Evaluating the effectiveness of current standards for designing Natural ventilation systems in hot climates and potential enhancements

تقييم كفاءة المعايير الحالية على تصميم انظمة تهوية طبيعية فى المناطق ذات المناخ الحار و تحسينات مقترحة

by

MOURAD MAGDY MOURAD AZIZ

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Abstract

Over the past decade, the ventilation of domestic buildings in hot climates has been dominated by the mechanical systems with its centralized and standalone forms. The domination was initially sparked by the global warming thread, but it was later promoted by a financial incentive to the landlords which is the increased leasable areas due to reduced floor-to-floor height and absence of vertical stacks, shafts or Atriums. Other triggers for the mechanical domination were the elevated standard of living, absence of firm regulations in the hot countries that enforces the consideration of natural ventilation and lack of Architects who understand the fluid dynamics and can design an effective naturally ventilated building in hot climate, which is much more complicated in design than mechanically ventilated buildings, from the architectural point of view.

However, the Natural ventilation strategies have recently been brought back to the scene by various local and international sustainability rating systems as potential tool for energy saving and clean indoor air quality. Due to the absence of local regulations and NV design guidelines, the sustainability ratings systems had to reference other codes and standards that were initially developed for cold and warm climates to set out their rules and targets.

In this study, four common design standards were explored and applied on a case study in hot climate to stand upon the level of effectiveness of such scheme. According to ASHRAE (2016), the hot climate has an annual cooling degree day between 3500 °C to 5000 °C for a base temperature of 10°C. The study also tested some additional strategies on the case study to understand the potential enhancements.

The study found that one standard only was able to achieve the targeted air flow rate, however, this air flow was achieved only at the window location and it was insufficient to

achieve thermal comfort inside the room. The single sided enhancement strategies have indicated a potential improvement of 250% while the cross-ventilation strategies have indicated a potential improvement over the 1000%. These findings suggest the need for a climate specific design standard that provides full guidance on all system parameters, including the internal clear heights, facades treatments, design of system components such as stack, atrium and air ducts.

الملخص

في غضون العقد السابق سادت انظمة التهوية الميكانيكية بنوعيها المركزي و المنفصل علي المباني السكنية في المناطق ذات المناخ الحار. كان الدافع الرئيسي لهذة السيادة هو التخوف من ارتفاع دراجات الحرارة داخل المباني بسسب الاحتباس الحراري ، لكنها عضدت بعد ذلك بدافع اخر مادي و هو زيادة المساحة الايجارية للوحدات السكنية نظرا لصغر مساحات المناور و قصر ارتفاع الادوار في المباني ذات التهوية الميكانيكية . من الاسباب الاخرة التي ساهامت في هذة السيادة ارتفاع مستوي المعيشة و غياب قوانين صارمة في البلاد ذات المناخ الحار تفرض وجود نظام تهوية طبيعي فعال في المباني السكنية . اخيرا ، توجت هذة الاسباب بندرة المعماريون الذين يعرفون هندسة الموائع و يتقنون تصميم انظمة تهوية طبيعية فعالة في البلاد ذات المناخ الحار ، التي هي اكثر تعقيدا من المباني ذات الانظمة الميكانيكية من الناحية المعمارية .

ولكن بالرغم من ذلك فان انظمة التهوية الطبيعية قد اعيدت مؤخرا الي الساحة من خلال بعض الجهات المعنية بالبيئة و المباني المستدامة علي المستوي العالمي ، بما لها من مميزات تجعلها سباقة في هذا المجال مثل توفير الطاقة و توفير تهوية صحية داخل الفراغات السكنية . نظرا لعدم وجود اكواد تصميم محلية لمثل هذة الانظمة في بعض البلاد ذات المناخ الحار فقد لجأت الجهات المعنية بالاستدامة الي الاستشهاد باكواد و مراجع عالمية كانت قد وضعت في الاصل للاستخدام في البلاد ذات المناخ البارد لتصميم نظام التهوية الطبيعية في البلاد الحارة .

في هذا البحث تم دراسة اربعة مراجع تصميم شائعة الاستخدام و تطبيقها علي دراسة حالة في مناخ حار للوقوف علي مدي فاعلية هذا التوجه.المناخ الحار هو المناخ الذى يتراوح فية المقياس الحرارى اليومى للسنة بين 3500 و 5000 درجة مئوية نسبة الى عشرة درجة مئوية. تناولت الدراسة ايضا بعض الاستراتيجيات الاضافية التى قد تؤدى الى تحسين اداء المراجع الاربعة

توصلت الدراسة الي امكانية مرجع واحد فقط من الاربعة على توليد تيار الهواء المستهدف. لكن هذا التيارا توالد عند فتحة التهوية فقط و لم يتغلغل داخل الفراغ, وبالتالى لم تحقق الراحة الحرارية المرجوه. اشارت نتائج المحاكاة الى امكانية تحسين اداء هذة المراجع عن طرق اضافة بعض الاستراتيجيات الاضافية بمعدل يصل الى 250% للاستراتيجيات ذات التهوية من جانب واحد و 1000% للاستراتيجيات ذات التهوية من جانبين. هذة النتائج تؤكد الحاجة الى مرجع تصميم خاص بالمناطق ذات المناخ الحار, يحتوى على معلومات متكاملة ولا

يقتصر على توصيف ابعاد الفتحات فقط, و ذلك يشمل الارفاعات الداخلية للفراغات, المعالجات الخاصة بالوجهات لتوجية الرياح و تصممصم المكونات الاخرى للنظام مثل البهو و المناور و فتحات التهوية

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Thanks to God for giving me this honorable opportunity

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Chapter I.

Introduction

1.1 Global view

The Natural ventilation has multiple advantages over the Mechanical ventilation, but in the same time it has become more complicated to adopt. Designing an effective Natural ventilation system in a hot climate region is a real challenge due to the intense solar irradiance and occasional presence of natural winds. Treating such designs in a superficial manner and assuming that it is as simple as adding a window in a room shall not yield the targeted ventilation in the livable spaces and moreover it will adversely contribute to strengthening the Landlord's perception about the ineffectiveness of natural Ventilation systems in hot climates.

CIBSE (2014) claims that Natural Ventilation can effectively ventilate a room if the heat gains inside the room is controlled within a range of 30 to 40 w/m2. ASHRAE (2016) urges that the natural ventilation can achieve acceptable thermal comfort conditions if the metabolic rate is within the range of 1.0 to 1.3 met (met is a unit used to express the metabolic rate) of metabolic , the occupants are free to adopt the level of clothing to 0.5 to 1.0 clo (clo is a unit used to express the thermal insulation by clothing) and the external temperature is within the range of 10 °C to 33.5 °C.

Earlier studies were undertaken to validate the reliability of empirical methods as an international standardized design tool for natural ventilation systems in all climate zones. Haung (2017) has investigated the reliability of three empirical methods through a lab experimental study in China, and Larsen (2018) has validated the equations of a European standard through a wind tunnel test to understand the level of accuracy of the equations. However, these two studies were carried out for warm and cold climates only, and they were only investigating the criteria of sizing the ventilation openings rather the holistic NV system. Other studies have investigated the importance of the windows' configuration on the effectiveness of the Natural ventilation system (Geo and Lee 2011). Similar to the two previous studies by Haung (2017) and Larsen (2018), this study was also focused on specific parameters rather than the holistic design approach.

The studies explored above suggest the need for a new study that examines the current standards in a holistic approach and suggests potential enhancements for higher effectiveness in hot climates specifically. A holistic approach should establish design criteria for the building's internal clear heights, openings' sizes, openings' locations and configurations, sizes of other components of the systems (ex. stack, air ducts, atrium …etc), guidance on the façade design at leeward and lateral wind orientations. These design criteria should be custom tailored for each different climate zone, urban density and building typology.

1.1.1 Sustainability Rating systems

The sustainability rating systems are nowadays promoting the natural ventilation systems and reviving their previous presence. This role is potentially going to result into a real change due to the fact that the majority of these rating systems have become obligatory in their local territories and even internationally in some cases. Estidama Pearl building rating system and LEED BD+C are two examples of the rating systems which are currently being applied in hot counties. Estidama Pearl building rating system is a local rating system used in Abu Dhabi, United Arab Emirates that was established by UPC (2010) and it has been mandated for all new buildings since 2010. LEED BD+C is a US established rating system that was established by USGBC (2014) and it has recently been mandated for all new federal buildings in the US. Both rating systems are having a credit for the natural ventilation, but it is an optional credit and it refers to the AM 10 standard by CIBSE (2014) to set the compliance requirements.

1.1.2 Barriers of the existing methods

CIBSE AM 10 and BS 5925 are British codes which were established in the UK for the design of naturally ventilated buildings. ASHRAE 62.1 and ASHRAE Fundamentals are International handbooks which were established originally in the United States for local guidance on the design of the mechanically ventilated buildings, but they were later expanded to cover the natural ventilation as well.

The applicability of these standards was not tested in some countries with hot climates such as Egypt, and their effectives for such climates is doubtable. For instance, these standards claim that buoyancy could be considered as driving force for the air, whereas Alex (2001) urges that the buoyancy ventilation requires a huge difference in temperature, up to 23 degrees approximately to be able to drive air.

Other concerns with using these codes and standards are the difficulty of understanding all terminologies and absence of comprehensive data that would be required for the completion of the design such as detailed historical weather data for the local climate and the required flow rates to be achieved for a healthy indoor environment. These concerns make it impractical for Architects to consider during the design stage. It is most likely that using these methods in hot climates will yield an ineffective natural ventilation system which will lead the occupants to go back to the mechanical solution and install standalone air conditioning units.

1.1.3 CFD and Wind tunnel Tests

As part of the recent design digitalization approaches, the CFD modelling has increasingly been used in the design of ventilation systems. However, the actual role of the CFD tool is to validate the design rather than establishing the design. For instance, the CFD tool cannot inform the design on the required volume of ventilation or the recommended sizes and configurations of the openings, it can only validate the assumptions made by the designer in the building. This perception is supported by CIBSE (2014) which urges that the CFD and the wind tunnel tests are suitable only for the final stages of Design. Whereas the mathematical estimations would be most applicable to be used in the concept design stage.

The use of CFD as a validation tool in the final stages might also be challenging due to the huge amount of information that is required to be inserted in the software and the difficulty of appointing a CFD expert as one of the project's design team in each project. The matter which raises the concern about the level of accuracy of the results and how far it is representing the actual case.

1.2 Research plan

The study will follow the work flow sequence elaborated in Figure 1.

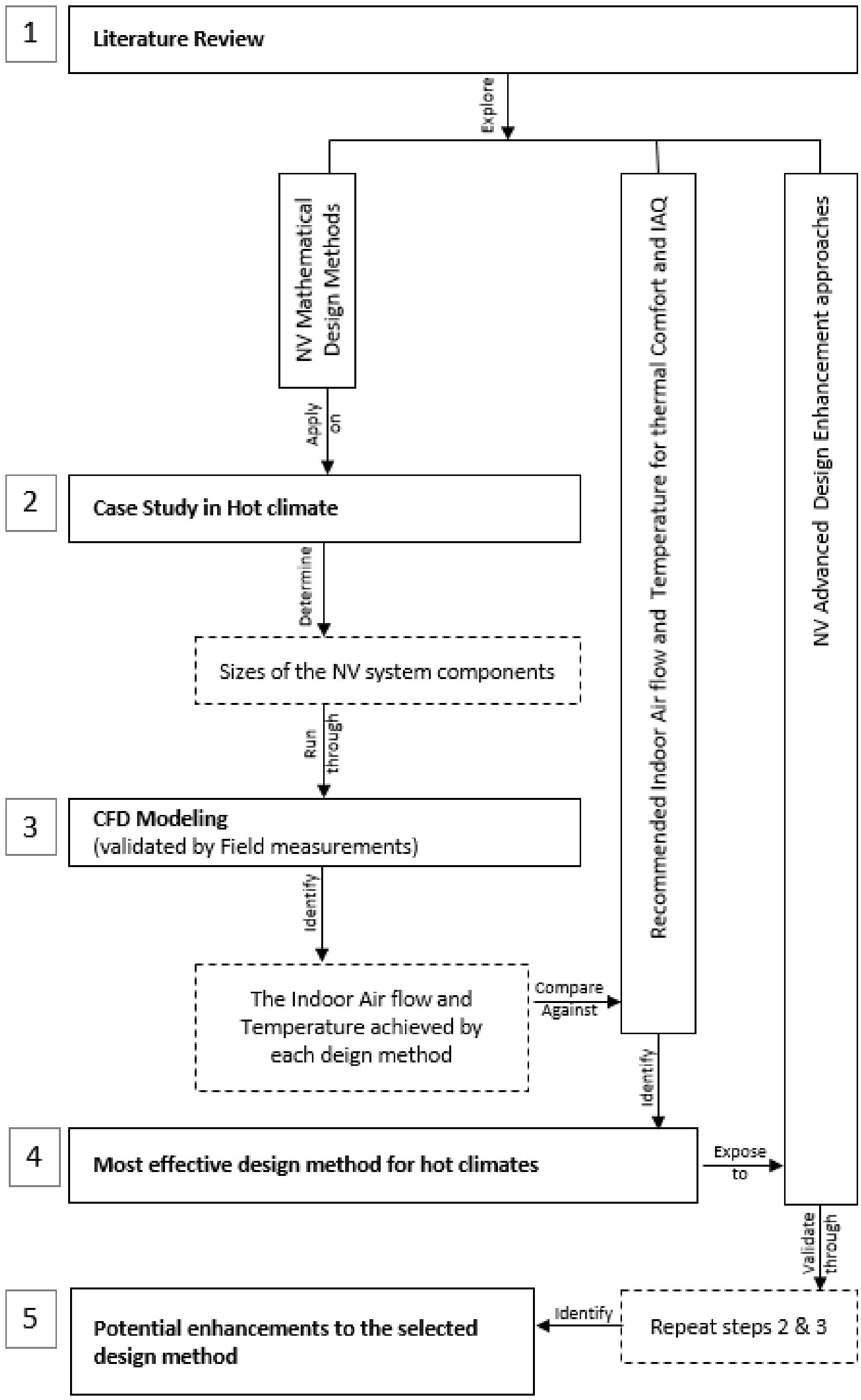


Figure 1. Research work flow

(Author)

The literature review will start by exploring the most commonly used guidelines in the design of naturally ventilated buildings. The review exercise will aim for extracting the direct design guidelines rather than surfing the theoretical air flow principals that are usually also described in these guidelines. The aim is to assess the provided information from the end user point of view, who in this case is the project architect during the design process.

The literature review will also investigate the acceptable conditions for thermal comfort and Indoor air quality as recommended by different codes and standards. The concluded values will be used to evaluate the effectiveness of the designs produced by the different design methods. Although the temperature will also be tackled in the study, the main focus of the study will be improving the air flow requirements.

An existing residential **Case study** will be selected in Egypt according to the selection criteria outlined in Section 3.1.3. The design guidelines extracted from each design method will be applied on the selected case study to conclude multiple design cases, one case for each method. The study will be limited to the living room only as being a sample of residential habitable spaces, however the results of the study will also be applicable to other habitable spaces of similar boundary conditions and heat gains such as bedrooms. Other rooms of different nature such as Kitchens and Bathrooms will not be addressed in this study due to their occasional usage pattern as well as their special operational conditions of increased heat gains and odor emission that would rather necessitate the use of mechanical extract systems.

The Computational fluids dynamics CFD will then be used to verify the air flow achieved by each design case. The process will start by validating the accuracy of the selected CFD software and boundary conditions through comparing the simulated air flow results of the 'existing' model against field measurements. After the validation, the different design cases will be simulated to obtain the air flow achieved by each design case. Each design case will be examined at different boundary conditions such as the different outdoor temperatures, absence and presence of wind. This is essential to understand the performance of the system under the different weather conditions. In order to broaden the extents of this study, each design case will also be examined for different wind directions boundary conditions.

