



**Double Skin Façade
for an office building in the extreme UAE climate**

واجهة مزدوجة الجلد
لمبنى إداري في المناخ القاسي لدولة الإمارات العربية المتحدة

by

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**Dissertation submitted in partial fulfilment
of the requirements for the degree of
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ABSTRACT

Regional climate change scenarios indicate ever-increasing building energy consumption trends which are a serious cause of concern for the built environment sector of the UAE. Mitigating the increasing energy trends is very well understood by employment of active technological changes in the building services systems. This research focuses on the other side of the coin which is the passive technologies in reducing building energy consumption, more specifically technologies related to the skin of the building. A conventional passive skin technology (external shading) is fielded against unconventional passive skin technology (double skin façade - DSF) on key metrics such as annual cooling energy, annual solar gain, temperature and velocity profiles. The course of the research takes a holistic approach starting with a review of existing studies leading all the way to intermodal comparison of the dynamic thermal simulation and CFD results. Promising results are obtained for the building with external shading with 9.2% annual cooling energy savings whereas the study shows an increase of +1.42% jump in annual cooling energy consumption with the DSF building as compared to a generic high rise tower base case. Intermodel comparison reflects upon the under estimation of the dynamic thermal simulations in predicting cooling energy savings as compared to CFD simulation. An additional CFD sensitivity analysis further sheds light into the ability of the k-e turbulence models and constant effective models in determining stable solutions for CFD simulation of large unrestricted vertical volumes in DSF cavities.

المباني في الطاقة استهلاك في باستمرار متزايدة اتجاهات إلى الإقليمي المناخ تغير سيناريوهات تشير من التخفيف إن .المتحدة العربية الإمارات دولة في المبنية البيئة لقطاع للقلق خطيراً سبباً تعد والتي خدمات أنظمة في النشطة التكنولوجية التغييرات توظيف خلال من جيداً مفهوم المتزايدة الطاقة اتجاهات طاقة استهلاك تقليل في السلبية التقنيات وهو العملة من الآخر الجانب على البحث هذا يركز .البناء التقليدية السلبية الجلد تقنية استخدام يتم .المبنى بجلد المتعلقة التقنيات تحديداً أكثر وبشكل ، المبنى المقاييس على (DSF - المزدوجة الجلد واجهة) التقليدية غير السلبية الجلد تقنية ضد (الخارجي التظليل) الحرارة درجة وملامح ، السنوية الشمسية الطاقة واكتساب ، السنوية التبريد طاقة مثل الرئيسية متعددة المقارنة إلى تقود التي الحالية الدراسات بمراجعة يبدأ شاملاً نهجاً البحث مسار يأخذ .والسرعة التظليل مع للمبنى واحدة نتائج على الحصول تم .CFD ونتائج الديناميكية الحرارية للمحاكاة الوسائط في 1.42% + قدرها زيادة الدراسة أظهرت بينما التبريد طاقة في سنوياً 9.2% توفير مع الخارجي بين المقارنة تعكس .عامة شاهقة برج قاعدة بحالة مقارنةً DSF بمبنى السنوي التبريد طاقة استهلاك بمحاكاة مقارنة التبريد طاقة بتوفير التنبؤ في الديناميكية الحرارية للمحاكاة الأقل التقدير على النماذج الفعالة والنماذج k-e الاضطراب نماذج قدرة على الضوء الإضافي CFD حساسية تحليل يلقي .CFD تجاوب في المقيدة غير الكبيرة العمودية للأحجام CFD لمحاكاة المستقرة الحلول تحديد في الثابتة DSF.

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ABBREVIATIONS

EUI – Energy Usage Index

CFD – Computational Fluid Dynamics

ADWEA - Abu Dhabi Water and Electricity Authority

DEWA - Dubai Electricity and Water Authority

UAE – United Arab Emirates

ASCE - American Society of Civil Engineers

EGBC - Emirates Green Building Council

SSF – Single Skin Façade

DSF – Double Skin Façade

WWR – Window to Wall Ratio

CSFS - Classical Single Façade System

CRFS - Climate Interactive Façade System

DBT - Dry Bulb Temperature

NFPA - National Fire Protection Association

kWh – kilowatt hour

MWh – Megawatt hour

deg. C – degree Celsius

GCC – Gulf Cooperation Council

LEED - Leadership in Energy and Environmental Design

USA – United States of America

DSL – Double Spectral glazing

DCL – Double Clear glazing

BMS – Building Management System

IWEC - International Weather for Energy Calculation

FCU – Fan Coil Unit

1. Chapter 1: Introduction

This section sets the tone, establishes and concludes to the context for this particular research. Beginning with the general overview of the national level energy consumption of the construction industry in the UAE thereby carefully categorizing the Emirate wise distribution of the construction sector. Further into the section a brief outline of the existing building stock is presented that gives an overall idea of the building stock constructed, specifically in the Emirate of Dubai. The third part of this section gives the scale of energy consumption for a typical building and how this energy is distributed among the various building services involved. The fourth part of this section highlights the ways to reduce the energy consumption of buildings in the UAE.

1.1. Energy footprint of building stock in the UAE

Majority of the building stock in the UAE comprises of facades with a complete glass cover and falls under the broad category of a single skin façade (SSF). Given this façade configuration and the extreme hot weather of the UAE requires huge energy consumption for cooling the indoor built environment and keeping the occupants thermally comfortable. Krarti & Dubey (2018) in their research work that revolves around the economic and environmental aspects of the building sector in the UAE, noted that around 90% of the electricity produced in the UAE is consumed by the building sector. The authors reported 8702 GWh/yr in energy savings for the 2013 commercial building stock of the UAE with employment of passive retrofit options. As seen in Figure 1, a major proportion of the national electricity consumption belongs to ADWEA (Abu Dhabi Water and Electricity Authority) and DEWA (Dubai Electricity and Water Authority) authorities. Figure 2 illustrates the electrical energy trend for the UAE and a gradual increment over the years is clearly visible. Krarti & Dubey (2018) also noted the high contribution of the air conditioning equipment towards electrical energy consumption for cooling buildings due to the prevailing hot climate, also roughly represented by the cooling degree days (Figure 3). They reported that the building stock of the Dubai (Table 1) and the made an assumption that the country wide building stock would be 2.7 times the building stock of the emirate of Dubai.

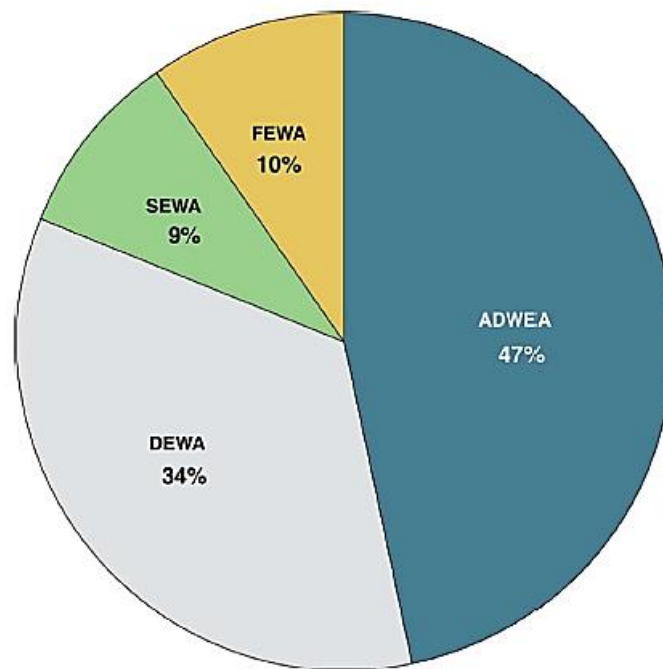


Figure 1: National electricity distribution based on authorities in different emirates for the year 2013 (Karti & Dubey 2018)

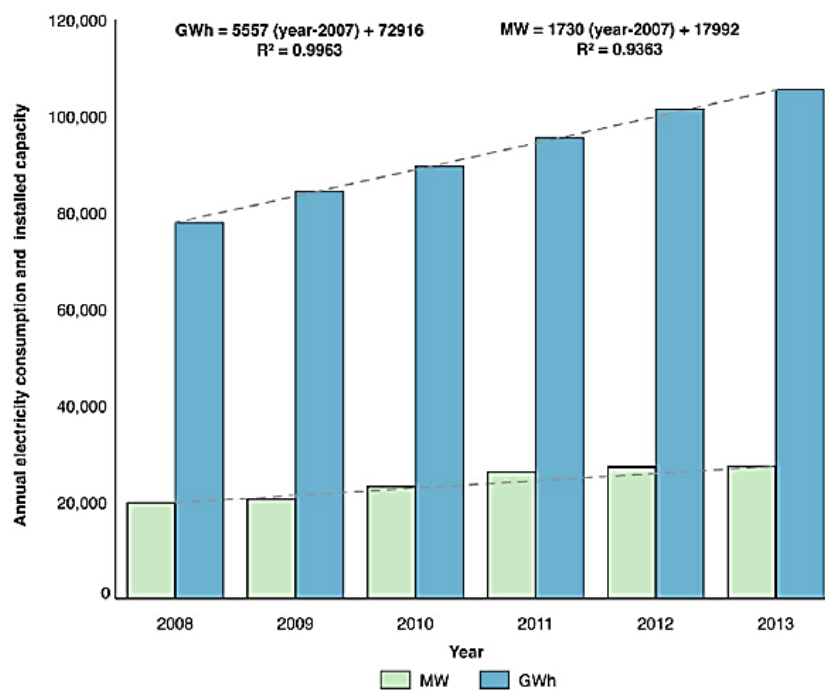


Figure 2: Annual electricity consumption trend from 2008-2013 in UAE (Karti & Dubey 2018)

1.2. Building stock of UAE and typical end use energy consumption

Table 1 depicts the no. of buildings falling under each building typology recorded in the year 2013 and 2014 for the emirate of Dubai. The highest percentage increase of the building category is 3.19 % with establishment type of buildings, followed by 2.91% for the multi storey type buildings. Krarti & Dubey (2018) noted that in the GCC construction scenario, Saudi Arabia leads the way in terms of investment on real estate followed by UAE at 29% total investment in the building sector.

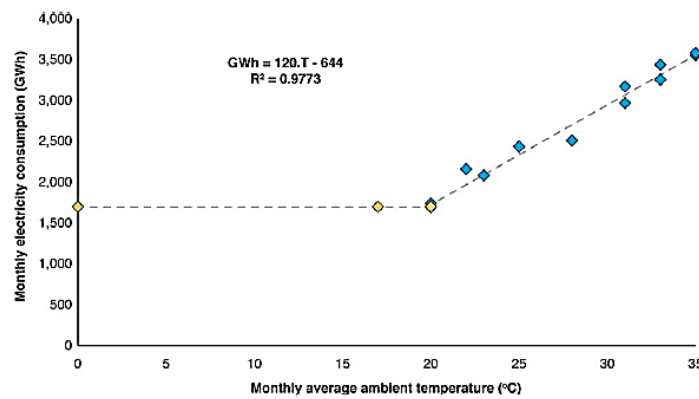


Figure 3: Electricity consumption with respect to the monthly average ambient temperatures for Abu Dhabi in 2014 (Krarti & Dubey 2018)

Category	2013	2014	Percentage increase
Private Villas	45,635	46,371	1.59%
Investment Villas	32,094	32,737	1.96%
Arabic Houses	8416	8434	0.21%
Establishment Buildings	6879	7106	3.19%
Industrial Buildings	836	850	1.65%
One-story buildings	1910	1920	0.52%
Multi-story buildings	11,094	11,426	2.91%
Floor Area ratio buildings	297	301	1.33%
Others (sheds, warehouses)	5321	5443	2.24%
Total	112,482	114,588	1.84%

Table 1: Building census for Dubai for the year 2013 and 2014 (Krarti & Dubey 2018)

Another such building stock compilation was done by Mwafy (2012) through the use of satellite images and actual site visits. Figure 4 represents the building stock in the city of

Dubai based on no. of floors segregated into a total of seven zones. It can be very well understood that the majority of the building stock is in the range of 1 - 4 floors. Further, Figure 5 indicates the building stock distribution as per the occupancy category (based on American Society of Civil Engineer's (ASCE) classification) and it can be inferred that the majority of buildings fall under the category II which denotes the residential and commercial occupancy category. The preceding data very well defines the need to study buildings in the category II encompassing the office and residential sector. As indicated in Table 2, commercial sector accounted for 35.9% of the total electricity consumption for the building stock in the UAE. The energy consumption and their segregation among various building services for a typical villa (Figure 6) can be roughly extrapolated to the energy segregation for a commercial building. As expected, the major energy consuming building service relates to the cooling followed by other equipment's at 11% and lighting at 5% (Karti & Dubey 2018).

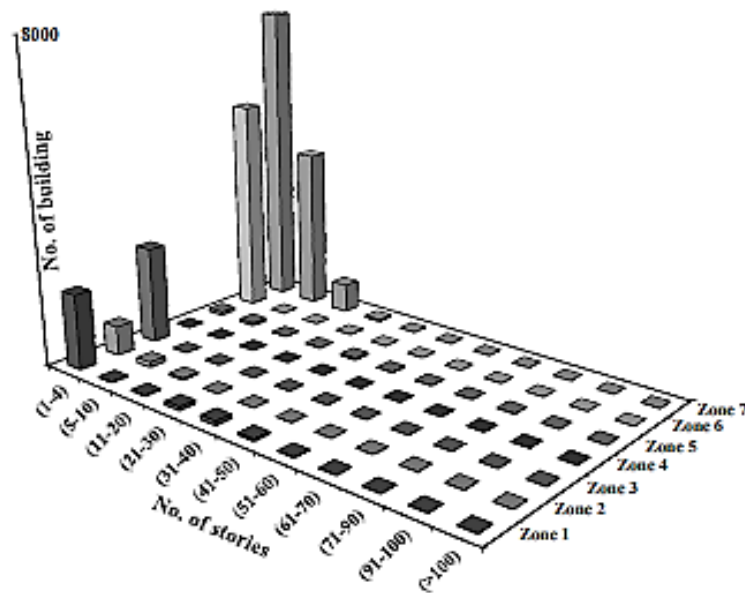


Figure 4: Building stock as per no. of storeys segregated into zones (Mwafy 2012)

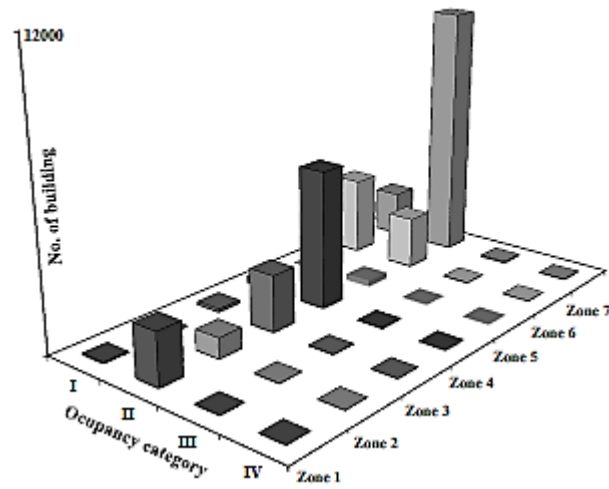


Figure 5: Building stock as per occupancy category (Mwafy 2012)

Authority	Residential	Commercial	Governmental/Others	Industrial	All
ADEWA	14,731	14,780	14,977	4779	49,267
DEWA	10,077	17,326	6291	2596	36,290
SEWA	4469	3977	4	1386	9836
FEWA	4015	1753	1990	2212	9970
Total	33,292	37,836	23,262	10,973	105,363
Percent	31.6%	35.9%	22.1%	10.4%	100.0%

Table 2: Building category wise energy consumption for UAE in the year 2013 (Krarti & Dubey 2018)

1.3. Mitigating energy consumption of buildings

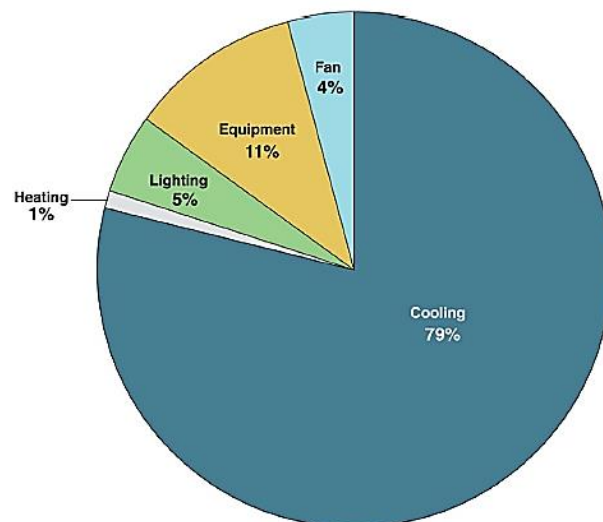


Figure 6: End use energy consumption for a villa in the emirate of Abu Dhabi (Krarti & Dubey 2018)

Krarti & Dubey (2018) analysed the various building retrofit options that aid in bringing reductions to the energy consumption of buildings. They divided the retrofit options within three levels namely Level-1: low-cost energy efficiency measures such as changing to LED light fixtures, Level-2: building retrofit options and energy efficient cooling systems and Level-3: capital intensive measures such as replacement of cooling equipment. Level 1 was reported to have 8% energy savings followed by Level-2 with 23% energy savings and then Level-3 with 50% energy savings. In addition to the above retrofit options, the UAE on a national level has established various rating systems specific to the building sector that aim towards a sustainable built environment. Prominent rating systems and standards in the UAE include the Pearl Rating System (PRS) in the emirate of Abu Dhabi, Al Sa'fat standards in the emirate of Dubai and LEED adopted from the USA is widely used in other emirates. Apart from these various standalone initiatives are also adopted such as the energy rationalisation strategy adopted by the emirate of Abu Dhabi, wherein it aims to cut down the energy consumption by 22% saving to a total of 19,000 GWh of energy (Bashir 2020).

Another study that highlights the importance of retrofits in reducing the energy demands for buildings is the one done by Shanks (2016). In this study he suggests effective strategies in reducing building energy demand taking into account the ever-increasing annual cooling demand increase by virtue of climate change. The analysis was performed on a high-rise office building in the UAE. The author noted that the cooling demand for buildings accounted for 80% of the electricity consumption in the year 2016 with projected increase of 22.2% by 2050 and 40% by 2080 due to the climate change effects. As shown in Figure 7, the solar gains take a major share in the cooling demand for buildings although the projected increase for solar gains over the years is insignificant as compared to other factors. Retrofit options like shading, reducing the solar gain properties of glazing and reduction of the glazing areas was established as the focus of the study. As noted in Figure 8, the effect of retrofit option with improved glazing helps in reduction of cooling demand but its contribution is insignificant. The retrofit option of external shading showed the best results wherein the solar gains were reduced from 30 MWh/yr in the base case to 16 MWh/yr. The external shading employed here was a simple overhang of 1.5m. Figure 9 represents the reductions brought in by the retrofit option applied to the external wall.

Year	External conduction gain (MWh/yr)	Infiltration gain (MWh/yr)	Total air system input / Ratio sensible: latent (MWh/yr)	Solar gain (MWh/yr)	Internal gains (MWh/yr)	Cooling + dehumidification demand (MWh/yr)
Current	3.0	3.6	31.6 / 2:1	30.6	80.0	172.9
2020	4.0	6.1	40.5 / 2:1	30.7	80.0	191.7
2050	4.9	8.5	50.6 / 1.3:1	30.6	80.0	211.3
2080	6.3	11.8	67.0 / 1:1	30.5	80.0	242.0

Figure 7: Base case heat gains over the years for a typical office building in the UAE (Shanks 2016)

Year	Basecase glazing annual conduction gain (MWh/yr)	Retrofit glazing annual conduction gain (MWh/yr)	Retrofit glazing reduction in annual cooling demand compared to Basecase (%)
Current	3.8	2.8	1.5
2020	7.3	4.5	1.5
2050	10.6	6.2	2.5
2080	15.4	8.7	3.1

Figure 8: Impact of retrofit option - improved glazing properties (Shanks 2016)

Year	Basecase external wall annual conduction gain (MWh/yr)	Retrofit external wall annual conduction gain (MWh/yr)	Retrofit external wall reduction in annual cooling demand compared to Basecase (%)
Current	3.0	1.6	0.5
2020	4.0	2.1	0.8
2050	4.9	2.6	0.9
2080	6.3	3.3	1.0

Figure 9: Impact of retrofit option - improved wall on the cooling demand reduction of buildings (Shanks 2016)

1.4. Regional warming in the UAE

The hot humid weather of the coastal regions of the UAE and the hot arid weather of the interior regions of the UAE is a known fact. The regional solar calendar of the UAE is divided into two broad climatic scenarios that is summer from April to October and temperate season from November to March (Conca et al. 2010). Global climate change phenomenon leading to global warming has been on the focus for quite some time now. Looking at the UAE from a similar perspective regional warming is a concern and has been investigated by Conca et al. (2010). In their research they focused on the variation of the near surface air temperatures and atmospheric humidity for three regions in the UAE that are Dubai, Abu Dhabi and Al Ain from the year 1982 to 2009. The near surface temperatures were recorded at the airports of these three regions. The authors noted that the near surface air temperatures in the region rose from 25.5 deg. C to 28.8 deg. C (+3.3 deg. C rise) in Dubai, 25.8 deg. C to 27.9 deg. C (+1.9 deg. C rise) in Abu Dhabi, 27.5 deg. C to 28.7 deg. C (+1.2 deg. C rise) in Al Ain. The mean annual temperature curve for the three regions from the year 1982 to 2009 is represented by the Figure 10. The authors noted an anomaly in between the years 1989 and 1999 where unexpected temperature peaks occurred in Al Ain recording 29.7 deg. C, followed by Dubai with 29 deg. C and Abu Dhabi with 28.6 deg. C. Figure 11 indicates the average temperature by the day of the year for the years 1982 – 2009 and it can be observed that July and August tend to be hottest months. The reported near surface air temperatures indicate a gradual increase over the years and generalization can be drawn that the temperatures are set to increase for the years to come. The authors noted that the extent of temperature rise in Dubai was higher as compared to that of Abu Dhabi and Al Ain. This was attributed to the fact that the temperature sensor locations for the three regions were their respective airports and Dubai airport is located in an urban area in contrast to the airports of Abu Dhabi and Al Ain airports that are located far away from the city.

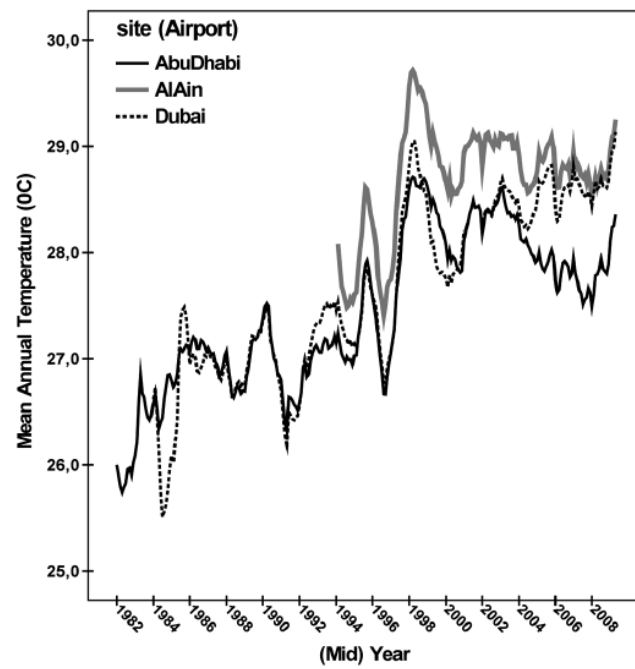


Figure 10: Mean annual temperatures recorded for the regions of Abu Dhabi, Al Ain and Dubai from the year 1982 – 2009 (Conca et al. 2010)

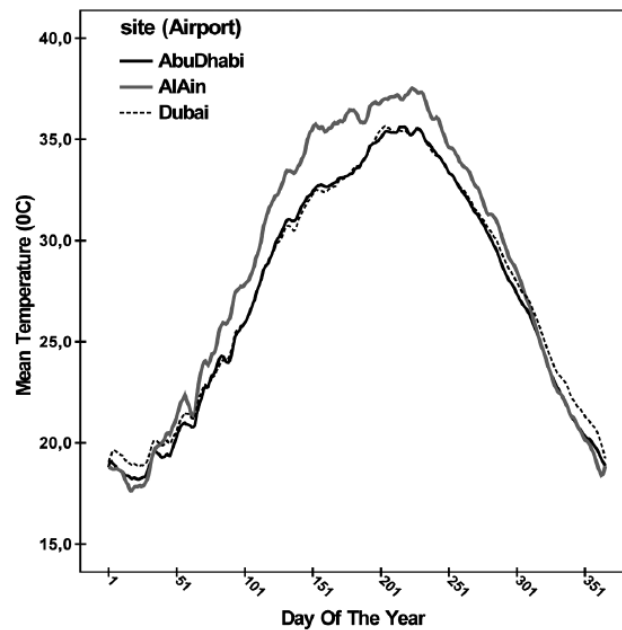


Figure 11: Averaged temperatures by the day of the year for the regions of Abu Dhabi, Al Ain and Dubai from the years 1982-2009 (Conca et al. 2010)

The preceding discussion clearly highlights the magnitude of energy consumption by the building sector, the projected energy profile for the building sector over the future years,

regional warming of the region and potential techniques to curb or reduce this energy consumption. Among the retrofit options discussed by Krarti & Dubey (2018) and Shanks (2016), façade related retrofit options have indicated major contribution to cooling energy reduction by virtue of reduction in external solar gains. This is where the passive design approaches like the Double Skin Façade (DSF) and external shading come into the picture. There is an expanse of literature available globally that indicate energy consumption reductions by these two passive techniques. Traditionally, on a global scale the DSF technology has largely been applied to buildings in temperate climates and there are several studies conducted worldwide that compliment this trend. This when compared to the studies conducted for the hot climatic conditions seems superior although the DSF applicability in hot climatic conditions has shown promising results. Such reported studies have been extensively covered under the literature review section (2). An external shading system (Figure 12) is projection on the building façade, placed in such a manner that it blocks the incoming solar radiations. On the other hand, a DSF (Figure 13) is simply defined as a hybrid façade system consisting of two façade layers with a layer of air column sandwiched in between them.



Figure 12: Simple overhang type of external shading
(Huang et al. 2011)

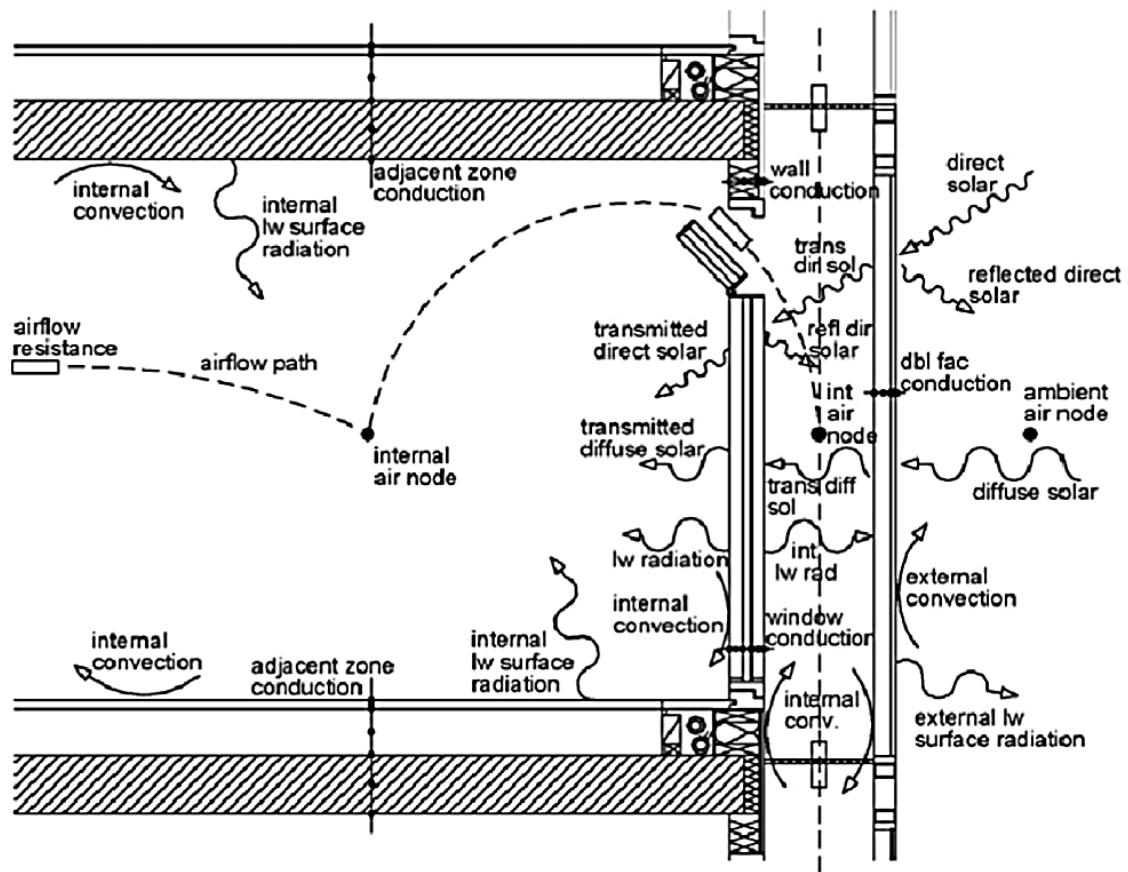


Figure 13: Cross section of a DSF cavity indicating the complex heat transfer mechanism and fluid movement (Høseggen 2008, cited in Pomponi 2016)

1.5. Research problem statement

Overall, it was inferred from the detailed literature review that the DSF applicability in the hot humid climate is still under development and calls for detailed studies indicating its feasibility. It is also worth noting that the number of studies related to DSF have a gradual increase for the hot climate type. The literature review reported in this research spanned over DSF applicability in various regions and with different building configurations. A majority of the research stock focused on the cooling energy reduction that was achieved by the application of the DSF whereas a few of the studies also focused on the detailed cavity temperatures and velocities. The studies that focused on the temperatures and velocities within the cavity did not delve more into the energy consumption aspect. This clearly highlighted a gap of comparison between the dynamic thermal simulations and CFD analysis. It is important to understand that generally, dynamic thermal simulations are

performed to realise the energy consumption scenarios and CFD is performed to analyse the temperature and velocity profiles of fluid domains (DSF cavity).

The need for validating the dynamic thermal simulations with CFD arise due the complex nature of a DSF system. This complexity can be attributed to the various external factors involved in the study of DSF and their high frequency of variation. As an example, many studies related to DSF have not considered the effects of external wind pressures on the cavity and how it impacts the air circulation within it. Additionally, dynamic thermal simulation is intended to study the heat transfer phenomena but the air movement inside the air cavity can be accurately analysed by the use of CFD only. Thus, such inter-model comparison ensures a level of certainty in the results obtained. Also, from an economical perspective, this is the only way to study the applicability of DSF rather than performing tests on full scale models or scaled down models. Further, analysing full scale models is impractical and the application of scaled down models is not yet established in the international literature.

As highlighted earlier, it would be interesting to study the comparison between external shading systems as opposed to DSF. Such a comparison is more important from mainly two perspectives. Firstly, due to the reported finding that DSF in hot humid climates provide cooling load reduction mainly through reduction of external solar gain which may also be achieved by an external shading system. Secondly, from an economic standpoint the external shading system comes at a lower cost as compared to DSF. Economic analysis of the DSF and external shading systems is not considered in this research.

1.6. Aims and Objectives

The objectives of this research are twofold, wherein the first part covers the cooling load/energy consumption comparison between a base case building, external shading case building and a double skin façade building. A second part of this research is dedicated to the validation of dynamic thermal simulations with CFD analysis on grounds of air temperature and air velocity/flow rates inside the DSF cavity. A third crucial part of this research is to analyse the sensitivity of the CFD simulation tool. The following can be considered as a list of consolidated objectives for this study.

- Determine and evaluate annual cooling savings of external shading and of double skin facade solutions using dynamic thermal simulation
- Compare theoretical dynamic thermal annual cooling energy savings in context of any similar published studies
- Model and theoretically determine internal temperature and air movement characteristics of the solutions noted above
- To conduct inter-model comparison between the obtained thermal dynamic simulation results and the results obtained from the CFD simulations to evaluate the suitability/reliability of annualised dynamic thermal cooling results.
- Evaluate sensitivity analysis of the CFD simulation tool for DSF's with large open cavity volumes by varying the simulation parameters such as the false time step and turbulence model.

2. Chapter 2: Literature review

This section aims to highlight the relevant studies conducted in the field of external shading and double skin façade. The studies reported in this section for external shading primarily comprise of a mix of building typologies studied over various climatic scenarios. Alhuwayil et al. (2018) analysed the effects of external shading on a 10-storey high hotel building in Saudi Arabia (representing a hot climate). Koç & Kalfa (2021) studied various shading configurations for the region of Turkey (representative of Mediterranean climate). Freewan (2014) studied the shading effects on a three-storey high office building located in Jordan (representative of hot and dry climate). Coleridge & Huh (2017) analysed fixed external shading for an office building located in Cape Town, South Africa (representative of Mediterranean climate). Shahdan et al. (2018) reported annual cooling reductions from external shading for a three-storey high school building located in Malaysia ((representative of hot climate). Brittle et al. (2013) recorded cooling energy savings for a single storey high commercial building located in the hot climate of Egypt.

Similarly, the studies reported in this section also cover the applications of DSF over various building typologies and climates. Pomponi & Piroozfar (2015) had surveyed buildings across Europe that employed DSF thus creating a database with key DSF characteristics implemented in the surveyed building stock. Abbadi (2018) reported the applicability of DSF as a retrofit option for a four-storey high residential building located in Jordan. Hamza (2007) in his research highlighted the potential of DSF for a seven-storey high building located in the hot climatic conditions of Egypt. Radhi et al. (2013) performed their study on a three-storey high educational building located in UAE. Johny & Shanks (2018) studied the applicability of DSF for a high rise 30 storey office building in the UAE. Andjelkovic et al. (2016) reported the positive and negative impacts of DSF by analysing the DSF for a seven-storey high building located in Serbia that has a temperate climate. More recent studies inclusive of the one done by Kim (2021) wherein he analysed the DSF performance for a four-storey high office building located in Saudi Arabia. Wang et al. (2021) investigated the DSF for a 12-storey high building located in hot and humid zone of China. Pourshab et al. (2020) studied the impact of horizontal and vertical shading elements for a five-storey high building located in Iran. Barbosa & Ip (2014) logged an extensive DSF related literature covering various key DSF parameters and spanning over various climate typologies. The most common type of DSF employed in the studies reported was the shaft type of DSF that

ranges over the entire height of the building with a few studies also incorporating the use of louvers withing the cavity volume.

2.1. Energy consumption of office buildings in the UAE

The unavailability of direct benchmark studies for energy consumption of office buildings in UAE necessitates the need to look at some simulation studies. These studies can be treated as an approximate reference to understand the energy performance of an office building in the UAE. The present benchmark available for the UAE region comes from the Emirates Green Building Council (EGBC) released in the year 2019 and is available for school, hotel and mall building types.

The Köppen climate classification makes the UAE fall under the Group B of climate types representing dry climate (arid and semi-arid). The exact symbol assigned for the UAE climate is BWh, wherein B represents Group B (i.e., arid), W represents desert and h represents hot. As per Köppen classification, similar climates to the UAE would be El Paso (Texas), Phoenix (Arizona), Doha (Qatar), Mecca (Saudi Arabia) and many more. Studies related to the aforementioned climatic profiles were looked upon to get an energy benchmark value to which the base case, external case and the DSF case could be compared. Thus, the literature was reviewed to obtain studies that reported office buildings energy consumption in neighbouring GCC regions such as Qatar and Saudi.

