where both openings on the interior facade of the building are open, the wind velocity values between two facades have been observed to fall down to 2-4 m/s while the exterior velocity values are about 8-10 m/s at building level while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C.

While it has been observed that the building exterior flow velocity value is 5 m/s, the flow velocity value approached the exterior flow level; and it has been observed in the 15 m/s exterior flow fixed value analysis that the instant flow velocity values between two facades fell down from about 15 m/s to 2-4 m/s. In this case, it has been observed that the wall effect of the exterior Facade reduced velocity values quite high in transition to between interior Facade. Besides, where exterior flow velocity is 15 m/s, it has been observed that the flow amount passing from the openings at the upper floor interior space was less compared to the 5 m/s velocity value.

Microclimatic Thermal Comfort and Temperatures of the Interior Wall

Since the air inside the double skin facade air gap is warmer than the outdoor air during the heating period, the interior part of the facade can maintain temperatures that are closer to the microclimatic thermal comfort levels. On the other hand, it is really important that the system and space between the double facade should well designed, so efficient heat extraction ensures that the temperatures inside the air gap do not increase dramatically, leading to high operative temperatures.

In the configuration where both openings on the interior facade of the building are open, the wind velocity values between two facades have been observed to fall down to 2-4 m/s, while the exterior velocity values are about 8-10 m/s at building level; while the peripheral temperature is 15 °C, exterior flow velocity is 15 m/s, fixed indoor temperature is 23 °C.

While it has been observed that the building exterior flow velocity value is 5 m/s, the flow velocity value approached the exterior flow level; and it has been observed in the 15 m/s exterior flow fixed value analysis that the instant flow velocity values between two facades fell down from about 15 m/s to 2-4 m/s. In this case, it has been observed that the wall effect of the exterior facade reduced velocity values quite high in transition to between interior facade.

Besides, where exterior flow velocity is 15 m/s, it has been observed that the flow amount passing from the openings at the upper floor interior space was less compared to the 5 m/s velocity value. In the configuration where both openings on the interior facade of the building are open, the building interior flow velocity has been observed that the flow toward the interior from the openings on the building change the building flow and temperature values when the exterior flow velocity is 5 m/s while the peripheral temperature is 15 °C, exterior flow velocity is 5 m/s, and fixed indoor temperature is 23 °C. It has been observed that while the ground floor indoor flow values are about 1.5 m/s close to the openings, the flow velocity values inward at the vicinity of the opening are about 0.4-0.7 m/s.

Conclusions

One of the main advantages of the double skin facade systems is that they can allow natural (or fan supported) ventilation. Different types can be applied in different climates, orientations, locations and building types in order to provide fresh air before and during the working hours. The selection of a double skin facade type can be crucial for temperatures, air velocity, and the quality of the introduced air inside the building. If designed well, the natural ventilation can lead to a reduction in energy use during the occupation stage and improve the comfort of the occupants. In this study, discussed analysis studies where the exterior flow rate is 5 m/s and 15 m/s and the flow temperature is 15 °C, it has been observed that the exterior flow and conditions have different values in terms of their effects on the ground floor or upper floor indoor space comfort, three different DSF configurations discussed, and different air gap scenarios of each configuration on the facade. The obtained results presented as a natural ventilation and microclimatic comfort of occupants

On examination of the indoor flow rate and operative temperature values of both the ground floor and upper floor where exterior flow is 5 m/s, it has been observed that the flow to the interior volume is the highest in the option were cavities are all open and in all three configurations (DSF-1, DSF-2, DSF-3) and the highest of the flow rate values were seen. It was seen that the indoor flow rate values are about 0.4 m/s, and the flow reduced the indoor temperature values by 4-5 °C. Accordingly, an examination of to what extent the flow indoors affects

indoors ADPI comfort percentage levels revealed that 80% and above values suggested by ASHRAE-55 standard were reached in downside closed options on the Facade in all three configurations (DSF-1, DSF-2, DSF-3).

However, it was observed that ADPI percentage is about 40-45% in all open options. 80% and above values for the upper floor indoor space ADPI comfort percentage have been seen in downside open and downside closed options. A comfort evaluation for the ground floor indoor space relative humidity percentages has shown that upper floor relative humidity percentage values are at higher levels. While values between 50% and 55% are obtained on the ground floor, the relative humidity percentage values for indoors on the upper floor are from 56% to 62%.

On examination of the indoor flow rate and operative temperature values of both the ground floor and upper floor, it has been observed this time that very different values and options emerge compared to analyses where exterior flow is 5 m/s. It has been seen that the highest indoor space flow rate values were realized at about 0.9 m/s in all three configurations (DSF-1, DSF-2, DSF-3) in downside open option for the cavities on the facade. The flow to the ground floor indoor space at this level of speed reduced the indoor temperature level down to about 17 °C.

An examination of to what extent the exterior flow affects indoors ADPI comfort percentage levels revealed that 80% and above values suggested by ASHRAE-55 standard were reached in downside closed option on the acade in DSF-1, and in downside open option of the facade cavities in DSF-2, and that 80% and above values were reached in both downside open and downside closed options in DSF-3. 80% and above values for the upper floor indoor space ADPI comfort percentage have been seen in downside open and downside closed options.In this study, detailed CFD calculations on three main different DSF, the influence of geometrical characteristics on airflows also was studied as a different aperture effects case compared with each DSF.

Although air gap width on DSF and windows openings or closed condition relatively influences on the amount of natural ventilation, it will directly change the value of ACH and indoor airflow coverage. For future studies on natural ventilated double-skin facade, closed window status can be disregarded, but a reasonable air gap width and dimension on DSF would be more practical because it provides a better indoor air distribution. Although there is more air in the wider air gap, when the air flow velocity values are compared, faster air flow was observed in the narrower air gap. Therefore, the use of both narrow and wide air gap of multiple facade in summer climatic conditions may be advantageous in terms of cooling the air warmed by solar radiation and natural ventilation.

Indoor and outdoor climate simulations have to be carried out already at an early design stage and then be refined during the actual design. This will ensure improved indoor and outdoor climate performance of the building. In order to achieve and improved microclimatic thermal environment it is essential to (a) validate the calculation methods, (b) carry out simulations on a component level in order, to gain the necessary background to the possibilities and limitations of the system, (c) prioritize the performance and quality requirements to be fulfilled and (d) carry out simulations on a different DSF width air gaps configurations and on a building level. Accordingly, the future Research s on should address the

performance characteristics of innovative materials used in multiple building facades, the number of layers and material relations, the relationship between DSF and the mechanical air conditioning used in the building.

Acknowledgments

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