After simulating all cases in all boundary conditions, the best performing design case will then be exposed to the potential design enhancement strategies. The enhancement strategies will initially be simulated separately to determine the enhancement percentage achieved by each strategy independently. Afterwards all strategies will be simulated incrementally in one model to determine the potential enhancement of applying all strategies collectively. A detailed methodology of the CFD modeling in outlined in section 3.3.2

1.3 Aims and Objectives

The main purpose of this research is to evaluate the applicability of using international standards for the design of a Natural ventilation system in hot dry climates, and propose potential enhancements. A hypothesis was made that such international standards would require some adjustments and enhancements to be applicable in hot climates. The hypothesis was examined on a residential case study in Egypt using CFD model to evaluate the effectiveness of the designs driven by these standards. The study examined the case study in various wind orientations and boundary conditions to broaden the benefits of the study and makes it applicable to other cases as well.

This global aim will be tackled through the following objectives:

- Investigate the weather challenges in Hot Arid climates
- Investigate the urban context of semi dense developments
- Investigate the sources of Heat buildup inside a residential living room

- Investigate the sources and levels of Pollutants and Carbon dioxide build up
  Investigate the acceptable thermal comfort conditions in residential living spaces
- Identify the required ventilation rates for a healthy indoor environment
- Explore few international design guidelines and test their applicability in Hot climates.
- Propose potential adjustments to these guidelines that would make it more effective when applied in the hot countries

Chapter II.

Literature Review

The findings of the literature review are presented and discussed in this chapter, with regards to the five following subjects: Standardization of Natural Ventilation design methods, Characteristics of Residential Spaces, Healthy Indoor Environments, Natural Ventilation System Design guidelines and Design calculations. Each subject will be presented in a separate section, with an overview of the different approaches among the literature.

2.1 Reliability of standardized Natural Ventilation design methods

The standardization initiatives elaborated in sections 1.1.1 and 1.1.2 have been questioned by many researchers for their potential drawbacks on the effectiveness of the Natural ventilation systems. Wang (2015) carried out field and desktop studies on existing LEED certified townhouse in Beijing. The townhouse was designed after an ‘International Architectural style’ as described by the researcher, being a replication of other projects that were designed and constructed in few other spots around the world. The aim of the study was to validate the suitability of such international design style for Beijing’s climate zone and investigate the impacts of the residents’ alterations on the original design. To validate the suitability of the international style design, he tested the same design in four different climate zones using computational simulations. Three out of the four climate zones were in China and one was in UK, London. The IES CFD tool was used to simulate the inflow and outflow air volumes at certain openings for the four climates zones. The results of the simulation indicated a significant variance in the air flow volumes among the four different climate zones, the matter which led the researcher to conclude that the International Architectural styles are not proper approaches to be followed in the design in case the effectiveness of the natural ventilation is of an essence.

Haung (2017) carried out an experimental study on a real sized test room in China to assess the reliability of three empirical methods for sizing the openings of natural ventilation system. He observed that the experiment results were not in agreement with the empirical calculations. The deviations were minimal in the first 20 minutes of the experiment, but then increased significantly to high levels afterwards. A similar study was carried out by Larsen (2018) who validated the equations of a European standard through a wind tunnel test to understand the level of accuracy of the equations. He concluded that the accuracy of the equations is 29%, with underestimation in 88% of the tested cases, which was deemed as a good result by Larsen. Peizhe (2016) carried out a similar experiment but in an actual academic building in China rather than test room. He reported that the measured airflow values were lower than the calculated values by 25%.

Geo and Lee (2011) studied the importance of the windows' configuration on the effectiveness of the Natural ventilation system. They compared between three design parameters to identify the most influencing parameter, the parameters are the Windows' configurations, windows' orientation and doors positioning. The study concluded that the windows configuration is the most influencing parameter. Ai and Mak (2014) conducted an experimental study on an existing high rise building in Hong Kong to validate the accuracy of 5 empirical methods on determining the ventilation rates in a single room. The case study room was located in the 12th floor of a 27-story building and they used the tracer gas method for air flow measurement. The study found that the closest empirical prediction was 25.7% higher than the measured rates and the farthest one was 78% less than the measurements. The researchers concluded that none of the empirical methods are applicable for determining the ventilation rates in a multi-story building, since they were originally established for a single room analysis and they do not account for the difference in ventilation characteristics between different rooms in the same building.

The literature above highlights the limitations of the empirical methods, specially when it comes to the international implementation, where climatical and contextual variances are expected among different locations. It also suggests the necessity of evaluating all aspects and components of the NV system rather than determining the sizes of the openings only.

2.2 Characteristics of Residential Living Rooms

The information related to the space characteristics is usually included in the 'Bases of Design' document of the project and it helps defining the expected thermal loads in the living space. The level of accuracy of this information correlates positively with the level of effectiveness of the design as claimed by CIBSE AM10 (2014). In absence of project specific values, typical values from the Literature can be referenced as relevant, such as the samples presented below.

2.2.1 Occupancy and type of activities

A residential living room is a place where people are expected to watch a TV, chat or work on a personal laptop. Such activities are not complicated in terms of heat generation, yet it is critical to study the behavior of each heat generating component in the space. The following parameters: number of occupants, the type of activities, level of clothing, the type of lighting features and the type of equipment.

Table 1. Characteristics of residential living rooms

(Compiled from various sources)

	ADIBC	CIBSE Guide A	ASHRAE 62.1	BSI BS EN 15259	ASHRAE Fundamentals	ASHRAE 55
Illuminance		50-750 lux *7 – 17 W/m2*				
Equipment					*109 w*	
Activity		58 – 70 w/m2			57 – 70 w/m2 1 – 1.2 met 103.4 – 126.4 w/person	60 - 70 w/m2
Clothing – summer		0.65clo				*0.54 – 0.57*
Maximum Occupant Load	*18.58* m2/person		*10* m2/person	*Number of bedrooms*	*Number of bedrooms + 1*	

The occupant load defined in Table 1 by the DMAT (2014) under the ADIBC is suggested for egress requirements only. The metabolic values indicated ASHRAE (2017) under ASHRAE fundamentals correspond to seating and relaxed standing activities. Housecleaning works and cooking activities have values of 2 to 3.4 met and 1.6 to 2 met respectively, however such activities are assumed to intermittent activities and will not be considered as bases of the design. The clothing insulation value of 0.57 clo indicated by ASHRAE (2016) under ASHREA 55 corresponds to a Trouser and a short sleeve shirt while the 0.54 clo value corresponds to a Knee-length skirt and short sleeve shirt. The illuminance values represent a rage of efficient and non-efficient fluorescent lights. The equipment heat gains correspond to one 55 inch screen and one laptop.

2.2.2 Envelope Thermal Insulation and shading

The building's envelope has a direct and significant impact on the thermal comfort inside the space, especially in the extreme hot and extreme cold climates. The parameters defining the performance of the façade are summarized in Table 2 with a comparison between the typical values of an insulated and non-insulated façade performance.

Table 2. Comparison between insulated and non-insulated façade insulation.
(Source: The unshaded cells are obtained from ASHRAE Fundamentals 2017. The Shaded cells are obtained from CIBSE Guide A 2007)

Element	***Parameter***	***Without Insulation***	***with Insulation***
Opaque	U value	1.05 $W/m^2.K$	0.2 $W/m^2.K$
	Y value	2.72$W/m^2.K$	3.05$W/m^2.K$
	Decrement factor	0.53	0.39
	Time lag (h)	7.4	9.2
	External Paint colour	Dark	Light
Fenestration	U value	6.98 $W/m^2.K$	1.93 $W/m^2.K$
	Y value	3$W/m^2.K$	3$W/m^2.K$
	SHGC	0.7	0.2
	Internal shading	0 No internal shading	0.6 Roller shutter - Opaque
	Shading by permeant overhang devise	0 No overhangs	1 Overhang is considered (In East and west façades, this value shall remain as zero despite the existence of overhang)
	Shading screen	1 no shading screen	0.4
	Decrement factor	1	1
	Time lag (h)	0	0
	Mean Solar gain factor to environmental node	0.76	0.15
	Swing in Solar gain factor to environmental node	0.5	0.11
	Mean Solar gain factor to air node	0	0
	Swing in Solar gain factor to air node	0	0

The U and Y values indicated in Table 2 represents the Thermal transmittances and admittance respectively. CIBSE (2017) defines the Decrement factor as the ratio of the rate of heat flow through the material to its steady state condition. The time lag is the time associated with such heat flow. The values of the solar gain factors correspond to a 'heavy weight' building type. The division of the solar radiation recipients into environment and air nodes is a recommendation made by CIBSE (2017) to account for the difference in wave length of the heat radiation. It can also be noticed in the table the CIBSE (2017) divides the solar gain into Mean and swing portions, which are discussed in more details in section 2.5.1.2.

2.3 Healthy Indoor Environments

A healthy indoor environment is a result of an acceptable Thermal comfort and Indoor Air quality, which will be discussed in the following section.

2.3.1 Thermal Comfort

De Dear (2004) analyzed a field measurements database of 21,000 building around the world in an ASHRAE sponsored research project and used the results to develop an Adaptive comfort standard 'ACS', which defines the temperature range that is deemed acceptable by occupants in naturally ventilated spaces. The adaptive thermal comfort approach is based on the fact that occupants in such spaces are having a margin of control and flexibility over their working hours, locations, and dress codes. ASHRAE 55 (2016) conducted several field experiments to study the thermal comfort expectations of occupants in the naturally ventilated spaces. The experiments concluded that the occupants can accept wider range of temperature swing only if they are given control of the operable windows. The same conclusion was documented by BSI (2007) after comparing the thermal responses of occupants in naturally ventilated building against mechanically ventilated buildings.

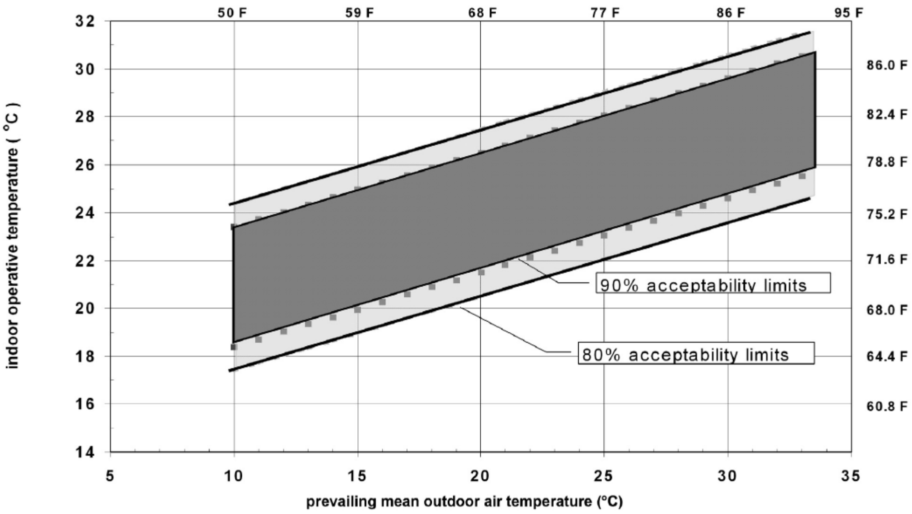


Figure 2. Acceptable Indoor Temperature in naturally ventilated spaces

(ASHRAE 55 2016)

ASHRAE 55 (2016) and BSI (2007) recommended the use of the Adaptive Comfort standard only for the spaces with metabolic rates of 1 to 1.3 met. The acceptable temperature ranges suggested by these two references along with other references are presented in Table 3.

Table 3. Acceptable Indoor Temperature in naturally ventilated spaces
(Compiled from various sources)

Reference	Design Temperature (ċ)
CIBSE Guide A 2017	23 - 25
BSI BS EN 15259 2007	25 – 31.8
Humphreys 1998 (Referenced by ASHARA Fundamentals)	31.1
De Dear 2004 (Referenced by ASHARA 55-2013)	24.5 - 31.5

BSI (2007) classifies the indoor spaces into three categories according to the occupants' expectations as follows: (1) high expectations, spaces occupied by sensitive person such handicapped or young children (2) normal (medium) expectations (3) acceptable (low) expectations. The values indicated in Table 3 corresponds to the 2nd category as it is the recommended category by BSI (2007) for new residential buildings. Using category one values would reduce the temperature threshold, while category 3 values will increase the temperature threshold.

ASHRAE (2017) and CIBSE (2017) have provided procedures for the calculations of the expected heat gains and peak summer temperature in the naturally ventilated space. These procedures are presented in section 2.5.1 and will be used to verify the feasibility of the natural ventilation in hot climates.

2.3.2 Indoor Air Quality

Oie et al. (1999) investigated the impact of various ventilation rates on young children's health in homes and found that ventilation rates below 0.5 ach (air change per hour) increase the risk of breathing problems. Bornehag et al. (2005) explored the correlation between the indoor ventilation rates and children's allergy in a sample of 390 homes. He noticed that the allergic symptoms in homes with ventilation rates between 0.05 and 0.24 ach are double the allergic symptoms in homes with ventilation rates between 0.44 and 1.44 ach. A similar study was conducted by Norback et al. (1995) on the correlation between poor ventilation rates in homes and the asthma symptoms for Adults. He found that the asthma symptoms increase in homes with higher CO_2 concentrations due to low ventilation rates. On the other hand, CIBSE (2017) urges that the increase in air flow rates above 8 L/s in hot climates will be causing discomfort.

In order to design healthy residential spaces, the designers should understand the minimum air flow rates requirements and design the building accordingly. The literature suggests various sources for obtaining such information, most of which can be categorized under one of the two following categories: Perspective rates' resources and Performance rates' resources. The two categories are presented and discussed in section 2.5.2.

2.4 Natural Ventilation Systems - Design Guidelines

Four design standards were explored in this study and will be presented hereafter in the following sequence: ASHRAE Fundamentals 2017, CIBSE AM10 2005, ASHARAE 62.1 2016 and BS 5925 1995.

2.4.1 ASHRAE Fundamentals 2017

ASHRAE Fundamentals provides the following guidance on the design of the Natural ventilation systems:

Openings' sizes shall be calculated according to the mathematical equations presented in section 2.5.3.2. ASHRAE (2017) claims that increasing the size of the inlet or the outlet over the other will increase the air flow but such increase will not be proportional to the increase in size.

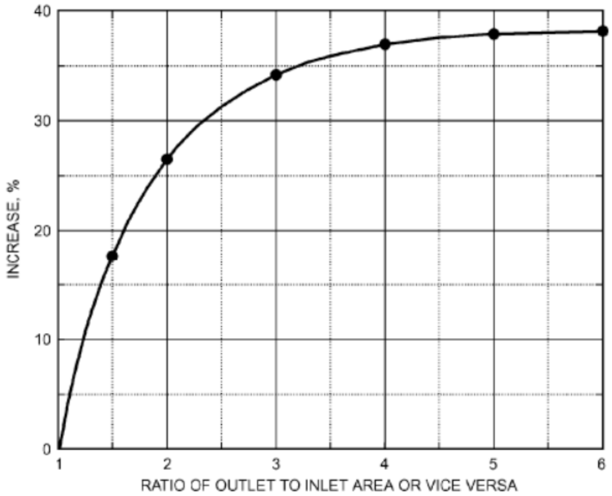


Figure 3. Increase in Air flow by increasing the area of one opening

(ASHRAE Fundamentals 2017)

Openings' location should be decided carefully such that the inlet opening is located at the positive pressure side while the outlet is located at the negative side. The inlet and the outlet opening shouldn't be at located the same level, vertical separation is required for better air distribution in the spaces as well as enhancing the stack effect. Openings at the neutral plane are least effective for buoyancy driven air flow. Openings on two sides of the space (perpendicular or opposite) are more advisable than single sided opening, however, if the room doesn't have more than one exterior wall, then the best air flow is achieved by two widely spaced openings on this wall.