As Afshari et al. (2014) noted in their paper that the cooling systems for a typical building in the UAE consume about 60% of the total energy consumed. The authors in their paper studied about the retrofit options on reducing the cooling load for a typical base case building, including air tightness, cooling temperature setpoint, chiller COP, glazing and insulation. They studied a 15-storey office building located in the emirate of Abu Dhabi with a total floor area of 23,212 sq. m. The cooling energy consumption for the base case building was measured to be around 4,03,4000 kWh giving a benchmark value of 173 kWh/m²/year. The characteristics of the base case building analysed were a 70% WWR, U value of 1.71 W/m²K for the envelope and U value of 2.4 W/m²K for the glazing. Johnny & Shanks (2018) reported the base case annual cooling load to be 262.23 kWh/m²/year. This base case was 30 floors in height with an individual floor area of 60 sq. m. No details regarding the U value were obtained in their research text.

Another representative study of office buildings cooling energy was obtained for the region of Qatar (Touma & Ouahrani 2017). They analysed a unit office space with respect to the cooling energy, lighting energy and other miscellaneous energy demands. The unit office space considered had a floor area of 30 sq. m with a height of 2.8m. The office space considered here had a wall façade in the west orientation and the two sub cases were developed with a fully glazed façade in the north direction and south direction respectively. The U value of the external wall was 2.37 W/m²K. The authors reported a EUI of 503.2 kWh/m²/year for the office case with the glazed façade in the south direction and an EUI of 393.8 kWh/m²/year for the office case with the glazed façade in the north direction. The maximum monthly EUI of 43.8 kWh/m²/year was observed for the office case with south façade in the month of October and a monthly EUI of 38.6 kWh/m²/year for the office case with the north façade in the month of August. The lower monthly demands over the entire year were EUI of 22.7 kWh/m²/year for south façade office case in December and EUI of 11 kWh/m²/year for the north façade office case in January. Shanks (2016) reported the value of EUI to be 149.6 kWh/m²/year for the base case of a high-rise office building with projected EUI values of 165.8 kWh/m²/year in 2020 and 182.8 kWh/m²/year in 2050.

2.2. External shading

Classification of solar shading devices can be broadly classified into two main categories namely the fixed type and the dynamic type. Further, classification of the fixed shading into three main categories which are the vertical devices, horizontal devices and egg-crate devices. All other types of fixed shading devices are merely a derivation of these basic types and have been indicated in Figures 14 and 15.

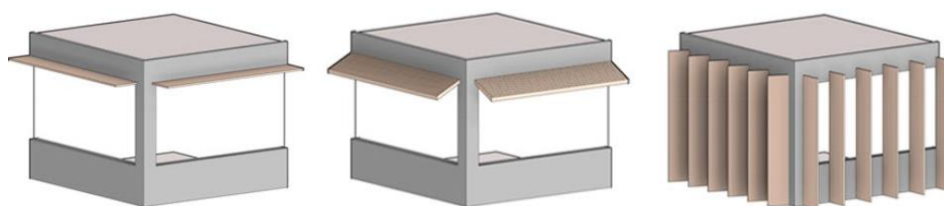


Figure 14: Fixed external shading types - horizontal overhang, inclined horizontal overhang, vertical fins (Adapted from Coleridge & Huh 2017)

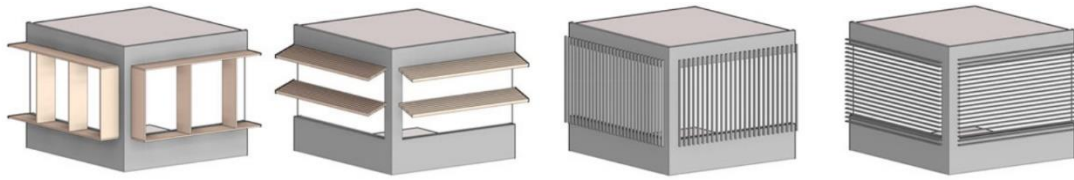


Figure 15: Fixed external shading types - eggcrate, inclined double overhang, vertical louvers and horizontal louvers (Adapted from Coleridge & Huh 2017)

It is quite evident from the expansive literature available that the external shading is one most effective strategy in the reduction of building energy consumption for hot climatic regions. As per Alhuwayil et al. (2018), the selection of passive shading strategies hugely depends on the geographic location, orientation, functionality and local climate of the region. In their paper they studied the impact of shading strategies on 10 storey high hotel building located in Dammam region of Saudi Arabia. Out of the four shading combinations they studied, the fourth combination wherein the north face was employed by vertical fins, south face by overhang shading and louvers and remaining northwest, northeast, southwest and southeast faces with overhang and fins was deemed as optimal. They reported that an overhang projection of 1.5m was optimal and provided a total cooling and heating energy savings of about 4.4% from the base case scenario (without any shading). Further, the fourth case employing the shading elements in all directions was reported to have the maximum cooling energy savings of around 21.9% and total energy savings of 20.5%. An interesting point to note here is that the heating energy was reported to be the highest in the fourth case which employed shading in all directions. These peak heating energies were primarily required during the heating months but was traded off with the energy savings potential of the external shading elements in the cooling months. The simulation software used in this study was the DesignBuilder package.

A study conducted by Koç & Kalfa (2021) analysed the impact of the different types of shading devices and their evaluation by varying associated parameters like depth, WWR ratio, sloping, direction, glazing type and depth. All in all, the study established, 1485 such scenarios and compared and contrasted their cooling energy, heating energy and overall energy with a base case (no shading elements). The types of the shading devices used in this

particular study were overhang, egg-crate, egg-crate with horizontal louvers, horizontal louvers and vertical louvers. The selected hypothetical building was located in the Mediterranean climate of Turkey and was one storey tall. On an overall level the research reported about 37%-49% annual cooling energy consumption reduction when compared to the base case with no shading and employing the Double Spectrally (DSL) selective glazing type whereas a figure of 73%-78% annual cooling energy was reported when compared to the base case fitted with Double Clear (DCL) glazing type. When a comparison was made between the different types of shading devices by keeping all the aforementioned parameters as constant, it was found the overhang type of shading device performed the worst in terms of cooling energy consumption savings with 23% whereas the egg-crate louvers type of shading device performed the best, providing an annual energy savings consumption of around 67%. When the various shading devices were pitted against each other with respect to the direction parameter. For the south direction, it was found that the horizontal louvers provided the optimal total energy consumption savings whereas for the east and west directions egg-crate louver type shading device proved to be the best option.

Freewan (2014) in his research studied the effect of shading devices for an office building (three storeys high) on parameters of air temperature and visual comfort, by employing vertical, diagonal and egg crate configurations. He compared all these cases to a base case (without any shading) and found that with regards to the air temperature the vertical fins provided a temperature reduction with a maximum of 2.75 deg. C, followed by diagonal fins indicating a maximum temperature reduction of 5.75 deg. C and egg crate configuration bringing about reduction in the temperature with a maximum value of 6.3 deg. C. The diagonal fins configuration was deemed to be the most optimal configuration in reducing the air temperatures within the occupied space which showed reduced air temperatures even after 1 pm as compared to other configurations. He also used the tool of thermal imaging indicating the temperature of the surfaces in the three shading configurations and the base case. Higher temperatures were noticed at the façade surfaces in the base case thus accounting for higher heat gains and consequently higher temperatures than all the other shading cases. The author claimed that the egg crate configuration could be beneficial keeping in mind both the winter and summer months.

- A study conducted by Coleridge & Huh (2017) on performance analysis of fixed external shading devices was done for an office building located in the city of Cape Town, South Africa. Therein, the authors analysed eight various external shading configurations including

horizontal overhang, inclined horizontal overhang, vertical fins, surrounding shading (combination of vertical fins sandwiched between horizontal overhang), inclined double horizontal overhang, vertical louvers and horizontal louvers. Out of the seven external configurations simulated using the DesignBuilder software, the authors found that the inclined double horizontal glazing, vertical louvers and horizontal louvers were the top three performers in terms of the annual cooling energy reduction with a value of 51%, 49% and 47% respectively. It was interesting to note that the solar gains reduction did not follow the same pattern as that of the annual cooling load reduction wherein the vertical louvers had 74% reduction in the annual solar gains followed by the inclined double overhang (64%) and horizontal louvers (60%).

Shahdan et al. (2018) studied the effect of external shading devices on the reduction of cooling energy consumption for a three-storey high school building located in Shah Alam, Malaysia. In their study they analysed seven different types of shading devices including horizontal single panel overhang, horizontal double panel overhang, horizontal double inclined overhang, horizontal louvers, vertical fins, vertical slanted fins and egg-crate configurations. Out of the seven external shading configurations it was found that the best configuration in terms of monthly cooling energy savings was the egg-crate (49.63%) configuration followed by the horizontal inclined double panel configuration (34.84%) and so on. The worst-case results were obtained for the horizontal single panel overhang shading type with 8.7% of cooling energy savings.

Brittle et al. (2013) studied the effect of fixed external shading device on the cooling load reduction in the commercial buildings in hot climates. For the purpose of the study, they considered a single storey high office building located in Aswan, Egypt. The types of shading devices studied under this research were horizontal overhang, inclined horizontal overhang, triple inclined horizontal overhang and vertical fins. They concluded that the most effective shading device among the four configurations studied was the triple inclined horizontal overhang for the south, east and west orientations. Significant reduction in the solar gain was observed in all the three directions. Reported annual cooling energy savings was around 25%.

Majority of the studies including the ones done by Alhuwayil et al. (2018) and Koç & Kalfa (2021) have reported that the application of shading devices on low performance glazing provided better results of energy savings as compared to the application of shading devices

on high performance glazing. All the studies under this section clearly demonstrate the potential of employing shading elements in reducing the cooling energy consumption of buildings. High performance glazing is the easiest option is bringing about the required energy reduction but as indicated in the study of Alhuwayil et al. (2018), the payback period for such glazing systems is not economically feasible and have unrealistic payback periods. Thus, as pointed out by Coleridge & Huh (2017), this makes the option of high performance glazing atypical in the built environment sector.

2.3. Double skin façade

A Double Skin Façade by definition is the combination of single skin façade layers with an air gap sandwiched between them. This unique combination gives rise to what is known as the chimney effect, wherein the warm air rises along the cavity height by effect of buoyancy. This air layer may consist of fixed or controllable air inlets and outlets. Overall, the DSF creates a thermal buffer zone and facilitates natural ventilation due to the thermal buoyancy effect. The width of the DSF is a variable and is further classified in the succeeding text. Before delving into the literature of DSF, it is essential to understand the various classifications of DSF available. The DSF façade system is generally classified on the basis of four main characteristics which are the geometry of the façade, the type of ventilation inside the cavity, the type of airflow inside the DSF cavity and lastly the cavity width (Figure 16).

Pomponi & Piroozfar (2015) described that, the partitioning of the cavity leads to the classification of the DSF in terms of the geometry. As seen in Figure 16, based on the geometry the available DSF configurations are box window, corridor type, shaft type and multi storey type. The second category of the classification is based on the mode of ventilation used within the cavity with natural mode of ventilation and mechanical ventilation as the options. The third category of classification is the based on the airflow concept which could be supply air, exhaust air, air buffer, external air curtain and internal air curtain. The fourth and last category of classification is based on the width of the cavity wherein a width less than 40cm is considered as narrow and width more than 40 cm is considered as wide.

A detailed literature review indicates there are only a small number of articles on the applicability of DSF for hot and humid climates such as the UAE as compared to a plethora of articles for temperate climatic zones. This is because DSF as a technique was originally created to satisfy the heating needs of buildings and when this technique is adopted for a completely opposite hot climate, creates a chance of overheating inside the DSF with subsequent negative impacts. But the number of studies relating to the applicability and performance of the DSF in the hot climate is increasing gradually over the years. A DSF on the larger context caters to the reduction in cooling loads in two prominent ways. Firstly, it reduces the direct solar gain reaching the indoor spaces and secondly, air stream flushing out of the DSF cavity further reduces the temperature of air inside the cavity which is in direct contact with the indoor spaces.

Pomponi & Piroozfar (2015) analysed in their research a total of 36 DSF refurbishment case studies across Europe. The authors noted that the multi storey type of the DSF was the most common form of DSF refurbishment attributing to less complexity and the generation of a single volume of space. Although the simplicity of the multi storey DSF garnered much attention towards its implementation, the downside with regards to the overheating at the upper floors required careful design of the cavity. Corridor type of DSF was reported to be used in few of the studied buildings. With respect to ventilation 78% of the buildings fell under the category of natural ventilation, followed by mixed ventilation and mechanical ventilation at 17% and 5% respectively. Around 60% of the buildings were considered to be naturally ventilated by coupling the supply air flow regime and natural ventilation mode. Ninety percent (90%) of the buildings employed the combination two air flow regimes. The air buffer airflow regime and the supply air airflow regime would be beneficial in winter whereas the combination of the exhaust air flow regime and external air curtain regime would be beneficial in summer. External air curtain and air buffer combination was also found in the stock of the studied buildings.

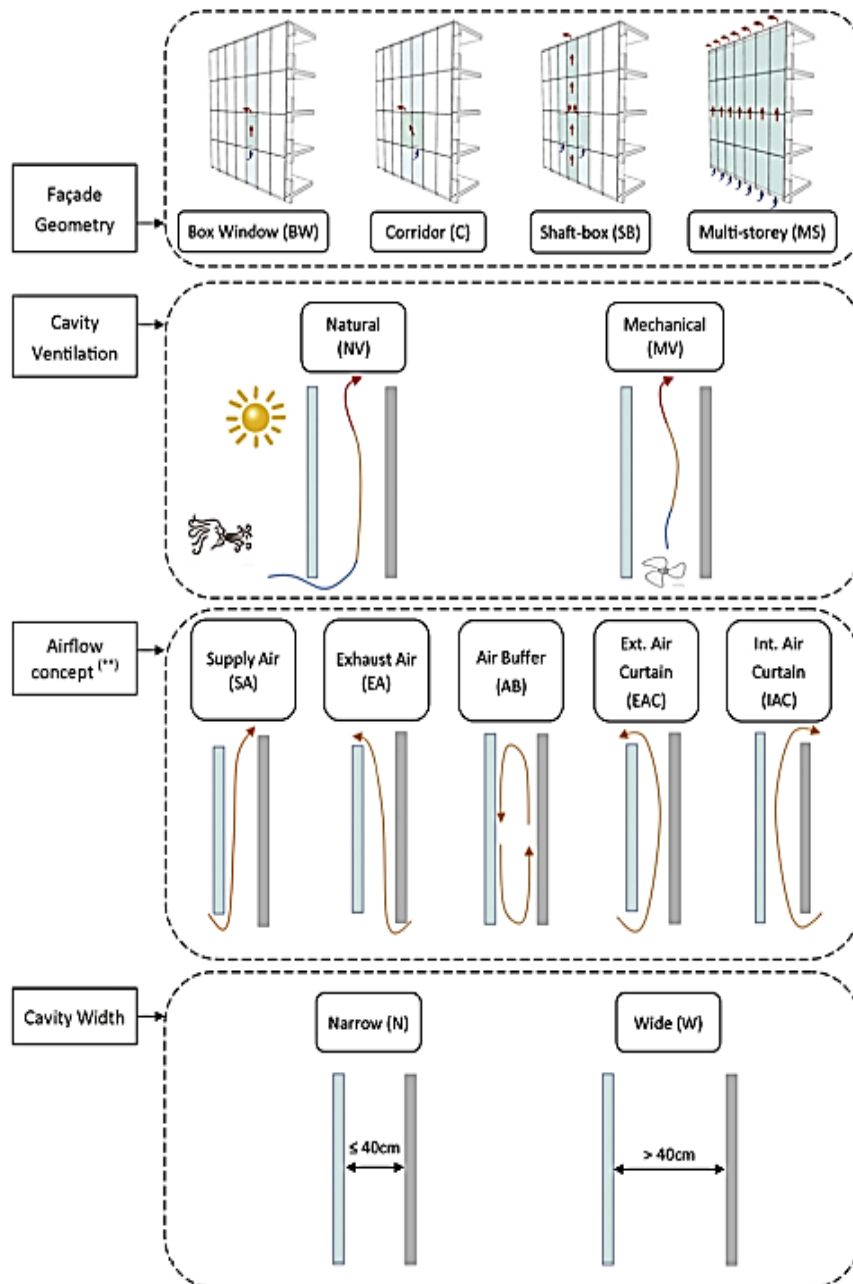


Figure 16: Classification of DSF's (Haase et al. 2009 cited in Pomponi & Piroozfar 2015)

Barbosa & Ip (2014) in their research categorized the findings of the DSF literature with respect to the parameters of the DSF namely the cavity, façade construction and the outdoor environment. Barbosa & Ip (2014) noted studies indicating the complexity of the thermal behaviour of the DSF and also the air movement within the cavity. They also highlighted studies that indicate concerns on the DSF with respect to the capital investment, construction, maintenance, structural weight, sound transmission and fire mitigation. The authors also

noted that the DSF technology was established in the year 1900s but true development began to happen around the 1990's.

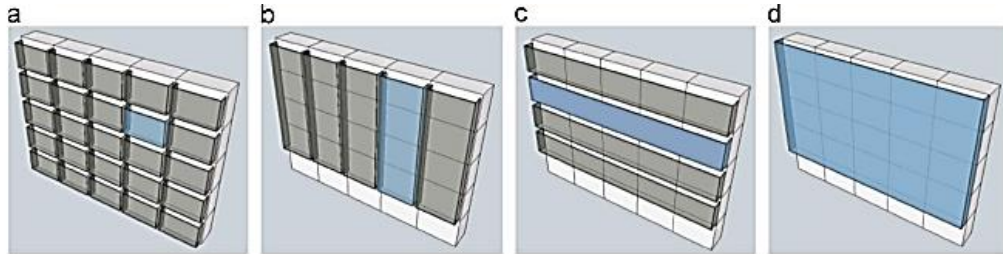


Figure 17: DSF classification based on geometry, a – box type, b- shaft type, c- corridor type and d- multi story type (Barbosa & Ip 2014)

Figure 17 shows the DSF types based on the façade geometry as described in the classification part of this section. The extensive literature base reported by Barbosa & Ip (2014) clearly indicates the wide variety of DSF technologies that has been studied. Studies reported have varied the following key parameters of the DSF, that is the cavity depth, shading device used within the DSF, outer skin glazing properties, structure of the DSF, openings of the DSF, inner skin materials of the DSF, wall to window ratio variations and height of the cavity and the number of floors. The possibility of combining these DSF parameters yields endless combinations that a particular DSF can have. It is worth noting that majority of the DSF studies reported in this research confirm to the multi-storey DSF type.

A relevant master's research thesis was conducted by Abbadi (2018) on the application of DSF for a four-storey high residential building located in Irbid, Jordan. The research spanned over an entire range of factors involving the study of various DSF configurations including the multistorey type, box type, corridor and shaft type along with the variation in the depth of the DSF cavity. The study also evaluated these configurations from an energy performance point of view by deriving the annual consumption in each of the cases. The author claims to have derived the optimal results with the box type DSF configuration. Further, the author observed that cavity temperature was six-eight deg. C higher in the winter months and had no considerable difference during the summer months for the box type

configuration and recorded the issue of overheating in the shaft and multistorey type of DSF. Annual energy savings were reported to be the best in case of multistorey type but with a lower index of thermal acceptability whereas the box type configuration had mediocre energy savings but a better index of thermal acceptability.

As mentioned earlier, amongst the few studies conducted for DSF applicability in hot climate zones is the one conducted by Hamza (2007). In his research he compared the cooling loads for a single skin façade (SSF) with that of a DSF. For this purpose, he selected a building located in Cairo, Egypt having a total of seven storeys. The DSF was characterized by a fully open inlet and outlet with the cavity itself starting from the first floor. A window to wall ratio (WWR) of 40% was used for the inner skin of the DSF. Hamza (2007) in his research was successful in breaking the hypothesis, that DSF only show better performance when they are compared to poorly constructed Single Skin Façade (SSF). For this very condition he analysed the thermal performance of various DSF constructions with the benchmark single skin façade. The benchmark single skin façade acts as the optimum construction that could be achieved in terms of glazing (reflective) and other parameters for a single skin envelope. He used three DSF constructions with varying outer skin glazing material (clear, tinted and reflective). An overall depiction of the thermal analysis results conducted by Hamza (2007) is represented by the Figure 18. It can be clearly understood that the DSF with the clear type outer glazing underperformed when compared to the benchmark single skin façade for all the orientations, whereas the tinted and reflective outer skin DSF performed better with respect to the benchmark SSF. The tinted outer skin DSF case had an annual cooling load reduction of 12% as compared to the benchmark SSF and the reflective outer skin DSF had an annual cooling load reduction of 30%. This study does not indicate anything related to the temperature profiles within the DSF cavity itself nor does it elaborate on the air movement or the velocities within the cavity.

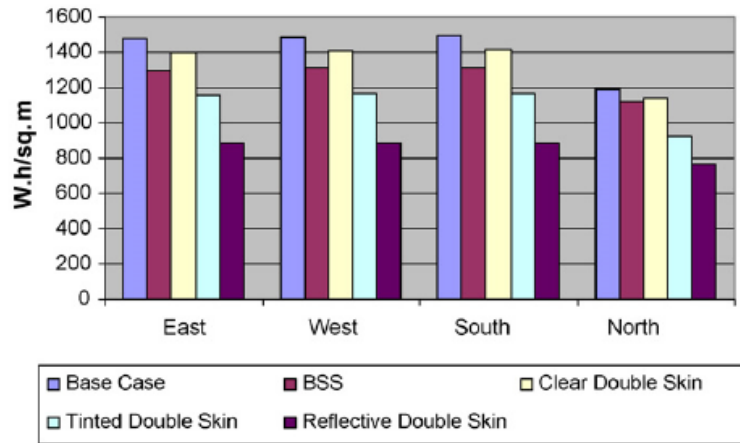


Figure 18: Annual cooling loads analysis summary (Hamza 2007)

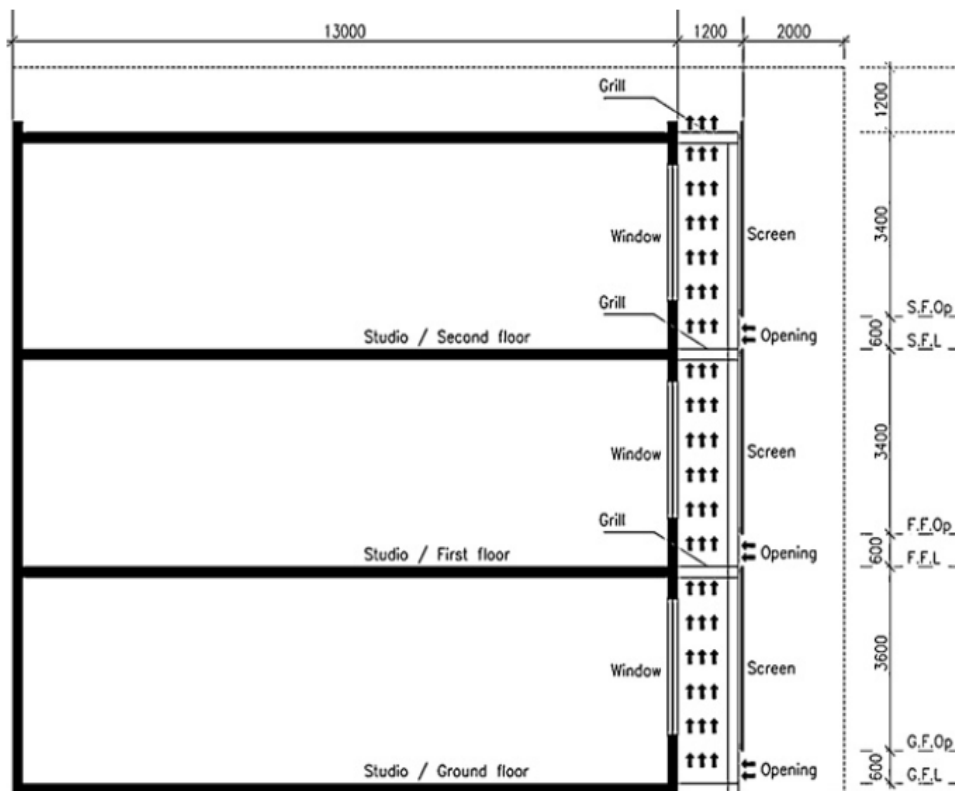


Figure 19: Cross section of the CRFS (Radhi et al. 2013)

Radhi et al. (2013) conducted the study for a three-storey high educational building located in the hot-arid climatic region of Al Ain, UAE. The authors employed the techniques of thermal simulations and CFD to compare the variation of the cooling loads when DSF was compared to classical single façade system (CSFS). Although the authors claimed and mentioned that the building under study houses the climate interactive façade system (CRFS)

which is not very different from a DSF. The CRFS in this case had an opening at the low level of each of the floors as indicated in the Figure 19. This makes the type of CRFS here to be similar to the multi-storey DSF as per the classification mentioned earlier in this section.

As would be expected to have reduced solar gain values for the CRFS than the CSFS and consequently lower heat transmission ratio for the CRFS when compared to the CSFS (Figure 20). This behaviour can be attributed to the fact that the solar radiation is filtered out by the outer skin of the CRFS thus having a reduction in the heat transfer rate through the inner skin of the CRFS. Lower solar gains to the inner skin of the CRFS would consequently mean lower cooling loads for the CRFS which are depicted in the Figure 20. The authors claimed that around 17% - 18% of the cooling energy could be saved by installing the CRFS but provided no numbers for this energy reduction comparison between the CRFS and CSFS.

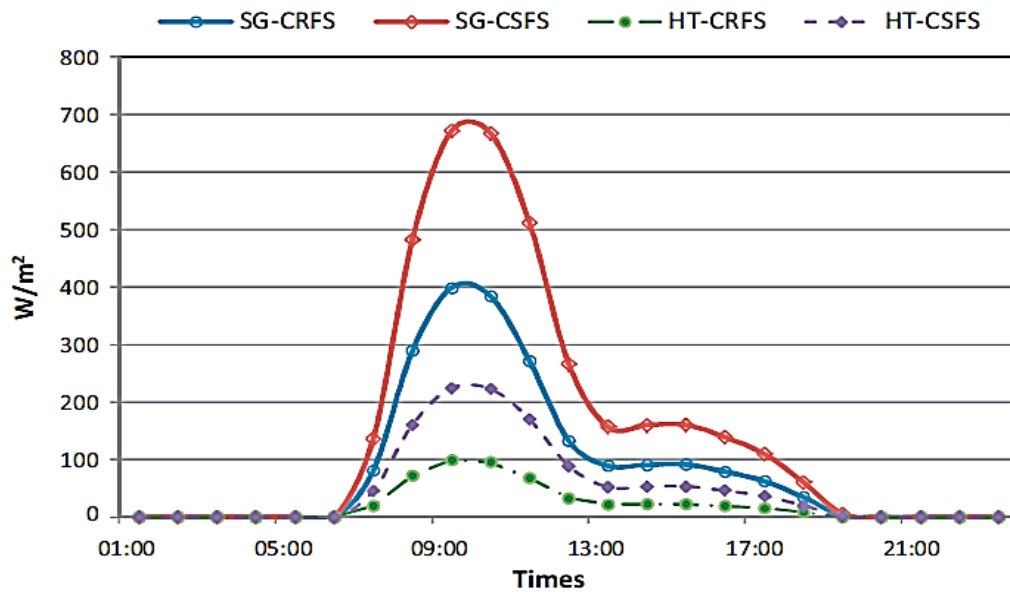


Figure 20: Solar gain and heat transfer summary – SG – Solar Gains and GT – Heat Transfer rate (Radhi et al. 2013)

A second part of this study constituted the analysis of the CRFS for the velocity and temperature profiles. The authors observed the distinctive characteristic display of the buoyancy effect whilst analysing velocity vectors for the CRFS. The velocity vectors reported also indicated airflow in two opposite directions wherein some part of the airflow was directed towards the top and some part towards the bottom. There was no clear

indication from the cut view of the velocity vectors regarding the formation of vortices. The velocity values shown in Table 3 indicate that there is high value of velocity in at the bottom most opening. There is also a trend of alternative increment and decrement observed in the velocity values as we move up the height of the CRFS cavity. The higher values of the velocity along the height of the CRFS are at the locations of the floor openings

Height (m)	CSFS				CRFS				
	Pressure (Pa)	Velocity (m/s)	Air tem (°C)	Radiant tem (°C)	Pressure (Pa)	Velocity (m/s)	Air tem (°C)	Radiant tem (°C)	Heat flux
0 (open-1)	121.38	2.30	31.18	37.45	113.44	3.32	31.23	37.62	-2.05
0.5	118.88	1.55	31.08	38.89	110.16	1.46	31.35	40.58	-25.46
2.2	118.40	2.08	31.07	40.55	109.99	0.54	31.35	43.32	14.72
4.4 (open-2)	123.65	2.94	31.06	40.91	110.91	4.50	31.91	39.61	0.62
6.8	128.76	2.08	31.05	41.17	105.82	0.44	31.88	43.30	15.37
8.6 (open-3)	132.44	1.57	31.05	40.97	95.21	6.16	31.87	39.49	5.68
10.8	130.66	2.81	31.04	40.93	78.92	1.88	31.41	43.26	15.02
12.0	121.94	4.36	31.03	40.44	80.37	2.32	31.40	42.85	8.73

Table 3: Variables recorded by Radhi et al. (2013) for the CRFS and CSFS facade configurations

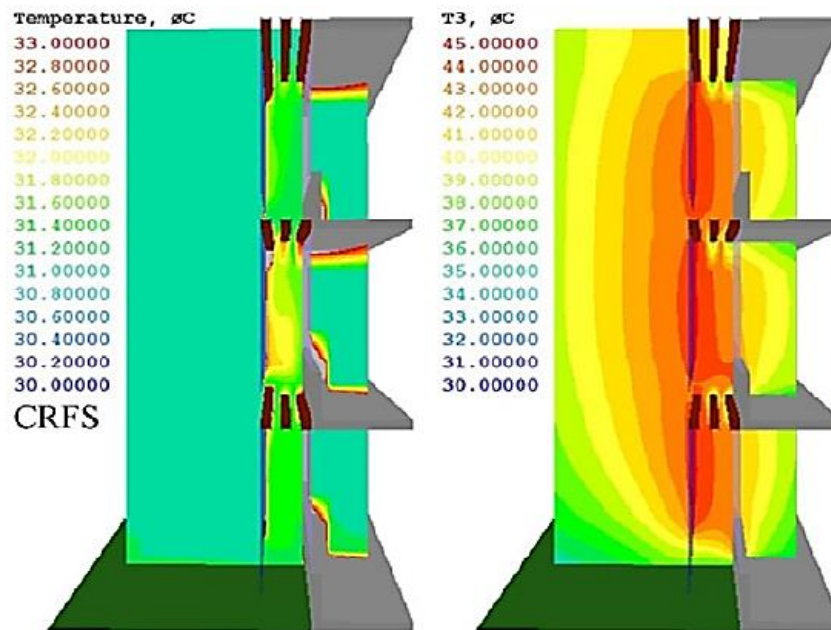


Figure 21: Air temperature contours and radiative temperature contours (Radhi et al. 2013)

Looking at the temperature profiles (Figure 21) recorded by the authors, it could be seen that there was no major difference between the cavity and the outside air temperatures. But the

radiative temperatures inside the cavity were higher as compared to the outside temperature possibly indicating towards the heat entrapment within the cavity itself. The surface temperatures of the inner skin of the CRFS were observed to be lower than the surface temperatures of the CSFS. Additionally, the authors noted that as the cavity depth is reduced, the heat transfer rates also drop.

Another extremely relevant study done for the hot climate of UAE was the one conducted by Johnny & Shanks (2018). All in all, the authors studied a total of 15 DSF models comprising of three primary models which were DSF with glazed outer skin (Model 1), DSF with concrete outer skin (Model 2) and DSF with PCM impregnated concrete outer skin (Model 3). The primary models were further sub divided by virtue of the number of perforations in the outer skin of the DSF. The impact of the DSF inlet and outlet on cavity performance were not considered in this study. Reporting previous studies, the authors adopted a cavity depth between 1m and 1.2m. The west facing DSF cavity was considered to be the worst-case scenario and was used for the dynamic thermal and CFD simulations. This is because of the reason that the west facing cavity showed the maximum average temperature when the glazed outer skin was simulated. As can be seen in the Figure 22, the west facing DSF has higher average temperatures at each of the regular floor intervals. The building under consideration was an office building with a total of 30 floors. The peak simulation time was taken to be on the 23rd of July at 15:30 hours. With regards to the turbulence model, the authors adopted the k-e turbulence model for the CFD simulations.

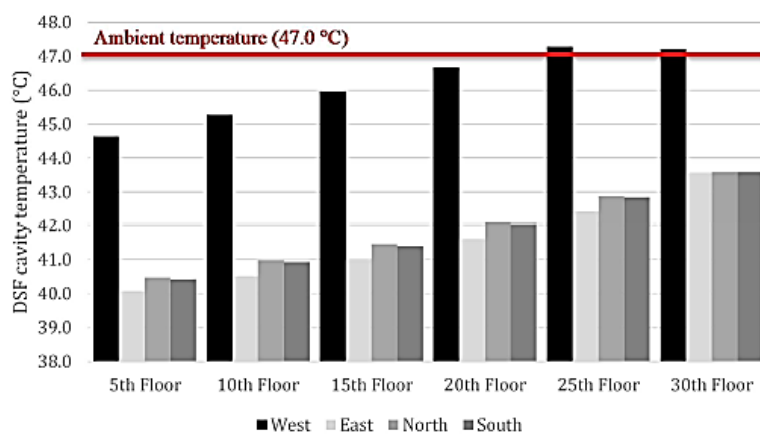


Figure 22: Dynamic thermal simulations of the DSF for a fully glazed outer skin (Johnny & Shanks 2018)

Figure 23 indicates the temperature profile of the west cavity along the height of the DSF for different amounts of perforations on the outer skin. It can be clearly seen that the lower floors are at lower temperatures than the ambient temperature of 47 deg. C and upper floors are at higher temperatures than the ambient. The higher temperature at the upper floors was attributed to the heat accumulation inside the DSF cavity and assuming the effect of wind near the outlet of the DSF cavity. Figures 24 and 25 indicate the temperature profile of the west DSF cavity with concrete and PCM outer skin and it can be clearly inferred that the concrete outer skin performs better than glazed outer skin model and the PCM model is the best performer when it comes to temperature reduction inside the cavity. In the case of the PCM model, the authors reported the maximum temperature at the upper floor near the outlet of DSF, hinting at concentrated heat accumulation.

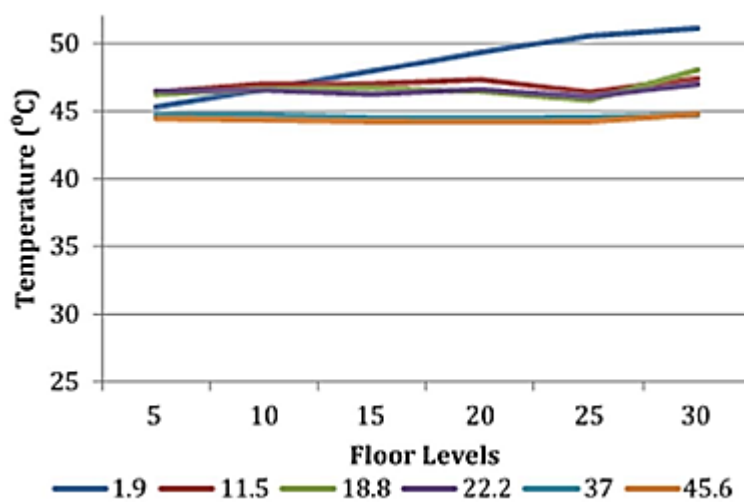


Figure 23: West cavity temperature profile with varying perforation levels on the glazed outer skin (Johnny & Shanks 2018)

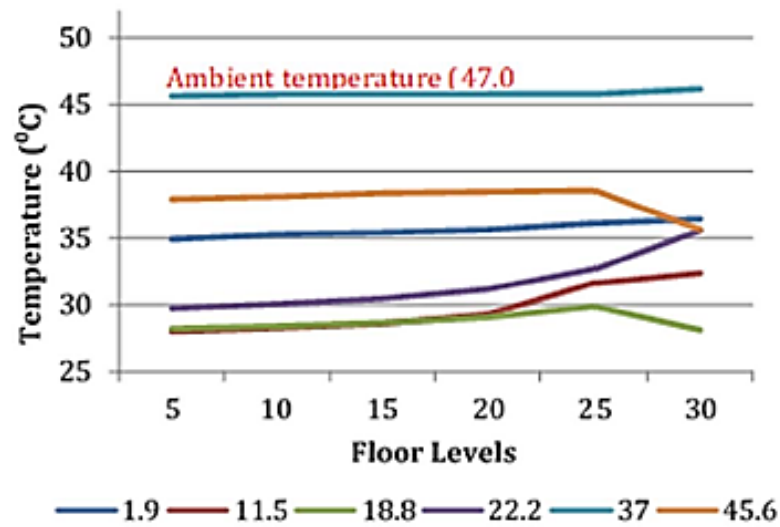


Figure 24: West cavity temperature profile with varying perforation levels with PCM impregnated outer skin (Johnny & Shanks 2018)

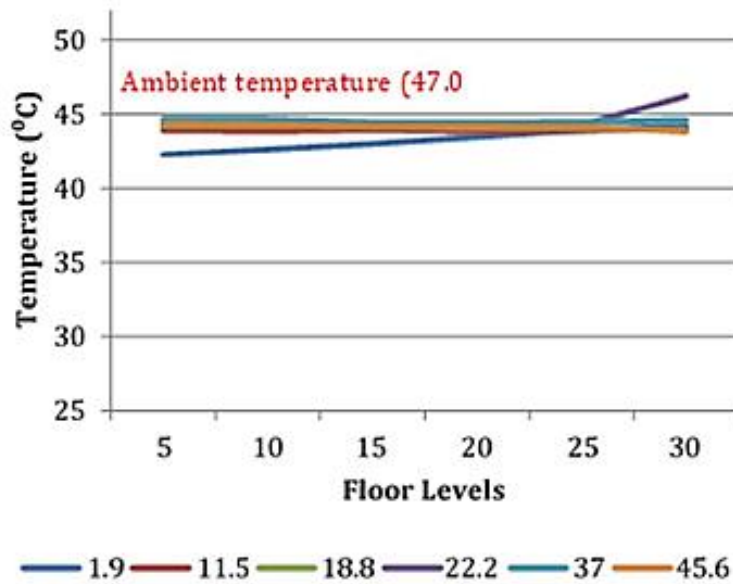


Figure 25: West cavity temperature profile with varying perforation levels with concrete outer skin (Johnny & Shanks 2018)

The authors compared the three primary models with respect to the annual cooling demand and annual solar gains. Figures 26 and 27 indicate the results obtained for these two parameters where it can be seen the annual cooling demand has a generic trend where the

PCM outer skin model is the best performer followed by the concrete outer skin model and then the glazed outer skin model. With respect to the solar gains reaching the inner skin, an inverse trend is observed where the glazed outer skin model allows more solar gains to pass through followed by the concrete model and the least is allowed by the PCM outer skin model. The authors also noted that the comparison of each of the individual glazed and concrete models with their sub models (varying perforation levels) have insignificant difference for the cavity temperatures as perforations were increased thus highlighting the importance of the DSF in reduction of solar gains leading to comparable annual cooling load reductions.

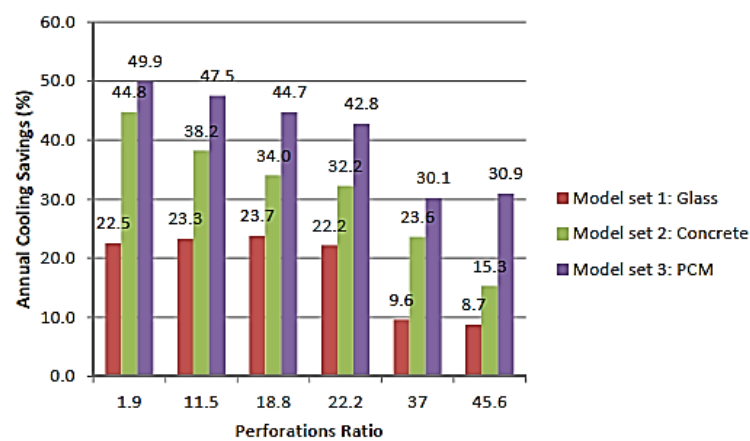


Figure 26: Annual cooling demand comparison of the models (Johny & Shanks 2018)

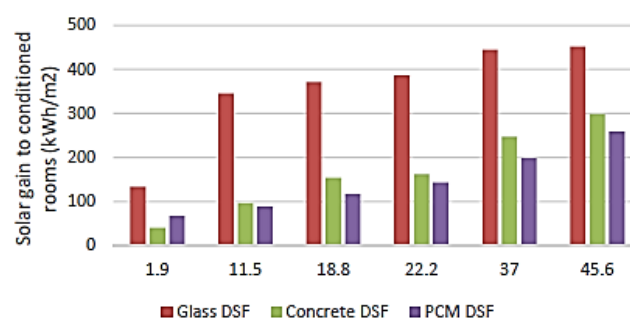


Figure 27: Solar gains by inner DSF skin for the three models (Johny & Shanks 2018)

On an overall level this research studied the DSF configuration and associated energy savings with respect to different glazing materials for the outer skin in combination with a constant glazed inner skin having different levels of perforations. They found that as the thermal mass of the outer skin of the DSF was increased the performance of the DSF also

increased proportionally, with the highest savings for a PCM based DSF in the range of 30%-50%. The authors stated the possible cause of higher temperatures in the upper part of the DSF could be attributed to non-optimized inlet and outlet openings. Although, it supports the greater idea of DSF applicability in the hot climate of UAE but at the same time calls for in depth analysis of DSF cavity involving inter model analysis i.e., involving both dynamic thermal simulation and CFD analysis.

Andjelkovic et al. (2016) reported studies relating to the positive and negative impacts of the DSF. In totality they studied a total of four building cases including a classical façade building, classical façade building with blinds placed inside, classical façade building with blinds placed outside and the DSF case (Figure 28). It is worth noting that the inner layer had a WWR of 45% and the building under this study was located in Belgrade, Serbia. The type of DSF as per the classification mentioned in the preceding section is the shaft type of DSF spanning across multiple floors. The building under consideration also had blinds placed between the two façade skins. The mode of ventilation employed here was natural and the blinds were controlled by the Building Management System (BMS).

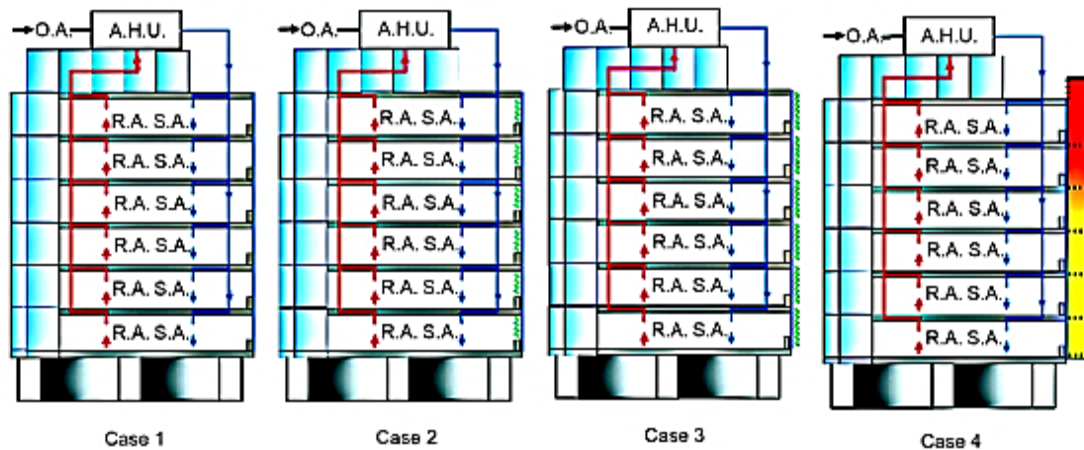


Figure 28: Building cases considered by Andjelkovic et al. (2016)

Since the building studied here is a real-world example the authors suggested to have control over the inlet and outlet of the DSF to have positive energy impacts on the building during the winter months. The authors performed energy simulations collaborating the results for the heating and cooling energy throughout the year. From the Figure 29, it can be observed that the cooling and the heating energy for the first three traditional cases were similar in nature which the authors accounted to the similar strategy adopted for the operation of the

blinds. Whereas the cooling and heating energy for the case 4 (DSF) is comparatively lower than the first three traditional cases. Further, in Figure 31 the authors also presented the distribution of the heating energy zone wise for all the four building cases. Looking closely at the case of the DSF, the lowest heating energy consumption is in the middle zone followed by the lower zone and then the upper zone. The authors attributed the higher energy consumption in the lower zone due to direct contact of cold outside air and in the upper zone due to the flat roof heat loss.

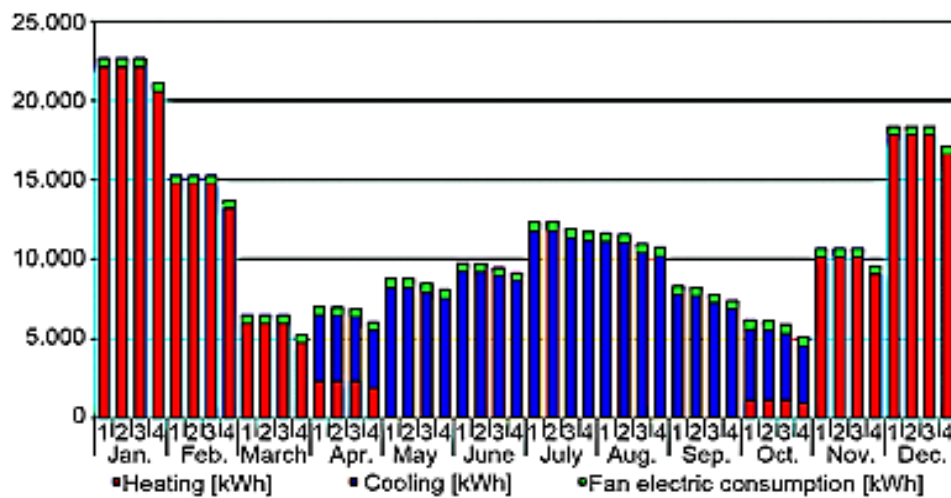


Figure 29: Cooling and heating energy analysis for the four building cases (Andjelkovic et al. 2016)

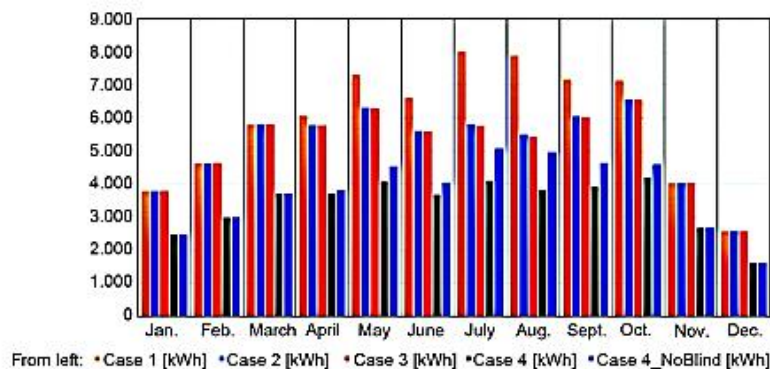


Figure 30: Solar radiation for all building cases (Andjelkovic et al. 2016)

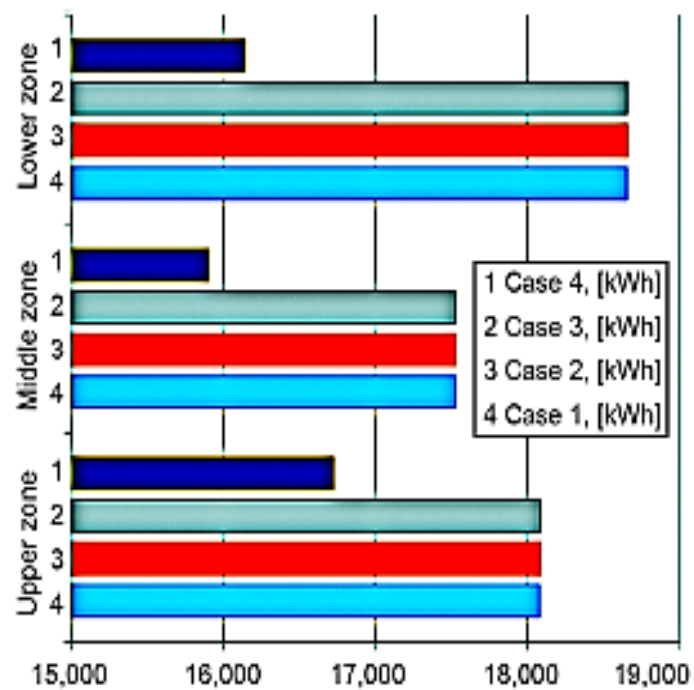


Figure 31: Heating energy consumption for all building cases - zone wise (Andjelkovic et al. 2016)

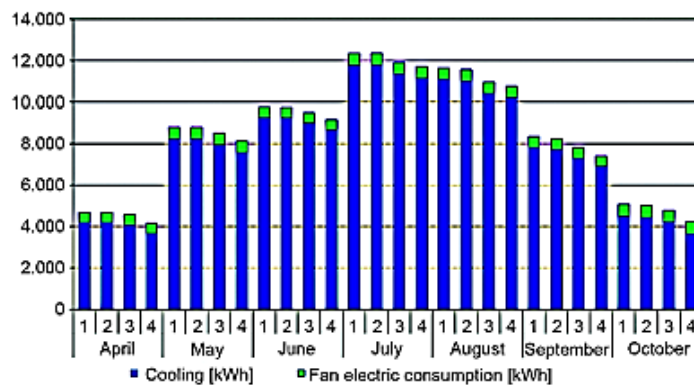


Figure 32: Cooling energy consumption for all four building cases (Andjelkovic et al. 2016)

The solar radiation value represented by the Figure 30, indicate that for the traditional façade building models (cases 1-3), the case 3 with the blinds outside proved to best performer. It

can be also be derived that the DSF model with no blinds tends to have higher solar gains from the months of May till October as compared to the DSF case with blinds. Overall, the solar radiation is the least for the DSF case with the blinds. The impact that the DSF can have in protecting the building from the solar gains is understood by the fact that the DSF case without blinds also performs better from the traditional façade cases.

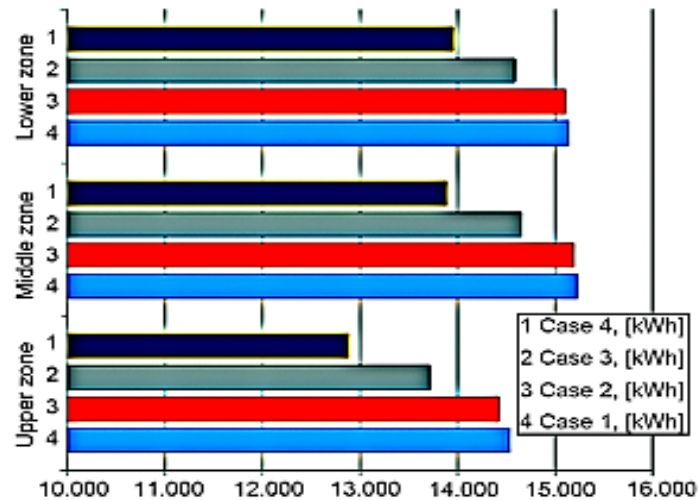


Figure 33: Cooling energy consumption zone wise for all four cases (Andjelkovic et al. 2016)

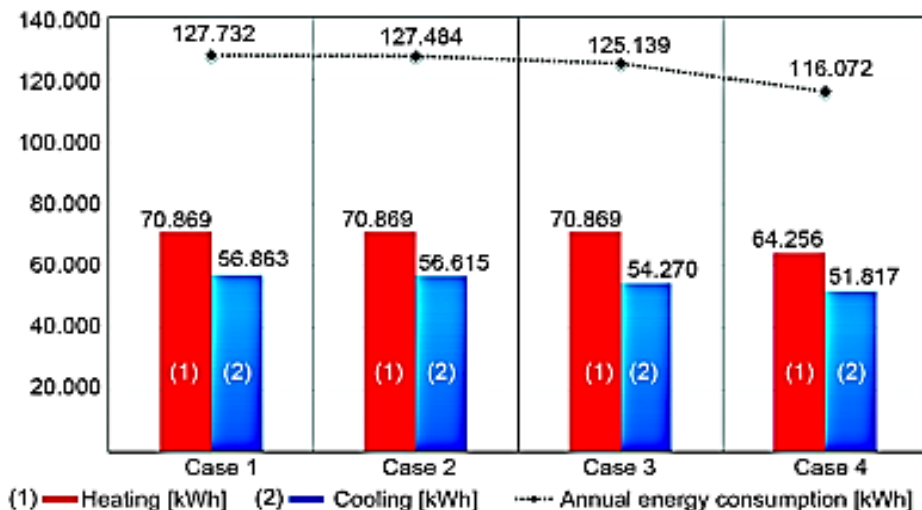


Figure 34: Summary of annual cooling and heating energy consumption for all the four cases (Andjelkovic et al. 2016)

As represented in the Figure 32, the cooling energy for the DSF is the least in comparison to all the other cases. The zone wise cooling energy consumption for all the four cases was reported as shown in Figure 33. For the case of DSF, the cooling energy is highest in the lowest zone followed by the middle zone and then the upper zone. Figure 34 shows the annual energy consumption for all the four cases that were considered and the DSF case had the lowest heating and cooling energy required. Overall, all the above results and graphs presented by Andjelkovic et al. (2016) hint at a clear indication on the potential of the DSF in reducing the overall energy consumption of the buildings. Conclusively, they reported a 9% of heating energy savings and 5% of cooling energy savings when the DSF case was compared to the best performing traditional façade case (blinds outside configuration).

Kim (2021) studied the performance of the DSF under the hot climatic conditions of Saudi Arabia. Kim (2021) in his study evaluated the thermal aspect of the DSF whilst studying the correlation of the DSF opening size and width on the cavity temperatures and velocity. Thus, making the DSF cavity width and opening size the control variables. Additionally, he studied the impact of shading device on the DSF cavity temperatures. It was noted by the author that for Saudi Arabia, which is quite similar to the UAE in terms of the weather profile, buildings accounted for 50% of the total energy consumption out of which 30% share is from the commercial sector. Keeping these ratios in mind, the author selected the appropriate model of G+3 office (Figure 35) building for the purpose of the study. The author confirmed that the majority of the studies related to DSF are accounted for the moderate climatic conditions and very few studies account for DSF under hot climatic conditions. The author highlighted that the investment cost of a DSF system is comparatively higher than that of a traditional façade system with the DSF indicating overheating of the cavity in the summer months. The primary tool used in this research was the use of CFD simulation tool employing the k-e turbulence model.

Since the author intended to validate the study with experimental results, the chosen DSF was single box window type which resembled the DSF as considered by Mei et al. (2007). In principle this single storey DSF was intended to be applied to a four-storey high office building. The author noted close agreement of the CFD simulation velocity values with that of the experimental data (Figure 36). It can be derived that the velocities ranged from 0.01 m/s with 0.35m cavity depth and 0.3 m/s with 0.55m cavity depth. Figure 37 shows the close-up view of the DSF also indicating the position of the blinds. In this particular study by Kim

(2021), the cavity depths of 0.3m, 0.6m and 1.2m were studied along with the opening sizes of 5%, 10%, 15% and 20%.

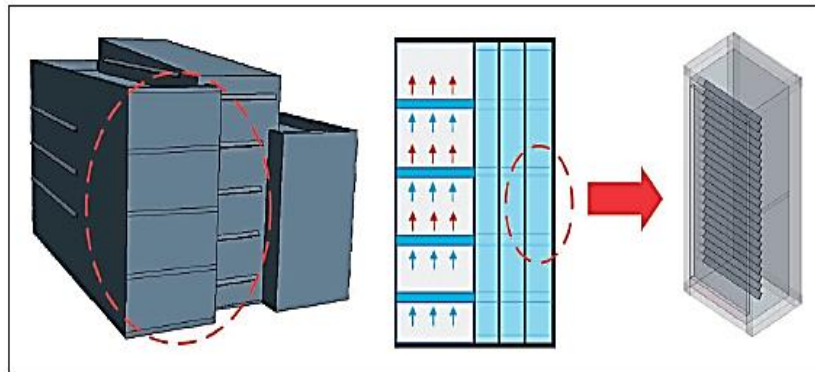


Figure 35: DSF model for G+3 office building (Kim 2021)

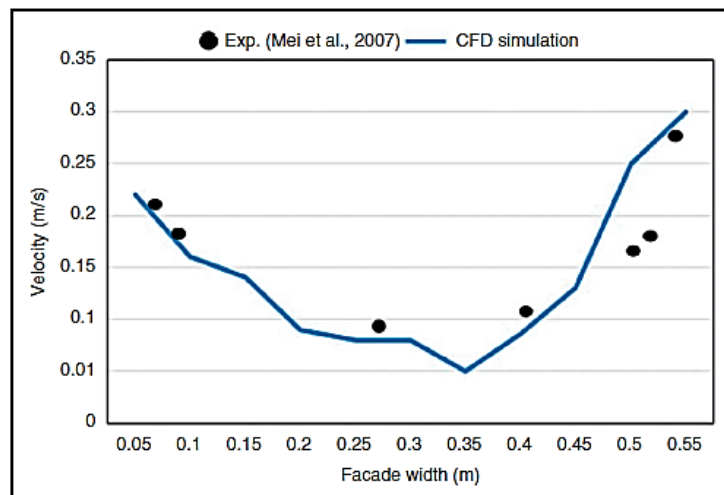


Figure 36: Velocity effect as a result of cavity depth and relation to experimental results (Kim 2021)

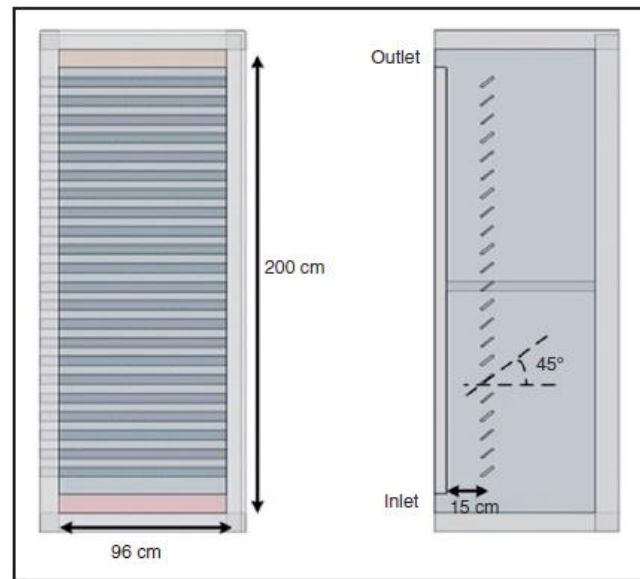


Figure 37: Close up view of the single storey DSF (Kim 2021)

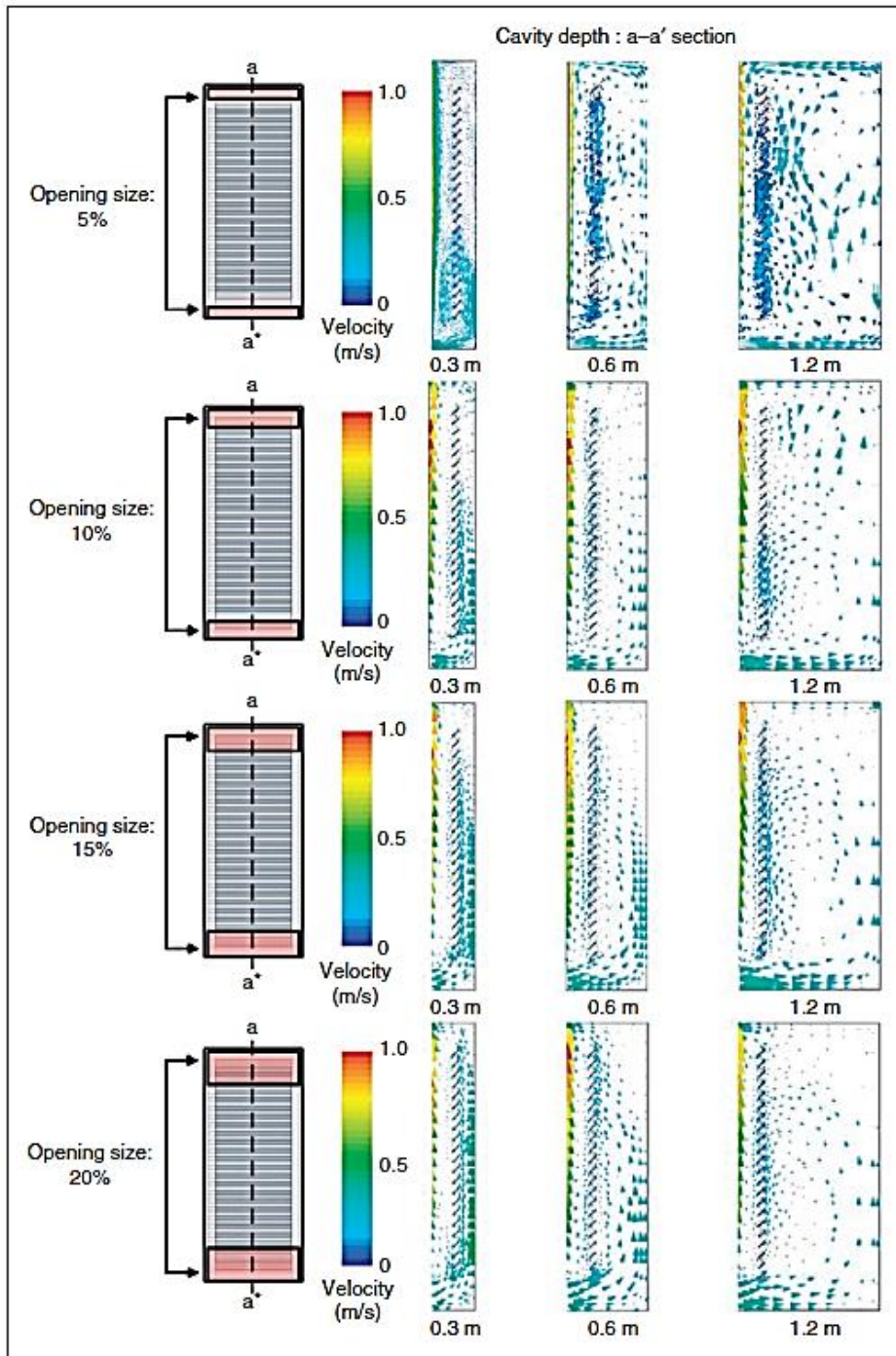


Figure 38: Velocity profiles with varying opening sizes and cavity depths from CFD simulations (Kim 2021)

Figure 38 represents the velocity values and airflow within the DSF with varying opening sizes and cavity depths and a preliminary observation indicates that the airflow becomes

more and more turbulent as the cavity depth is increased. Higher velocities were noted near the blind locations and eddies formed below the shading devices. Looking at the case of 1.2m cavity depth it was observed that the opening sizes did not have an influence when the cavity depth exceeded the value of 1.2m. The highest average velocity of 0.23 m/s was reported from the CFD results in the case of 0.3m cavity depth with 20% openings and lowest average velocity of 0.11 m/s was reported from the CFD results in the case of 0.3m cavity depth with 5% openings (Figure 39).

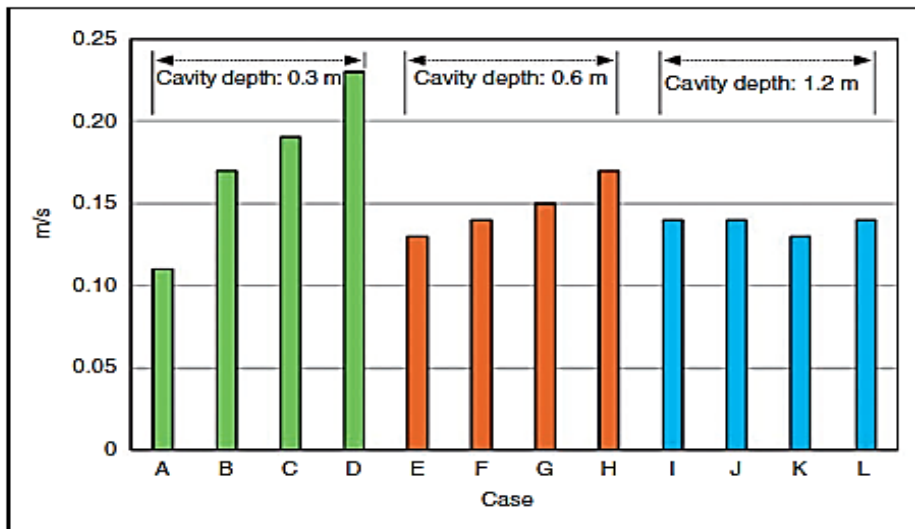


Figure 39: Average velocities for all the cavity depths with the letters indicating incremental opening percentage (Kim 2021)

Moving on to the temperature distribution as shown in Figure 40, the reported maximum and minimum temperatures were 25 deg. C and 65 deg. C respectively. The temperature distribution was more even as the cavity depths were increased. The opening percentages also had a major impact in bringing down the temperatures inside the cavity wherein the 20% opening configuration for the all the cavity depth cases shows negligible difference in the surface temperatures. Analysing the average temperatures from Figure 41, it can be said that the highest average temperature of 50 deg. C was in the case of 1.2m cavity depth with 5% opening and lowest average temperature of 28 deg. C was noted for all the cavity depth cases with 15% and 20% opening.

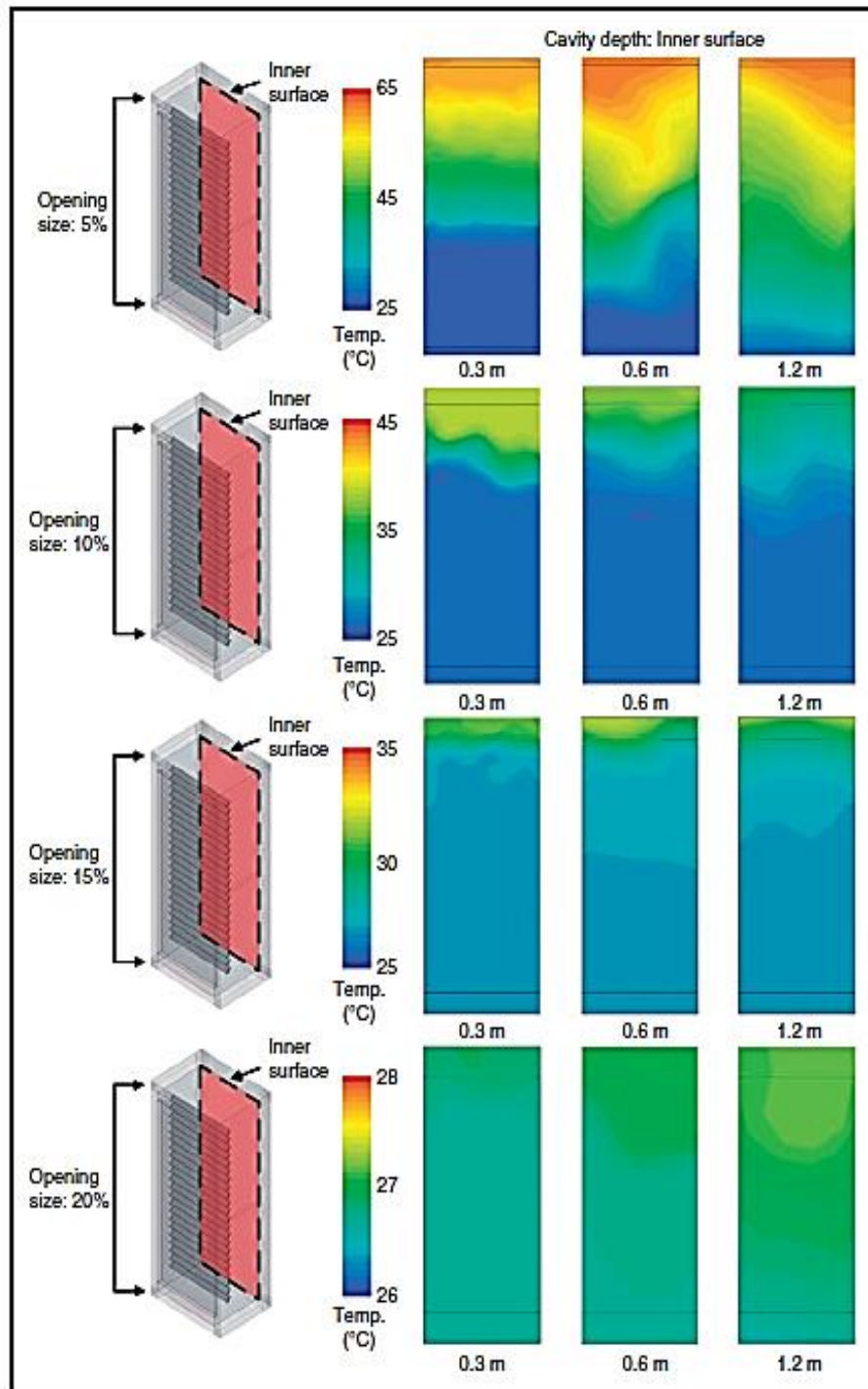


Figure 40: Inner skin temperature profile of the DSF cavity with varying cavity depths and opening percentages (Kim 2021)

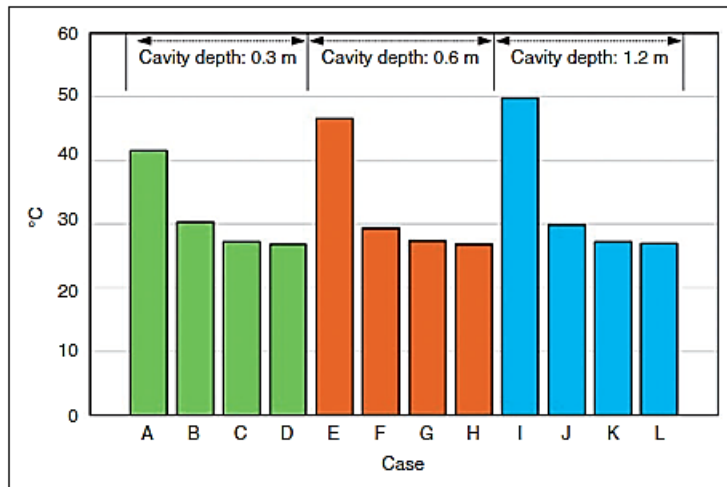


Figure 41: Average temperatures for all the cavity depths with the alphabets indicating incremental opening percentage (Kim 2021)

The author concluded that the opening size and cavity depth had little influence on velocity whereas the temperature was highly affected by the opening size and was less sensitive towards the cavity depth. To understand the impact of the shading device on the cavity, the author ran simulations on the DSF case without the internal blinds and found the average velocity to be 0.12 m/s and the average temperature to be 1 deg. C (Figure 42). It is not clear as to what time period these simulations were run for? It is also worth noting that the DSF velocities are affected by thermal stratification taking place inside the cavity and impacted by the external wind velocity and direction.

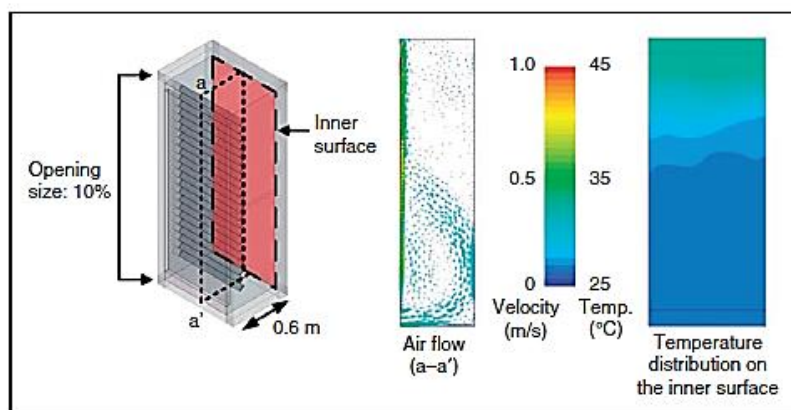


Figure 42: DSF cavity profiles for 0.6m cavity depth without any internal blinds (Kim 2021)

Wang et al. (2021) investigated the DSF study under the hot and humid climate of China using the DesignBuilder software package. In their research the authors investigated the HVAC energy consumption and made a comparison between the Single Skin Façade (SSF) system and Double Skin Façade (DSF) system. They firstly laid out the foundation of their research with HVAC energy consumption for the two models and expanded their study further to determine the optimal parameters for the DSF. The selected building for this purpose was 12 storeys high. In their research the authors rightly pointed out the need for building energy simulation to understand the aspects of DSF. The authors decided to disregard the first and the twelfth floors due to their proximity to the DSF openings. The authors studied the DSF based on five parameters including WWR, external wall construction, glazing type and blind type. The DSF model was set with a cavity depth of 1m and the DSF type was External Air Curtain (EAC) as mentioned earlier in this section. The DSF was employed on the south façade as shown in Figure 43. The inlet for the DSF was at the bottom and the outlet at the top.