Building geometry and orientation define the pattern of air movement around its facades and hence it should be considered early in the initial design stages in a way that maximize the exposure of commonly used spaces to prevailing wind. The long façade should face the prevailing wind direction. Architectural wind directing elements such as wing walls and overhangs are suggested by ASHRAE to redirect the wind in cases where the wind is not perpendicular to the opening. ASHRAE Highlights the importance of increasing the Floor to floor height in the naturally ventilated buildings beyond the 2.4 to 3 m heights used conventionally in the mechanically ventilated buildings.

Table 4. ASHRAE Fundamentals – Extents of Design guidance.
(Author)

	ASHRAE FUNDAMENTALS 2017			
	SSS	SSD	CV	SV
Space Height	○	○	○	○
Openings' Size	•	-	-	-
Openings' locations	•	-	•	-
Sizes of other components of the system (ex. Stack, air ducts, wing wall, Atrium, shading devices .. etc)	-	-	-	-
Guidancefor the design of rooms facing the leeward (opposite to wind direction)	-	-	-	-
Guidance for the design of the facades parallel to wind direction	○	○	○	○

Key:
- • Detailed Guidance provided
- ○ Partial Guidance provided
- \- No guidance provided

2.4.2 CIBSE AM10 2014

CIBSE AM10 2014 was established to guide the natural ventilation designs in non-domestic buildings, however, the guidelines may apply to other spaces of similar conditions such as living rooms in residential spaces. The design procedure follows a logic that is presented in Figure 4.

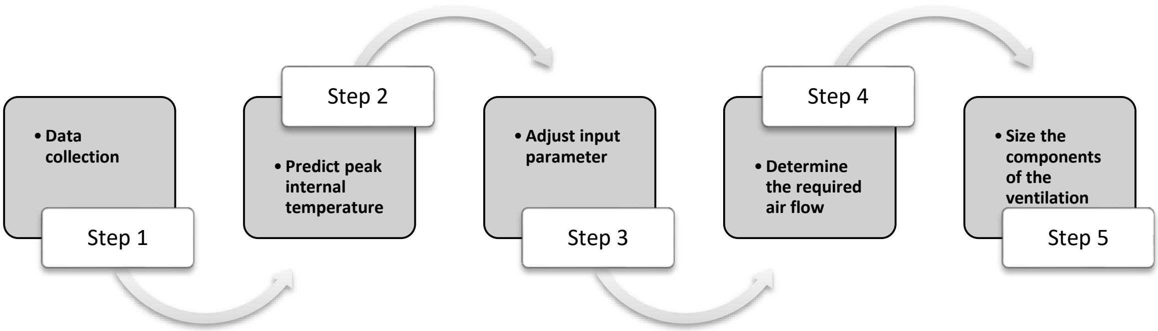


Figure 4. Design work flow of natural Ventilation systems

(CIBSE AM10 2014)

The Data collection stage aims for gathering information about the local weather conditions, building geometry, orientation and materials, type of activities and users. The peak internal temperature should be estimated based on the actual internal heat gains of the space as claimed by CIBSE (2014) in the design guidelines. However, it is also claimed somewhere else in the guidelines that the difference between the outdoor and indoor temperatures should be assumed as 3 K disregarding the magnitude of the internal heat gains.

Adjusting the input parameters is a stage in which the design carries out some iterations to the unfixed variables such as the envelope’s heat transmittances characteristics and the shading elements, to try and reduce the peak internal temperature as much as possible. The required flow rate shall be determined according to the IEQ criteria outlined in the previous section.

Selection of the appropriate system and sizing its components is the last and most critical step in the procedure. The selection should be made according to the systems' capabilities outlined in the coming paragraph. CIBSE (2014) recommends using the 'Envelope flow models' design tool for the sizing of the systems' components in the initial stages of the design process. The 'Envelope Flow' calculation method consists of two main models: Explicit Methods and Implicit Methods. Explicit methods deal with the purpose-provided openings only, while the Implicit Methods deal with both the purpose-provided openings as well as the adventitious openings (i.e leakage through cracks, services penetrations, external doors … etc). Another difference between the Implicit methods and Explicit method is that the Implicit methods accounts for the change in Neutral height while the Explicit model does not. Neutral plane is a virtual plane that separate the air intake portion of the opening from the air discharge portion. The explicit method is presented in details in Section2.5.3.2.

Single sided ventilation can effectively ventilate a room with a depth of twice the room's internal height as claimed by CIBSE (2014) for the single opening schemes. CIBSE (2014) also claims that considering two openings - spaced vertically – will increase the ventilated room depth up to 2.5 times the room's internal height. The vertical distance measured from the lower window's sill up to the head of the upper window should be 1.5 m approx.

Cross ventilation extends the depth of the ventilated room up to 5 times the rooms internal height as claimed by CIBSE (2014), assuming that the ventilation openings are located at the two far ends of the room**.** Courtyard buildings can also utilize the cross-ventilation strategy, however this strategy will be less effective in the rooms which have one of its walls facing the courtyard and the other wall facing the leeward, this is due to that the fact that the wind pressure will be almost the same between the two areas which will not drive air movement. Wind scopes can enhance the cross-ventilation strategy by harnessing free wind from upper levels where the wind speed is usually higher, however, attention should be given to the direction of the wind. In the locations where the wind direction varies significantly, multiple inlets should be considered in the wind scope with the automatic control. Ventilation ducts can be used in the deep plan spaces with single external wall, to create pathway for cross ventilation and overcome the limitations of single sided ventilation. CIBSE (2014) highlights the importance of designing these supply ducts for low pressure drops.

Stack ventilation also can extend the depth of the ventilated room up to 5 times of the rooms internal height as claimed by CIBSE (2014). The stack outlet should be located above the up most ceiling of the building with a distance equivalent to half the height of one floor. The outlet should also be located carefully in a negative pressure zone (ex leeward) in order to create the required pressure difference and drive air flow. Chimney ventilation is one form of stack ventilation, where the air inside the chimney should be maintained at a higher temperature than the outside air. This can be achieved by considering glazed walls facing sun, internal absorbing surfaces and protection from direct wind exposure. As mentioned above, the outlet should be located at a negative pressure zone to ensure the streamlining of the air flow.

CIBSE (2014) provide some guidance in the AM 10 manual on the sizing of the Stack ventilation components, however, the guidance does not cover the full system. For instance, there is no information provided about the minimum area requirements of the stack plan cross section nor the sizing of the stack outlet.

Some other natural ventilation schemes are given a mention by the CIBSE (2014) but with no guidance on the Design requirements. Examples of these systems are the double skin ventilation and the Night Ventilation.

Table5. CIBSE AM10 – Extents of Design guidance.

(Author)

	CIBSE AM10			
	SSS	SSD	CV	SV
Space Height	-	-	-	-
Openings' Size	•	•	•	○
Openings' locations	•	-	•	-
Sizes of other components of the system (ex. Stack, air ducts, wing wall, Atrium, shading devices .. etc)	-	-	-	-
Guidancefor the design of rooms facing the leeward (opposite to wind direction)	-	-	-	-
Guidance for the design of the facades parallel to wind direction	-	-	-	-

Key:
- • Detailed Guidance provided
- ○ Partial Guidance provided
- \- No guidance provided

2.4.3 ASHRAE 62.1 2016

ASHRAE 62.1's design recommendation agrees with CIBSE AM10 about the limitations of the Single sided and cross ventilation schemes, which can only ventilate a room with a depth of two times and five times the room's internal height respectively.

The sizes of the openings shall be estimated based on the procedure outlined in Section 2.5.3.1.

Table 6. ASHRAE 62.1 – Extents of Design guidance.

(Author)

	ASHRAE 62.1			
	SSS	SSD	CV	SV
Space Height	-	-	-	-
Openings' Size	•	-	-	-
Openings' locations	•	-	-	-
Sizes of other components of the system (ex. Stack, air ducts, wing wall, Atrium, shading devices .. etc)	-	-	-	-
Guidancefor the design of rooms facing the leeward (opposite to wind direction)	-	-	-	-
Guidance for the design of the facades parallel to wind direction	-	-	-	-

Key:
- • Detailed Guidance provided
- ○ Partial Guidance provided
- \- No guidance provided

2.4.4 BS 5925 1995

BSI (1995) assumes that the building is having standard leakage rates which assist in the ventilation process as a 'background ventilation', and it provides sizing rates for the main ventilation openings 'Rapid ventilation' as listed in Section 2.5.3.1.

Table 7. BS 5925 1995 – Extents of Design guidance.
Source: Author

	BS 5925			
	SSS	SSD	CV	SV
Space Height	-	-	-	-
Openings' Size	•	-	-	-
Openings' locations	•	-	-	-
Sizes of other components of the system (ex. Stack, air ducts, wing wall, Atrium, shading devices .. etc)	-	-	-	-
Guidance for the design of rooms facing the leeward (opposite to wind direction)	-	-	-	-
Guidance for the design of the facades parallel to wind direction	-	-	-	-

Key:

- • Detailed Guidance provided
- ○ Partial Guidance provided
- \- No guidance provided

2.5 Natural Ventilation Systems - Design Calculations

The calculation procedures suggested by different standards will be presented in this section with regards to the following subjects: Heat gains and Peak internal temperature, Recommended Ventilation flow rates and Areas of ventilation openings.

2.5.1 Heat Gains (q_s) and Peak Indoor Temperature (T_s)

The factors contributing to heat build-up inside an internal living space are summarized in Figure 5. Two different procedures will be presented for the calculation of the heat gains, which are: ASHRAE Fundamentals by ASHARE (2017) and Guide A by CIBSE (2017).

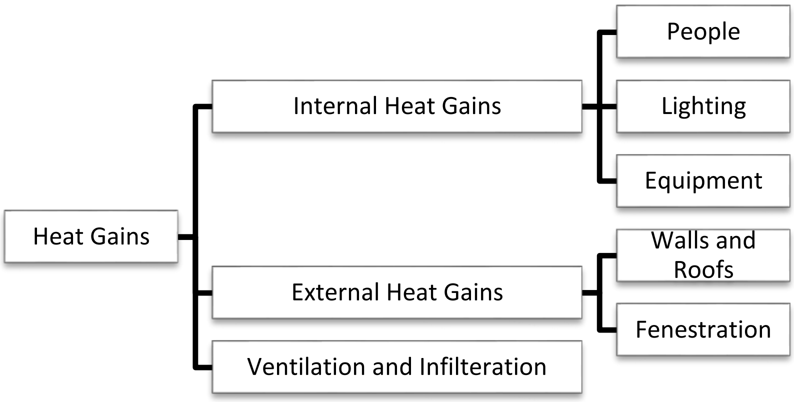


Figure 5. Sources of Heat Gains inside a Residential Living Room

Source: Author

2.5.1.1 ASHRAE Fundamentals 2017

ASHRAE (2017) urges that the method of estimating the residential Heat gains should differ from those used for other types of buildings. This is due to the unique characteristics of residential spaces, such as the low internal gains and wide variety of uses inside a single space.

ASHRAE (2017) reviewed two methods for the calculation of residential cooling loads, one of which is derived from the other, and suggested the use of the '*Residential Load Factor -RLF'* method for the initial design stages as it is simpler and doesn't require special software for calculation. This method was mainly developed for wooden framed buildings, however ASHARE (2017) urges that it can be used for masonry constructions, but it will slightly overestimate the heat gain from external walls and hence the results will be a bit conservative.

ASHRAE (2017) urges that the heat emitted by any source into an indoor livable space is basically composed of two main components: Radiative and convective heat portions. The convective portion immediately becomes a Heat gain while the Radiative portion takes time until it becomes a Heat gain since it must be absorbed by the internal surfaces first and then transmitted to the internal environment by convection. This split is adopted by ASHRAE (2017) in the non-residential and the 'Radiant time series' methods only. Whereas the '*Residential Load Factor -RLF'* method assume that the load is total convective portions.

Another split highlighted by CIBSE (2014) and ASHRAE (2017) is the fractions of sensible heat and Latent heat in the heat emissions generated by some specific sources. The latent portions exist in the Heat emissions generated by Occupants, Food preparation and saturated outdoor ventilation air only, the remaining portion of these Heat emissions, as well as the full amount of Heat emissions generated by all other sources is considered Sensible Heat gain. CIBSE (2014) claims that the fraction of Sensible to latent components various depending on the dry bulb temperature, the matter which is not considered by ASHRAE (2017). CIBSE (2014) urges that only the sensible loads should be considered when assessing the peak temperature in summer.

Internal Heat gains

The sources of these gains are mainly the occupants, appliances and Lighting.

Table 8. Internal Heat Gains – ASHRAE Fundamentals 2017

Source: Building America 2004 (referenced by Barnaby 2005 and ASHRE Fundamentals 2017)

Sensible Load	Latent Load

$q_{ig,s} = 136 + 2.2A_r + 22N_{oc}$ (1)	$q_{ig,l} = 20 + 0.22A_r + 12N_{oc}$ (2)

Where:
$q_{ig,s}$ is the Sensible cooling load from internal gain, W
$q_{ig,l}$ is the Latent cooling load from internal gain, W
A_r The area of the room, m^2
N_{oc} The number of occupants

External Heat gains

The sources of these gains are the walls and fenestrations that are directly exposed to the outdoor environment

Table 9. External Heat Gains – ASHRAE Fundamentals 2017
Source: Barnaby 2005 (referenced by ASHRE Fundamentals 2017)

Opaque surfaces	Transparent Surfaces
$q_{opq} = A_{opq} \times CF_{opq}$ (3)	$q_{fen} = A_{fen} \times CF_{fen}$ (5)
$CF_{opq} = U_{opq}(OF_t\Delta t + OF_b + OF_r DR)$ (4)	$CF_{fen} = U_{fen}(\Delta t - 0.49DR) + PXI \times FF_s \times IAC \times SHGC$ (6)

Where:

q_{opq} Opaque surface cooling load, W
A_{opq} Net Surface Area, m^2
CF_{opq} Opaque Surface cooling factor, W/m^2
U_{opq} Construction U-Factor, W/$m^2.K$
Δt Design dry bulb Temperature (Outdoor -Indoor), K
DR Daily Range of Outdoor Dry bulb temperature, K
OF_t, OF_b, OF_r Opaque Surface cooling factors
IAC Interior shading attenuation coefficient

q_{fen} fenestration surface cooling load, W
A_{fen} fenestration Area (including frame), m^2
CF_{fen} fenestration Surface cooling factor, W/m^2
U_{fen} fenestration U-Factor, W/$m^2.K$
PXI Peak Exterior irradiance including shading modification, W/m^2
$SHGC$ Fenestration solar heat gain coefficient
FF_s Fenestration coefficient

The opaque surfaces calculations outlined above are applicable to non-slab surfaces. **The Opaque Surface cooling factors**$OF_t, OF_b, OF_r$for walls with solar exposure are assumed by Barnaby 2005 as 1, 7.9 and -0.34 respectively.

The Peak Exterior Irradiance values shall be calculated as follow:

$$PXI = T_x E_t \qquad (7) \text{ (unshaded fenestration)}$$

$$PXI = T_x[E_d + (1 - F_{shd})E_D] \qquad (8) \text{ (shaded fenestration)}$$

Where:

T_xTransmission of exterior attachments

E_t, E_d, E_DPeak Total, diffuse and Direct irradiance for exposure

F_{shd}fraction of fenestration shaded by permeant overhang

Exterior attachment Transmission measures the magnitude of reduction in solar gain due to external window coverings such insect screes or shade screens. In absence of any window coverings, this value should be assumed as 1 (no reduction at all). An exterior insect screen can reduce this value to 0.6, and a shade screen can reduce it down to a range of 0.4 to 0.6 depending on the manufacturer’s SC value.

Permanent shading is caused by overhangs, fins or environmental obstacles. The fraction of the exterior shading shall be calculated using the following equation:

$$F_{shd} = min\left[1, max\left(0, \frac{SLF \times D_{oh} - X_{oh}}{h}\right)\right] \qquad (9)$$

Where:

SLFShade line factor

D_{oh} Depth of the overhang from plane of fenestration (m)

X_{oh} Vertical distance from top of fenestration to overhang (m)

h Height of fenestration (m)

Shade line factor is the ratio between the vertical distance the shadow falls below the overhang to the depth of the overhang. Barnaby (2005) urges that the value of SLF for an East Façade at latitude of 32° N should be assumed as 0.8.

Interior attenuation coefficient measures the magnitude of reduction in solar gain due to internal window coverings such as drapes, roller shades or blinds. It can be estimated using the following equation:

$$IAC = 1 + F_{cl}(IAC_{cl} - 1) \quad (10) \text{ (shaded fenestration)}$$

Where:

F_{cl} is the shade fraction (0 to 1)

IAC_{cl} is the interior attenuation coefficient of fully closed configuration

ASHRAE (2017) urges that the interior attenuation coefficient of fully closed configuration ranges between 0.34 to 0.88 depending on the characteristics of the internal shading element and the glass. The lower value corresponds to an opaque white roller shade attached to a clear single glass window while the upper value corresponds to a dark – closed weave – drapes attached to double low e low solar glass window. It should be noted that the effect of the interior attenuation will be more beneficial when it is attached to a clear glass rather than low e glass, this is because the Low e glass trapes the heat inside the space while the clear glass allows the heat to exit the space. For instance, the best (lowest) interior attenuation coefficient that can be achieved with a low e glass is 0.6 which corresponds to an opaque white roller shade, while the same shading material can achieve an interior attenuation coefficient as low as 0.34 if attached to a clear glass.

Fenestration solar loads factor represents the percentage of the solar heat gain contributing to heat buildup inside the indoor space and hence, it differs from one orientation to the other. Table 12 presents the values suggested by Barnaby (2005) for the different orientations. Barnaby (2005) urges that the value of FF for an East Façade should be assumed as 0.17.

Natural Ventilation and Infiltration

The heat buildup caused by introducing hot air from the outdoor environment into the indoor space shall be calculated using equations in Table 10.

Table 10. Heat Gains by Ventilation – ASHRAE Fundamentals 2017
(Barnaby 2005- ASHRAE Fundamentals 2017)

Sensible Load	Latent Load
$q_{vs} = C_s Q \Delta t$ (11)	$q_{vl} = C_l Q \Delta W$ (12)
Total	
$q_{vt} = C_t Q \Delta h$ (13)	

Where:

q_{vt} Total Ventilation load, W
q_{vs} Sensible Ventilation load, W
q_{il} latenat Ventilation load, W
C_s Air Sensible heat factor, 1.23 W/(L/s).K
C_l Air latent heat factor, 3010 W/(L/s)
C_t Air total heat factor, 1.2 W/(L/s)·(kJ/kg)
ΔW Change in Humidity Ratio
Δt Change in dry bulb Temperature (Outdoor - Indoor), K
Δh Change in enthalpy (Outdoor -Indoor), kJ/kg (Btu/lb)
Q Air flow rate, L/s

The heat gains caused by infiltration (leakage) through cracks will be ignored in this study due to its negligible contributions to heat buildup in naturally ventilated building

There are few other sources of internal heat gains considered by ASHRAE (2017) such as the Partitions to unconditioned spaces, distribution ducts, combustion air from heating systems and mechanical ventilation systems (whole building ventilation, heat recovery and centralized exhaust systems). These sources will be ignored as they fall outside the scope of this study which deals only with Naturally ventilated buildings. The Domestic water heaters and local exhaust fans operated manually are also sources of heat gains, however ASHRAE (2017) urges that it is generally neglected due to its minimal contribution to the overall heat gain build up.

2.5.1.2 CIBSE Guide A 2017

The method proposed by CIBSE (2017) is slightly different than the RLF method by ASHRAE in the essence that it takes in consideration the time factor of heat transfer by conduction between different objects inside the space. It subdivides the heat gains' recipients into environment node and air node as described in section 2.2.2.

Internal Heat gains

Table 11. Internal Heat Gains – CIBSE Guide A
(CIBSE 2017)

	Mean	Swing	Peak
Environment Node	$\bar{q}_i = \frac{\Sigma(q_{ii}t_{ii})}{24}$ (14)	$\tilde{q}_i = \hat{q}_i - \bar{q}_i$ (15)	sum of all internal heat gains in the space
	Where: $\bar{q}_i$ is the mean internal heat gain, W $\tilde{q}_i$ is the swing in internal heat gain, W $\hat{q}_i$ is the peak internal heat gain, W q_{ii} is the instantaneous heat gain from internal sources, W t_{ii} The duration of the internal heat source, h		

Ventilation gains

Table 12. Heat Gains by Ventilation – CIBSE Guide A

(CIBSE 2017)

	Swing	
Air Node	$\tilde{q}_v = C_v \tilde{T}_o$ (16)	
	$\tilde{T}_o = T_o - \bar{T}_o$ (17)	$C_v = \frac{1}{3} NV$ (18)

Where:

$\tilde{q}_v$ is the swing in heat gain due to ventilation, W

$\bar{T}_o$ is the mean outside Temperature, °C

$\tilde{T}_o$ is the swing in outside Temperature, °C

$\hat{T}_o$ is the peak outside Temperature, °C

N is the Air change per hour, ach

V is the volume of the space, m^3

The Air change per hour rate shall be assumed according to Table 16

Table 13. Effective mean Ventilation rates for openable widows

(CIBSE 2017)

Location of openable windows	Usage of windows		Effective mean ventilation rate	
	Day	Night	Air changes per hour / h^{-1}	Ventilation loss / $W \cdot m^{-2} \cdot K^{-1}$
One side of building only	Closed	Closed	1	0.3
	Open	Closed	3	1.0
	Open	Open	10	3.3
More than one side of building	Closed	Closed	2	0.6
	Open	Closed	10	3.3
	Open	Open	30	10.0

<u>Solar Heat gains</u>

Table 14. Solar Heat Gains – CIBSE Guide A

(CIBSE 2017)

	Mean	Swing
Environmental Node	$\bar{q}_{se} = \bar{S}_e \bar{I}_T A_g$ (19)	$\tilde{q}_{se} = \tilde{S}_e A_g (\hat{I}_T - \bar{I}_T)$ (21)
Air Node (only if there are blinds installed)	$\bar{q}_{sa} = \bar{S}_a \bar{I}_T A_g$ (20)	$\tilde{q}_{sa} = \tilde{S}_a A_g (\hat{I}_T - \bar{I}_T)$ (22)

Where:

$\bar{q}_{se}$ is the mean solar heat gain to the environment node, W

$\bar{S}_e$ is the mean solar gain factor at the environment node, W

$\bar{q}_{sa}$ is the mean solar heat gain to the air node, W $\tilde{q}_{se}$ is the swing in solar heat gain to the environment node, W $\tilde{q}_{sa}$ is the swing in solar heat gain to the air node, W $\bar{I}_T$ is the mean total solar Irradiance, W/m2 $\bar{I}_T$ is the peak total solar Irradiance, W/m2	$\bar{S}_a$ is the mean solar gain factor at the air node, W $\tilde{S}_e$ is the swing in solar gain factor at the environment node, W $\tilde{S}_a$ is the swing in solar gain factor at the air node, W A_g is the Area of the glass, m2

Fabric Heat gains

Table 15. Fabric Heat Gains – CIBSE Guide A

(CIBSE 2017)

	Mean	Swing
Environmental Node	$\bar{q}_f = \sum(A\ U)\,\bar{T}_{eo}$ (23)	$\tilde{q}_f = \sum_n f_n A_n U_n \tilde{T}_{eo} + \sum_n f_{gn} A_{gn} U_{gn} \tilde{T}_{ao}$ (24) $\tilde{T}_{eo} = T_{eo} - \bar{T}_{eo}$ (25)

Where:

$\sum(A\ U)$The sum of the products of all surface areas and the corresponding thermal transmittance, W/K $\sum(A\ Y)$The sum of the products of all surface areas and the corresponding thermal admittance, W/K $\bar{q}_f$ is the mean fabric heat gain, W $\bar{T}_{eo}$ is the mean sol-air temperature, °C $\tilde{q}_f$ is the swing in fabric heat gain, W $\tilde{T}_{eo}$is the swing in sol-air temperature, K $\tilde{T}_{ao}$ is the swing in outside air temperature, K at time t	T_{eo} is the sol-air temperature °C at time $(t - \emptyset)$, t is the time of day at which the peak space temperature occurs, Ø is the time lag associated with decrement factor h f_n is the decrement factor for opaque surface n A_n is the area of opaque surface n U_n is the thermal transmittance of opaque surface n, W/$m^2.K$

Total heat gains

Table 16. Total Heat Gains– CIBSE Guide A

(CIBSE 2017)

	Mean	Swing
Environmental Node	$\bar{q}_{te} = \bar{q}_{se} + \bar{q}_f + \bar{q}_i$ (26)	$\tilde{q}_{te} = \tilde{q}_{se} + \tilde{q}_f + \tilde{q}_i$ (28)
Air Node	$\bar{q}_{ta} = \bar{q}_{sa} + C_v \bar{T}_o$ (27)	$\tilde{q}_{ta} = \tilde{q}_{sa} + \tilde{q}_v$ (29)

Where:

$\tilde{q}_v$ is the swing in heat gain due to ventilation, W
$\bar{T}_o$ is the mean outside Temperature, °C
$\tilde{T}_o$ is the swing in outside Temperature, °C
$\bar{q}_{ta}$ is the mean total gain at the air node, W
$\bar{q}_{sa}$ is the mean solar heat gain at the air node, W
$\bar{q}_{se}$ is the mean solar heat gain at the Environment node, W
$\bar{q}_f$ is the mean fabric gain, W
$\bar{q}_i$ is the mean internal gain, W
C_v Ventilation loss, W/K
$\tilde{q}_{te}$ is the total swing in heat gain at the Environmental node, W
$\tilde{q}_f$ is the swing in fabric heat gain, W
$\tilde{q}_i$ is the swing in internal heat gain, W
$\tilde{q}_{ta}$ is the total swing in heat gain at the air node, W
$\tilde{q}_{sa}$ is the swing in solar heat gain at the Environment node, W
$\tilde{q}_v$ is the swing in ventilation heat gains, W

Operative Temperature

Table 17. Internal Temperature– CIBSE Guide A *(CIBSE 2017)*

Mean	Swing	Peak
$\bar{T}_s = \frac{\bar{q}_{ta} + F_{cu}\, \bar{q}_{te}}{C_v + F_{cu}\, \sum(A\, U)}$ (30)	$\tilde{T}_s = \frac{\tilde{q}_{ta} + F_{cu}\, \tilde{q}_{te}}{C_v + F_{cu}\, \sum(A\, Y)}$ (32)	$\hat{T}_s = \bar{T}_s + \tilde{T}_s$ (34)
$F_{cu} = \frac{3(C_v + 6\sum A)}{\sum(A\, U) + 18\sum A}$ (31)	$F_{cy} = \frac{3(C_v + 6\sum A)}{\sum(A\, Y) + 18\sum A}$ (33)	

Where:

$\bar{T}_s$ is the internal space meanTemperature, °C
$\tilde{T}_s$ is the internal space swing Temperature, °C
$\hat{T}_s$ is the internal space total Temperature, °C
$\bar{q}_{ta}$ is the mean total gain at the air node, W
$\bar{q}_{te}$ is the mean total gain at the Environmental node, W
$\tilde{q}_{ta}$ is the total swing in heat gain at the air node, W
$\tilde{q}_{te}$ is the total swing in heat gain at the Environmental node, W
C_v Ventilation loss, W/K
F_{cu} Conduction factor
F_{cy} Admittance factor
$\sum(A\, U)$ The sum of the products of all surface areas and the corresponding thermal transmittance, W/K
$\sum(A\, Y)$ The sum of the products of all surface areas and the corresponding thermal admittance, W/K

2.5.2 Ventilation Flow rates calculations (q)

The two procedures mentioned in high level at Section 2.3.2 will presented below in details to identify the recommended ventilation flow rates to be targeted in the design.

2.5.2.1 Prescriptive procedures

These resources provide set values of air flow rates for each type of building. The values are provided per person or per unit area of the ventilated space, irrespective of the actual components of that space, external climate conditions or envelop characteristics of that space. The values are expressed either in liter per second per person or liter per second per square meter.

Table 18. Prescriptive Ventilation Rates
(Compiled from various sources)

Reference	***Ventilation Rates***	
	$L.s^{-1}$ per person	$L.s^{-1}$per m2
BS EN 13779 2007 (referenced by CIBSE Guide A and CIBSE AM10 2014)	8	-
Building Regulation Part F 2006	10	-
BS 15251 2007 (1)	7	0.42
ASHRAE 62.1 2016 (referenced by ASHRAE Fundamentals 2017) (2)	2.5	0.3

(1) The sum of all values shall be considered
(2) Only the higher value shall be considered

The ventilation rates values indicated in Table 18 under BS 15251 (2007) corresponds to the 2nd category of occupant's expectation which is 'Normal expectations'. A description of the three categories is provided in the Section 2.3.1.

Building Regulation Part F (2006) classifies the indoor spaces into four categories according to the level of Indoor Air Quality (IAQ) as follows:(1) High IAQ with CO2 concentration lower than 400 ppm (2) Medium IAQ with CO2 concentration in the range of 400 – 600 ppm (3) Moderate IAQ with CO2 concentration in the range of 600 to 1000 ppm (4) Low IAQ with CO2 concentration above 1000 ppm. The values indicated in Table 21 under the Building Regulation Part F correspond to the 3rd category.

2.5.2.2 Performance procedures

The Performance procedures provide detailed methodologies for the calculation of the required ventilation rates based on the exact components of an indoor space, characteristics of its external envelop and conditions of the local outdoor air. The performance procedures yield more accurate results and better bases of Design. The performance calculations cover the control of the summer overheating as well as the IAQ requirements as detailed below.

Ventilation requirements to control summer over heating

ASHRAE (2017) suggests the equation in Table 19 for the estimation of the ventilation requirements for overheating control.

Table 19. Ventilation requirement to control summer over heating
(ASHRAE 2017)

	Ventilation required for overheating control
ASHRAE Fundamentals 2017	$Q_{temp} = \frac{0.007865\ q_s}{\rho \Delta T C_p}$ (35)

Where:
q_s Sensible heat load, Btu/h
Q_{temp} Air flow rate required to control the overheating, L/s
C_p Specific heat of air, $Btu/lb_m.$°F
ρ Air density, lb_m/ft^3
ΔT Temperature difference between the indoor and outdoor, °F

Ventilation requirements to control IAQ

BSI (2007) outlines three main roles for the IAQ ventilation, as follows: General ventilation in all rooms, exhaust ventilation in wet areas and fresh air in bedrooms and living rooms. In the mechanical cooling schemes, a certain percentage of the ventilation air is usually mandated to be fresh or treated air, whereas in the Natural ventilation schemes, the full amount of the air is considered as fresh air. Since that the scope of this study is limited to living rooms, the study will be investigating only the requirements of the General ventilation.

The level of acceptance of the IAQ is assessed by the level of contaminates concentration. The contaminates in an indoor space can be introduced either by contaminated outdoor air or indoor sources in the space. Table 20 presents a list of the most common contaminants, its sources and acceptable level of concentration.