The results for the thermal simulation are shown in Figure 44 indicating the cooling energy consumption. In March the outside temperatures are lower (heating season) for the particular region under consideration and hence the energy consumption values of the DSF are lower than that of the SSF which the author attributes to the ability of the DSF to trap the heat and prevent the heat loss from the indoors to the outdoors. But in the month of July where the outside temperatures are higher (cooling season) the energy consumption is not very different when compared to the SSF case because the heat trapped in the DSF now increases the cooling requirement.

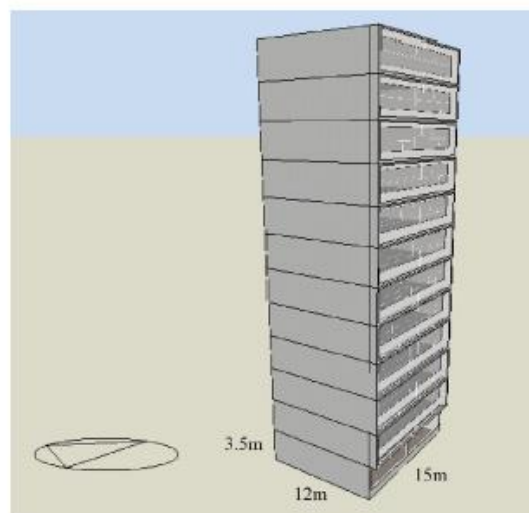


Figure 43: DSF on the south façade
(Wang et al. 2021)

For the month of December, the authors noted that the SSF had higher energy consumption on the upper floors attributing to greater heat loss and the DSF had higher cooling energy consumption at the upper floors because of the heat trapped at the upper floors. The reported average energy consumptions per each floor are indicated in the Table 4. The authors noted the average energy consumption for the SSF to be 60 MWh and for the DSF to be 50 MWh which is a 16% reduction (Figure 45).

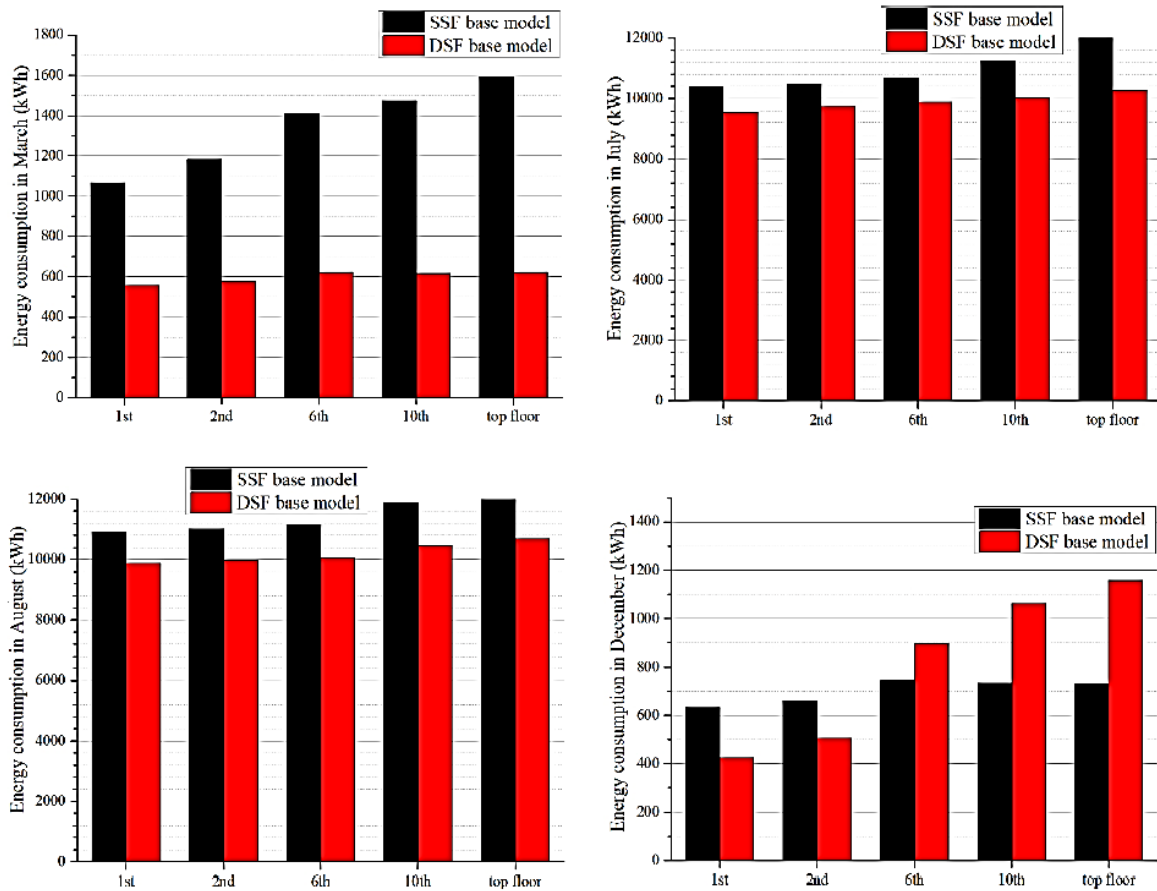


Figure 44: Critical floors cooling energy consumption for SSF and DSF cases (Wang et al. 2021)

Month/Case	SSF (kWh/floor)	DSF (kWh/floor)
March	1400	600
July or August	11200	10000
December	700	800

Table 4: Summary of average energy consumptions over the months (Wang et al. 2021)

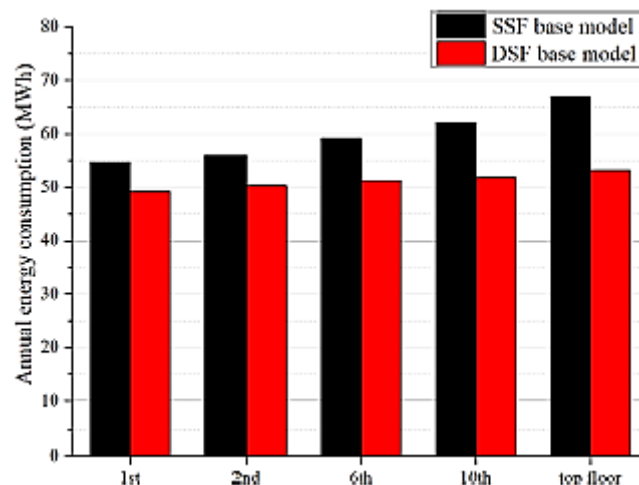


Figure 45: Annual cooling energy consumption between the SSF and DSF (Wang et al. 2021)

A recent study by Pourshab et al. (2020) studied the issue pertaining to overheating of the DSF cavity due to the heat trapped at the upper floors and determine if at all this heat trapped can aid in increasing the natural ventilation flow within the cavity. They also analysed the behaviour of the vertical & horizontal solar shading elements within the DSF cavity and its effect on the air movement and heat transfer within the cavity. For the purpose of the study, they considered a five-storey high building with a typical floor area of 80 sq. m and 3m in height located in Isfahan, Iran. The DSF cavity was designed in such a way to have cross ventilation with the inlet being on the northern side and the outlet being on the southern side (Figure 46). It was also interesting to note that the cavity was extended up to 2 m higher the roof of the building and that the intermediate floors had openings facilitating natural ventilation. Figure 47 indicates the cross sections of the building with the horizontal louvers (indicated as case A) and the vertical louvers (indicated as case B). The CFD simulations were performed at 12 PM on a summer day and when the peak radiation occurred.

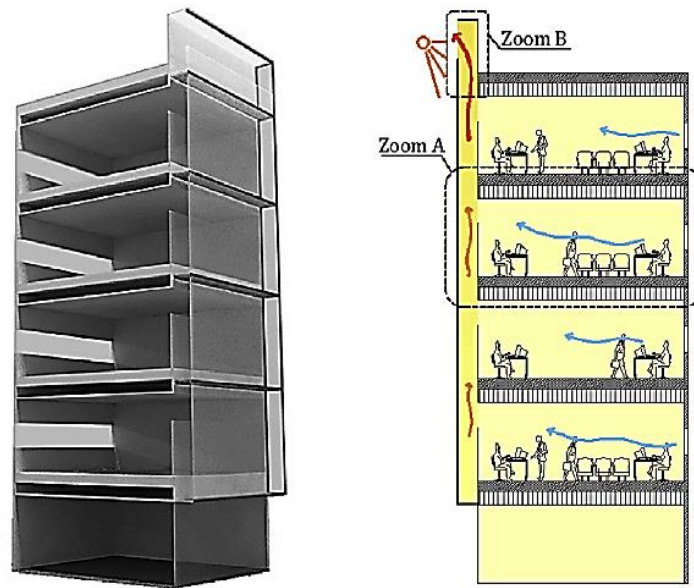


Figure 46: Overall building and cross section of the DSF cavity (Pourshab et al. 2020)

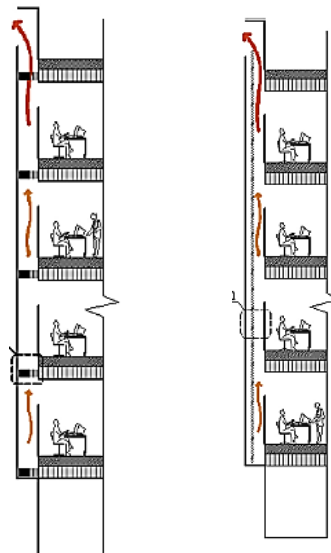


Figure 47: Cross section with horizontal and vertical louvers (Pourshab et al. 2020)

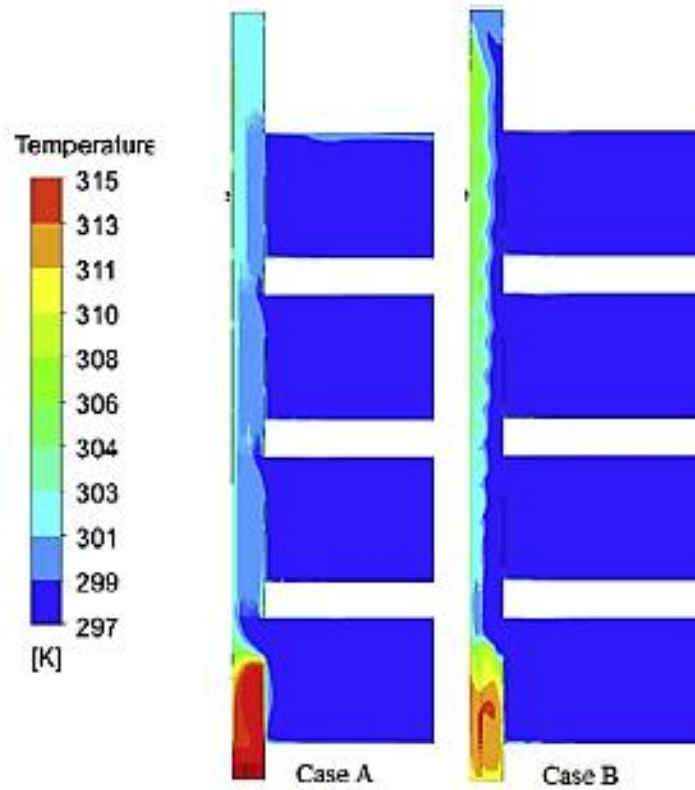


Figure 48: Temperatures profiles from the CFD simulations (Pourshab et al. 2020)

Figure 48 indicates the temperature profile inside the cavity for both the cases. The authors noted higher temperatures at the lower floors of the DSF cavity and attributed it to the direct solar radiation on the lower floors as consequence of heat trapping phenomena because of inadequate ventilation. It was noted by the authors that the cavity temperatures profiles were divided into the external zone (in front of the louvers) and internal zone (behind the louvers). It can be observed that in the case A with the horizontal louvers, the temperatures in the cavity at the first two floors is around 300K (26.8 deg. C) and on the upper floors it is about 301K (27.8 deg. C). In the case B with the vertical louvers, there is very clear distinction between the external and internal zones, with the temperatures of the internal zones being about the same as that of the occupied space that is around 297K (23.8 deg. C) and the temperature at the external zone gradually increases from 301K (27.8 deg. C) to 308K (34.85 deg. C).

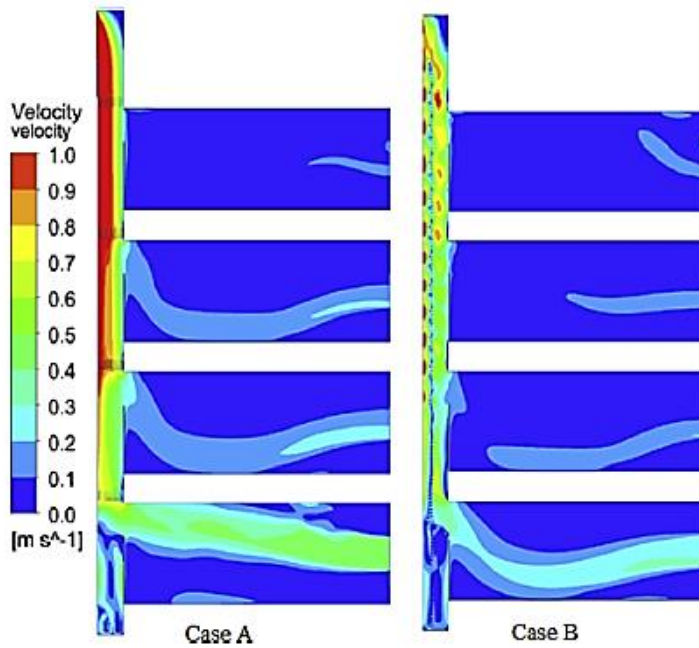


Figure 49: Velocity contours of the two cases (Pourshab et al. 2020)

The velocity contours for both the cases are indicated by Figure 49, and the authors noted gradual increase in the velocity values moving along the height of the cavity. The maximum reported velocity value was 1m/s in the case of horizontal louvers whereas patches of 1m/s could be seen in the case of vertical louver at the upper floors while at the lower floors the velocity ranged from 0.22 m/s to 0.55 m/s in both the cases. The authors noted that the horizontal louvers received much higher radiation as compared to the case with the vertical louvers, which had lower value of radiation due to the occurrence of self-shading occurrence phenomenon. But it was noted that the convection heat transfer rate was higher for the case A as compared to case B, due to better airflow movement. The air temperature on the internal zone of the case B were also lower indicating lower heat transfer to the interior spaces as compared to the case A.

Kim (2021) in his study reported that most commonly k-e or k-w turbulence model has been used in the literature for the analysing the airflow within the cavity. He also used the k-e turbulence model in his study. Among the reported studies by Kim (2021) that used the k-e turbulence model for the studying the airflow within the cavity are Gurardo et al. (2011), Iyi et al. (2014), Suet et al. (2017) and Pasut & Carli (2012).

Delving more into detail to the study of Pasut & Carli (2012), where they analysed applicability of the k-e and k-w turbulence models on simulating naturally ventilated DSF's.

The authors used the results by Mei et al. (2007) to understand the results of CFD simulation and effect of varying the turbulence models. The simulated model was adopted similar to that of Mei et al. (2007) which was a single storey DSF. The authors noted the findings of Zhang et al. (2007) as shown in Table 5. As per ratings and as noted by the authors both turbulence models predict the mean temperature and mean velocities very well. Reported temperature predictions with the various models are summarized in Table 6 with the following scale for the ratings: A (error less than 10%), B+ (error in between 10% and 20%), B (error in between 20% and 30%), C (error in between 30% and 50%), D (error greater than 50%).

Natural convection	Compared items	Turbulence models	
		k- ϵ RNG	k- ω SST
	Mean temp.	A	A
	Mean velocity	B	A
	Turbulence	C	C

A = good, B = acceptable, C = marginal, D = poor.

Table 5: Ratings of turbulence models for simulation of naturally ventilated DSF in internal lab conditions (Zhang et al. 2007 cited in Pasut & Carli 2012)

Simulation features	Points						
	1	2	3	4	5	6	7
1 2D, k- ω SST	C	C	C	C	B	C	B
2 2D, k- ϵ RNG	B	B	B	B	B	C	B
3 2D, k- ω SST, with external environment	B	B+	B+	B+	B+	B	B+
4 2D, k- ϵ RNG, with external environment	B	B+	B	B	B+	B	B+
5 3D, k- ω SST	B	B	B	B	B	B	B
6 3D, k- ϵ RNG	B	B	B	B	B	C	B
7 3D, k- ω SST, with external environment	B	B+	B	B	B	C	B
8 3D, k- ϵ RNG, with external environment	B	B	B	B	B	B	B

Table 6: Temperature prediction ratings for simulation of naturally ventilated DSF at various monitor points (Pasut & Carli 2012)

Simulation features		Points						
		1	2	3	4	5	6	7
1	2D, k- ω SST	C	B	D	C	A	C	D
2	2D, k- ϵ RNG	C	B	C	D	A	C	C
3	2D, k- ω SST, with external environ.	C	C	D	D	C	C	A
4	2D, k- ϵ RNG, with external environ.	C	B	C	D	A	B	B
5	3D, k- ω SST	B	A	C	C	C	B	D
6	3D, k- ϵ RNG	C	A	B	D	B	B	C
7	3D, k- ω SST, with external environ.	B	A	D	C	D	B	D
8	3D, k- ϵ RNG, with external environ.	B	A	B	C	B	B	C

Table 7: Velocity prediction ratings for simulation of naturally ventilated DSF at various monitor points (Pasut & Carli 2012)

Further assigning the rating values with fixed points such as A with 10 points, B+ with 7 points, B with 3 points, C with 2 points and finally D with 1 point. In terms of the temperature prediction the highest total comes out for the case 3 that is 2D k- ω SST with external environment setup (45 points) followed by the case 4 2D k- ϵ model RNG with external environment setup (36 points). Comparing the velocity predictions with the different setups as indicated in Table 7, the highest tally of points is for the case 8 followed by the case 4 and case 6. Collectively the authors reported that in case of RNG turbulence model, addition of the external environment has improvement in the results prediction whereas the inverse was true for the SST model. They highlighted the insignificant difference in the prediction between the 2D models and the 3D models backing with the fact 2D simulations would save substantial computational time. In conclusion, they highlighted that the k- ϵ is the best suited for DSF CFD study in terms of prediction and stability.

In summary, the Hamza (2007) reported cooling load reductions of ranging from 12% to 30% whereas Radhi et. al (2013) reported 17%-18% of cooling energy reduction. Johnny & Shanks (2018) reported 8% - 50% load cooling load reductions over varying the outer skin material and configurations. Andjelkovic et al. (2016) reported a cooling savings of 5%. Wang et al. (2021) reported 16% cooling energy reduction. Kim (2021) and Pourshab et al. (2020) basically highlighted the temperature reductions within the cavity but did not report specifically about total energy savings or cooling energy savings.

3. Chapter 3: Methodology

The methodology here defines the various stages (Table 8) of this research and in what sequence they were carried out. The first stage covers an extensive literature review analysing the studies related to Double Skin Façade in both hot and temperate climates. This aided in establishing the optimum DSF and external shading configurations which would form as the building cases for this study. The second stage involved the use of the energy plus engine in the DesignBuilder software to perform the dynamic thermal simulations thus producing temperature profiles, velocity profiles and air flow rates. The third stage of the study involved the use of the internal CFD analysis to obtain the temperature profiles, velocity profiles and air flowrate and paths. It is to be noted that both the stages 2 and stage 3 were followed by subsequent results interpretation. The fourth stage of the study revolved around the intermodel validation that is to compare and contrast the results obtained in both the dynamic thermal simulations and the internal CFD analysis. The fifth stage and last stage of the study consisted of a sensitivity analysis for the internal CFD analysis thereby working on the effect of CFD simulation parameters on the convergence of the CFD results. Additionally, the flowchart (Figure 50) gives a detailed overview of the research flow and the steps involved.

Stage – 1	Advanced literature review thus establishing benchmark models for study
Stage – 2	Dynamic thermal simulations
Stage – 3	CFD simulations
Stage – 4	Intermodel validation of results
Stage – 5	CFD sensitivity analysis

Table 8: Stages of research (Author 2021)

The air properties and movement inside the DSF cavity are influenced by several factors including the spatial configurations, cavity width, vertical wind pressure differences and variation in the outside air temperature along the height of a building. All this, deems the heat transfer mechanism and air movement inside a DSF cavity to be of a very complex

nature. Although the heat transfer mechanism can be very well analysed using a dynamic thermal simulation software such as IES-VE or DesignBuilder but gives little insight into air movement inside the cavity. Thus, the use of CFD modelling software like ANSYS, Open Foam or the CFD component of DesignBuilder to study the air movement becomes necessary. This type of inter model verification of analysis results using two different software tools is rare in the existing literature and serves as the crucial part of this research. Such complimentary design analysis increases the certainty of implementing the DSF to buildings and minimize the risks involved.

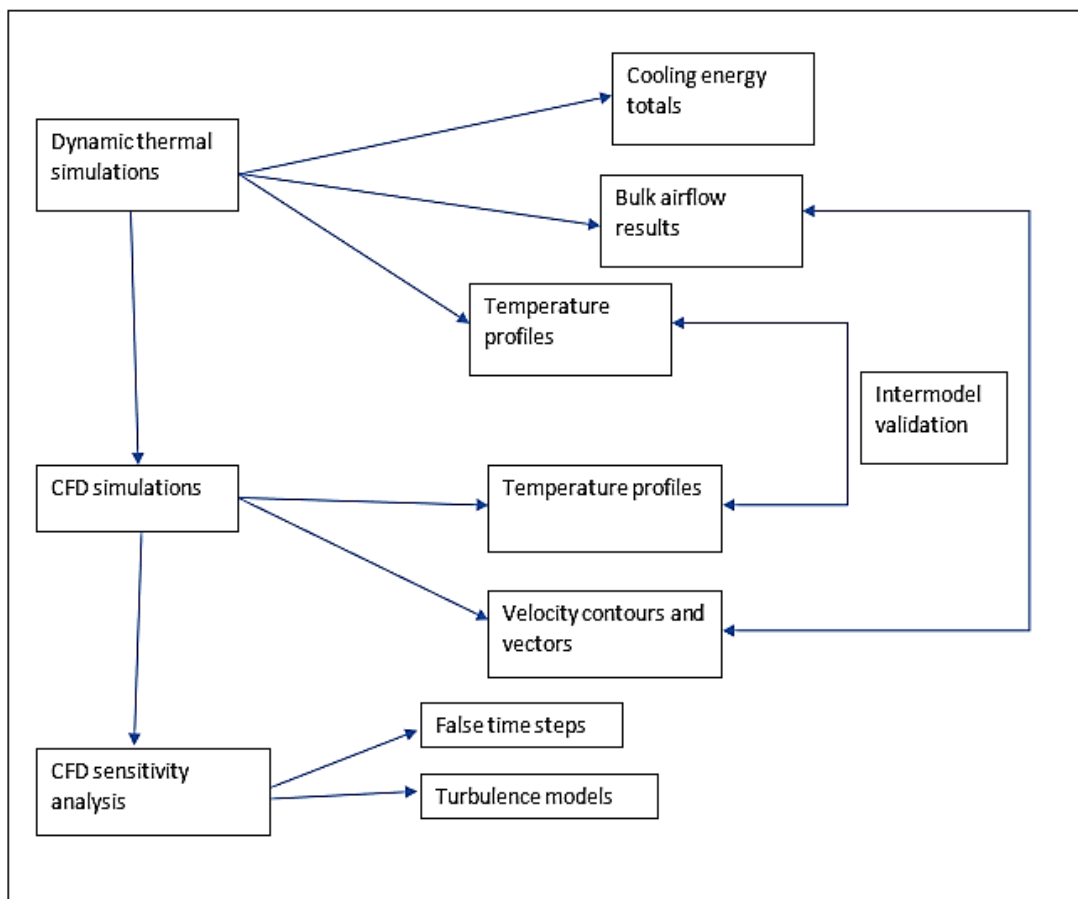


Figure 50: Flowchart of the research elements (Author 2021)

As discussed in the literature review section regarding the building stock of the Dubai, it was decided to go for a high-rise office building that very well represents the majority of the building stock of Dubai and the type of occupancy. To limit and focus of the study and

felicitate towards easier comparison between the different building cases of base case, external shading case and DSF case a common orientation of the building was studied which would serve as the worst-case scenario. As per Manz & Frank (2005), they highlighted that the west direction was the worst affected because the peak outside air temperatures coincided with the peak irradiance and the higher temperatures occurred during the summer day on the west orientation. Figure 51 clearly indicates the solar irradiance of the west coincides with the peak outdoor air temperature. Therefore, a similar strategy was considered and all the building cases were compared based on the west orientation for the temperature and velocity profiles.

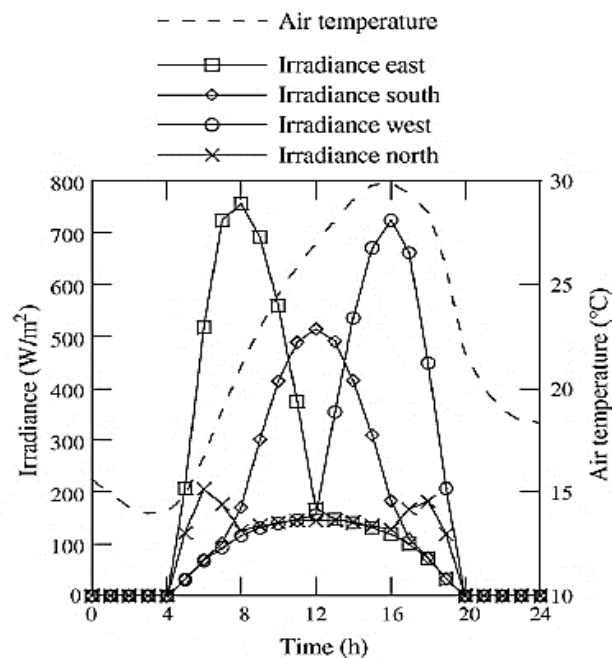


Figure 51: Graph indicating the coincidence of the peak air temperature and irradiance in the west direction (Manz & Frank 2005)

The next step was to determine the design day and design hour based on the available weather data file in DesignBuilder. The design day and hour are when the thermal dynamic and CFD simulations were run although dynamic thermal simulations also cover the entire year scenarios. The weather file used by the DesignBuilder software is that of Abu Dhabi and is in the IWEC format. By default, the summer design week considered by the weather file ranges from 20th of July to the 26th of July. To determine the exact design day and design hour, further investigation was carried out within this summer design week period by zeroing

in on the day with the highest average outside temperature. Table 9 shows the average outside dry bulb temperatures for each of days of summer design week. As it can be observed that the maximum Dry Bulb Temperature (DBT) occurs on the 24th of July, hence it was selected as the design day for this study. The design hour was further determined by studying the average temperatures on the design day. The average temperatures on the 24th of July have been indicated in Table 10 and Figure 52, show that the maximum average temperature is at 4 PM but the time of 2 PM is the selected as the design hour.

Date/Time	Outside Dry-Bulb Temperature (°C)
20/07/2002	36.29
21/07/2002	35.66
22/07/2002	34.32
23/07/2002	35.77
24/07/2002	38.33
25/07/2002	37.71
26/07/2002	36.55

Table 9: Summer design week average outdoor DBT for Abu Dhabi (DesignBuilder 2021)

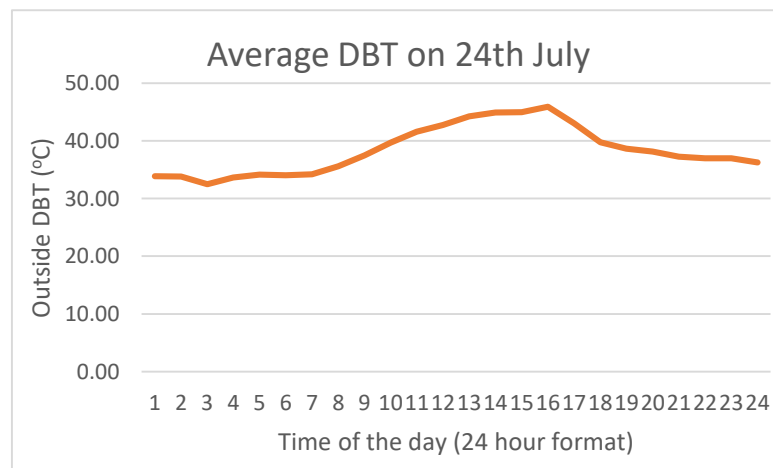


Figure 52: Outside air temperature profile on the design day for Abu Dhabi (DesignBuilder 2021)

Time of the day	Outside Dry-Bulb Temperature (°C)
1	33.90
2	33.80
3	32.50

4	33.65
5	34.13
6	34.03
7	34.23
8	35.58
9	37.50
10	39.73
11	41.58
12	42.75
13	44.28
14	44.93
15	45.00
16	45.90
17	43.05
18	39.75
19	38.63
20	38.13
21	37.25
22	37.00
23	37.00
24	36.25

Table 10: Design Day average outdoor DBT for Abu Dhabi (DesignBuilder 2021)

Next part of the methodology involved defining the building cases for this particular study. Reiterating the conclusion from the literature review section it was understood, that the passive technologies such as external shading and double skin facade can bring about promising reductions in the building energy consumption. Therefore, the three building cases considered for the purpose of this study are base case without any external shading, the external shading case and the DSF case. Another reason for choosing these three cases is because, they uniquely represent the different levels of the construction that developers would opt for the built environment sector of the UAE. The base case represents a simplistic construction followed by the external shading case representing a cost-effective way to reduce the solar gains and finally a Double Skin Façade (DSF) case representing much complex and sustainable passive approach. All three cases are considered to be 13 storeys high with a uniform square shaped building footprint. This makes all the buildings a G+13 configuration. Since this is an office building, the ground floor is considered as a main entrance area into the building and does not have any office spaces. The centre of the building consists of a typical core accommodating the necessary circulation corridors,

elevator shafts and stairwell areas. All the following typical floors have four offices each along with a central core. The office is considered to be open space office and there is no further sub division considered within these four offices. Further, an office building is considered for the study under consideration due to its near fixed operating hours and higher energy consumption in the shorter span of operating hours.

The intention of the study was also to ensure a high-rise building is considered and hence a 13 storey building was selected. Because, as per the NFPA 101 – Life Safety Code, a high-rise building needs to have a height of more than 23m. So, for the case under consideration, an office building with 13 storeys or 43.3m high is taken into consideration with each floor being 3.3 m in height. The dimensions of the office building are indicated in the Figure 53. The dimension of one side of the building is 40 meters in length for the base case and the external shading case. Thus, the floor area at each floor is a total of 1600 square meters. Out of this 1600 sq. m area, the core area occupies 324 sq. m followed by each office zone occupying 319 sq. m. Figure 54 to Figure 56 indicate the plan view, perspective and 3D slice of a typical floor in the base case building.

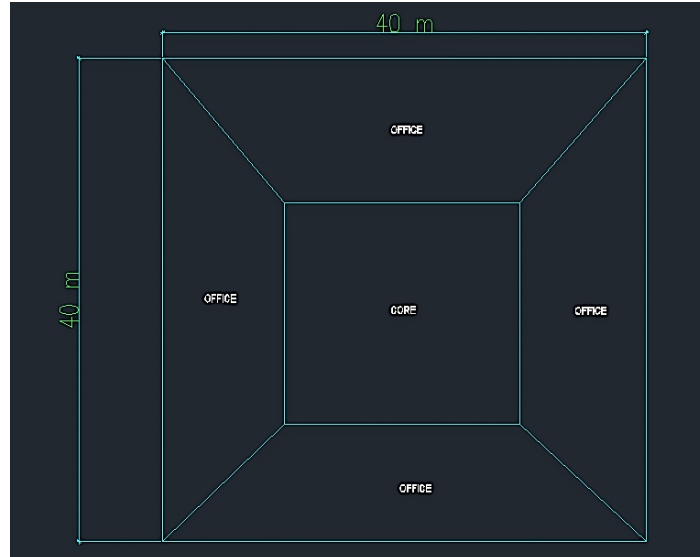


Figure 53: Dimensions of the base case building (Author 2021)

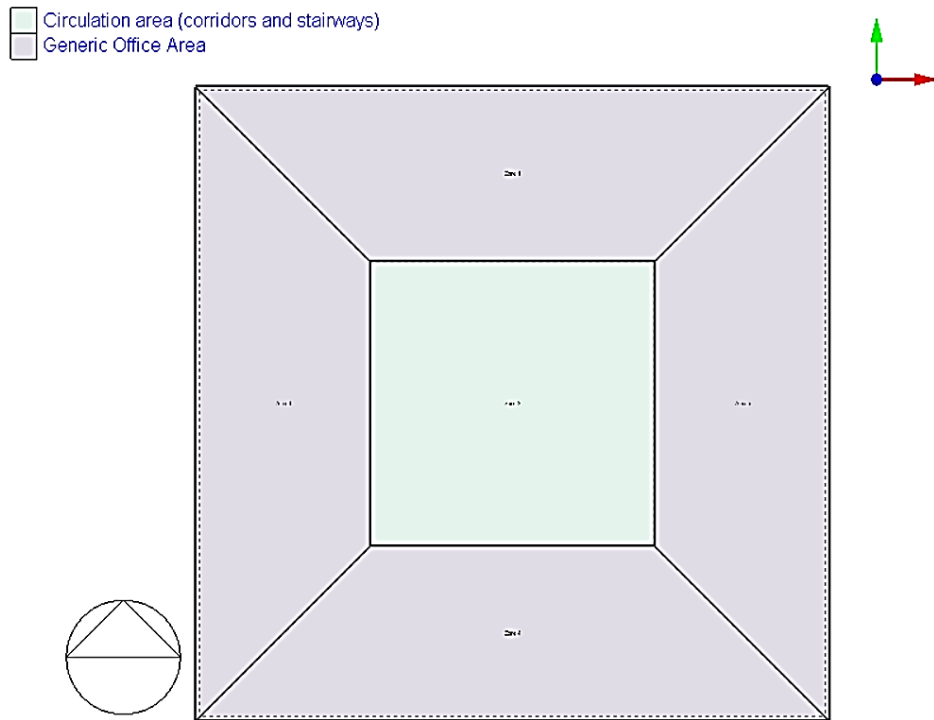


Figure 54: Schematic plan view of the base case building (Design Builder 2021)

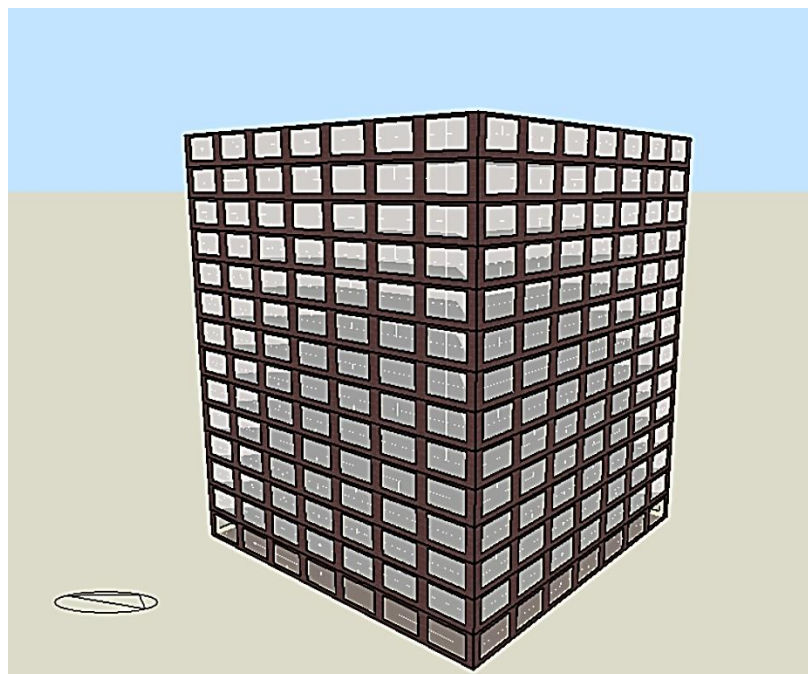


Figure 55: Perspective view of the base case building (Design Builder 2021)

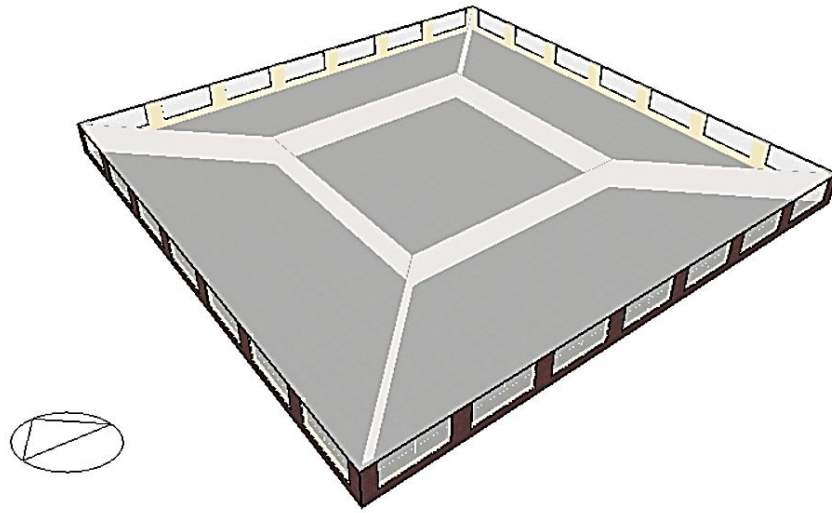


Figure 56: Perspective of a typical floor of the base case building
(Design Builder 2021)

Figure 57 – Figure 59 indicate the plan view, perspective and 3D slice of the external shading building. The type of external shading with reference to the types discussed in the literature review section is the overhang type which is most common form of external shading. The overhang covers entire length of the window and is projected from the wall on which the glazing is placed. Figure 60 to Figure 63 indicate the plan view, perspective and a 3D slice of the DSF building case. In the case of the DSF model, the overall building dimensions are slightly extended due to the inclusion of the DSF cavity making it a total length of 42m each side with 2m cavity width of DSF along one side of the building. The DSF configuration adopted for this particular study in view of the classification discussed in the literature review section will be a multi storey façade system allowing natural ventilation with an air flow concept of External Air Curtain (EAC) and a wide cavity depth.

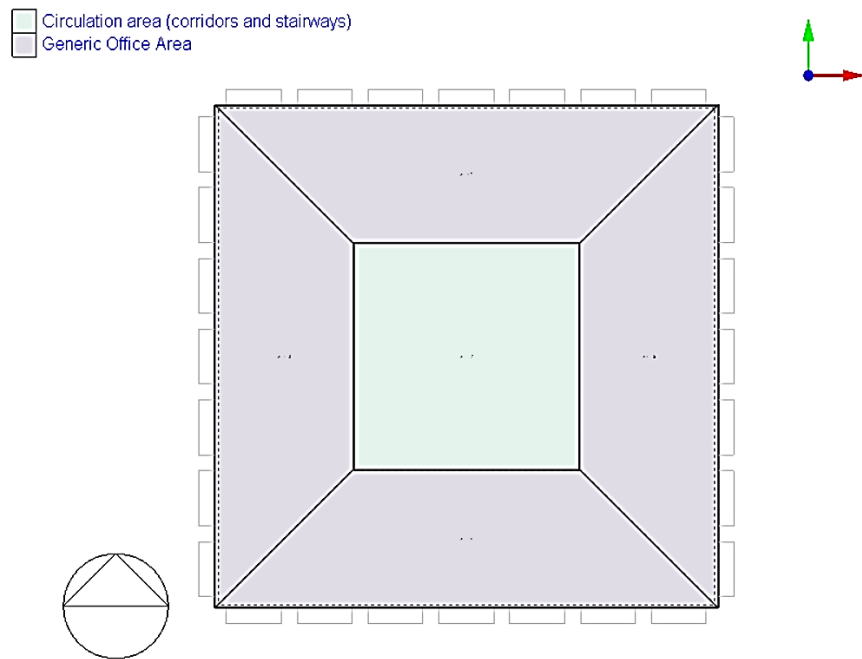


Figure 57: Schematic plan view of the external shading case building
(Design Builder 2021)

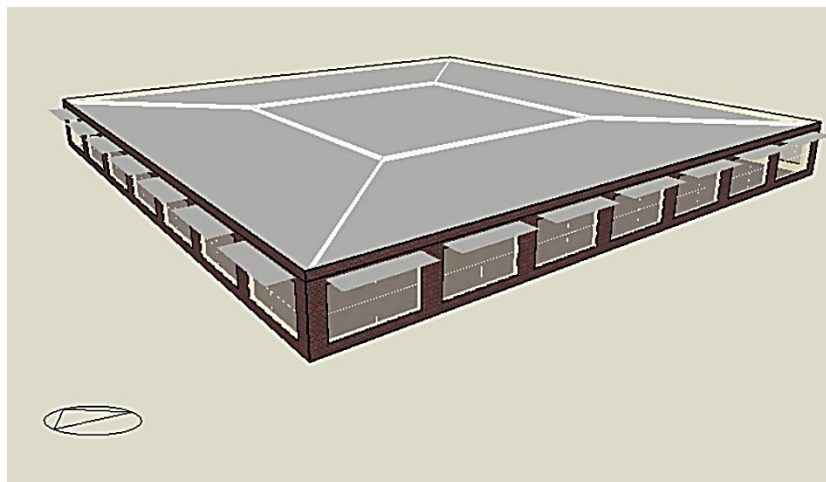


Figure 58: Perspective a typical floor depicting external shading elements
(Design Builder 2021)

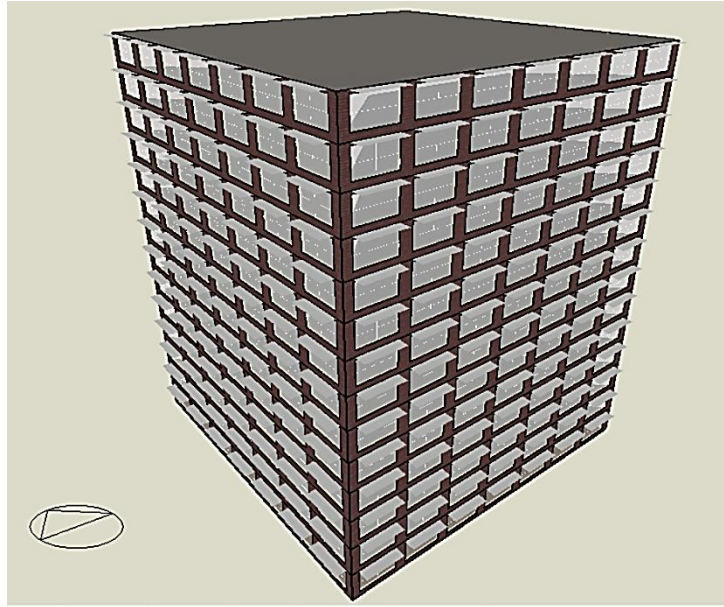


Figure 59: Perspective view of the external shading case building
(Design Builder 2021)

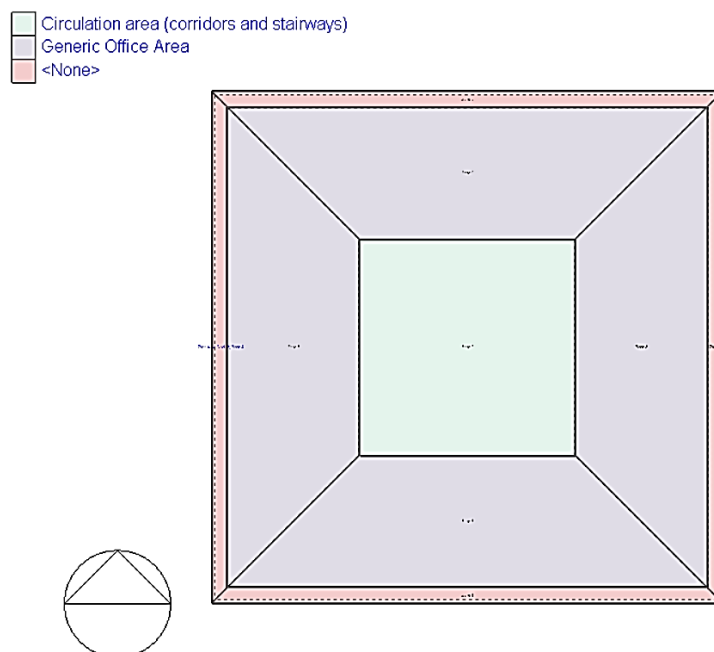


Figure 60: Plan view of a typical floor plan in the DSF model
(Design Builder 2021)

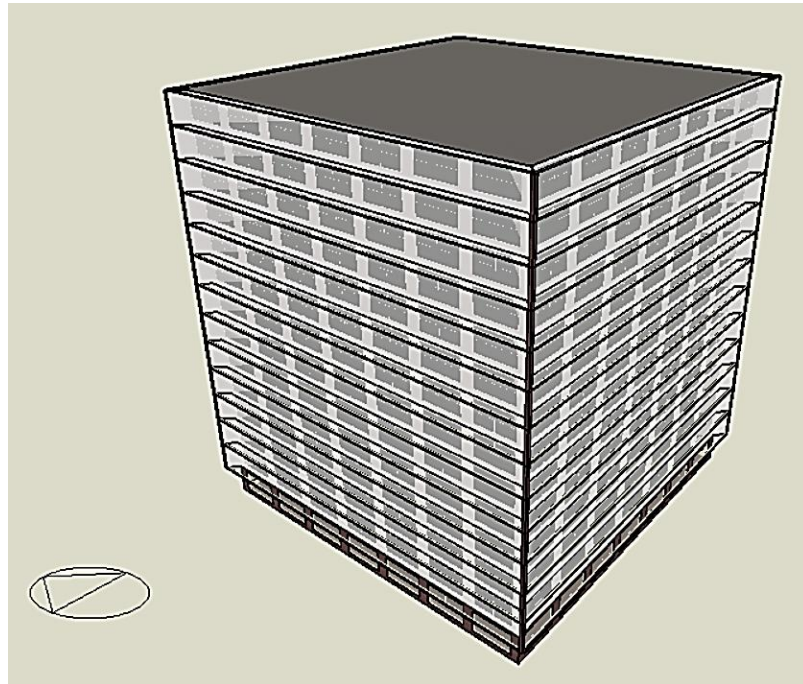


Figure 61: Perspective of the whole building for the DSF
(Design Builder 2021)

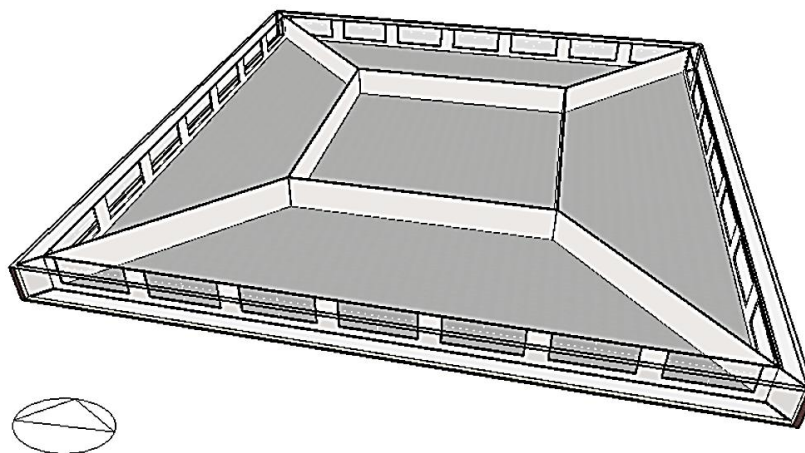


Figure 62: 3D slice of a typical floor in the DSF model (Design Builder 2021)

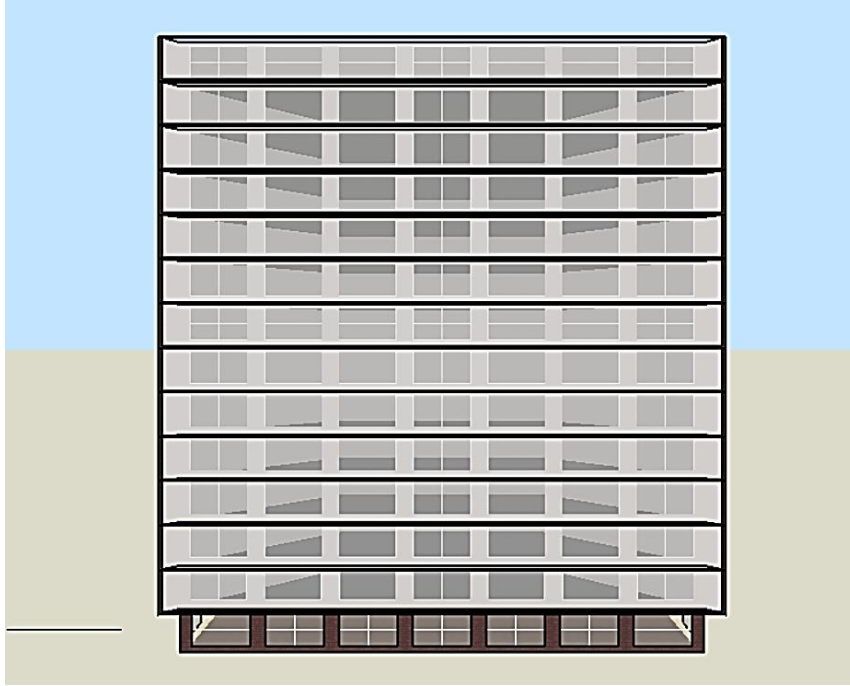


Figure 63: Section of the building in DSF case (Design Builder 2021)

The window to wall ratio in all the three building cases is 60% which is the bare minimum required by the Dubai Al Sa'fat guidelines. For 60% WWR the construction details of the glazing need to have a U value of $1.9 \text{ W/m}^2\text{K}$ and a shading coefficient of 0.25 (Al Sa'fat 2020). Each of the window is 4.4m in width and 2.5m in height covering an area of 11 sq. m and there are seven windows in total covering a total area of 77 sq. m. The total wall area of the internal skin of the DSF is 133 sq. m, thereby making a WWR of 60%. The construction details for the building elements are show in Table 11.

Building element	U value ($\text{W/m}^2\text{K}$)	Remarks
External wall	0.57	As per Al Sa'fat
Flat roof	0.25	
Ground Floor	0.57	As per Al Sa'fat
Internal floor	2.9	
Internal wall	2.1	
Internal glazing	1.9	As per Al Sa'fat
External glazing	1.9	

Table 11: Construction details of building elements (Author 2021)

The office spaces are set with a 2 pipe Fan Coil Unit (FCU) and the default schedule of open office is applied to the office spaces having an operating schedule from 8 AM – 6 PM. Further, the core is applied a default office circulation schedule. The cooling setpoint for the office spaces and other zones is kept at 24 deg C with a setback of 28 deg C. The DSF cavity zone in the DSF model has been set with the cavity option available within the DesignBuilder software. By doing so DesignBuilder automatically considers the zone as unoccupied and also applies the appropriate convection and solar distribution algorithms that will be required for the dynamic thermal simulations.

The method of ventilation employed in the study is calculated mode of ventilation that tends to take into account the effects buoyancy, wind pressures and generates the airflow rates accordingly based on the cracks and holes. In this particular study of the DSF cavity, inlet and outlet are defined as a hole. Also, the infiltration is considered to be zero throughout the building facade in all the three cases. This setting was also important to account for the CFD simulations since the CFD simulations were not possible with infiltration option as active.

4. Chapter 4: Results and discussions

As mentioned in the previous methodology section, the study comprises of using the dynamic thermal simulations and CFD tools to determine the outcome of this study. This section encapsulates the results of the dynamic thermal simulations such as the annual cooling energy consumptions, annual solar gains, temperatures profiles, airflow rates and velocities. The CFD simulations throw light on the temperature profiles, velocity profiles and airflow regime within the cavity.

4.1. Dynamic thermal simulations

The annual simulations were performed for all the three cases under consideration and the summary of the results is available in Table 12 and the following Figure 64. In Figure 64, the exterior windows denote the windows on the exterior skin for base case, external shading case and the DSF case. The interior windows are applicable only in the case of DSF wherein they represent glazing on the inner skin of the DSF. As can be seen from the Table 12 that with regards to the total cooling energy the maximum consumption is in the case of the DSF which is contrary to what would be typically expected. The second-best performer is the base case with comparatively lower total cooling energy consumption. The best case seems to be the one with the external shading.

A baseline Energy Usage Index was also calculated to give a clear picture of the best building scenario. Again, the external shading was the best case as compared to the base case and the DSF case. The baseline EUI when compared to that reported by Afshari et al. (2014) which is 173 kWh/m²/year seems to be higher but when compared to the EUI reported by Johnny & Shanks (2018) indicating a value of 262.23 kWh/m²/year seems acceptable. Comparing the EUI of buildings in different geographic locations is not advisable, firstly because it does not give a clear picture of the comparison and differences could be due to the local construction standards, ambient temperatures and different internal heat gains.

It is to be noted that there is a small amount of solar gains that reaches the inner skin of the DSF and is represented by the fourth column in the Table 12. In principle the exterior window solar gains of the base case and the external shading case needs to be compared with the internal window solar gains of the DSF case. It is interesting to note that although the base case has the highest solar gains, its corresponding cooling energy is lower whereas solar

gains thorough the interior skin of the DSF are lower but the total cooling energy is the highest. This infers to the fact the higher cooling energy consumption in the DSF case is not because of the solar gains but because of the phenomena taking place in the DSF cavity itself. An initial assumption to be attributed to the overheating that may occur within the cavity and lead to more convective and conductive heat transfer to the occupiable spaces thus raising the total cooling energy demand. A similar observation was also reported by Wang et al. (2021). The answer to this very question is further investigated downstream in the report by understanding the temperature profiles for the three cases.

Building case/Thermal simulation parameters	Total annual cooling energy (kWh)	Total annual solar gains (kWh) through exterior windows	Cooling energy consumption (kWh/m ² /year)	Total annual solar gains to indoor conditioned spaces (kWh)
Base case	5,415,831.10	2,117,563.10	241.78	2,117,563.10
External shading case	4,917,278.30	1,576,710.90	219.52	1,576,710.90
DSF case	5,495,538.00	1,690,906.90	245.34	115,192.04

Table 12: Annual simulations comparison between the three cases (Author 2021)

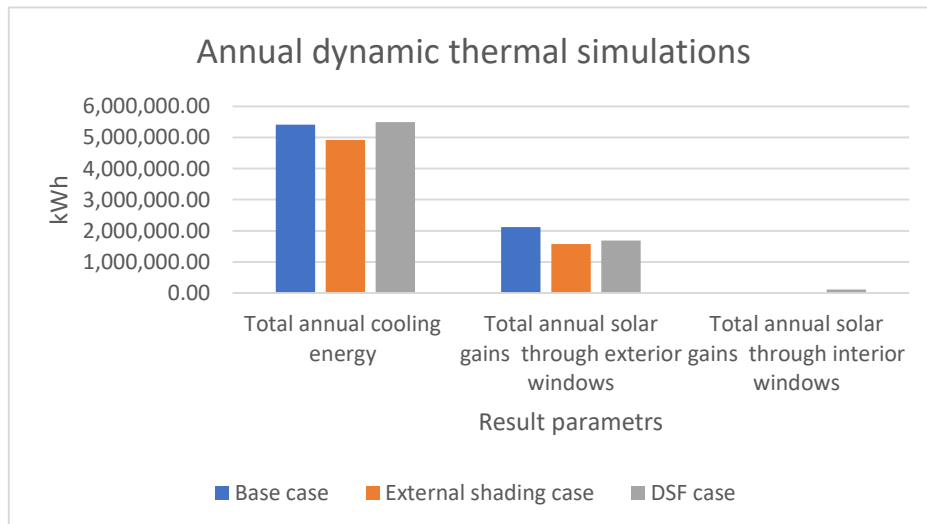


Figure 64: Graphical representation of the annual dynamic thermal simulation results (Author 2021)

Table 13, Figure 65 & 66 represent the total cooling energy for all the three cases along a month-wise distribution. The maximum value is 6, 16, 742.7 kWh occurring with the base

case in the month of July. The least amount of total cooling energy is seen with the external shading case in the month of February accounting to 2,70,700 kWh. Looking the individual trends, the base case and external shading case have a gradual upward trend until the month of July and tends to have downward curve from July until December. On the other hand, for the DSF case there is a upward trend till May, followed by a decrease in June and then an increase in July. The percentage of cooling energy savings depicted by the external shading case with respect to the base case is 9.2%. On the other hand, the DSF case depicts a 1.42 % jump in the annual cooling energy as compared to the base case.

Month/Cases	Base case	External shading case	DSF case
January	309420.9	271859.4	352712.1
February	313445.1	270700	349025.3
March	361843.4	317982.7	367426.9
April	413551.1	370640.9	437019.3
May	505351.5	466011.7	522327.3
June	505040.9	469402	496551.8
July	616742.7	575044.4	599401.9
August	574879.8	535131.3	563975
September	544231.4	495708.3	527924.9
October	520806.3	468045.3	509274.2
November	415827.4	377388.4	406107
December	334690.6	299363.9	363792.3
Totals	5415831.1	4917278.3	5495538

Table 13: Monthly distribution of the total cooling energy – kWh for all cases (Author 2021)

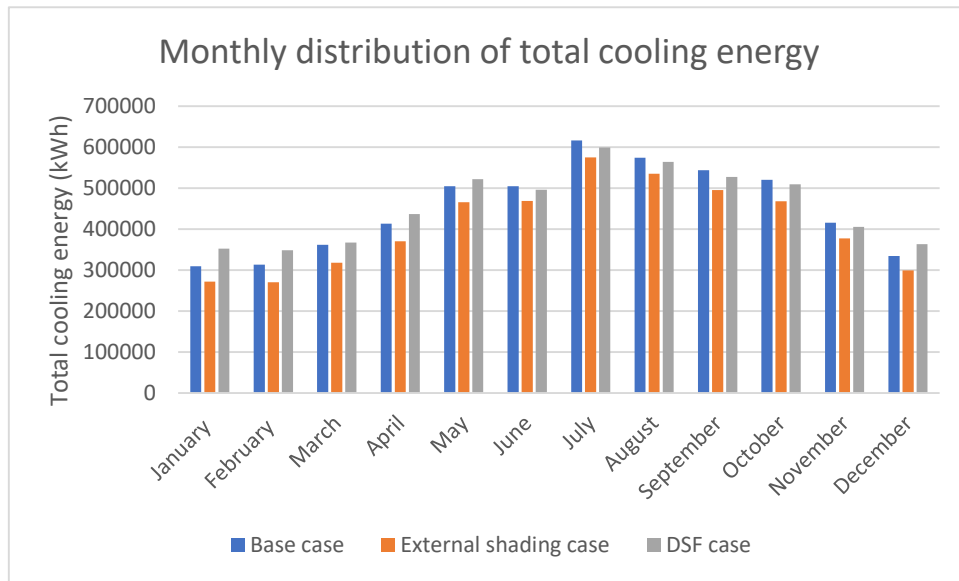


Figure 65: Graphical representation of the monthly cooling energy distribution for all three cases obtained from dynamic thermal simulations (Author 2021)

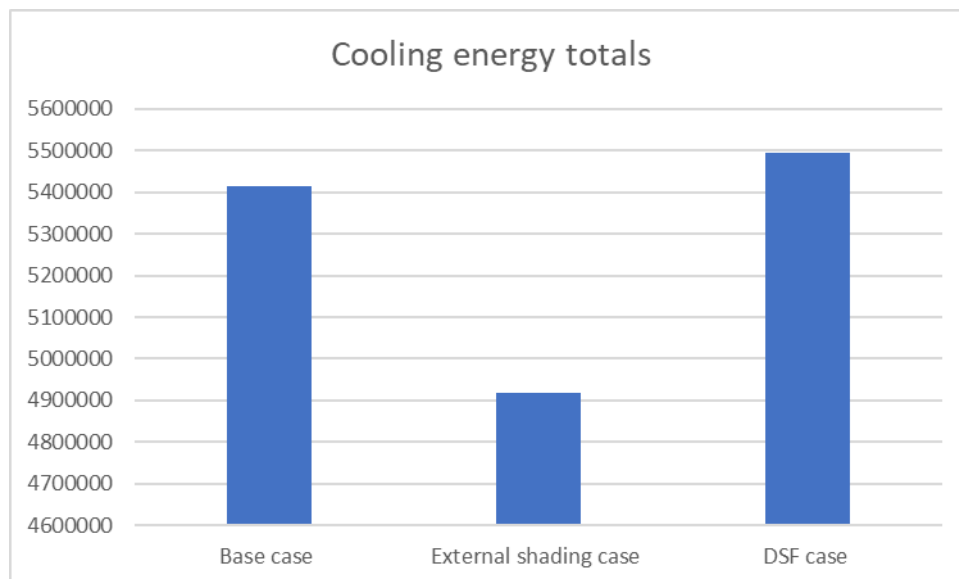


Figure 66: Cooling energy totals for each of the three cases obtained from dynamic thermal simulations (Author 2021)

Looking at the EUI's obtained for the three cases, it can be observed that the EUI for the DSF case is the highest with a value of 245.34 kWh/m²/year followed by the base case at 241.78 kWh/m²/year and 219.52 kWh/m²/year for the external shading case. Comparing the reported EUI's to the EUI's reported from the literature review, all EUI's are

closely comparable with the EUI of 263 kWh/m²/year reported by Johnny & Shanks (2018). The EUI's are also in close proximity to the ones reported by Shanks (2016). The EUI by (Touma & Ouahrani 2017) for the Qatar office case study seem to be very high when compared to the values obtained in this research.

Month/Cases	Base case	External shading case	DSF case
January	13.81	12.14	15.75
February	13.99	12.08	15.58
March	16.15	14.20	16.40
April	18.46	16.55	19.51
May	22.56	20.80	23.32
June	22.55	20.96	22.17
July	27.53	25.67	26.76
August	25.66	23.89	25.18
September	24.30	22.13	23.57
October	23.25	20.89	22.74
November	18.56	16.85	18.13
December	14.94	13.36	16.24
Totals	241.78	219.52	245.34

Table 14: Table of monthly EUI's obtained from dynamic thermal simulations (Author 2021)

Table 14 gives a glimpse of the monthly EUI's for all the three cases. The maximum EUI was observed for the base case in the month of July and minimum EUI was observed for the external shading case in the month of February. Table 15 and Figure 67 represents the solar gain values for all the three cases along the months of the year. The highest value of the solar gains is with the base case in the month of October and least value of solar gains is with DSF case in the month of September. Figure 68 indicates the total of the solar gains for all the three cases. The trends depicted by the solar gains is quite different from what was observed for the total cooling energy. The base case has a slightly variable downward trend until July and starts to increase after that. For the external shading case there is a gradual decrease until May and starts to rise up again after September. The DSF almost receives a steady value of solar gains with an average value of 9,599 kWh.

Month/Cases	Base case	External shading case	DSF case
January	182819.3	141955	10381.26
February	183686.5	136568.8	9891.18
March	175316	124793.1	8933.119
April	166487.4	122542.1	8973.42
May	176281.2	133451.9	9922.979
June	169878.3	128159.6	9495.875
July	168620.4	127245	9435.89
August	168528	125192.7	9269.194
September	172437.6	120322.1	8639.681
October	191888	135770.2	9724.703
November	183339.9	139956.1	10200.79
December	178280.5	140754.3	10323.95
Totals	2117563.1	1576710.9	115192.041

Table 15: Month wise solar gains - kWh distribution for all three cases obtained from dynamic thermal simulations (Author 2021)

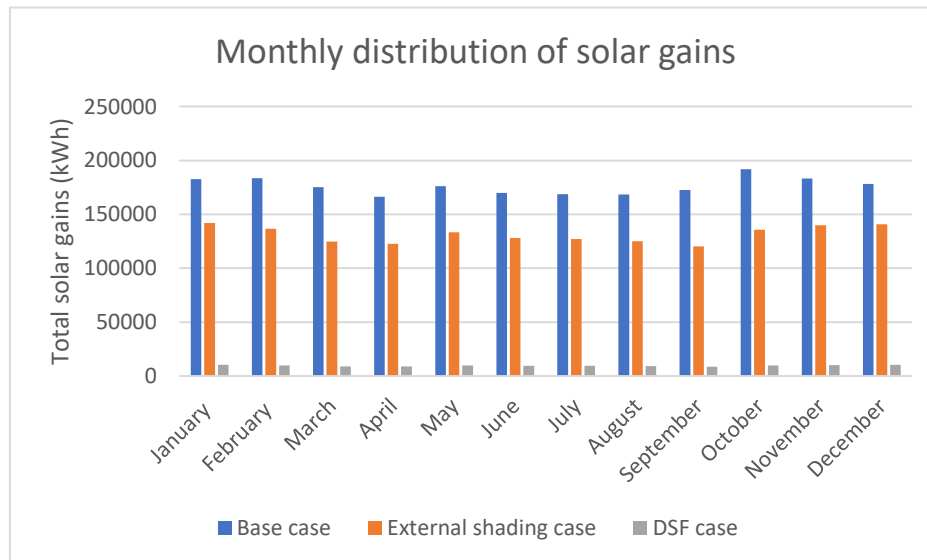


Figure 67: Graphical representation of the month wise solar gains from dynamic thermal simulations (Author 2021)

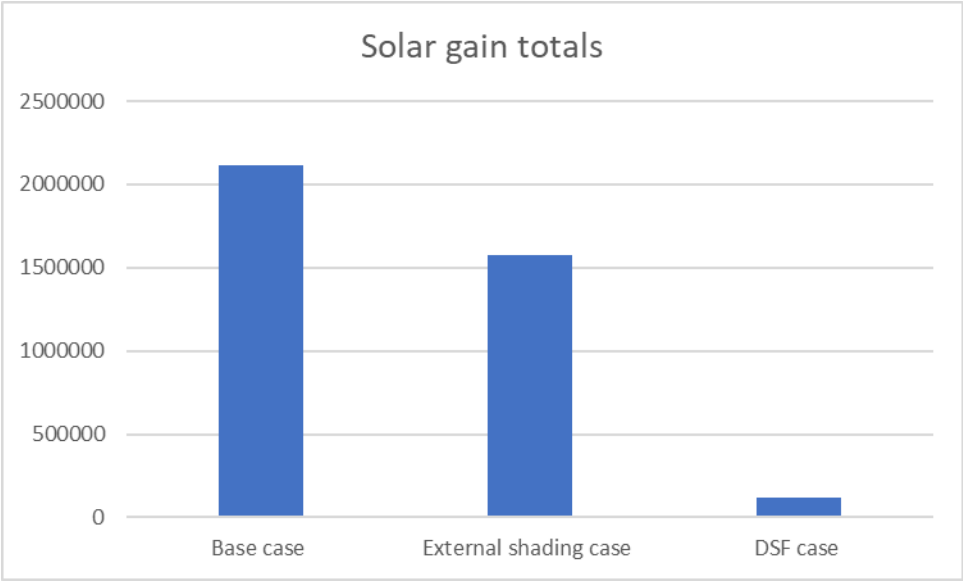


Figure 68: Solar gain totals - kWh (Author 2021)

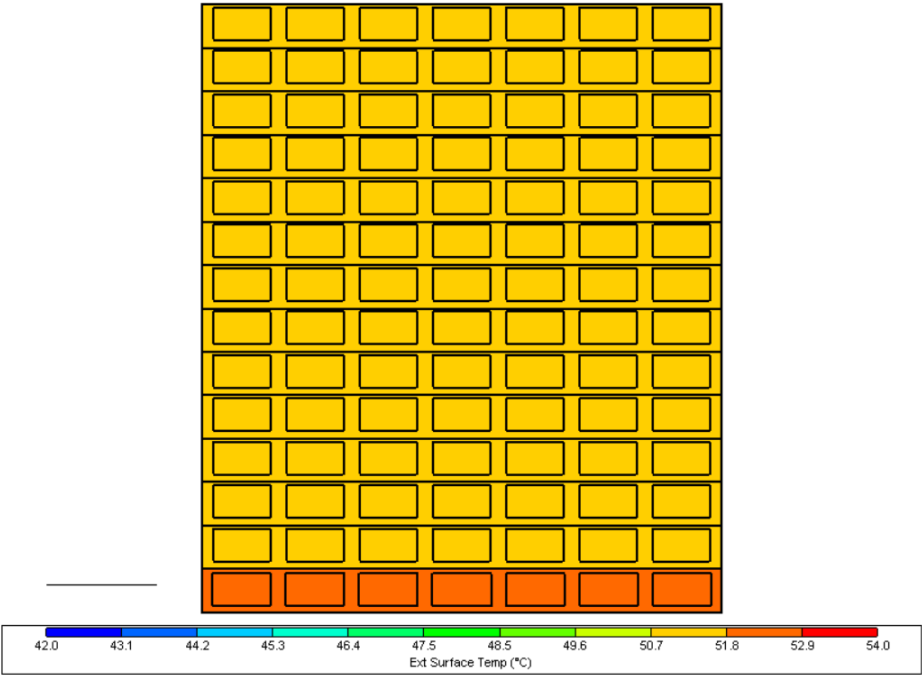


Figure 69: West orientation external surface temperature profile for the base case at the design hour from dynamic thermal simulations (Design Builder 2021)

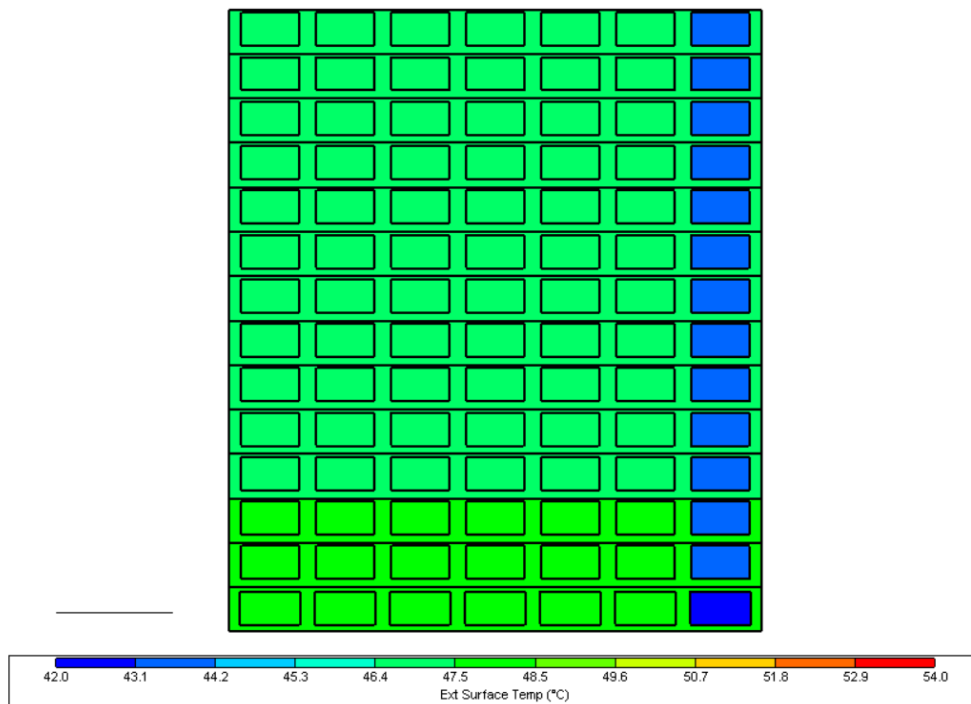


Figure 70: West orientation temperature profile for the external shading case at the design hour from dynamic thermal simulations (Design Builder 2021)

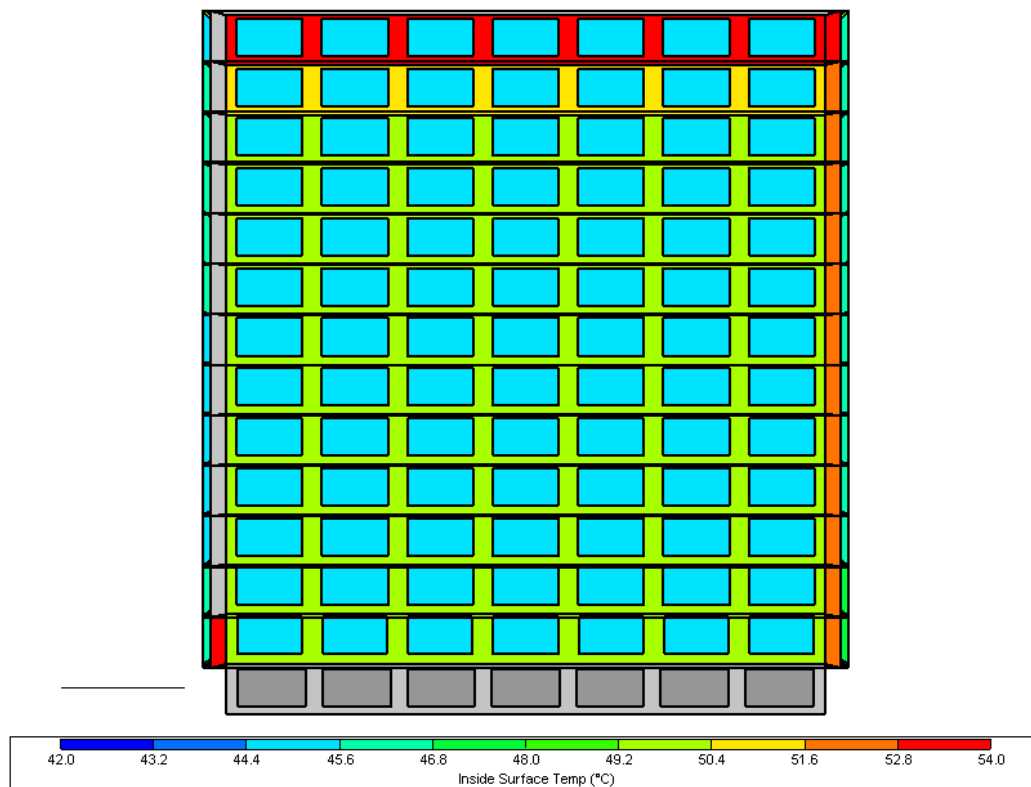


Figure 71: West orientation temperature profile for the DSF inner skin from dynamic thermal simulations (Design Builder 2021)

The surface temperature profiles for all the three cases are indicated from Figure 69– Figure 71. All the temperature comparisons are indicated on a similar temperature scale to have a clear comparison. The temperature profiles of the base case and the external shading case are very straight forward and not much happening in terms of the temperature variation along the height of the surface. The reported temperatures for the base case is 52 deg. C in the ground floor whereas in the upper floors it is 51 deg. C. Looking at the surface temperatures of the external shading case, it can be seen that the windows on the right side of the west façade are at lower temperatures (about 42 deg. C) from the rest of the surface. The first three floors are at 49 deg. C and the remainder of the floors are at 47 deg. C.