Table 20. Sources of Air contaminates and acceptable level of concentration
(Compiled by ASHRAE 62.1 2016 from various sources)

Contaminant	Source	Accepted levels
Carbon Dioxide	[1][2]	1000-1200 ppm (700 ppm above outdoor level) 3500 - 5000 ppm (0.5% - 0.25% by BS 5925)
Carbon Monoxide	[1][3][4]	9 ppm
Formaldehyde	[11]	9 - 55 $\mu g/m^3$
Lead	[12][3]	1.5 $\mu g/m^3$
Nitrogen Dioxide	[1][3][4]	100 $\mu g/m^3$
Ozone	[3][6]	100 $\mu g/m^3$
PM2.5	[1][3][4][5]	15 $\mu g/m^3$
PM10	[3][9][10]	50 $\mu g/m^3$
Radon	[7]	4 pCi/L
Sulphur Dioxide	[3][14]	80 $\mu g/m^3$
VOCs	[3][4][8][15]	Var.
Odor	[1][2][3][4][5][12]	CO2 can be used as indicator

Where:

[1] Combustion appliances
[2] Occupants
[3] Outdoor Air

[9] Dust
[10] Deteriorating Material
[11] Furniture and Furnishings

[4] Parking [5] Cooking [6] Electro static appliances [7] Soil [8] New building materials and Furnishings	[12] Paint Dust [13] Sewage and bio-waste facilities [14] Unvented Space Heaters [15] Consumables & Maintenance materials

The acceptable levels of contaminants indicated in Table 20 were concluded by ASHRAE 62.1 (2016) after analysing different codes and standards. The outdoor contaminates, such as PM10, PM 2.4 and Ozone, are expected to exist only in industrial or densely developed areas with heavy traffic. In such cases ASHRAE 62.1 2016 suggests using a local air purifier to clean the indoor air from the excessive pollutants. Elsewhere, In the rural areas or less developed communities, the outdoor air is not expected to hold any concerning contaminates and it will have a composition similar to the dry air new sea side as presented in Table 21 .

Table 21. Compositions of Normal outdoor dry air composition near sea level *(Compiled from various sources)*

Content	**BS 5925**	**ASHRAE 62.1**	**ASHRAE Fundamentals**
Carbon Dioxide	0.035%	300 -500 ppm	0.04% (330 -370 ppm) Urban environment will be higher
Oxygen	20.94%	-	21%
Nitrogen	79.03%	-	78%
Argon	-	-	1%
Inert gases	traces	-	-

The contaminates highlighted in grey colour in Table 20 are those which may occur in an existing residential living room. These contaminates are summarized in Figure 6 , which is followed by a brief calculation methodology for the ventilation rates required to dissipate each separate contaminate. The BSI (1995) suggested considering the highest rate out of all calculated rates as the reference for designing the system, not the accumulative sum of all rates.

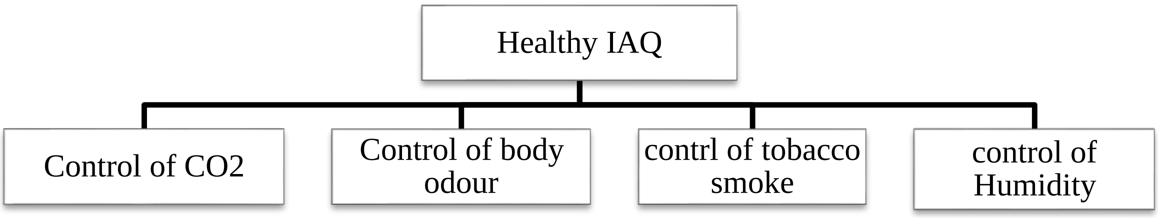


Figure 6 . Role of IAQ Ventilation in Residential Living rooms.

(Author)

<u>Control of Carbon Dioxide</u>

CIBSE (2014) claims that the level of concentration of the CO2 can be used as proxy for the evaluation of the indoor IAQ. BS (1995) urges that the most critical pollutant in an indoor space is the Carbon dioxide, and it identifies the main sources of CO2 build up in an indoor space as to be the occupants and heating appliances. Table 22 presents mathematical equations for the estimation of contaminant concentration in a living room, as well as the air flow required to dilute these contaminates.

Table 22. Ventilation requirements for the control of CO2

(Compiled from various sources)

	CO2 inflow rate	**Ventilation required to control CO2**
BS 5925 1995	$q_{co} = 0.00004MN_{oc}$ (36)	$Q_{co} = q_{co}\left(\frac{1-C_o}{C_s-C_o}\right)$ (37)
ASHRAE 62.1 2016	See Figure 7	$Q_{co} = \frac{q_{co}}{C_s-C_o}$ (38)

Where:

q_{co}CO2 inflow rate, L/s

Q_{co} air flow rate required to control the CO2, L/s

MThe Metabolic rate, W

N_{oc}The number of occupants

C_s	CO2 concentration in the space, %
C_o	CO2 concentration in outdoor air, %

ASHRAE 62.1 (2016) urges that the level of CO2 emission by occupants depends on the activity they do in the space, which is usually expressed in the Metabolic rate. Figure 7 shows the relation between the metabolic rates and the level of CO2 emissions.

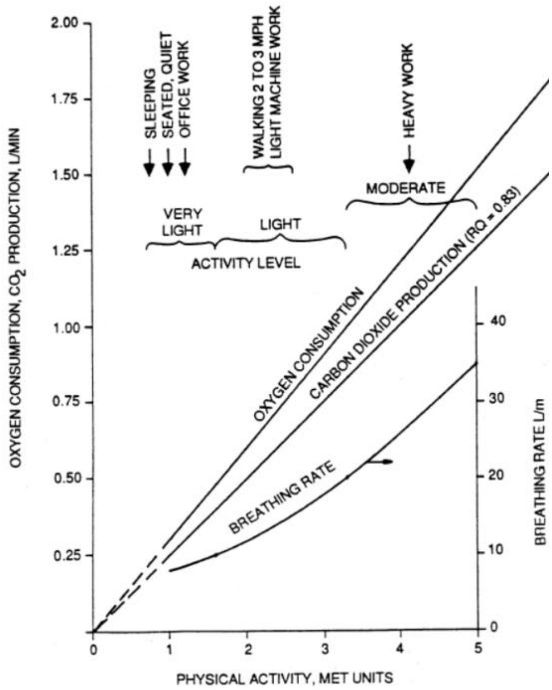


Figure 7. Relation between Metabolic rates and CO2 emissions

(ASHRAE 62.1 2016)

Control of Body Odor

BSI (1995) urges that a rate of 8 L/s of ventilation is required for each person in the indoor space to avoid inconvenient or unpleasant odors.

Removal of Tobacco smoke

BSI (1995) urges that each cigarette requires 120 m3 of air volume for the removal of the smoking Odor. The flow rates should be calculated based on the smoking duration.

Removal of Humidity

The sources of Humidity build up in indoor living space is the human respiration and outdoor saturated air. BSI (1995) urges that the production rate of water vapor by respiration is 0.05 Kg/h per person and suggests using an equation similar to the one used for the calculation of CO2 ventilation requirements.

Table 23. Ventilation requirements for the control of indoor Humidity
(compiled from various sources)

	Water vapor inflow rate	**Ventilation required for Humidity control**
BS 5925 1995	$q_{hu} = 0.05N_{oc}$ (39)	$Q_{hu} = 0.277\left[\frac{q_{hu}\left(\frac{1-C_O}{C_S-C_O}\right)}{\rho}\right]$ (40)
ASHRAE Fundamentals 2017	-	$Q_{hu} = \frac{0.007865\ q_l}{\rho \Delta W(1061+0.444T)}$ (41)

Where:
q_l Latent heat load, Btu/h
q_{hu} Humidity inflow rate, Kg/h
Q_{hu} Air flow rate required to control the Humidity, L/s
N_{oc} The number of occupants
C_s Humidity concentration in the space, kg/kg
C_o Humidity concentration in outdoor air, kg/kg
ρ Air density, Kg/m^3 (lb_m/ft^3 for ASHRAE's equation)
ΔW Humidity ratio difference between the indoor and outdoor, $lb_m water/lb_m air$
T average of Indoor and outdoor temperatures, °F

The outdoor humidity ratio C_o and ΔW can be obtained from the local weather stations while the desirable indoor humidity ratio C_s can be obtained from figure 8 by knowing the indoor temperature and relative Humidity. The air density shall be considered as 1.165 Kg/m^3 when air temperature is 30 °C.

(b)

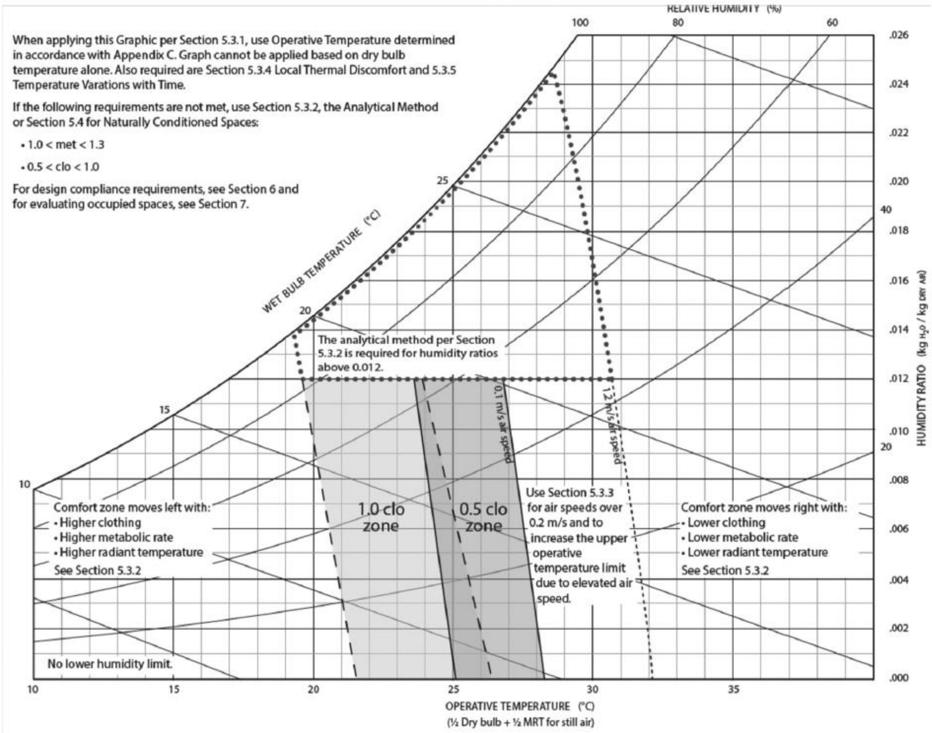


Figure 8. Acceptable range of operative temperature and Humidity for Residential buildings *(ASHRAE 55 2016)*

2.5.3 Area of Ventilation opening (A)

The design guidelines of the opening sizes are categorized under two groups according to the calculation methodology. The first group includes the Perspective methods which provide specific rates irrespective of the project's specific design conditions such as: number of occupants, level of envelope insulation and shading, orientation of the window opening in regard to the prevailing wind direction, the intensity of the solar irradiances and the external temperature. Whereas the performance tools analyze the specific conditions of the space under design and calculate the opening sizes accordingly. The references of the prescriptive and performance methods are presented in Figure 9 .

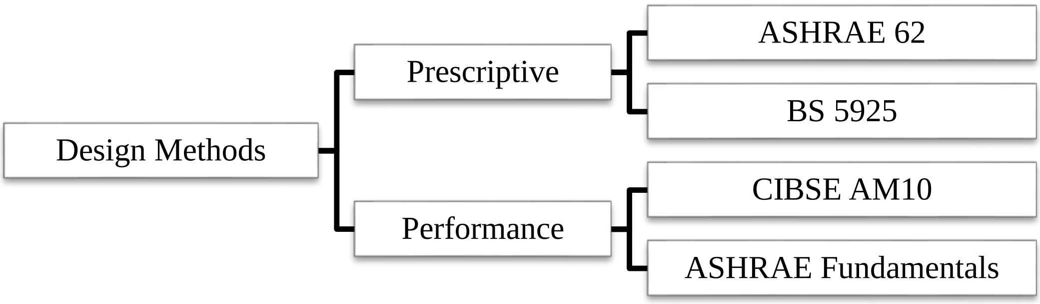


Figure 9. design Methods for sizing the ventilation openings

(Author)

2.5.3.1 Prescriptive Methods

The prescriptive values suggested by ASHRAE 62.1 (2016) and the BS 5925 (1995) are presented in Table 24

Table 24. Sizing the openings: Prescriptive values
(Compiled from various sources)

	ASHRAE 62.1	*BS 5925*
Area of Opening [(1)]	≥ 4 % of floor area	≥ 5% of floor area
Location of Opening	-	Some part at least 1.75 m above FFL

1) Openable net free unobstructed Area

The values presented in Table 24 correspond to living rooms with direct access to outdoor. The ASHRAE 62.1 (2016) values are limited to the rooms with depth of two times the room height in case of single sided ventilation or five times the room height in case of cross ventilation. The BSI (1995) values are limited to the buildings having a normal infiltration rates through adventitious cracks or background ventilation opening, and not tightly fitted with vapor barriers.

2.5.3.2 Performance Methods

The performance methods established by ASHRAE Fundamentals (2017) and the CIBSE AM10 (2014) are presented in this section.

Area of the opening - Master Equations

The opening's areas are determined through the mathematical equations presented in Table 25, with regards to the three following driving forces: Wind only, Buoyancy only and combined wind and Buoyancy forces.

Table 25. Sizing the Openings: Performance equations

(Compiled from various sources)

Reference Code	**Wind Only**	**Buoyancy only**	**Combined wind and Buoyancy**
CIBSE AM10	$A_w = \frac{Q}{C_v U_z}$ (42)	$A_b = \frac{Q}{C_d}\left(\frac{T_i+273}{\Delta T g h}\right)^{1/2}$ (43)	$A = \frac{Q}{C_d S}\left(\frac{\rho}{2\Delta p}\right)^{1/2}$ (44)
ASHRAE Fundamentals	$A_w = \frac{0.001\ Q}{C_v U_z}$ (45)	$A_b = \frac{0.0015\ Q}{C_d}\left(\frac{T_i}{2\Delta T g \Delta H_{NPL}}\right)^{1/2}$ (46)	$A = \frac{0.00012\ Q}{C_d}\left(\frac{\rho}{2\Delta p}\right)^{1/2}$ (47)

Where:

$\Delta p$is the pressure difference across the opening, Pa (in. of water for ASHRAE's equations)

ρis the air density Kg/m^3 (lb_m/ft^3 for ASHRAE's equation)

$U_z$is the reference wind speed at height z, m/s (mph for ASHRAE's equations)

C_d is the discharge coefficient

AEffective area of the opening, m^2

A_w Effective area of the opening for wind calculation, m^2

A_b Effective area of the opening for buoyancy calculation, m^2

ΔT is the difference between the internal and the external Temperatures, K (°R for ASHRAE's equations)

T_i is the indoor temperature, ℃ (°R for ASHRAE's equations)

h is the height of the opening (incase of single opening), or the height between the centerlines of the two openings (in case of two openings),m

C_v effectiveness of the opening

H_{NPL} is the height of the Neutral plane, ft

Q is the ventilation Flow rate m3/s (cfm for ASHRAE's equations)

S is the is the sign of the pressure difference.

g is the gravitational force per unit mass, m/s^2 (Type equation here. for ASHRAE's equations)

The effectiveness of an opening $C_v$is estimated by ASHRAE (2017) as 0.5 to 0.6 for the openings perpendicular to wind direction and 0.25 to 0.35 for the openings inclined to wind directions. While CIBSE (2014) urges that the reported values of this coefficient ranges between 0.01 to 0.05.