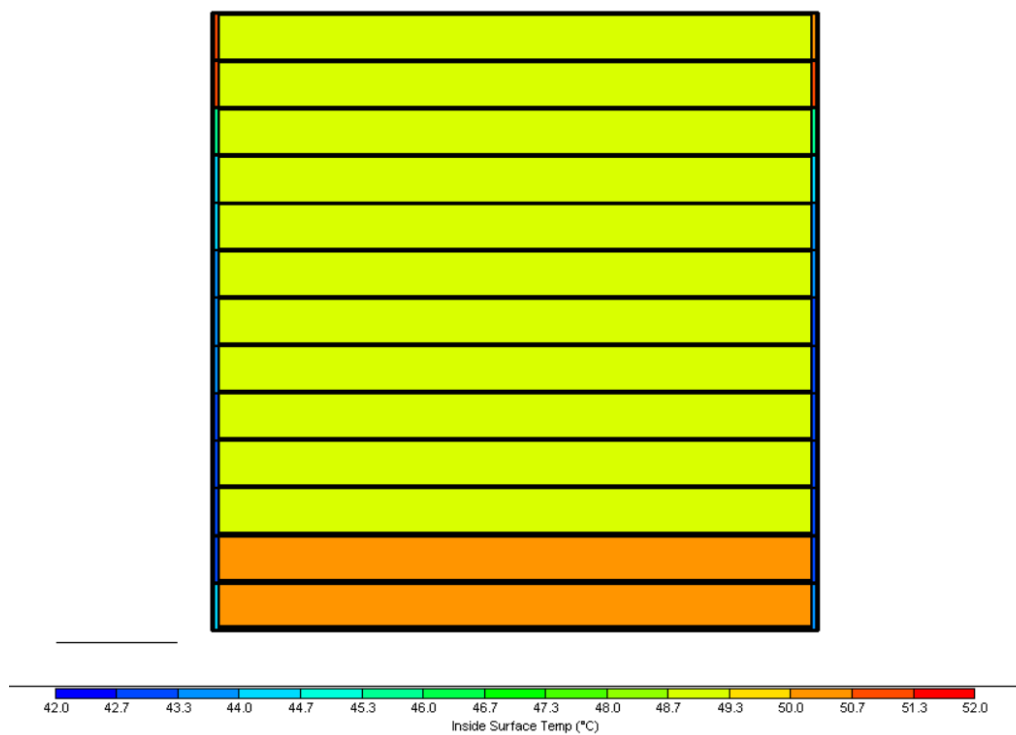


Figure 72: Surface temperature of the inner side of the outer skin from dynamic thermal simulations (Design Builder 2021)

There is a quite a complex temperature profile for the DSF inner skin wherein it can be seen that all the window surfaces are a uniform temperature of 45 deg. C. The wall between the glazing surfaces is at 50 deg. C. The upper most floor is at the highest temperature of 54 deg. C. The right edge of the DSF is at 52 deg. C which is most probably due to the sun's position at the design hour. Comparing to the temperature values to that reported by Kim (2021) which is 27 deg. C with the 20% of openings and 1.2m cavity depth. A correlation could not be drawn here because of the fact the exact simulation time employed by Kim (2021) is

not known. Additionally, it is worth observing the surface temperatures of the inner side of the outer skin of the DSF (Figure 72). The temperature values at the lower end of the outer skin are at 50.5 deg. C and the at the upper floors it is at 49 deg. C.

The next portion of the dynamic thermal simulations consisted of the bulk airflow results which were confined only to the DSF case. As can be seen in Figure 73, the direction of the airflow is from the bottom to the top of the DSF. Table 16 indicates the airflow values through the inlet and outlet of the DSF. When running the dynamic thermal simulations, no infiltration scenario was assumed and airflow through the cracks was also disabled. Although these settings were implemented there is a mismatch between the inlet and outlet flows accounting for 1.27 m³/s. This bulk airflow analysis was mainly carried out to determine the velocities inside the DSF cavity by the aid of dynamic thermal simulations. The velocities were obtained by dividing the inlet and outlet flowrates with the area of the inlets and the outlets respectively. The area of the inlet and the outlet are the same which is 40 sq. m. Therefore, the inlet velocity comes out to be 0.64 m/s and the outlet velocity is 0.68 m/s. Comparing these values with that reported in the literature review section: Kim (2021) reported an average velocity of 0.12 m/s in the DSF cavity. Radhi et al. (2013) reported values of 1.4 m/s (at 0.5 m in the DSF), 0.54 m/s (at 2.2 m), 0.44 m/s (at 6.8 m), 1.88 m/s (at 10.8 m). But it is important to understand the velocity values calculated here do not give an indication of the average velocity within the DSF and just the inlet and outlet velocities.

Particulars	West zone DSF cavity airflow on 24 th July at 2 PM – L/s	Flow in m ³ /s	Average velocity (m/s)
Airflow In	25,768.70	25.77	= 25.77/40 = 0.64 m/s
Airflow out	27,039.20	27.03	= 27.03/40 = 0.68 m/s
Difference in the airflow between inlet and outlet	1270.5	1.27	-

Table 16: Bulk airflow results (Author 2021)

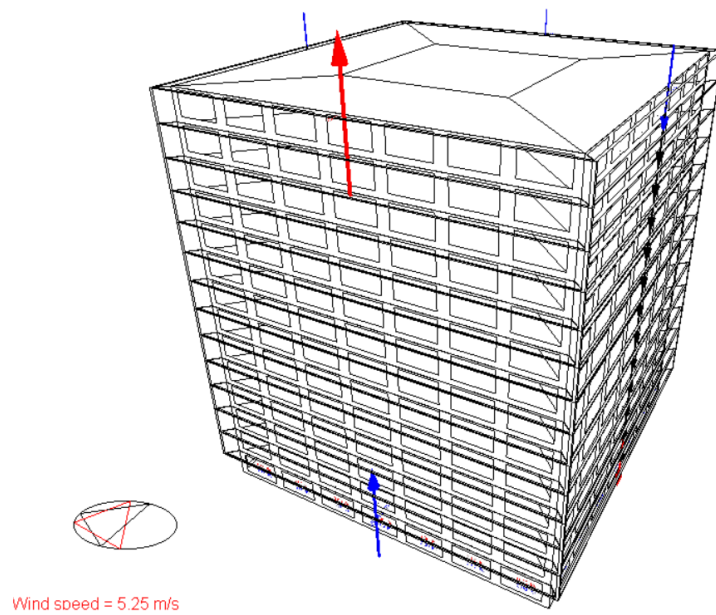


Figure 73: Bulk airflow direction for west orientation at 2 PM
(Design Builder 2021)

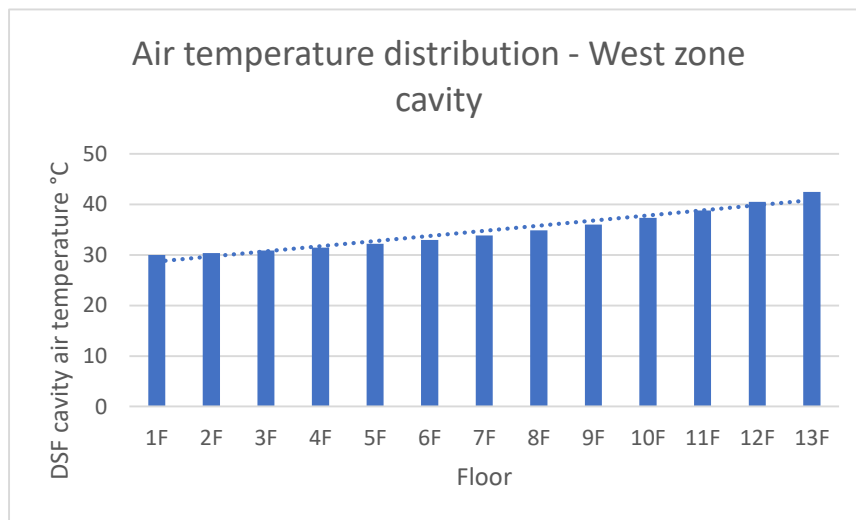


Figure 74: Air temperature distribution of the west zone cavity from dynamic thermal simulations at 2 PM on 24th July (Author 2021)

Figure 74 depicts the air temperature distribution along the height of the DSF and these results are derived from the dynamic thermal simulations. It can be observed that as we go up the floors, the temperature tends to have a gradual increment until the outlet of the DSF. Figure 75 – Figure 77, indicates the temperature profile inside the west zone DSF cavity

throughout the day along the height of the DSF. It is clear from the graphs that from 1 AM to 7 AM, the temperature variation along the height of the DSF is not significant with only 2 deg. C variation among the levels. It is from 8 AM that the variation in air temperature starts to increase gradually with time increments (that is exceeding the 2 deg. C difference). From 8 AM until 11 AM, the temperatures of the lower floors are higher as compared to the temperatures of upper floors, indicating a downward trend as we move the height of the DFS cavity. From 12 PM until 4 PM, the trend reverses and now the upper zones are at a higher temperature than the lower zones. From 5 PM, this trend starts to change again, similar to the one that was observed from 8 AM until 11 AM. From 9 PM until midnight the temperature variation among the various floors of the cavity is insignificant and within a threshold of 2 deg. C, similar to what was observed from 1 AM – 7AM.

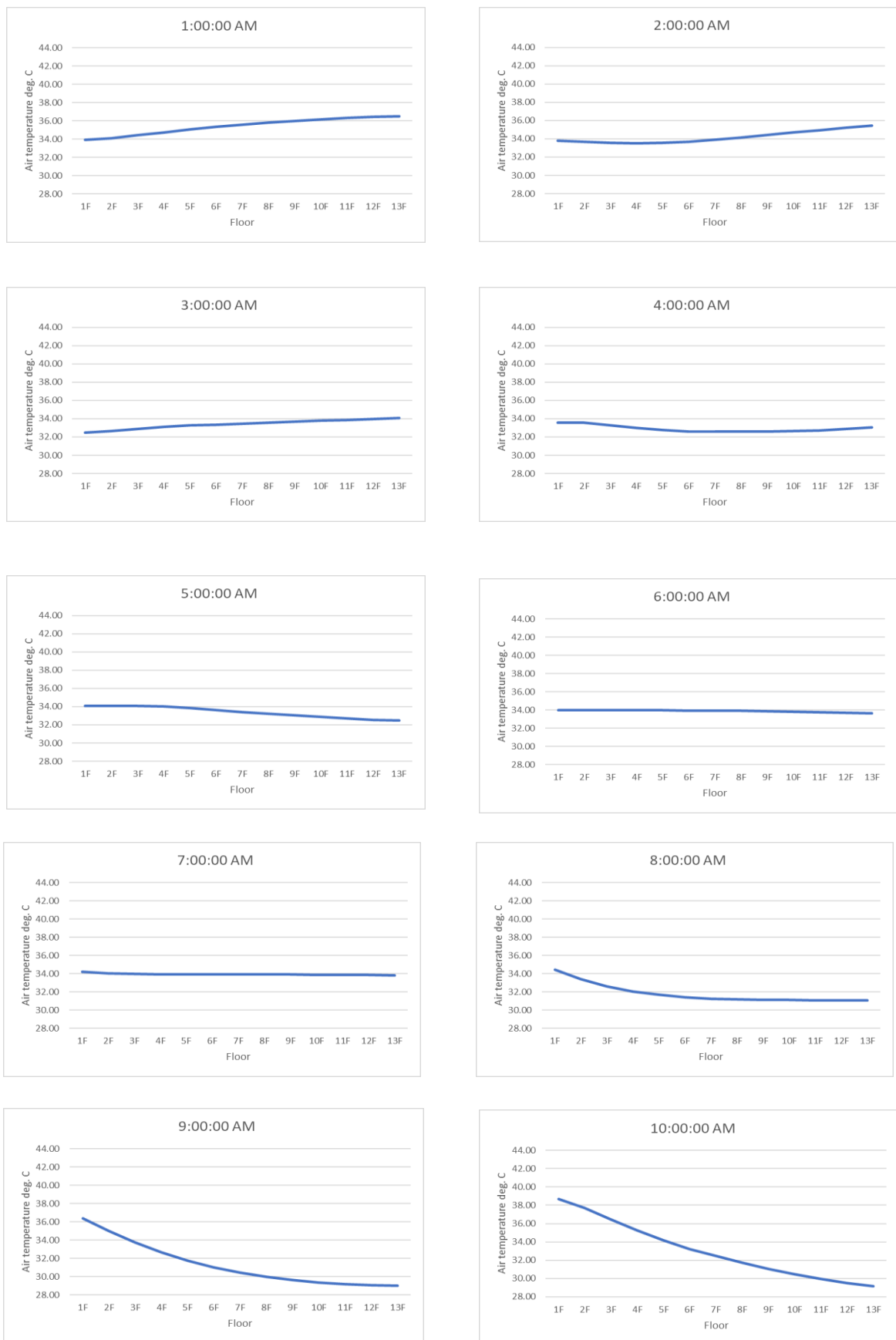


Figure 75: Air temperature values in west zone DSF cavity throughout the day from dynamic thermal dynamic thermal simulations (Design Builder 2021)

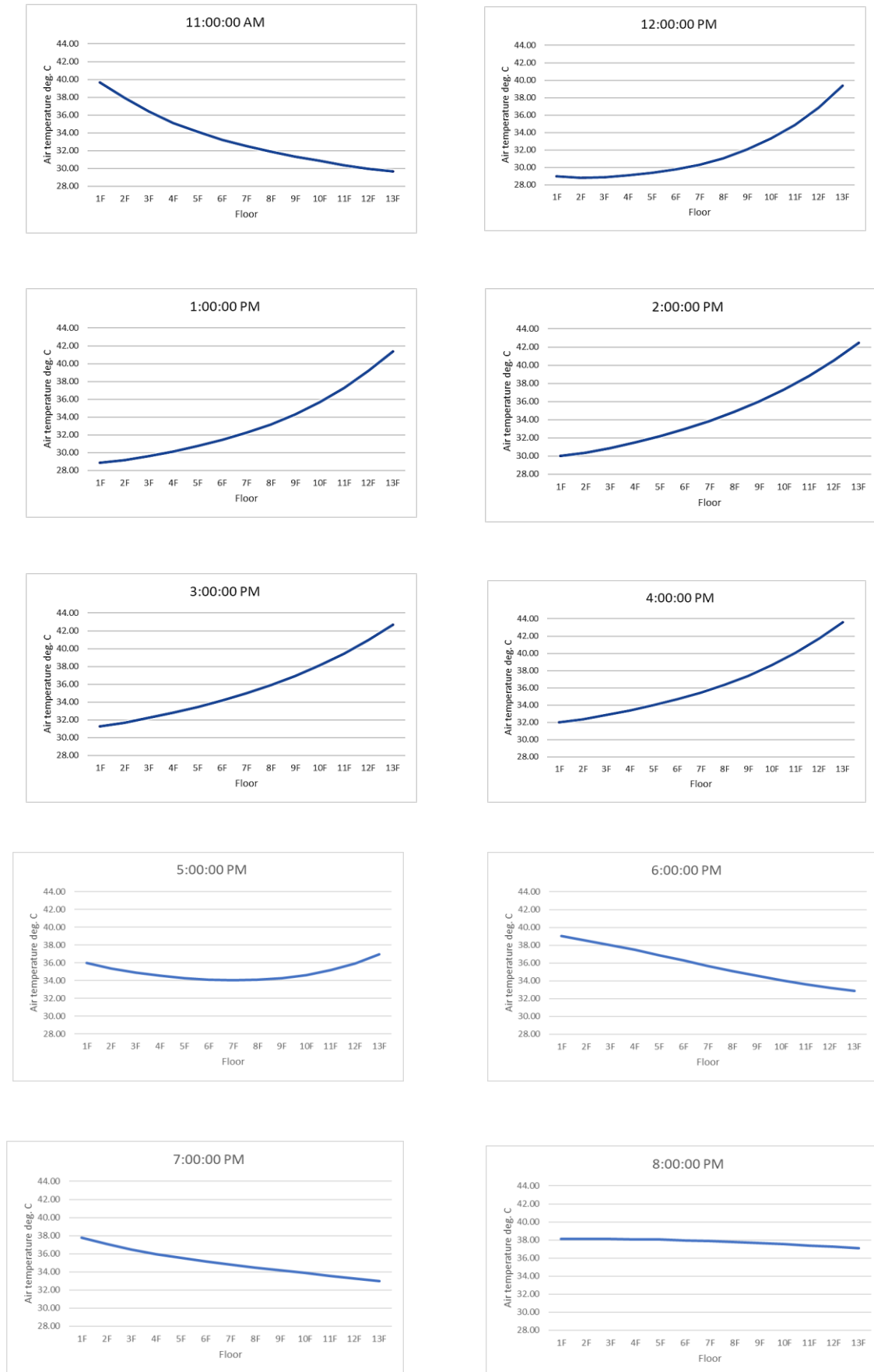


Figure 76: Air temperature values in west zone DSF cavity throughout the day from dynamic thermal dynamic thermal simulations (Design Builder 2021)

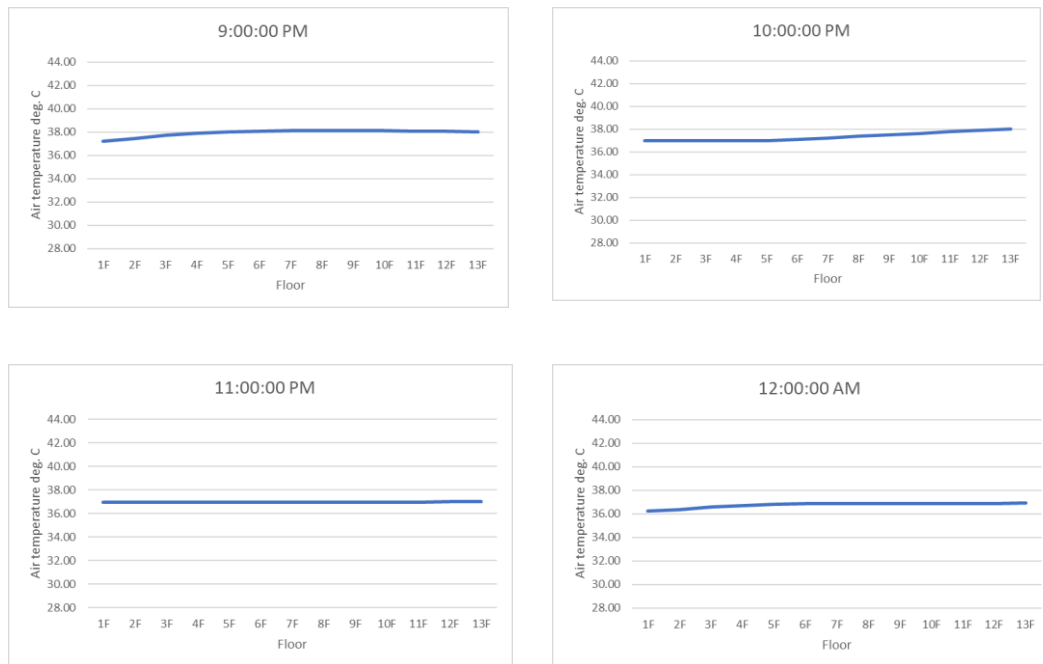


Figure 77: Air temperature values in west zone DSF cavity throughout the day from dynamic thermal simulations (Design Builder 2021)

4.2. DSF Cavity Internal CFD analysis

Following the dynamic thermal simulations, internal CFD simulations were performed for the DSF case thereby deriving the temperature profiles, velocity profiles and the airflow behaviour within the cavity. Figure 78 indicates the temperature profile of the inner skin of the DSF. It can be easily observed that there isn't much difference over the temperature values throughout the height of the DSF. All the window surfaces seem to be at a constant temperature of 49 deg. C. At the lower part of the DSF indicated by the yellow patches, the temperature is around 45 deg. C. Figure 79 depicts a close up of the inner skin of the DSF indicating that there is slight dip in the temperature between the glazing surfaces. The possible reason could be the intermediate flooring between the DFS cavity at different levels. It is worth noting that the flooring is also part of the flooring of the occupiable spaces and since the temperature in the occupiable spaces is regulated at specific setpoints, this could be the probable justification for the temperature dip. Further, it needs to be noted that the modelling of the DSF in the DesignBuilder software has been done by generating holes in the intermediate floors and the whole area of the floor could not be created as hole and therefore some residue of flooring is left in the DSF zone levels. Basically, some part of the flooring is also part of the DSF cavity (Figure 80). Figure 82 represents the slice of the DSF

from the centre of the of the cavity that is at 0.5m thus indicating the air temperatures inside the cavity. It can be noted that the temperature of 46 deg. C is a constant throughout the height of the cavity. Figure 81 depicts the temperature profile of the inner side of the outer skin of the DSF and it shall be noted that the temperature is 45 deg. C at the lower floors, 46 deg. C at the upper floors and the edges are at 48 deg. C.

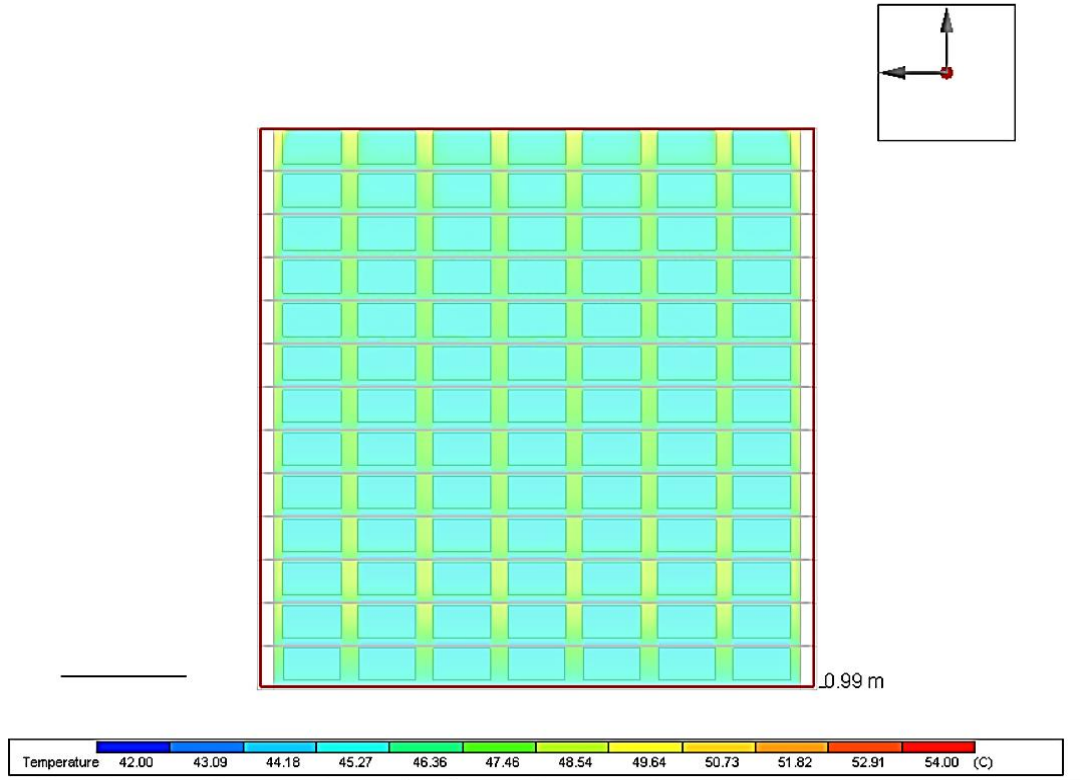


Figure 78: Temperature of the inside surface of the DSF from the CFD simulations (Design Builder 2021)

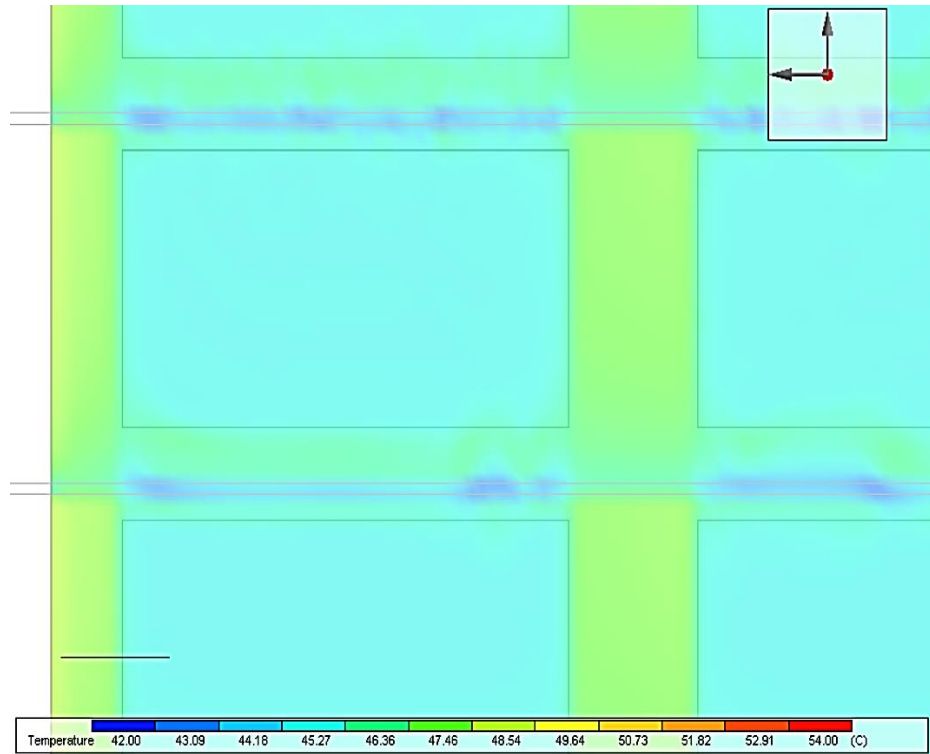


Figure 79: Close up of the surface temperature profile of the inner skin of DSF cavity from CFD simulations (Design Builder 2021)

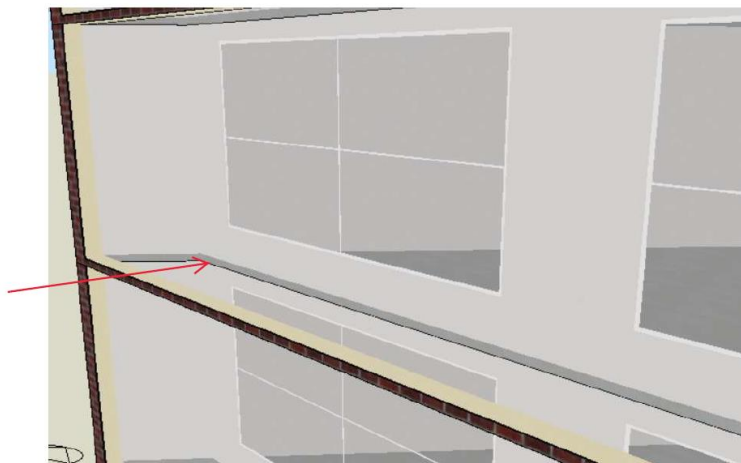


Figure 80: Perspective of the DSF zone show intermediate flooring between the floors (Design Builder 2021)

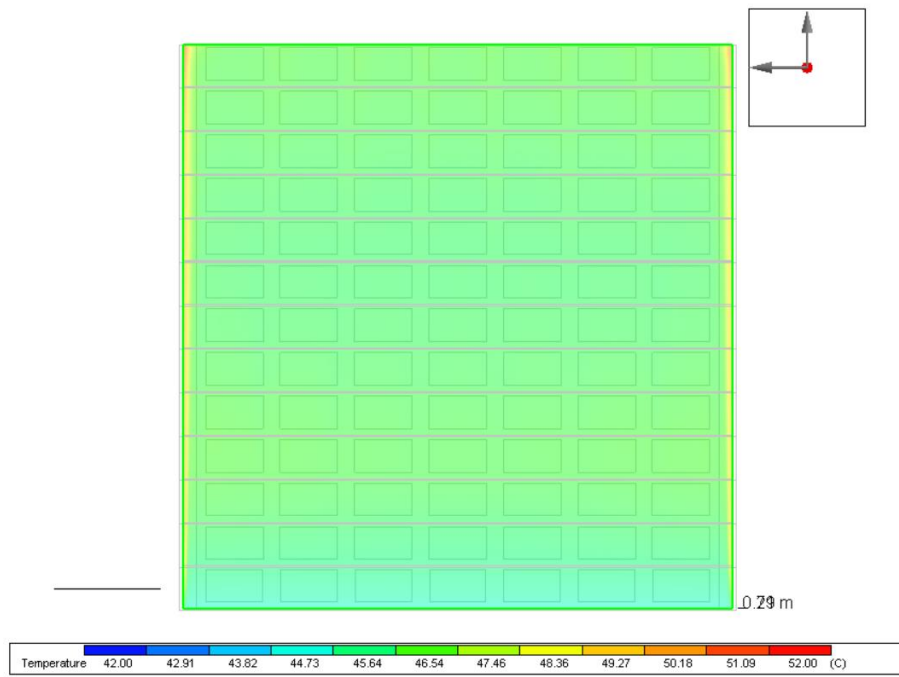


Figure 81: Surface temperatures of the inner side of the outer skin of the DSF from CFD simulations (Design Builder 2021)

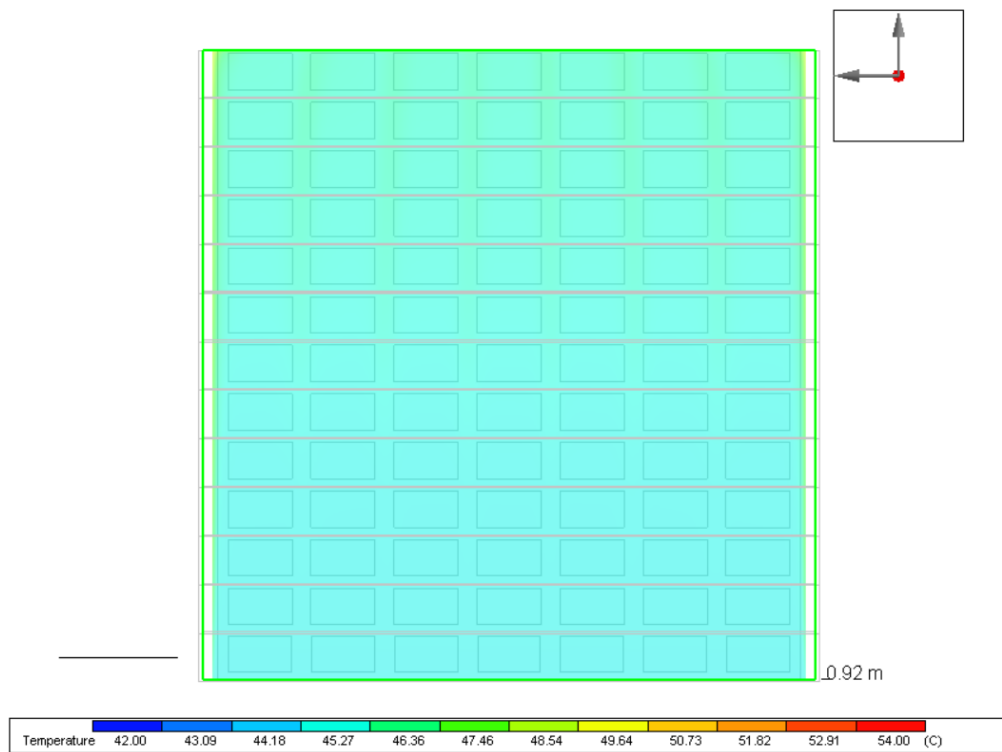


Figure 82: Slice from the DSF cavity from center of the cavity (0.5m) from the CFD simulations (Design Builder 2021)

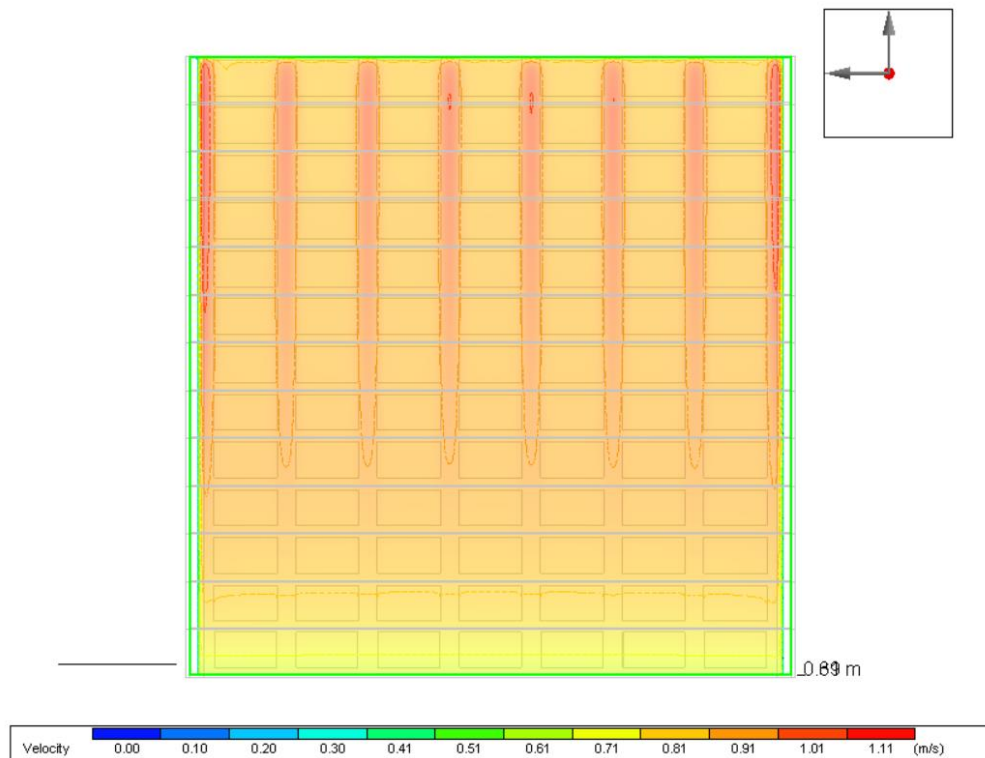


Figure 83: Velocity contours from obtained from internal CFD simulations for a slice in the middle of the DSF cavity (Design Builder 2021)

As can be seen in Figure 83, velocity values gradually increase from the bottom of the cavity as we move up the cavity. The lowest velocity value of 0.71 m/s is noticed at the bottom of the cavity. The transitioning of the velocity happens from the 0.71 m/s to a higher value of 0.81 m/s after the second floor. It is interesting to see vertical plumes in between the window columns showcasing a velocity of 1.01 m/s. Figures 84 – 86 show the vertical slice of the velocity contours and associated zoomed in images. They represent similar velocity profiles as the horizontal slice (Figure 83).

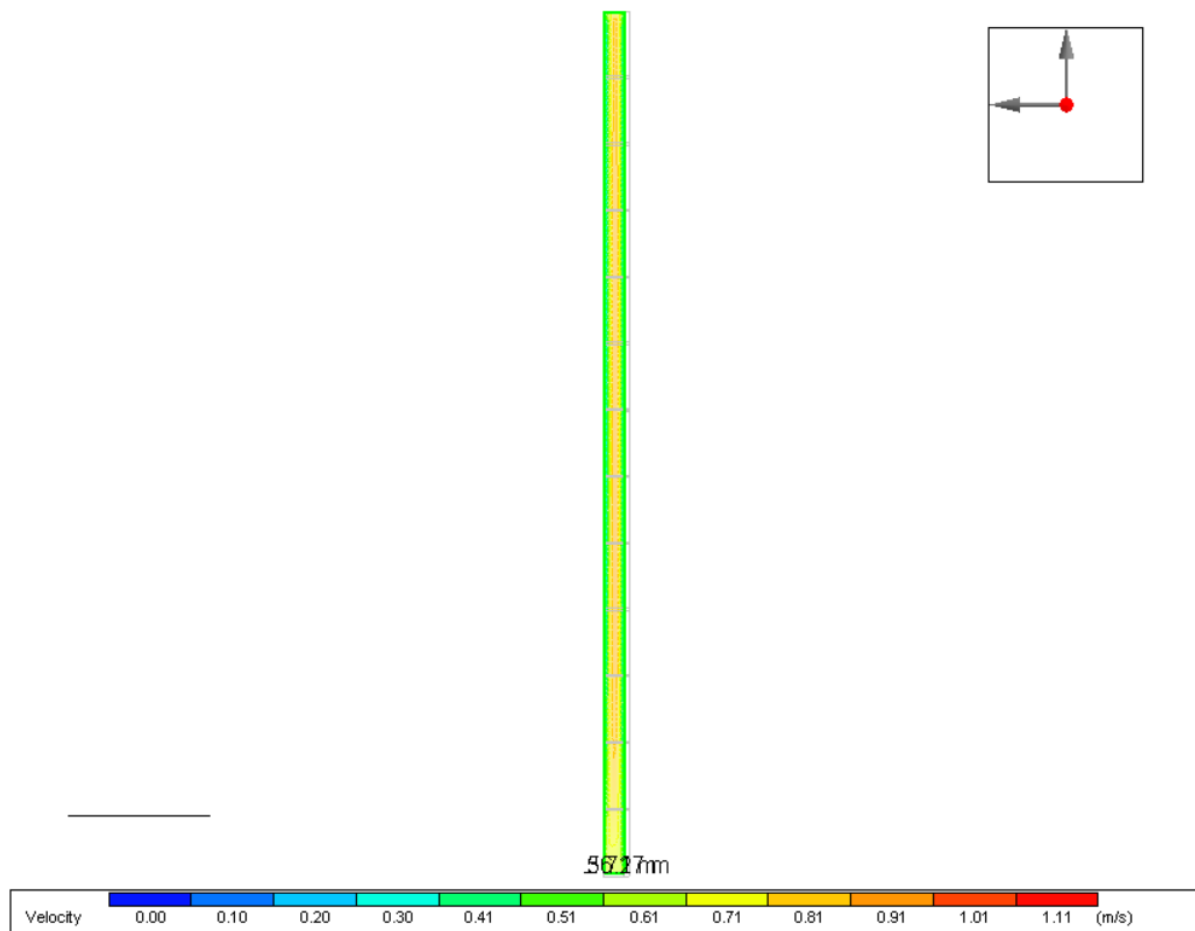


Figure 84: Vertical slice of velocity contours from the middle of the cavity from internal CFD simulations (Design Builder 2021)

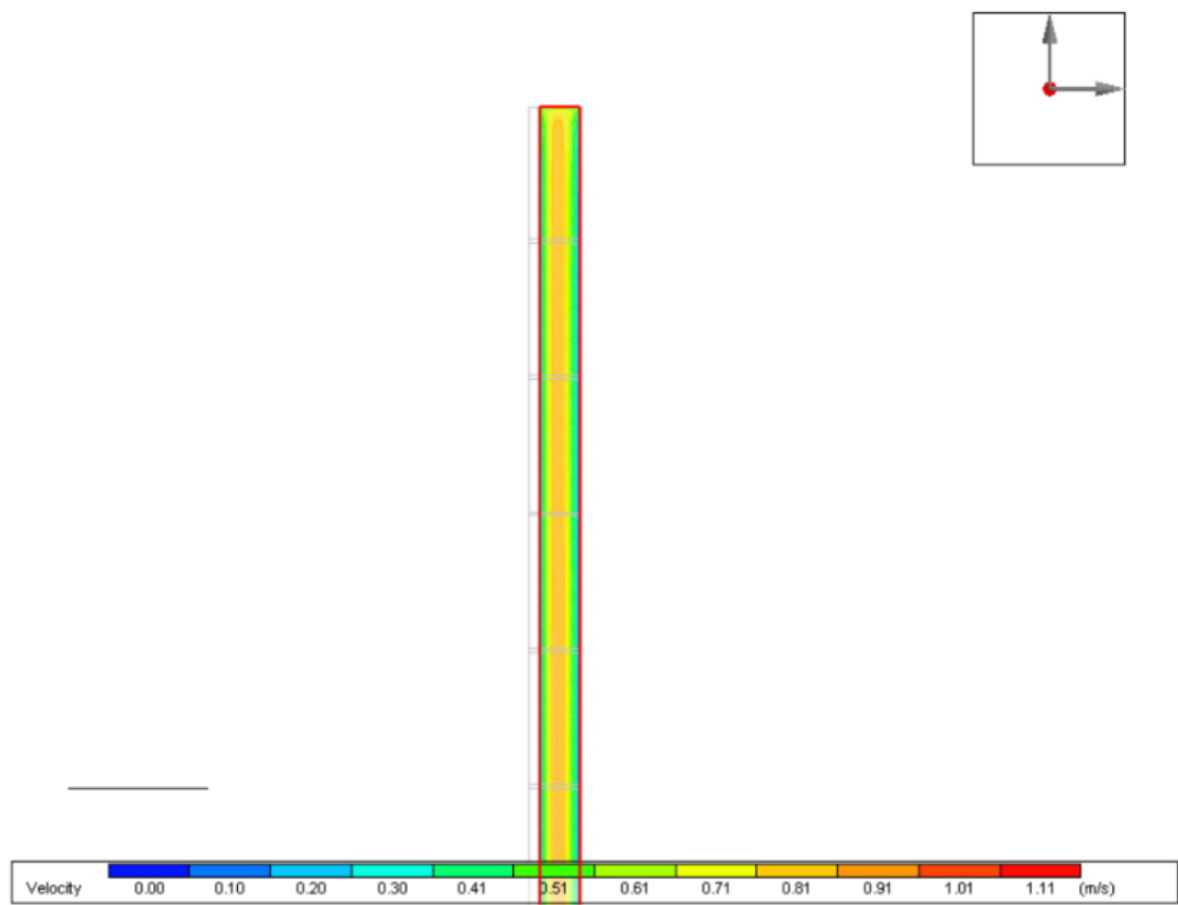


Figure 85: Zoomed in image of the velocity contours from internal CFD simulations for the upper floors of the cavity (Design Builder 2021)

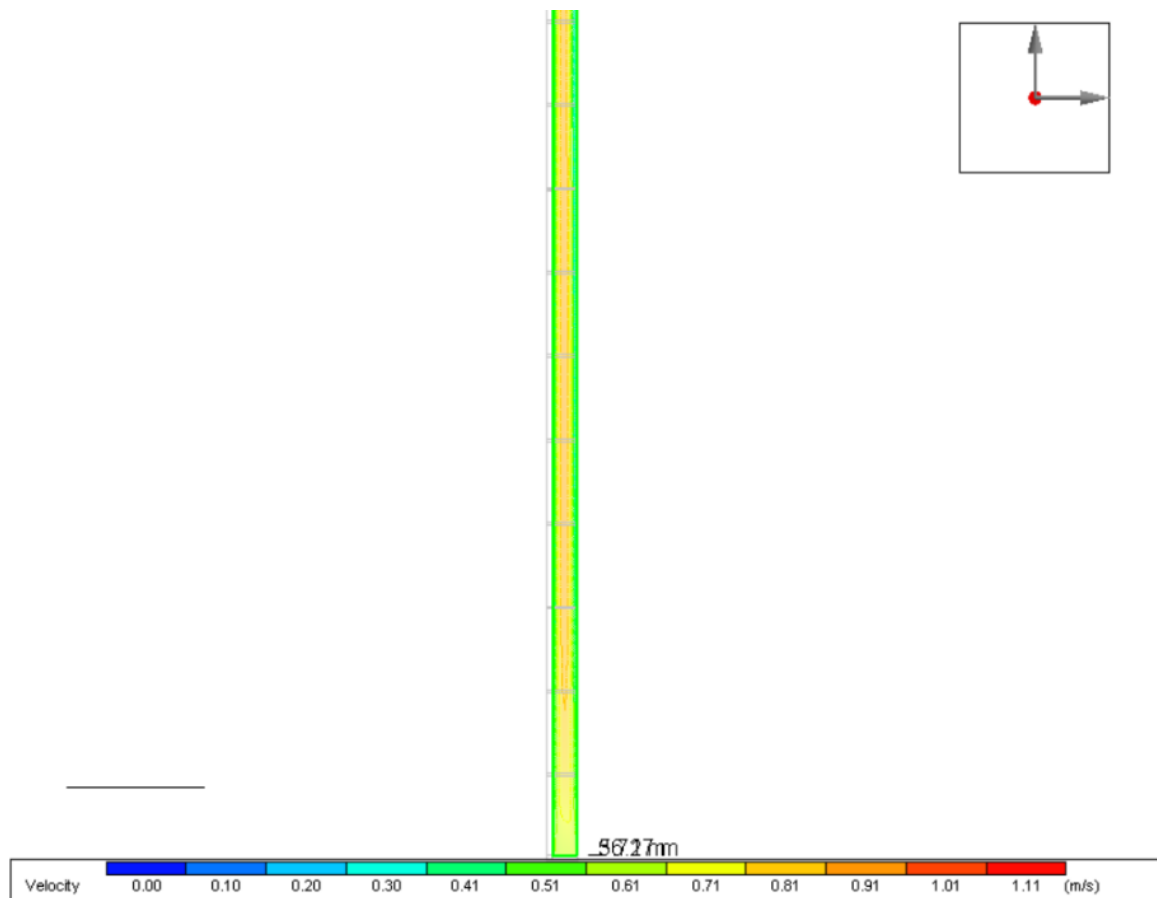


Figure 86: Zoomed in image of the velocity contours from internal CFD simulations for the lower floors of the cavity (Design Builder 2021)

4.3. Sensitivity analysis for CFD simulations

The first set of the internal CFD simulations were run for a period of 14,000 iterations (Figure 87) and using the k-e turbulence model. The boundary conditions for running the CFD analysis were imported from the dynamic thermal simulation results. It was necessary to ensure that the airflow was balanced between the inlet and outlet in order to start the CFD simulations. It is worth noting that the original intended building of 30 floors was facing issues with the CFD tool in the DesignBuilder software, wherein the simulations would run for 1000 iterations before the software would crash. It was assumed that either the CFD simulator could not handle the complex airflow that was generated in the 30-storey high DSF cavity or the available hardware resources were incapable to handle the load of the high intensity simulations. Since, the CFD simulations were quite time expensive taking about 36

hours to perform 1000 iterations, it was decided to move on with a similar category building that would still be a high-rise tower and would accelerate and make the study simple. Therefore, a model of 13 storeys was considered with the same floor area as was considered for the original model of 30 floors.

As can be seen from the residual monitors (Figure 87) for the initial CFD simulations there was a very erratic behaviour of the variables and it was taking significant amount of to complete these simulations and without any convergence. Hence it was decided to run a sensitivity analysis for the CFD simulations by varying the false time steps and also by using the other turbulence model available within DesignBuilder that is the constant viscosity turbulence model. The initial CFD simulations were set up with default false time step of 10 and employed the k-e turbulence model. It is also worth noting that the termination residuals settings were modified in order to make the variables converge faster.

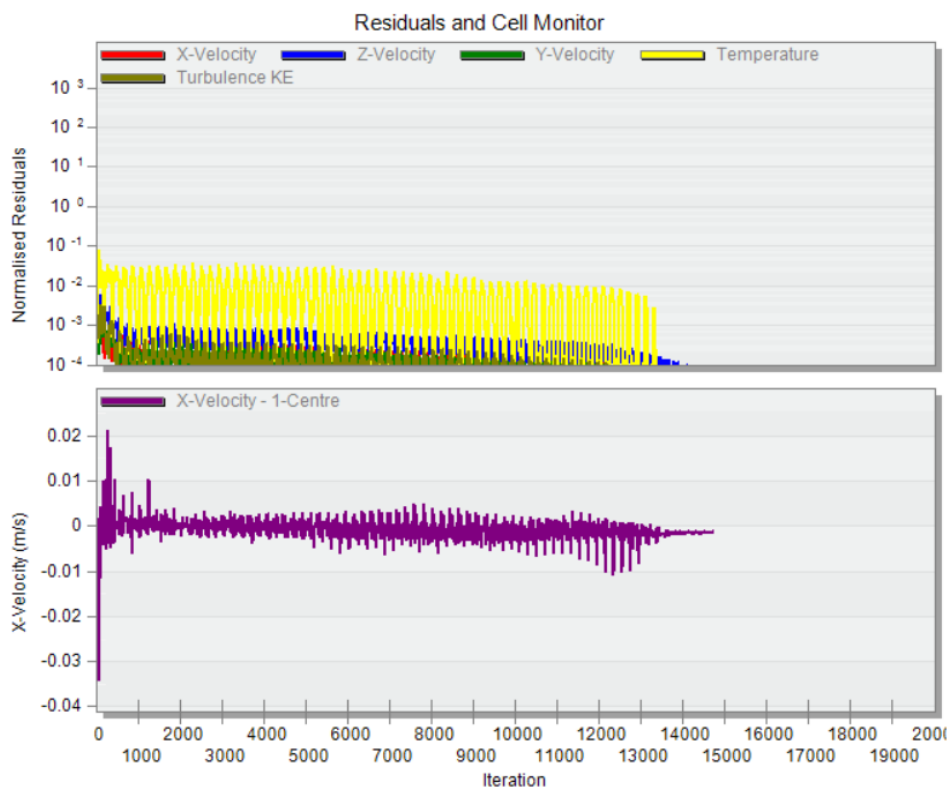


Figure 87: Residual monitors for initial CFD simulations (Design Builder 2021)

Before we discuss the intricacies of the sensitivity analysis, it is important to get hold of the basic idea of the CFD simulation settings that were varied as part of this sensitivity analysis. The basic mathematical difference between the constant effective viscosity turbulence model and the k-e turbulence model is that the former uses a constant effective viscosity value to perform the iterations and the latter uses the effective viscosity value in between the simulation iterations. For this reason, the constant effective viscosity turbulence model is less expensive computationally and the k-e is more complex making it very time consuming in terms of the simulations (DesignBuilder Help V7 2021). Also, the results of the constant effective viscosity turbulence model stabilise much faster than the k-e turbulence model. The sensitivity analysis discussed further clearly highlights this difference.

It is well understood that the CFD calculations are taking place for a particular time determined by the requirement of the analysis in question. For example, the CFD simulations for this research analysis are on the design day (24th July) at 2 PM. Even though the simulations are for a particular snap of time it is formulated in a transient manner to arrive at a stable solution. That means the partial differential equations are available for a particular time but its calculation involves working the equation with incremental time steps known as pseudo time steps or more commonly known as the false time steps. This technique is also known as pseudo time stepping or pseudo-transient continuation. In simple terms, if a solver is specified to run for 10 seconds with a false time step of 0.1, then the solver starts to solve from 0 up to 10 seconds with increments of 0.1s. The reduction in the false time step has the effect of slowing down the change in the dependent variable thus mitigating the risk of unsteady solutions. Thus, the effect of false time step is studied and discussed in the following text.

The first part of sensitivity analysis consisted of varying the false time step by keeping the turbulence model constant. Referring from Figure 88 – 91, representing the simulations for 3000 iterations with the k-e turbulence model and varying false time steps of 10, 5, 1 and 0.2. An initial glance gives the picture of erratic behaviour of the variables in all the four cases. The temperature oscillations represented in yellow seem similar for the false time step 10 and 5 and are similar for the false time step of 1 and 0.2. The oscillations are much narrower in case of time steps 10 and 5 and wider in case of time steps 1 and 0.2. It can be easily noticed that the turbulence residual has a spike in the case of false time step of 1. The x-velocity residual is quite similar in the case of false time step of 10, 5 and 1 and has

dampening effect as we move from false time step of 10,5 and then to 1. The unusual behaviour with the time step of 0.2 has much steeper oscillations covering up the range of values shown in the graph.

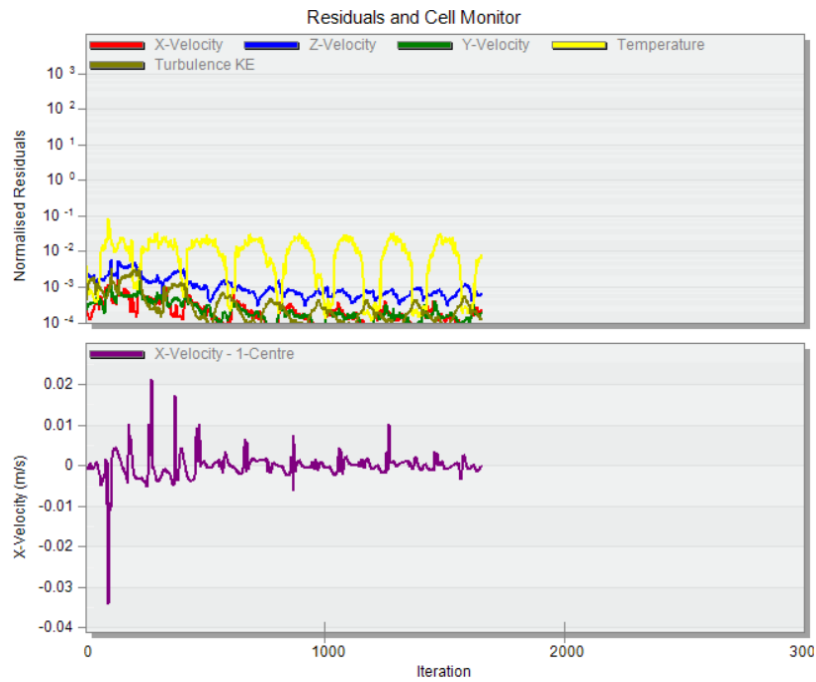


Figure 88: Residual graph of turbulence model k-e with false times steps of 10 (Design Builder 2021)

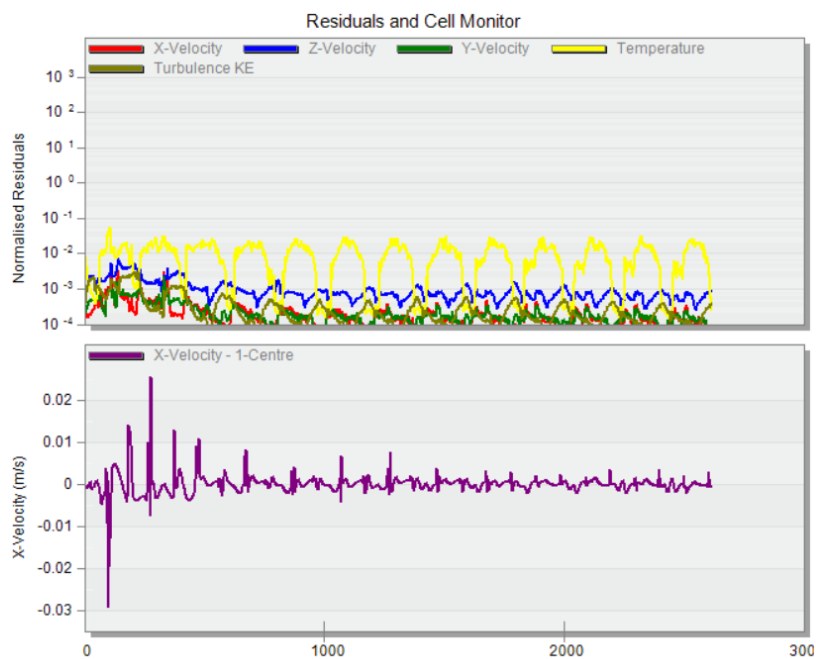


Figure 89: Residual graph of turbulence model with false time steps of 5 (Design Builder 2021)

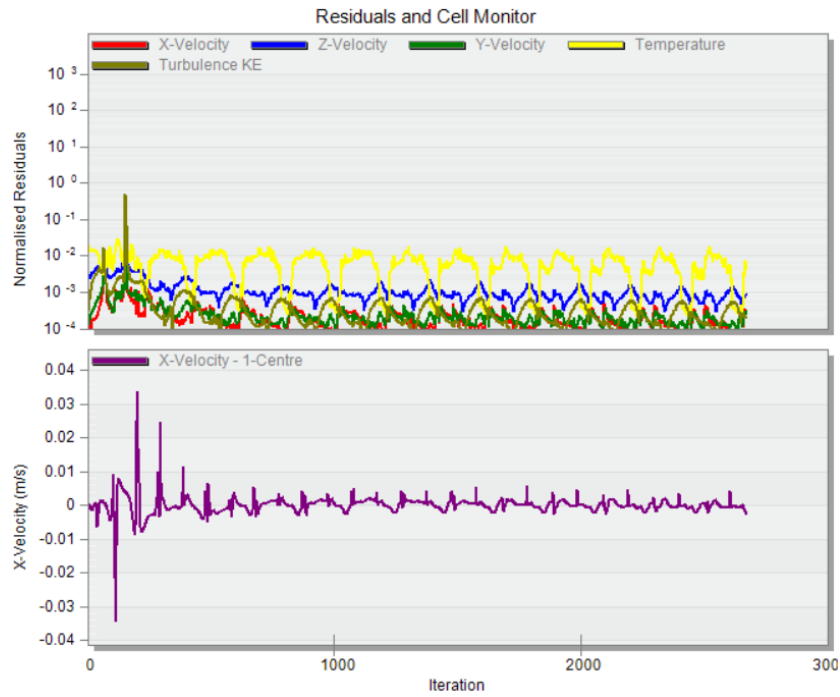


Figure 90: Residual graph of turbulence model with false time steps of 1 (Design Builder 2021)

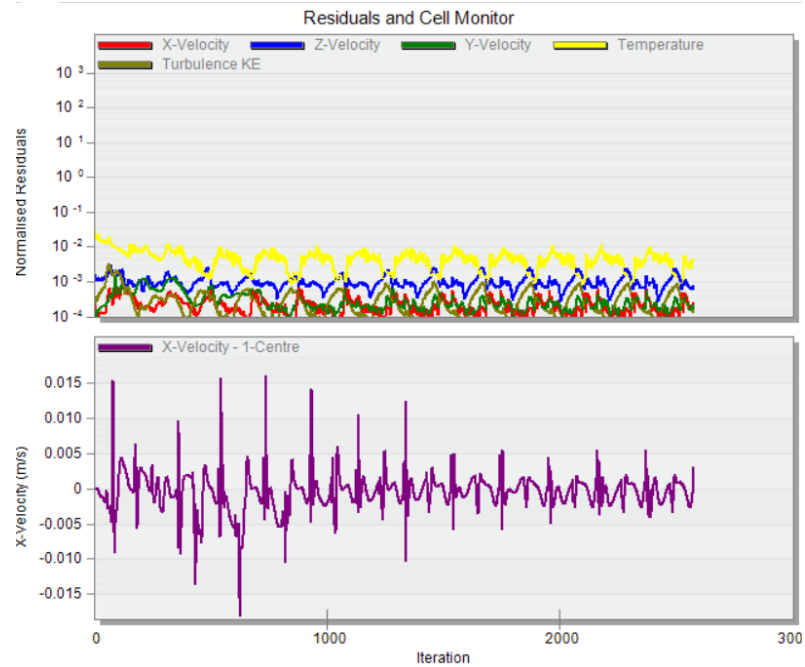


Figure 91: Residual graph of turbulence model with false time steps of 0.2 (Design Builder 2021)

The second part of the CFD sensitivity analysis consisted of changing the turbulence model from k-e to constant viscosity and having the false time step of 0.2, to understand the effect on the residuals of the CFD analysis. Additionally, monitor points were added to the cavity domain to check the residual values at various heights within the cavity. Figure 92 – Figure 94 show the location of the monitor points in the CFD domain. The default monitor is exactly located at the centre of the cavity. Point 1 is located on the upper floors of the cavity and point 2 is located at the lower floors in the cavity. The central monitor point is at 43.30m along the height of the cavity.

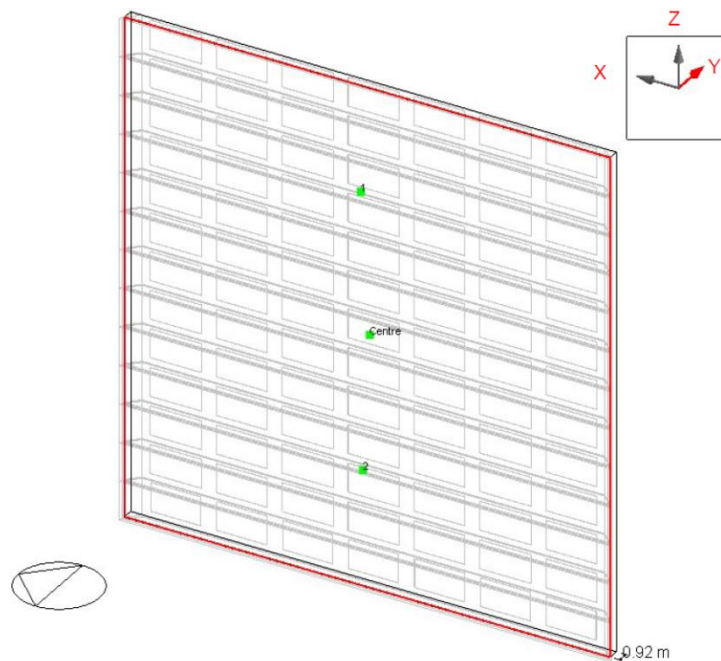


Figure 92: Location of the CFD analysis monitor points (Design Builder 2021)

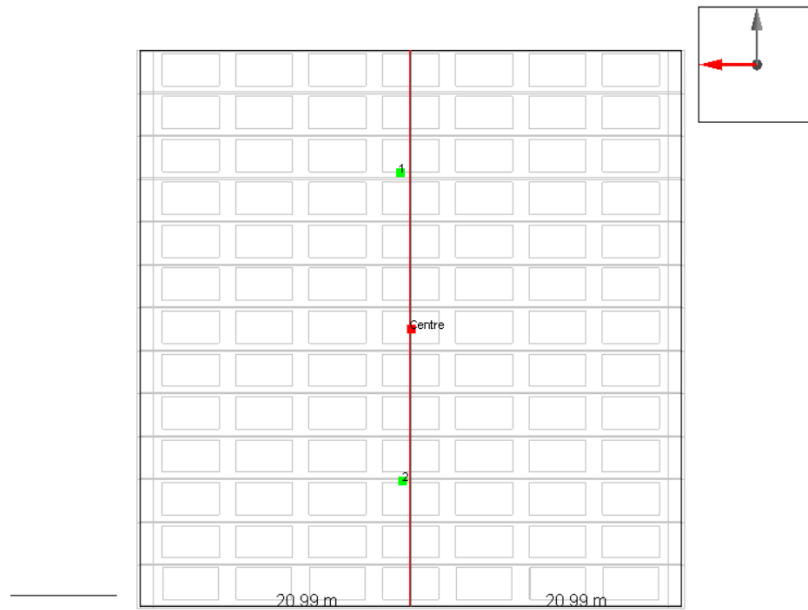


Figure 93: Front view of the DSF showing the location of the monitor points (Design Builder 2021)

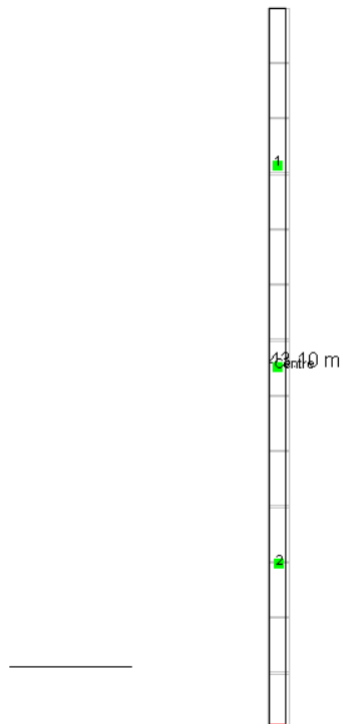


Figure 94: Sectional view showing the locations of the monitor points along the vertical of the DSF (Design Builder 2021)

The residuals graphs are indicated from Figure 95 to Figure 97. Wherein it can be seen that the x-velocity component is converging to a value of zero at the three monitor points. At the central monitor point, the behaviour of the x-velocity is quite haphazard and its value

converges to zero after 1000 iterations. At point no.2 in the lower floors the x-velocity variation is less erratic as compared to the central monitoring point and again subdues after 1000 iterations. Monitor point no.1, located in the upper floors has initial spikes and it also converges to 0 after 1000 iterations. It is interesting to note that the x- velocities tend to stabilize after 1000 iterations, which was not the case when the simulations were being run in the k-e turbulence model. The variation of the temperature in all the three images above is quite similar with negligible difference.

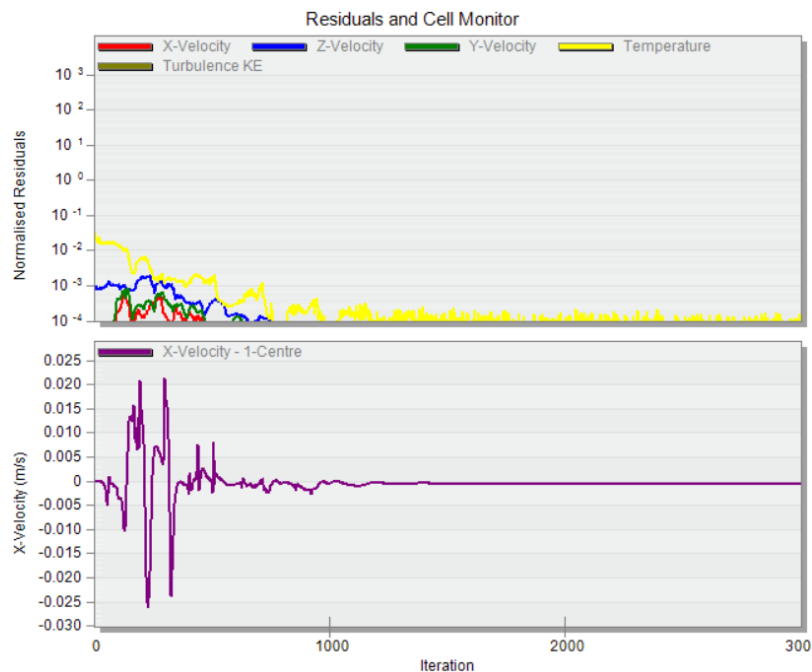


Figure 95: Residuals graph for central monitor point for x-velocity
(Design Builder 2021)

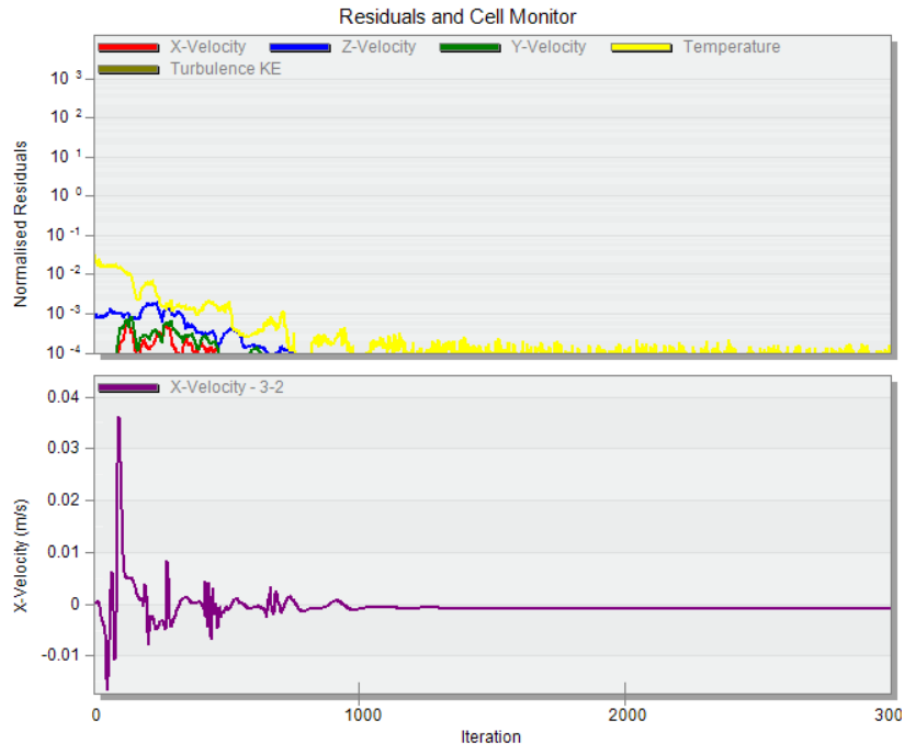


Figure 96: Residuals graph for monitor point no.2 in the lower half of the DSF domain for x-velocity (Design Builder 2021)

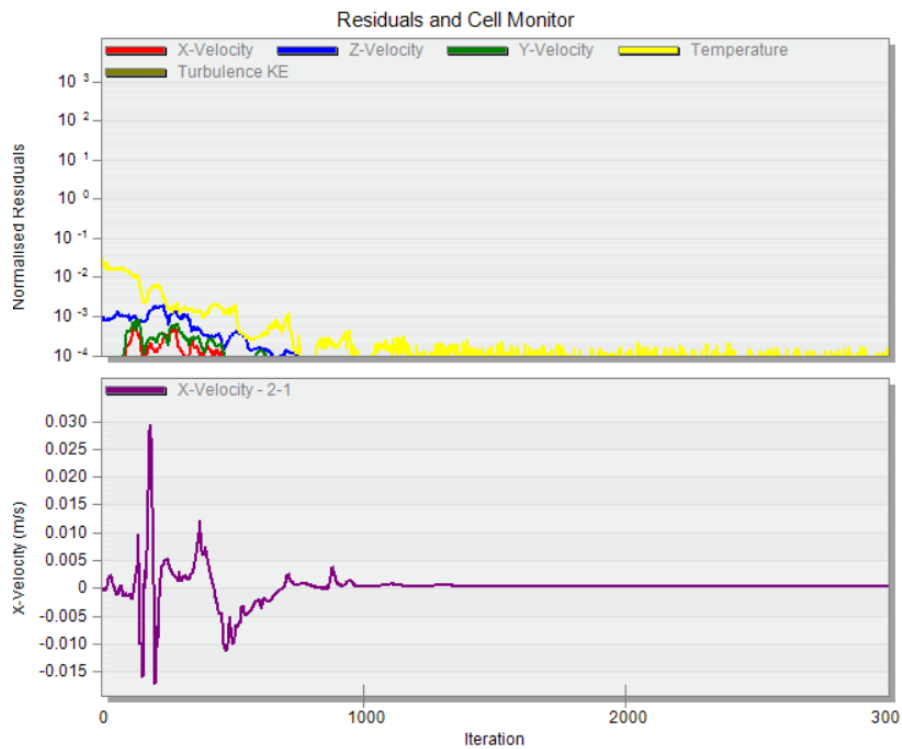


Figure 97: Residuals graph for the monitor point no.1 in the upper half of the DSF for x-velocity (Design Builder 2021)

At this stage, it was important to understand that if the values of the y velocity and z velocity were also converging to zero. Figures 98,99,100 show the graphs for y velocity at the three monitor points. An initial glimpse indicates that the y-velocity also converges to zero as x-velocity. Figure 101 to Figure 103 depict the residual monitor graphs for the z-velocity component. The residual values for the z-velocity are converging to a definite value and potentially indicate that the air flow is only in one direction in the cavity that is from the bottom of the cavity to top of the cavity. Table 17 shows the summary of the velocity values obtained at the three monitor locations. Further to validate the direction of the airflow, a CFD slice was generated from the middle of the CFD domain as shown in the Figure 104. The velocity vectors represented from Figure 105 to Figure 108, clearly show the unidirectional flow of air within the cavity. The zoomed in images at each of the three monitor points also indicate a streamlined flow.