The neutral plane is the plane at which he pressures difference is zero. ASHRAE fundamental (2017) urges that the Neutral plane in a space with a single window opening is assumed to be at the mid height of this opening. In this case the ΔH_{NPL} shall be assumed as half the height of this window opening.

If thermal stratification is occurring inside the ventilated spaces, ASHRAE (2017) suggests taking an average value for T_i.CIBSE (2014) urges that the difference between the internal and the external Temperatures ΔT should be estimated based on the historical weather information and the actual internal heat gains of the space. However, it also claims somewhere else that such difference should be assumed as 3 K for spaces with height of 2.75 m approximately, disregarding the magnitude of the internal heat gains.

The resultant area shall be considered as the clear, effective or equivalent area of the opening. The ventilation rates shall be obtained from the calculation procedures outlined in section 2.5.2. The air density is dependent on the air temperature and it shall be obtained from the local metrological data. The sign of the pressure difference S is positive for the inlet openings and negative for the outlet openings. The details of other factors such as Wind speed (U_z), Pressure Differences (Δp_i) and Discharge Coefficients (C_d) are presented hereafter.

Wind speed (U_z),

The wind speed at height z shall be estimated in accordance to the equations described in Table 26.

Table 26. Wind speed calculations

(Compiled from various sources)

	Wind Speed
CIBSE AM10 2014	$U_z = U_{met} K z^a$ (48)
ASHRE Fundamentals 2017	$U_z = 0.44704\, U_{met} \left(\frac{\delta_{met}}{z_{met}}\right)^{x_{met}} \left(\frac{z}{\delta}\right)^{x}$ (49)

Where:

U_z is the wind speed at height z, m/s
U_{met} is an equivalent wind speed measured at height of 10m in open country side, m/s (mph for ASHRAE's equations)
z is the height above ground, m (ft for ASHRAE's equations)
K and a are the Terrain constants
δ_{met} meteorological atmospheric boundary layer
x_{met} meteorological atmospheric exponent
z_{met} is the height at which U_{met} is measured, ft
δ is the local atmospheric boundary layer thickness, ft
x is the local atmospheric exponent

The reference wind speed U_{met} is typically measured at height Z_{met} of 10 m (33ft) and its value should be obtained from maps or tabulated metrological records. BSI (1995) recommends considering only the values that are exceeded for 50% of the time. The height z is measured from the grade level up to the center line of the vertical opening or up to the air outlet. The Terrain Coefficients K and a are dependent on the development density of the local building under design. Table 30 provides typical values of these coefficients for four different terrains.

Table 27. Terrain Coefficients – CIBSE AM 10 2014

(Baker N V – - referenced by CIBSE AM 10)

	Terrain	*K*	**a**
1	Open flat country	0.68	0.17
2	Country with scattered wind	0.52	0.2
3	Urban	0.35	0.25
4	City	0.21	0.33

Typical values of the local atmospheric boundary layer δ and the exponent x, and the meteorological atmospheric boundary layer δ_{met} and the exponent x_{met} are presented in Table 28. The meteorological measurements are typically taken in an open terrain (category 3).

Table 28. Atmospheric boundary layer conditions
(ASHAE 2017)

	Terrain	x	δ
1	Large city centers (buildings height more than 80 ft)	0.33	1500
2	Urban and sub urban areas	0.22	1200
3	Open terrain with scattered obstructions (height less than 30 ft)	0.14	900
4	Flat unobstructed areas	0.10	700

Pressure Differences (Δp_i)

It defines the pressure difference across the opening i

Table 29. Pressure Differences Calculations
(CIBSE AM10 2014)

Reference Code	**Combined wind and Buoyancy**
CIBSE AM10	$\Delta p_i = \Delta p_0 - \Delta \rho_0 \, g z_i + 0.5 \, \rho_0 \, U_z^2 \, C_{wi}$ (50)
	$\sum \Delta p_i = 0$ (51)
	$\Delta \rho_0 = \rho_0 \left(\frac{\Delta T}{T_E + 273}\right)$ (52)

Where:

Δp_i is the pressure difference across the opening i, Pa
ρ_0 is the air density Kg/m^3
U_z is the reference wind speed at height z, m/s
C_{wi} is the wind pressure coefficient at opening i
z_i is the height of opening i above the ground, m
$\Delta \rho_0$ is the density difference at the ground level, Kg/m^3
g is the gravitational force per unit mass, m/s^2
Δp_0 is the pressure difference at ground level, Pa
ΔT is the difference between the internal and the external Temperatures, K
T_E is the external temperature, °C

Wind pressure coefficient (C_w)

It defines the drop in wind pressure due to the Building's Form and Surroundings. The building surroundings may include the adjacent buildings, Hard and Soft scape elements, fencing and any other obstructions. It is also highly affected by the Urban Density and topographic features such as valleys and mountains

The wind pressure coefficients can be estimated from the graphs developed by Davenport and Hui (1982) where the distribution of the wind pressure on each facade is represented in the form of contour lines. The graphs were prepared for a high-rise building located in an Urban Terrain.

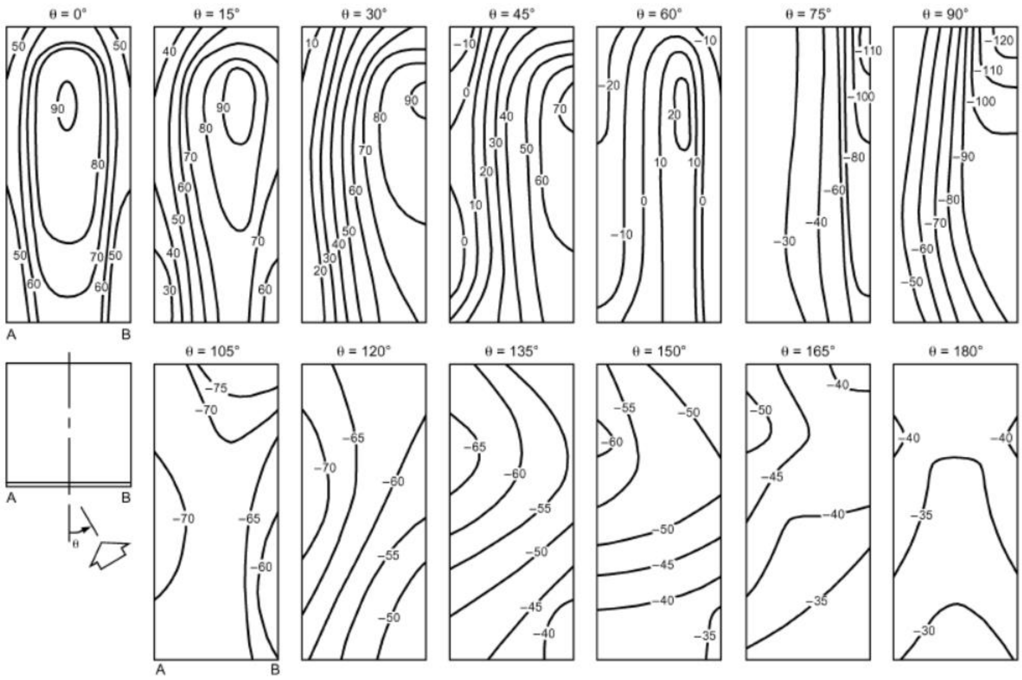


Figure10. Wind pressure coefficient

(Davenport and Hui 1982's - referenced by ASHAE Fundamentals 2017)

Another C_w determination methodology is suggested by BS (1995), but it is less précised method than Davenport and Hui (1982)'s method as it assumes a uniform wind pressure distribution across each façade, and disregards the variation in wind distribution across the façade.

If the building has sharp edges the pattern of air flow for a specific wind direction is independent of the wind speed, and hence C_w is independent of the wind speed.C_w is used to calculate the surface pressure at a specific point of the building envelope. Neglecting this factor in the design process will lead to the External wind speed being assumed unrealistically in the calculations, which will consequently leads to unrepresentative outcome.

Discharge Coefficients ($\boldsymbol{C_d}$)

ASHRAE (2017) urges that the discharge coefficient accounts for all viscous effects such as the surface drag and interfacial mixing. Holford and Hunt (2001) carried out an experimental study and observed that $\boldsymbol{C_d}$is dependent on the Reynolds number (Density contrast) across the opening. Large densities contrast may reduce $\boldsymbol{C_d}$ significantly. For horizontal openings, the $\boldsymbol{C_d}$ will remains constant with small buoyancies (densities), while with larger buoyancies, the $\boldsymbol{C_d}$ decreases as the buoyancy increases. Whereas for vertical opening, the $\boldsymbol{C_d}$ decreases as the buoyancy increases above zero.

Table 30 presents two estimation methods for the $\boldsymbol{C_d}$. The CIBSE (2014) method is more of a prescriptive method while the ASHRAE (2017) is a performance method. Other sources suggested by CIBSE (2014) for the estimation of $\boldsymbol{C_d}$is the manufacturer data sheets, computational fluid Dynamics CFD, Tabulated loss coefficients (used for the calculation of Mechanical pressures loss) and scaled models.

Table 30. Discharge coefficients
(compiled from various sources)

	Bidirectional air flow (Single opening)	**Unidirectional Air flow (cross ventilation)**

CIBSE AM10	0.25	0.6
ASHRE Fundamentals	$C_d = 0.40 + 0.0025(T_i - T_o)$ (53)	0.65

Where:

C_d is the discharge coefficient
T_i is the Indoor Temperature, $°R$
T_o is the Outdoor Temperature, $°R$

Holford and Hunt (2001) urges that using a simplified estimation method will result into unrealistic flow rate predictions, which might reach up to 16% greater than the true values according to an experimental study.

Chapter III.

Methodology

The methods used currently for the evaluation of Natural ventilation systems will be presented and discussed in this section. Each method has its own strengths and limitations, which makes it more applicable for a specific purpose than the other. The discussion in this chapter will focus on the applicability and relevance of each method to various applications, ventilation schemes and/or different design stages.

3.1 Overview of Evaluation Methods

Four methods are presented in this section as being the most common methods used currently, which are: Empirical methods, Computational fluid dynamics, Experimental methods and Combinations of these methods.

3.1.1 Empirical methods

These methods depend on mathematical equations for the calculation of openings' sizes, given the air flow rate to be pursued. The calculations take in consideration numerous factors, such as wind speed, wind pressure, air density, indoor and outdoor temperatures. These factors represent the environmental conditions of the building under design, and they are described in detail in Chapter 2 due to their relevance to this study.

3.1.2 Computational Fluids dynamics

The CFD is a rapidly evolving tool which simulates the air movement in indoor and outdoor spaces. It uses turbulences models to simulate the actual behavior of air movements. The input parameters in CFD simulation tool are divided into two main divisions: Building geometry and Boundary conditions. The geometry includes the shape of the building, locations and sizes of the openings and the specification of the building materials. The Boundary conditions cover all other parameters, such as the wind, temperature, air turbulence, solar irradiance and pressure. The CFD simulates the air flow at the specific points in the model based on a virtual grid or mesh that is applied either automatically by the software or customized by the modeler.

3.1.3 Experimental methods

The Experiments methods depend of physical model to understand the behavior of air flow under specific conditions. The physical models are subdivided into two divisions as follows:

3.1.3.1 Small scale experiments

These experiments use scaled physical models that are constructed in a lab facility to test the air flow. The source of wind in this type of experiments is usually a fan that flows air at different speeds and angels. A common application of this type is the wind tunnel test which is used frequently to measure the pressure on tall buildings.

3.1.3.2 Large scale methods

This type of experiments uses a full-scale model to test the behavior of air flow. The full-scale model can be either an the actual building being studied, or a full scale model that is constructed in a lab facility for the testing purpose. The source of wind in this type of experiments is usually the natural wind, and the means of wind measurements are either anemometer devices or thermal images of tracer gas.

3.1.4 Combined Methods

It is also common that two or more methods are combined together to address a certain evaluation requirement, examples of which are listed below.

3.1.4.1 CFD and Network Air flow models

The Network air flow models were developed to study the air flow between different zones of the building. They assume that each zone has a node in its center and they study the air flow between these nodes. This type of combinations is useful for the evaluation of entire buildings.

3.1.4.1 CFD and Building Energy simulation models

The Building energy simulation tools are used to study the energy performance of the building. The details of all energy consuming fixtures in the building should be inserted in the software, which then simulates the overall energy performance of the building.

3.1.4.2 CFD and Experimental

In such combinations, the experiments are carried out in the early stage of the evaluation process to validate the accuracy of the CFD results. The accuracy validation covers the reliability of the selected software, correctness of the simulation settings, boundary conditions and wind turbulence settings. After the CFD simulation has been validated, the software can then be used to test numerous options and determine the air flow performance in each option with a great confidence in its results.

3.2 Comparison between Evaluation methods

For the three main methodologies presented above, the cost, time, accuracy and limitations for each one will be discussed in this section with respect to natural ventilation applications.

Table 31. Comparison between Evaluation methods

(Author)

	Empirical	CFD	Experimental
Cost	Low	Medium	High
Time	Low	Low	High
Accuracy	Low	Medium	High
Limitations	High	Low	High

The least costly method is the empirical calculation, as it involves no special tools or specialists. The CFD is the second lowest method in terms of cost as it involves only the software price and computer hardware. In some cases, it's required to appoint a CFD specialist in the project team depending on the project complexity, which applies an additional cost to the process. However, the knowledge of CFD is spreading day after the other and many project Architects and Mechanical engineers have started simulating their projects on their own. One main reason for that is the new Interface adopted by many software developers, which has become more user friendly and less complicated. In most of the cases, the Experimental methods have the highest ranking in terms of price, especially when they are carried in a lab where the physical model is constructed from scratch and measuring tools are rented or bought to measure the parameters being examined. The experiments carried out in existing buildings are less costly than the lab experiments as it involves only the cost of renting or buying the measuring tools.

The ranking above is turned the other way round when it comes to Accuracy. The Experimental methods have the highest level of accuracy due to the high resemblance of the experiment domain to the actual conditions. The lab experiments are less accurate than the field experiments due to the scale factors and variances from the actual weather conditions, which might lead to some deviations in the results. The CFD methods are slightly less accurate than the field experiments due to difficulties in mimicking the actual turbulence conditions of natural wind in the computer-based tool. The level of CFD accuracy is dependent on the accuracy of the simulation programme and professionality of the modeler. Omrani (2017) urged that the correct modeling inputs are more crucial than the selection of the simulation programme. The Empirical methods is the least accurate method due the limitations of the mathematical equations and the high amount of theoretical assumption that are made in such calculations.

Limitations of the method refer to its applicability for examining different options of building geometries and different weather conditions. The limitations also cover the level of complexity of the building that can be tested by the respective method. From this perception, the CFD comes at the top of the list with the least level of limitations, followed by the empirical and Experimental methods respectively.

3.3 Selected Method

One of the main objectives of this research is to evaluate the accuracy of the Empirical methods, which have already been questioned by Haung (2017), Ai and Mak (2014) and Peizhe (2016) as elaborated in section 2.1, hence, these methods cannot be used as the evaluation tool in this study.

Another objective of this research is to propose multiple enhancement options, which will also need to be tested to understand their performance quantitively. hence the experimental methods cannot be used solely as the evaluation method due to their limitations in testing alternatives and options.

The Network airflow models cannot provide detailed results about the air flow in a single zone as urged by Tan (2005), and it cannot be used for outdoor simulations neither.