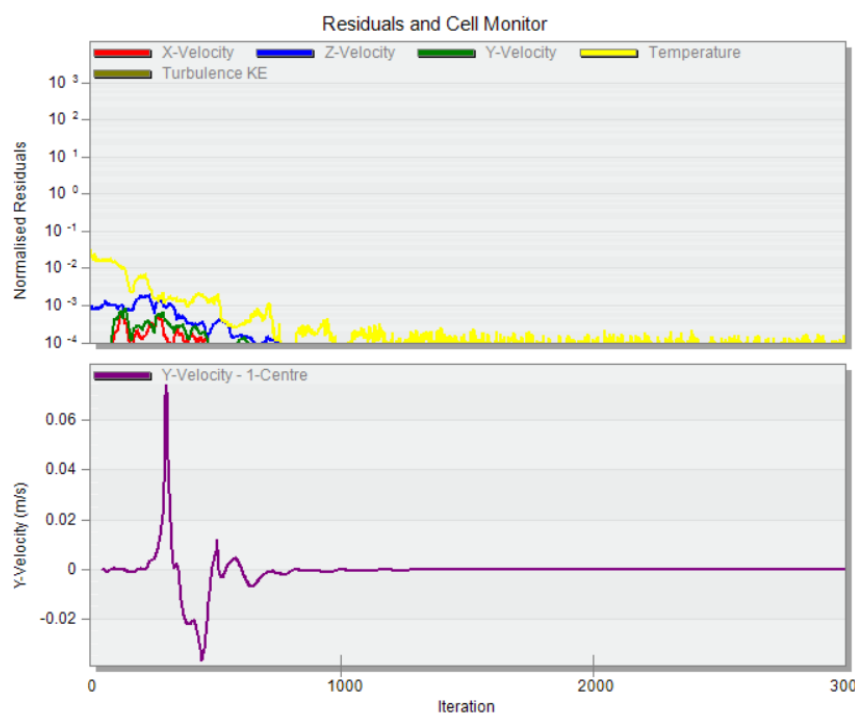


Figure 98: Residuals graph for the central monitor point in the upper half of the DSF for y-velocity (Design Builder 2021)

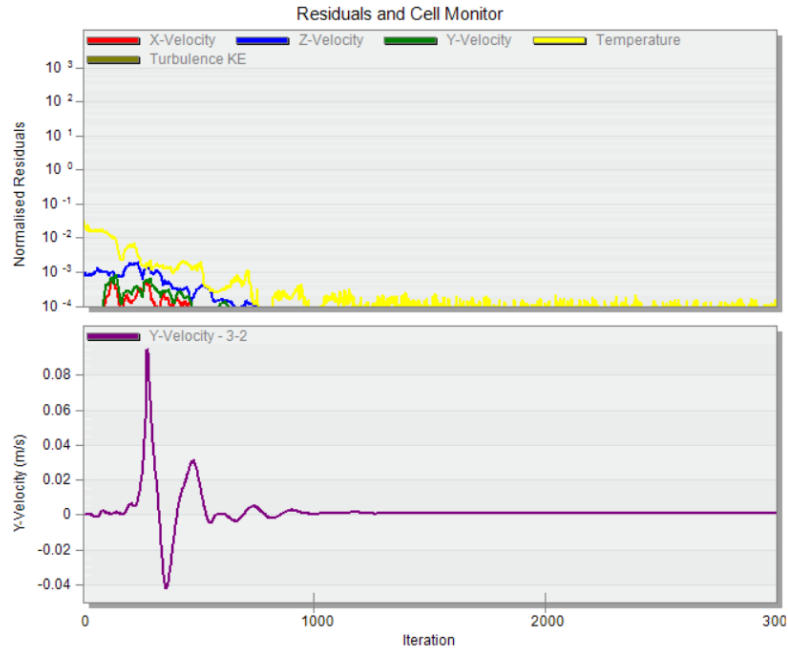


Figure 99: Residuals graph for the monitor point no.1 in the upper half of the DSF for y-velocity (Design Builder 2021)

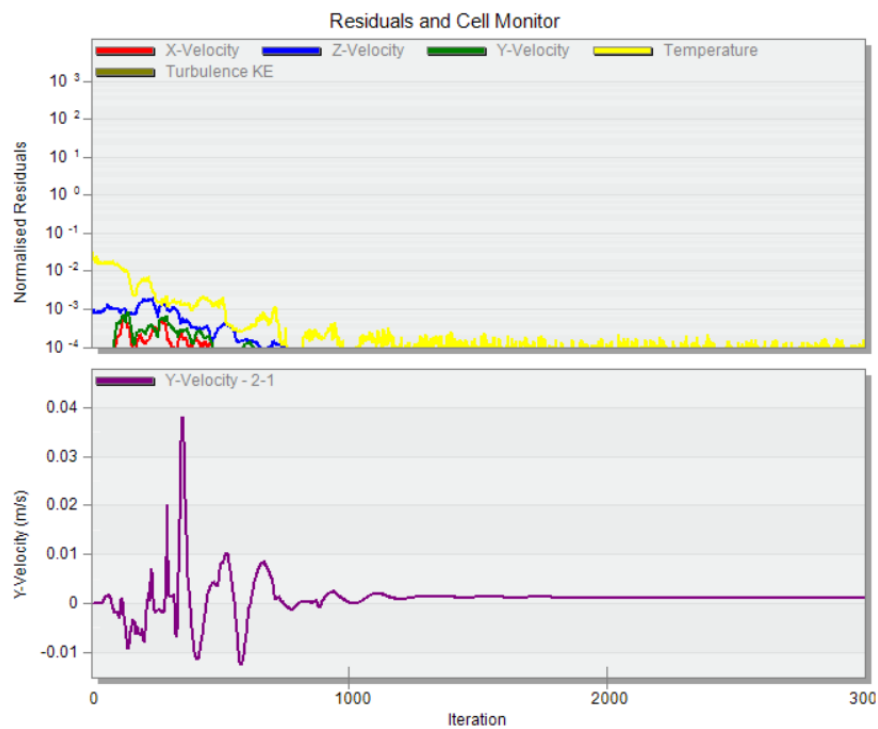


Figure 100: Residuals graph for the monitor point no.2 in the lower of the DSF for y-velocity (Design Builder 2021)

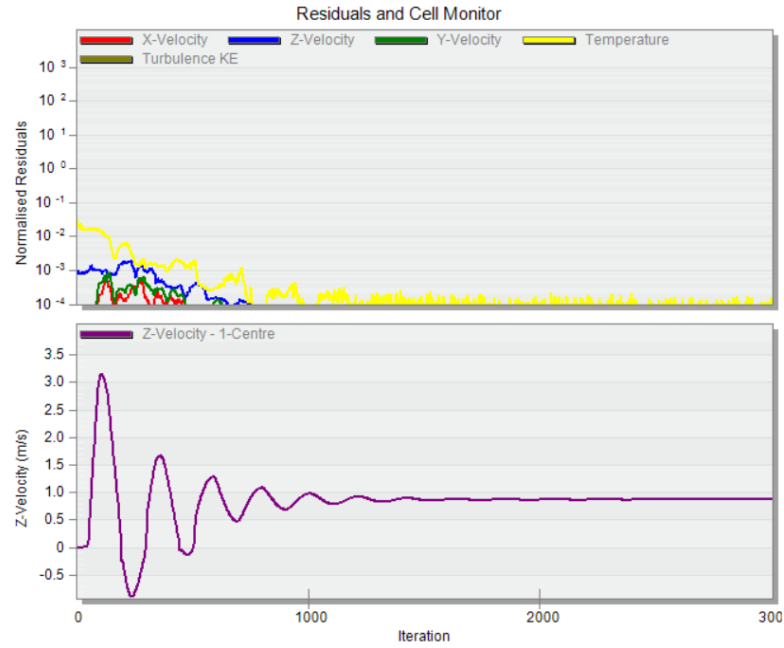


Figure 101: Residuals graph for the central monitor point in the upper half of the DSF for z-velocity (Design Builder 2021)

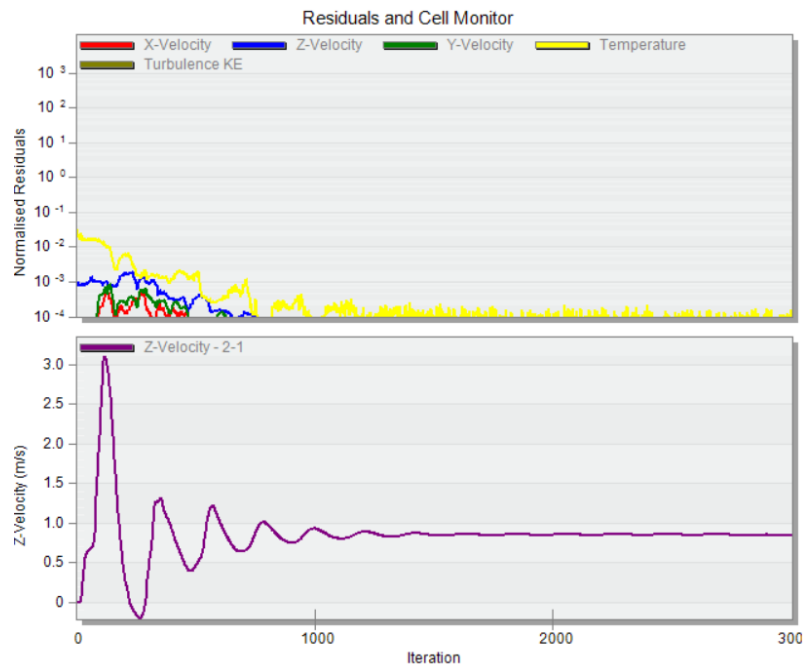


Figure 102: Residuals graph for the monitor point no.2 in the lower half of the DSF for z- velocity (Design Builder 2021)

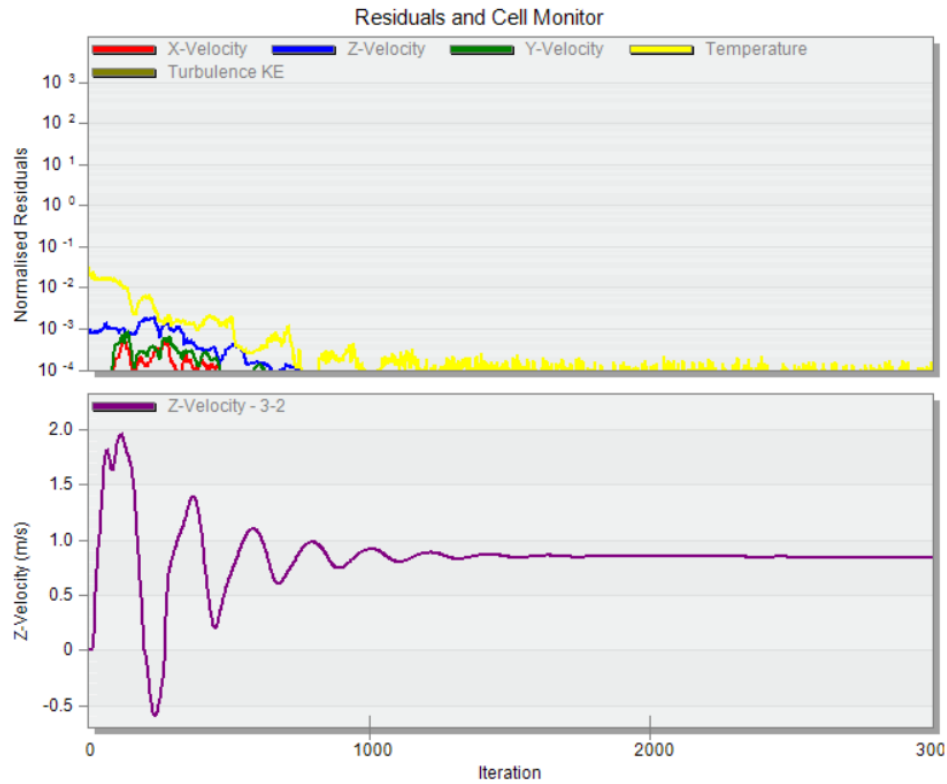


Figure 103: Residuals graph for the monitor point no.1 in the upper half of the DSF for z- velocity (Design Builder 2021)

Velocity component/Monitor point	Lower zone monitor point	Central monitor point	Upper zone monitor point
X – velocity (m/s)	0	0	0
Y – velocity (m/s)	0	0	0
Z- velocity (m/s)	0.9	0.9	0.8

Table 17: Summary of velocities for all the three monitor points (DesignBuilder 2021)

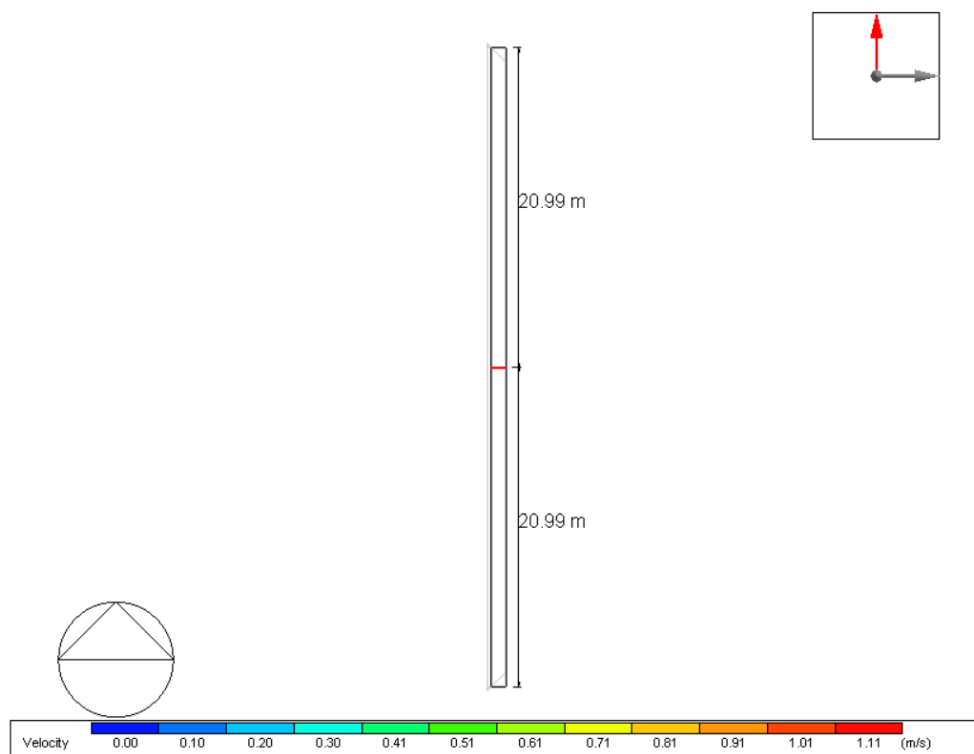


Figure 104: Plan view of the slice location within the cavity for velocity profile (Design Builder 2021)

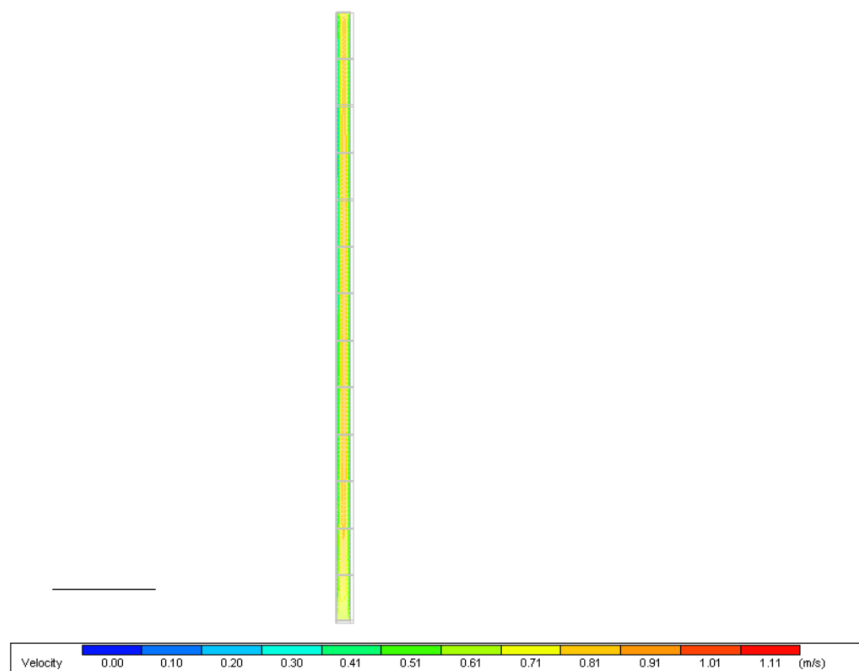


Figure 105: Velocity contours along the vertical direction in the DSF (Design Builder 2021)

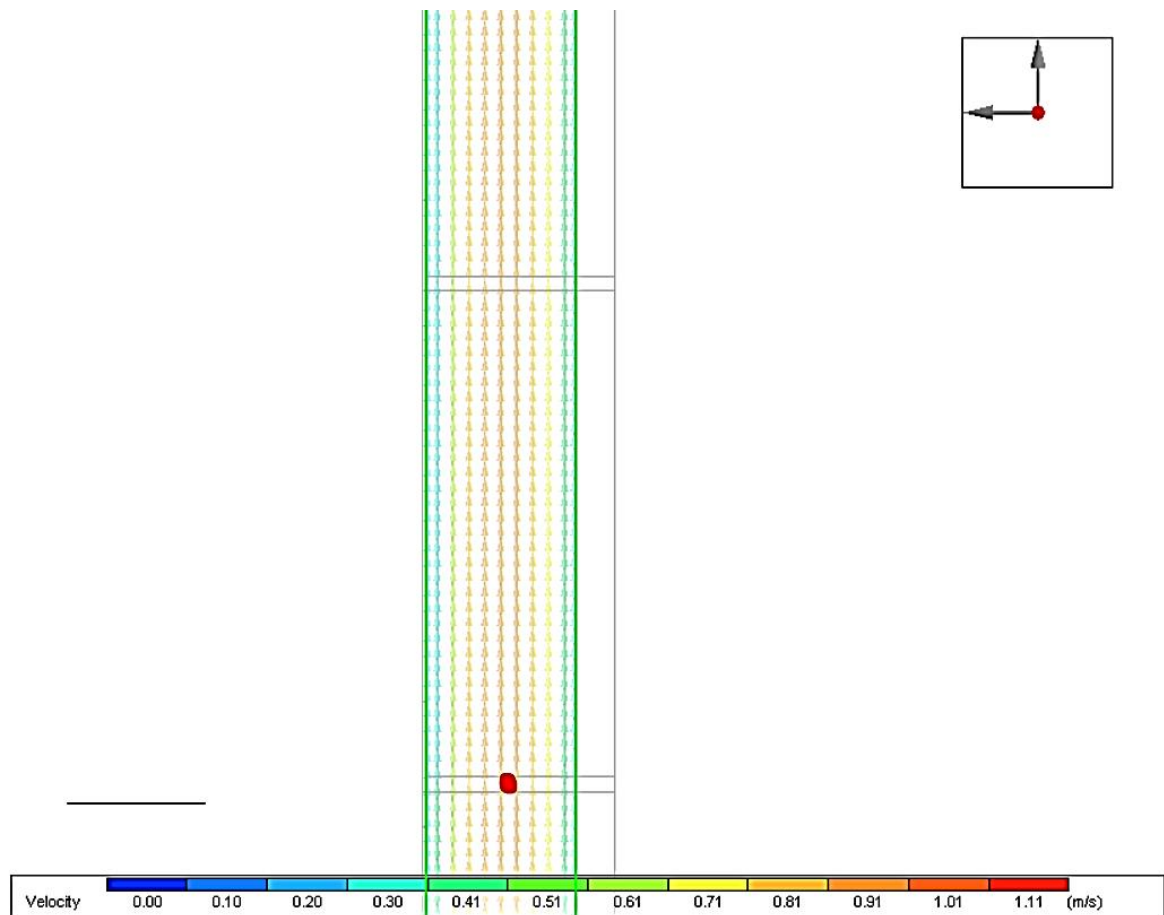


Figure 106: Velocity vectors at the lower zone monitoring point which lies in between the 3rd and 4th floor (Design Builder 2021)

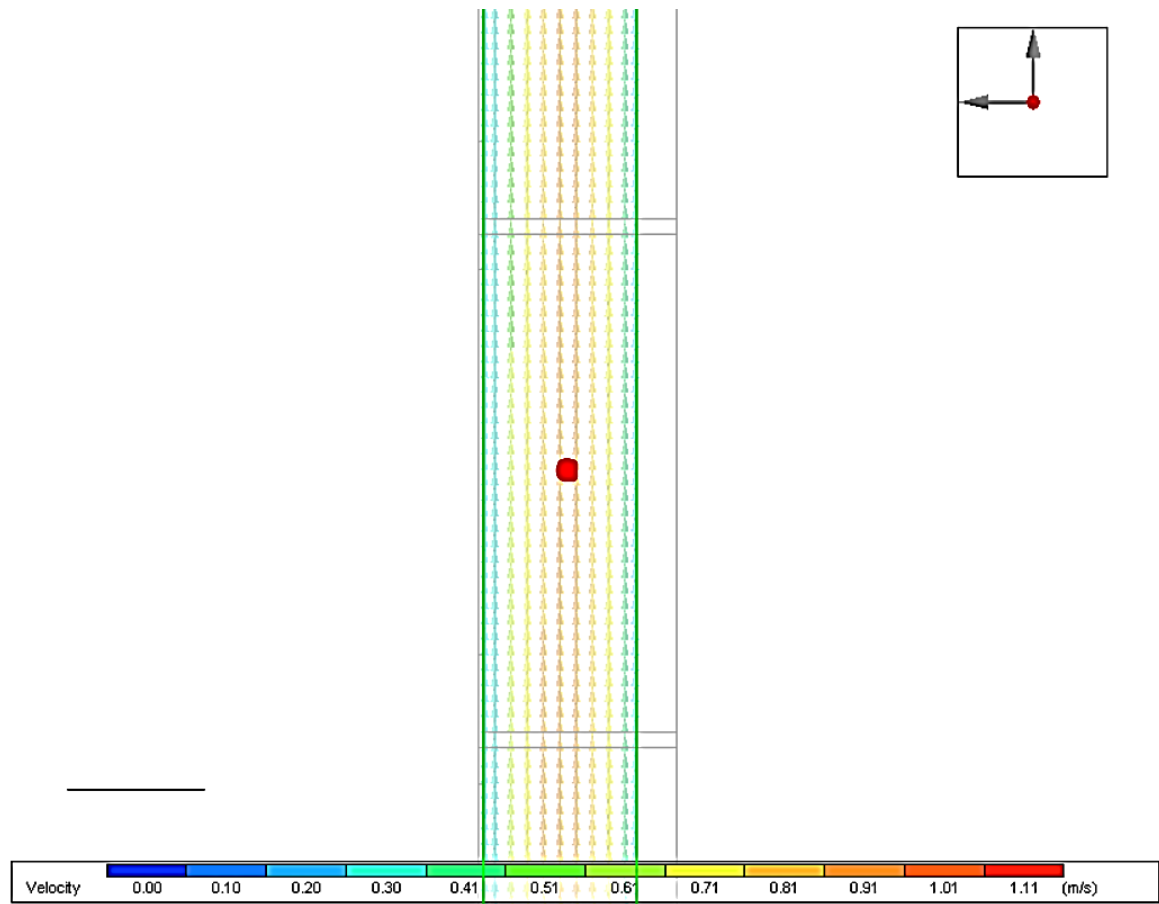


Figure 107: Velocity vectors at the central monitoring point, which is on the 7th floor (Design Builder 2021)

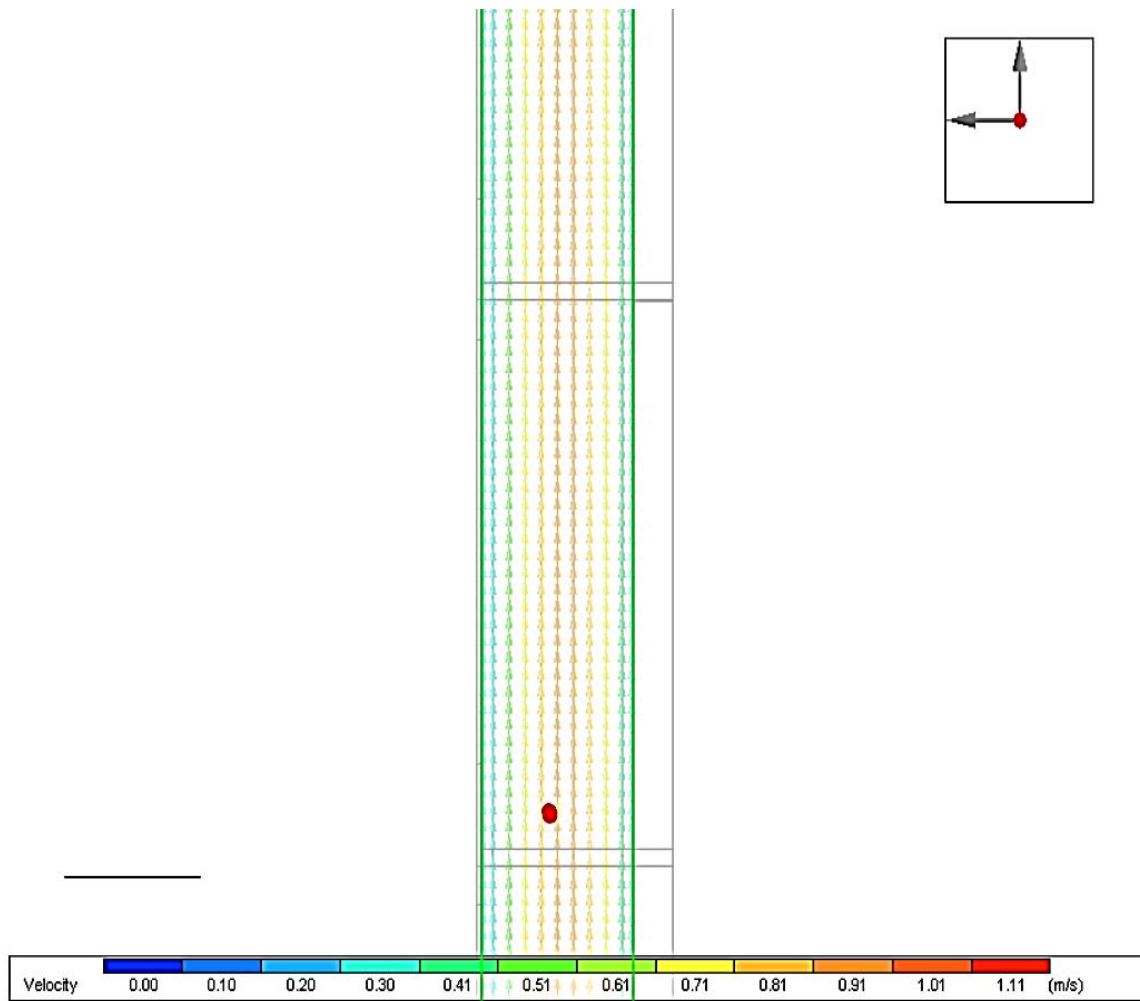


Figure 108: Velocity vectors at the upper zone monitor point, which is on the 11th floor
(Design Builder 2021)

5. Chapter 5: Intermodel comparison

This section compares and discusses the results of the dynamic thermal simulations with that of the internal CFD analysis results for the DSF cavity.

5.1. Temperature profiles

From the Figures 71 and 78 that represent the inner skin surface temperatures, it can be observed that the results from the dynamic thermal simulations indicate a higher temperature than the CFD simulations. For example, the temperature at the top of the DSF as per thermal simulations is 53 deg C whereas as per the CFD it is 49 deg C, approximately a difference of around 4 deg. C. At lower part of the DSF the temperatures is around 49 deg C and for the same location as per the CFD it is around 45 deg C. A generalization can be drawn here that there is a difference of around 4 deg. C between the temperatures that are reflected from the dynamic thermal simulations and the CFD simulations. Therein the dynamic thermal simulations show higher temperature as compared to CFD. These differences in computed temperatures clearly lead to the conclusion that dynamic thermal simulations underestimate the impact of the DSF on annual cooling savings. This goes some way to explain the differences in annual cooling demands tabulated in Table 12 section 4.1.

Looking at Figure 82, that shows the air temperature within the cavity derived from the internal CFD analysis and Figure 74 which represents the air temperature within the cavity from the dynamic thermal simulations, it can be observed that in case of the CFD analysis the temperature value of 46 deg. C is uniform throughout but in the case of dynamic thermal simulations, the temperature starts at 30 deg. C at the first floor thereby gradually increasing until the value of 41 deg. C at the 13th floor. In this case the temperature results obtained from the CFD analysis are higher.

Comparison of the inner side temperatures of the outer skin of the DSF by both dynamic thermal simulations (Figure 72) and CFD simulations (Figure 81). The dynamic thermal simulation results indicate temperatures at the lower levels of around 50 deg C while at the higher floors it is around 48 deg C. Looking at the results from the CFD simulations, it can be said that the inside temperatures of the DSF outer skin is around 45 deg C throughout the cavity. At the edges a slightly higher temperature of 48 deg. C is observed. The maximum

temperature difference between the dynamic thermal results and CFD results here is 5 deg. C and 3 deg. C.

5.2. Velocity profiles

Dynamic thermal simulations don't produce the values of the velocity by default and needs to be derived through the bulk air flowrate values. The method employed in Section 4.1, gave us an inlet velocity of 0.64 m/s and outlet velocity of 0.68 m/s.

The velocity profile indicated in section 4.2 which is obtained from the CFD results show a velocity value of 0.71 m/s in the lower floors of the DSF cavity and a velocity value of 1.01 on the higher floors of the DSF cavity. As mentioned earlier, the transition point for the velocity is at the second floor of the DSF cavity. Although the velocity values obtained from the dynamic thermal simulations are only for the inlet and outlet, it can be seen that the velocity value at lower floors from the CFD analysis (0.71 m/s) are in close proximity to the velocity values obtained from the dynamic thermal simulations (0.64 m/s). The velocity value at the upper floors from dynamic thermal simulations (0.68 m/s) when compared to the values obtained from the CFD simulations (1.01 m/s) indicate a marginal difference and are lower. This could be correlated to the earlier statement that dynamic thermal simulations underestimate the cooling effect of the DSF which is indicated by the lower value of velocities. The higher value of the velocities by the CFD simulations indicate a better cooling effect thus expelling the heat away from the cavity. Similar observations were also established for the intermodel comparison of the temperature profiles in the previous section.

6. Chapter 6: Conclusion and future works

This research was carried out for understanding the overall view of the effect of the passive technologies in mitigating the energy consumption of buildings in the hot climatic conditions of the UAE region. With respect to the UAE region, conventional passive technology (external shading) and unconventional passive technology (Double Skin Façade) were reviewed under the parameters of annual cooling & monthly cooling demands, annual & monthly solar gains, temperature and velocity profiles. The two passive technologies were pitted against a Business As Usual (BUA) building for comparative analysis on aforementioned fronts. The tools used for these analyses mainly involved the dynamic thermal simulator and the internal CFD solver both available within the DesignBuilder software package. All this, with a supporting detailed literature review aided in gauging the applicability of the passive techniques within the region and identify potential gaps thus propelling the current research. The succeeding section discusses the findings in view of the stated objectives for this research.

On an overall level, the dynamic thermal simulations indicated that the annual cooling energy consumption of the external shading case is less than the base case by 9.2% whereas for the DSF case the annual cooling energy savings were more by 1.42% when compared to the base case. The temperature profiles of the external skin of all the three cases indicate different temperature values. The highest temperature being from the DSF case with 54 deg. C and lowest temperature being from the external shading case with 42 deg. C on the glazing elements. The outlet and inlet velocities were derived from the results of the dynamic thermal simulations with a value of 0.64 m/s for the inlet and 0.68 m/s for the outlet. As part of the dynamic thermal analysis the west orientation cavity temperature profile was also studied in much detail. The results obtained therein depicted the average air temperature within the cavity and indicated a gradual incremental trend over the height of the DSF.

The second part of the research analysis consisted of performing internal CFD simulations for the DSF façade configuration wherein the temperature and velocity contours were extracted. The other two façade configurations of the base case and external shading case were not applicable for the internal CFD analysis. The inner skin of the DSF was reported to have an average temperature of 45 deg. C. The reported air temperature within the cavity was 46 deg. C and a average temperature of the 45 deg. C on the inner side of the outer skin of the DSF. Reported velocity values from the velocity contours indicated a value of 0.71 m/s near the inlet of the DSF and 1.01 m/s near the outlet of the DSF. The sensitivity analysis

carried for the internal CFD simulations in terms of varying the false time steps and turbulence models revealed the dampening effect in the values of the dependent variables as false time steps were reduced from 10 to 0.2. Varying the turbulence model from k-e to constant effective viscosity impacted the simulations to converge faster although the initial erratic behaviour was the same as observed in the case of the k-e turbulence model.

The final part of the research covered the comparison of the results obtained via the dynamic thermal simulations and the internal CFD simulations. A variation of approximately 4 deg. C was noted between the temperature readings of the dynamic thermal simulations and the CFD analysis. The higher temperatures were reported from the dynamic thermal simulation and CFD reported temperatures were lower which brings to the conclusion that dynamic thermal sims underestimate the potential cooling energy savings that could be brought about by the DSF technology. The velocity values from both the analysis could not be compared directly as dynamic thermal simulations aided in determining only the inlet and outlet velocities but showed a level of similarity at the inlet of the DSF.

Overall, the research highlighted the potential of DSF's for the hot climate of the UAE and has showed promising reductions in annual cooling energy savings. Further research avenues could be the optimization of the DSF for hot climates by selecting the optimal combination of the DSF variables. Investigation could also be carried out to find if placing blinds within the DSF cavity do any good to the exiting results.

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