Van Hooff (2017) urged that the experimental studies are essential to determine the most suitable settings of CFD simulation. The researcher compared between different settings to assess the level of accuracy of each one. The case study used in the simulation was selected from the literature based on the availability of wind tunnel results. The readings recorded during the wind tunnel experiment were used by Van Hooff (2017) to validate the accuracy of various turbulence settings in simulating five wind parameters: mean velocity, turbulent kinetic energy, ventilation flow rater, incoming jet angle and spreading width. The researcher found that each different turbulence setting has resulted into the most accurate result for one of the five parameters, the matter which concluded the necessity of validation experiments for an accurate CFD simulation.

Based on the criteria outlined above and since that the case study is an existing apartment, it was found that the best tool to be used in this study is the combined method of CFD and field Experiment. The field experiment will be used to validate the CFD results and determine the most accurate simulation settings, while the CFD will be used to simulate and examine the various options and proposal being studied in this research. This combination was also recommended by Omrani (2017) who has reviewed many evaluation methods and concluded the combined CFD and field Experiment method yields the best reliable results.

Chapter IV.

Case Study Analysis

4.1 Case Study

4.1.1 Description

The case study is an existing residential apartment in Egypt's capital – Cairo. The apartment occupies quarter the area of the fourth floor in an eight-story building. The building is located in a semi congested neighborhood with a mix of attached and standalone buildings. Figure 11 illustrates the location of the case study apartment in the context of the neighborhood.

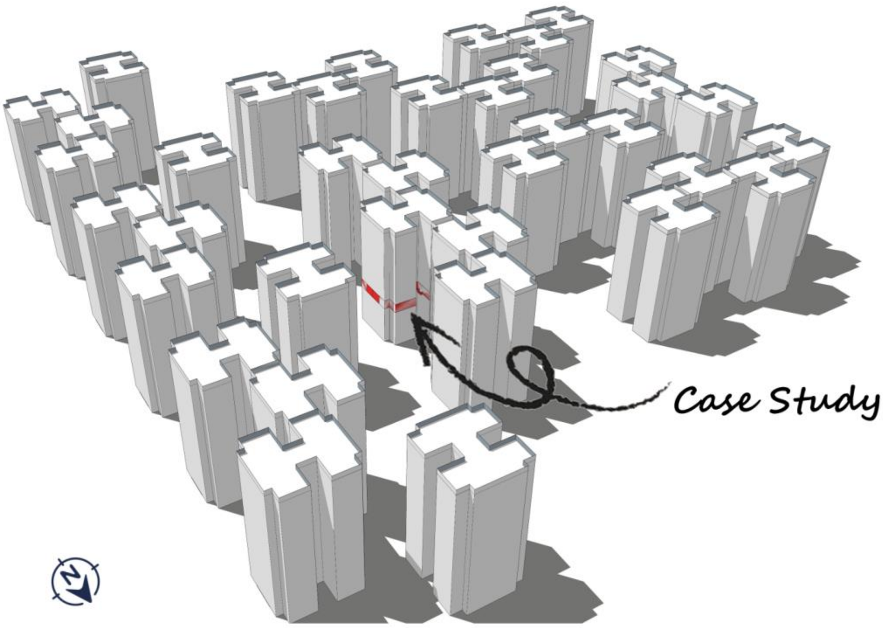


Figure 11. Case Study – Site context

(Author)

The apartment is composed of a living room, 3 bedrooms, Kitchen and a toilet with a total area of 91.5 m2. As discussed in Chapter I, the study will be limited to the living room as a sample of residential livable spaces. The area of the Living room in the case study apartment is 32 m2 and it has a north-east window with an area of 5.6 m2 and a maximum opening area of 2.8m2. The living room is having one external wall and three internal walls, one of which is common with kitchen. The common wall with the kitchen is having a big opening as per the existing setup, which will be considered as closed in this study due the different internal boundary conditions of the living room compared to the kitchen. The living room is attached to two small lobbies, one of each is serving as the main entrance of the apartment and the other is an internal lobby leading to the bedrooms and then toilet. For the purpose of this study, all doors located at these two lobbies leading to the rooms will be considered as closed during the simulation.

An isometric plan of the existing case study apartment is shown in Fig 12 with a highlight on the living room under study.

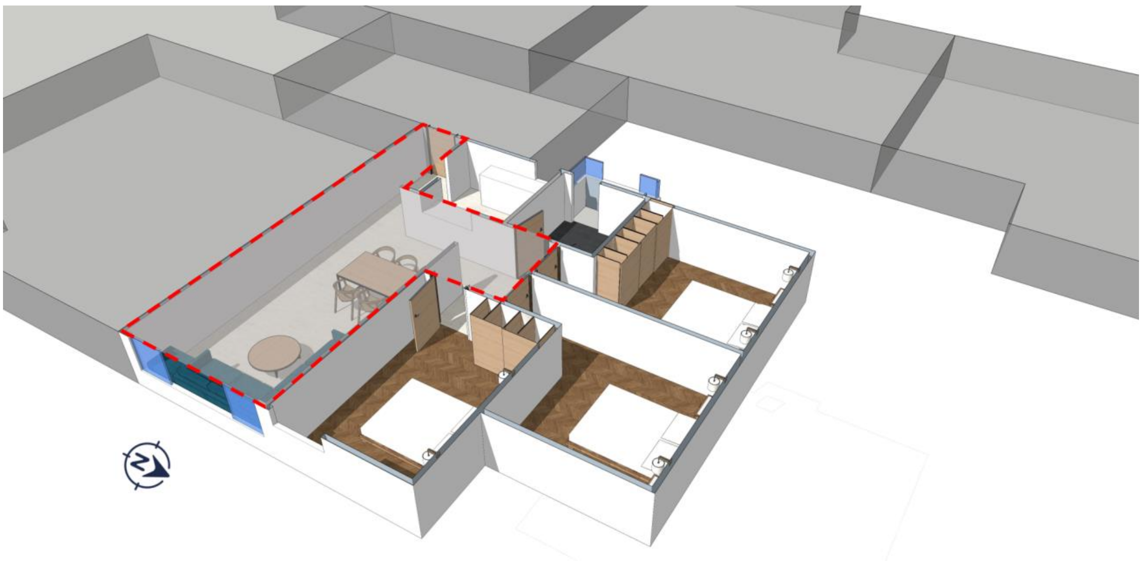


Figure 12. Case Study Apartment

(Author)

4.1.2 Local Climate

Cairo is located at latitude 30.13 and longitude 31.4, with a climate zone classification of 2B as per ASHRAE 90.1(2016) which refers to a hot dry weather conditions. Figure 13 illustrates the different climate zones across the world as established by ASHRAE 90.1.

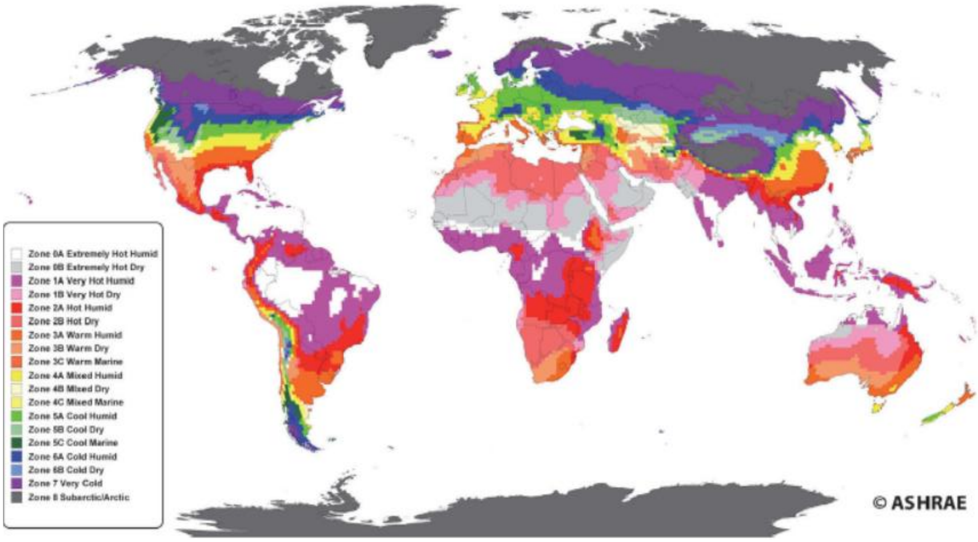


Figure 13. World climate zones

(ASHRAE 90.1 2016)

According to ASHRAE 90.1(2016) the hottest month in Cairo is August. The temperature, wind speed and solar irradiances of August as well as the average values of the full year are elaborated in Table 34. The table also presents the extreme values over the full year. Since that this study is aiming to improve the natural ventilation in the hot seasons, August average values will be used as reference for the sizing of the system components.

Table 32. Cairo climate – August

Source: ASHRAE Fundamentals 2017 (except shaded cells which are obtained from CIBSE Guide A 2017)

	Average	low	high
Dry bulb Temp	302.35 K 84.6 F 29.2 °C		315.09 K 107.5 F 41.94°C
Daily Dry bulb range (K)	10.5		
Wind speed (m/s)	3.35		
Humidity	66 % 17.8 g/kg dry air	62 % 17 g/kg dry air	70 % 18.2 g/kg dry air
Enthalpy (Kj/Kg)	92.8	90.7	95.36
Diffuse Solar irradiance at east façade (W/m^2)	-	-	166
Direct Solar irradiance at east façade (W/m^2)	-	-	650
Total Solar irradiance at east façade (W/m^2)	-	-	816
Total Solar irradiance at east façade (W/m^2)	186	-	793
Air Density (Kg/m^3)	1.1644 -1.2	-	-
Specific heat of air ($Btu/lb_m.°F$)	0.24	-	-

The prevailing wind directions during the month August is elaborated in Figure 14 according to the climate consultant software which retrieves its information from the US department of Energy’s data base. It can be noticed that the prevailing wind direction is the North, followed by less wind frequencies from the North west and the North East

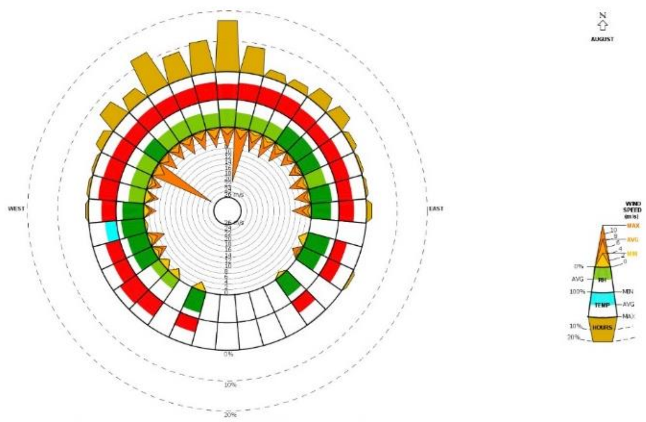


Figure 14. Cairo wind wheel – August

(Climate consultant)

4.1.3 Selection Criteria

The case study was selected based on the criteria elaborated in figure 15.

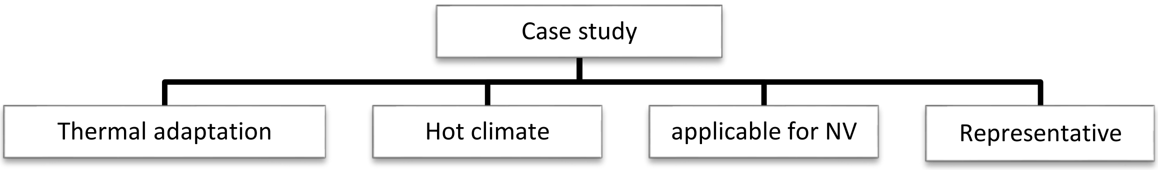


Figure 15. Case Study Selection Criteria

(Author)

The Residential type of use was selected for this study due to the flexibility of it's occupants to adapt to the varying thermal conditions. The adaptive thermal comfort is usually adopted by the residential occupants through controlling the level of clothing and the timing in which they carry out the heavy activity. ASHRAE 55 (2016) highlighted the importance of giving the occupants control over the operable windows for the effectiveness of a natural ventilation system. In other type of uses, where it is difficult for the occupant to take control over these parameters, applying the natural ventilation system will be less practical and consequently less beneficial. The residential places are also featured by the extended stay of the occupants compared to other type of places, which makes the benefit of enhancing the natural ventilation system more meaningful and advantageous.

The attention was also given to the applicability of the case study to Natural ventilation. Figure 16 shows the ventilation scheme' selection chart established by CIBSE (2014) with a red marking on the compliance criteria of the case study.

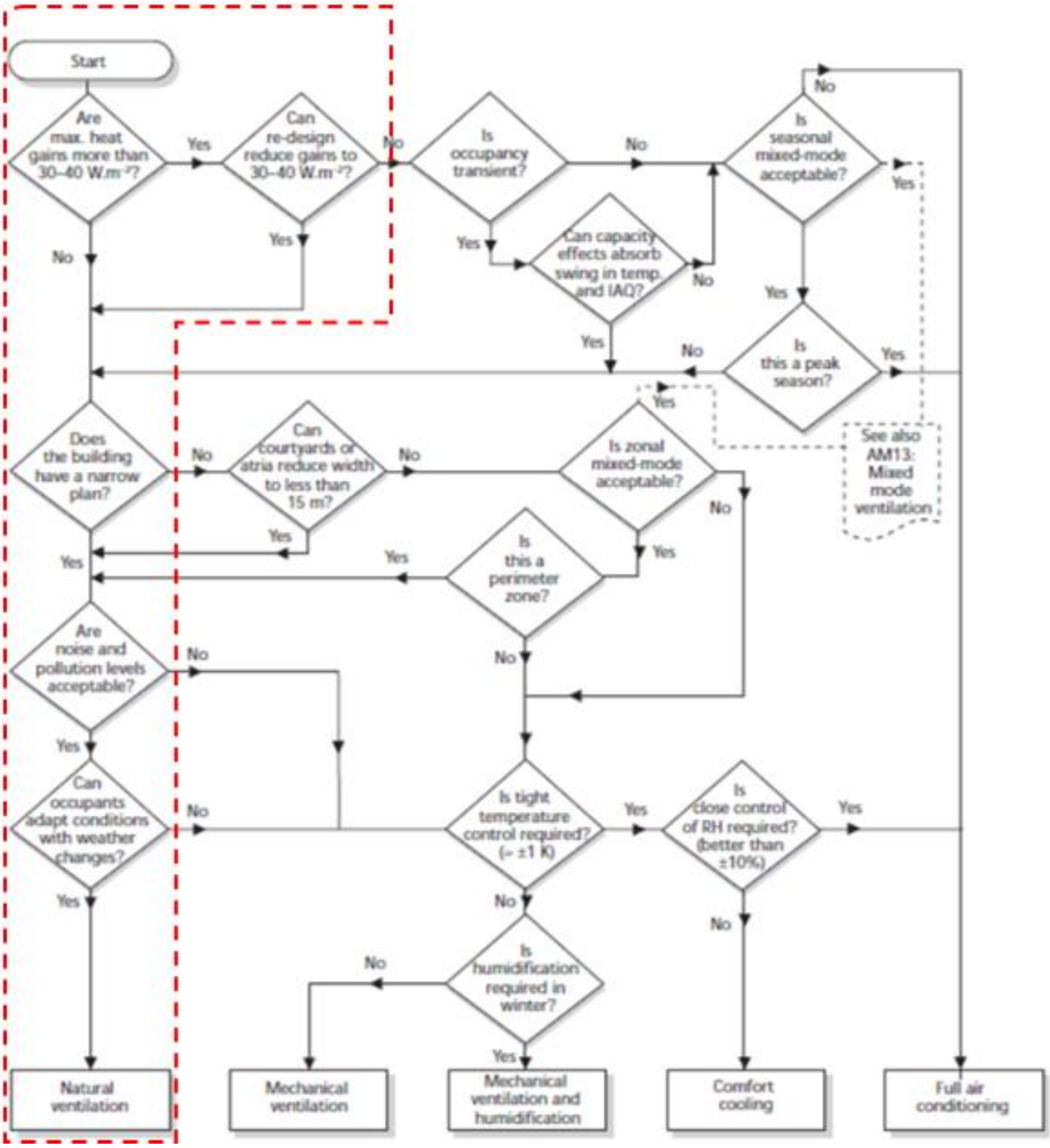


Figure 16. Selection of Ventilation Strategy

(CIBSE 2014)

The location was selected in Egypt's capital – Cairo, as one of the hot climate countries according to ASHRAE 90.1 (2016).

Lastly the case study was selected in a semi congested neighborhood, with a single window overlooking a narrow street and oriented away from the free wind stream, which makes it a representative sample to a wide range of the residential units in Egypt as urged by AbdelRahman (2017).

4.2 Heat Gains and Internal Temperature

The expected Sensible heat gains in the case study were calculated twice for insulated and non-insulated envelope scenarios. This is to examine the effect of insulation on the performance of air flow. The latent heat gains, the average internal temperature and peak internal temperatures were also calculated in accordance to the codes cited in Table 33, in which the results of these calculations are presented.

Table 33. Final Space Heat gains and Indoor Temperature
Source: Author

	CIBSE Guide A 2018		ASHRAE Fundamentals 2017		
			Sensible		Latent
	without Ins.	with Ins.	Without Ins.	with Ins.	
Internal Gain	-	-	9.2 w/m^2	9.2 w/m^2	75 w
External Gains	-	-	8.45 w/m^2	0.46 w/m^2	-
Ventilation Gains	-	-	27.6 w/m^2	27.6 w/m^2	4120 w
Total	-	-	**45** w/m^2	**37.34** w/m^2	**4195** w
Indoor Temperature	32 °C to 51 °C	31°C to 46 °C	-	-	-

The external gains of the transparent surfaces in the non-insulation scenario were based on a1/8 inch single operable glass, with aluminum framing and vertical installation, and without thermal break. Whereas the Insulation scenario was based on a 1/2 inch double low e glass (e=0.05) operable glass with argon fill and vertical installation, and wood framing with thermal break. The external gains of the opaque surfaces in the non-insulation scenario were based on 8-inch Light Weight Cement Masonry Units with fill insulation. The Insulation scenario was based on the same configuration in addition to a layer of R-22 batt insulation and gypsum boards. The technical data of these materials is elaborated in section 2.5.2. The Sensible heat gains will used to calculate the minimum ventilation requirements for overheating control while the Latent heat gains will used to calculate the minimum ventilation requirements for Humidity control.

It is assumed that the rooms adjoining the case study room are having the same operative temperature and hence no heat gains were assumed from the separating partitions. The Sol-air temperatures required by CIBSE Guide A (2017) to calculate the Internal temperature were estimated based on ASHRAE Fundamentals' equations, which led to mean and peak values of 39.2 °C and 71.1°C respectively for the non-insulated option and 34.2 °C and 50.2°C respectively for the Insulation option. The non-insulated and insulated values correspond to dark and light paints respectively. The Insulated option also considered the presence of an overhang for shading, with a depth of 1 m and vertical displacement of 0.1 m above the window.

4.3 Design Ventilation rates

The required ventilation rates were calculated based on the performance and the prescriptive procedures outlined in section 2.5.2 and the results are summarized in Table 34.

Table 34. Final Ventilation requirements

(Author)

	Performance				Prescriptive
	Temperature	Carbon dioxide	Body Odour	Humidity	
BS 13779 2007 (referenced by CIBSE Guide A 2007 and CIBSE AM10 2014	-	-	-	-	32 l/s
Building Regulation Part F 2006	-	-	-	-	40 l/s
BS 15251 2007	-	-	-	-	28 l/s
ASHRAE 62.1 2016 (referenced by ASHRAE Fundamentals 2017)	-	4.34 l/s	-	-	19.6 l/s
BS 5925 1995	-	4.34 l/s	32 l/s	8.0 l/s	-
ASHRAE Fundamentals 2017	6.33 l/s	-	-	24.1 l/s	-

The following assumptions were made for the performance calculations:

- The space is not newly constructed, or if newly constructed, a proper flush out activity has been performed after construction to remove the VOCs emitted by new furniture and finishing materials.
- No tobacco smokes.
- No outdoor contaminates. In case existed intermittently, it is assumed that a local purifier will be used as suggested by ASHRAE 62.1 (2016)

4.4 Baseline and Design Cases

The baseline and a total of 15 design cases will be analyzed to understand the performance achieved by each case. The Baseline represents the exiting case study conditions. The design cases are divided in to three groups, Group one includes the cases that are designed after the codes and standards, while Groups two and three include the enhancement proposals.

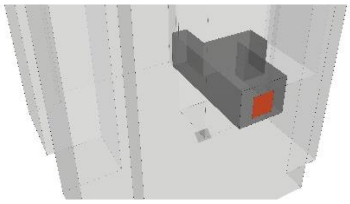
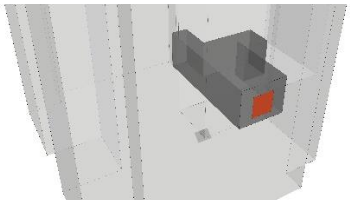
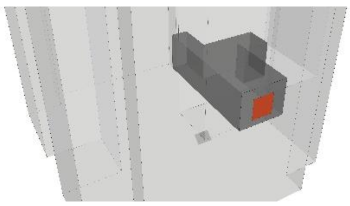
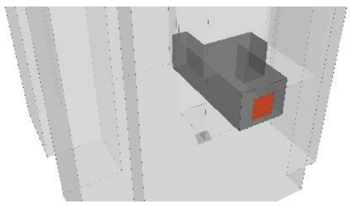
The first two cases in Group number one were designed and sized according to the prescriptive guidelines presented in sections 2.4.3, 2.4.4 and 2.5.3.1. Design cases number three and four were designed according to the performance guidelines presented in sections 2.4.1, 2.4.2 and 2.5.3.2. The sizes of the openings of the performance-based design cases were calculated three times for the three following conditions: Buoyancy only, wind only and combined wind and buoyancy, and the biggest sizes were selected. For the CIBSE AM 10 (2014) these values were 1 m^2,0.81 m^2 and .089 m^2 respectively. For the ASHRAE Fundamentals (2017), these values were 0.23 m^2,0.16 m^2 and 0.88 m^2 respectively. The solar gains were calculated based for east facing orientation according to the case study. The delta T value considered as 3 °C as recommended by CIBSE AM10 (2014). The targeted ventilation rate was taken as 40 l/s, as it is the highest calculated rate as presented in table 35.

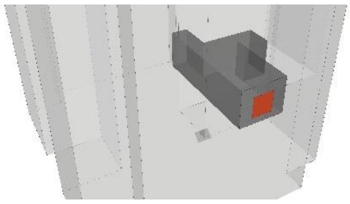
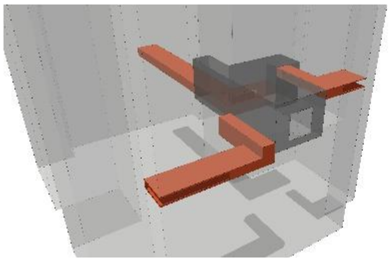
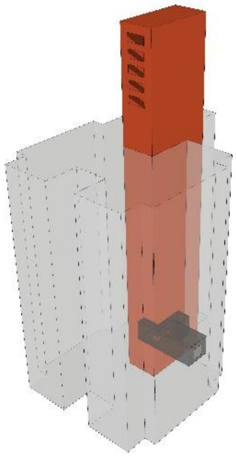
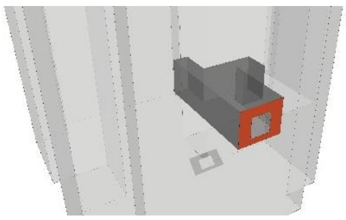
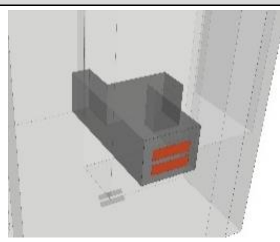
Group number two included six design cases representing six enhancement proposals to raise the performance of Group one's design cases. The six proposals are then combined incrementally in Group three, which includes five design cases representing an incremental combination of these proposals together, until they are all combined in a single design case at the end.

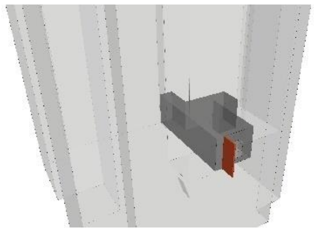
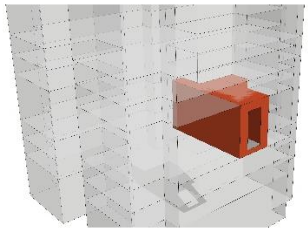
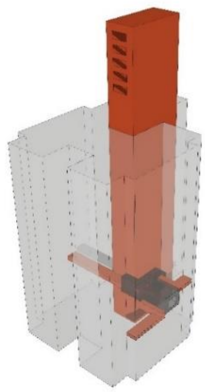
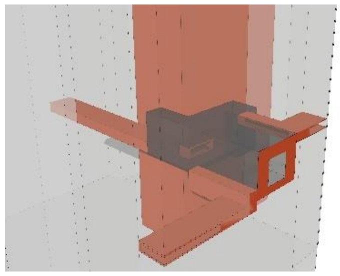
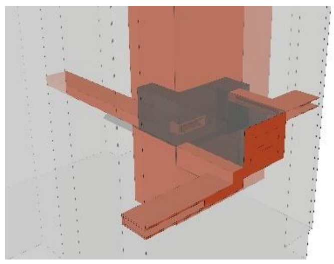
Table 35 presents the details of the common and the variable factors among the different design cases, and it also shows the references after which each case was designed. The features of each design case and the related illustration image are also presented in the table.

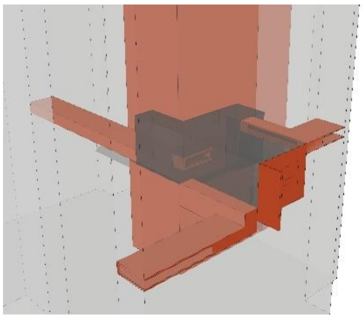
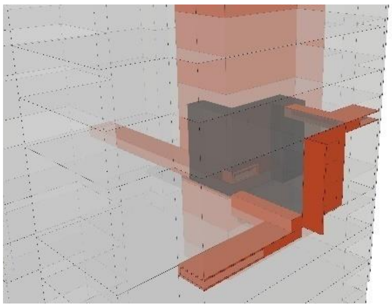
Table 35. Design Cases Description

(Author)

A	Common Factors		
1	Room Volume	86.4 m^3	
2	Room floor area	32 m^2	
3	Area of external walls	5.35 m^2	
4	Area of all internal surfaces	145 m^2	
5	Occupancy pattern	Occupied 9:00 -15:00 by 2 persons and 19:00 -22:00 by 4 persons	
B	Variable Factors		
1	**Baseline**: Existing		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 2.8 m^2	
	Internal Clear height	2.7m	
	Specific features	-	
2	**Design Case 1:** ASHRAE 62.1 2016		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 1.3 m^2	
	Internal Clear height	2.7m	
	Special features	-	
3	**Design Case 2:** BS 5925 1995		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 1.6 m^2	
	Internal Clear height	2.7m	
	Special features	-	
4	**Design Case 3:** CIBSE AM 10 2014		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 1m^2	
	Internal Clear height	2.7m	
	Special features	Thermal Insulation and External Shading	

5	**Design Case 4:** ASHRAE Fundamentals 2017		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening $0.88m^2$	
	Internal Clear height	2.7m	
	Special features	-	
6	**Design Case 5:** Air Ducts		
	Ventilation Scheme	Cross vent.	
	Openings' numbers and sizes	4 openings 2 nos:2.8 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	2.7m	
	Special features	Air ducts	
7	**Design Case 6:** Stack		
	Ventilation Scheme	Stack vent.	
	Openings' numbers and sizes	2 openings 2.8 m^2 each	
	Internal Clear height	2.7m	
	Special features	Stack	
8	**Design Case 7:** Enhanced Insulation		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 2.8 m^2	
	Internal Clear height	2.7m	
	Special features	Thermal Insulation and External Shading	
9	**Design Case 8:** Single side double opening		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	2 openings 1.6 m^2 each	
	Internal Clear height	2.7m	
	Special features	Double openings	

10	**Design Case 9:** Wing wall		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 2.8 m^2	
	Internal Clear height	2.7m	
	Special features	Wing wall	
11	**Design Case 10:** Increased Floor Height		
	Ventilation Scheme	Single Side	
	Openings' numbers and sizes	1 opening 6.1 m^2	
	Internal Clear height	5 m	
	Special features	Increased floor Height	
12	**Design Case 11:** Air ducts + Stack		
	Ventilation Scheme	Cross Venti.+ Stack	
	Openings' numbers and sizes	4 openings 2 nos: 2.8 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	2.7m	
	Special features	Air ducts + Stack	
13	**Design Case 12:** Air ducts + Stack + Insulation		
	Ventilation Scheme	Cross Venti.+ Stack	
	Openings' numbers and sizes	4 openings 2 nos: 2.8 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	2.7m	
	Special features	Air ducts + Stack + Insulation	
14	**Design Case 13:** Air ducts + Stack + Insulation + SSD		
	Ventilation Scheme	Cross Venti.+ Stack	
	Openings' numbers and sizes	5 openings 1 nos: 2.8 m^2 2 nos: 1.6 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	2.7m	
	Special features	Air ducts + Stack + Insulation + SSD	

15	**Design Case 14:** Air ducts + Stack + Insulation + SSD + Wing wall		
	Ventilation Scheme	Cross Venti.+ Stack	
	Openings' numbers and sizes	5 openings 1 nos: 2.8 m^2 2 nos: 1.6 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	2.7m	
	Special features	Air ducts + Stack + Insulation + SSD + Wing wall	
16	**Design Case 15:** Air ducts + Stack + Insulation + SSD + Wing wall + Increased floor height		
	Ventilation Scheme	Cross Venti.+ Stack	
	Openings' numbers and sizes	5 openings 3 nos: 2.8 m^2 each 2 nos: 0.93 m^2 each	
	Internal Clear height	5 m	
	Special features	Air ducts + Stack + Insulation + SSD + Wing wall + Increased floor	

4.5 CFD Simulation

The Autodesk CFD (2018) software will be used to simulate the various design cases and determine the performance of the natural ventilation system in each design cases.

The size of the domain enclosing the building under study was determined based on the Autodesk recommendation for the width, depth and height to be 5, 6 and 3 times the respective building dimension respectively. The depth should be assumed parallel to the wind direction and the building should be located closer to the wind inlet.

The heat gains inside the room will be represented as distributed load over the floor area, rather than point sources. This assumption follows the recommendations made by ASHRAE (2017) and CIBSE 2017 in regard to the distribution of the heat gains inside the rooms, which assumes that not all of the heat gains are emitted directly to the rooms air, Alternatively, some portions of the heat gains are transmitted from the sources to other objects in the rooms before it gets retransmitted into the rooms air via conduction by time.

4.5.1 CFD Validation

Before starting the simulation, it was necessary to validate the simulation process to ensure the accuracy of the input boundary conditions and the reliability of the obtained results. The accuracy of the simulation tool was validated by taking field measurements inside the case study apartment and comparing it to the simulation results of the exiting case study conditions

The field measurements were taken by a handheld anemometer device which reads wind velocities between 0.3 and 40 m/s. the locations of the measurements are indicated in Figure 17. Readings were taken at different timings across the day in presence of single occupant. The wind velocity was recorded for all measurement events.

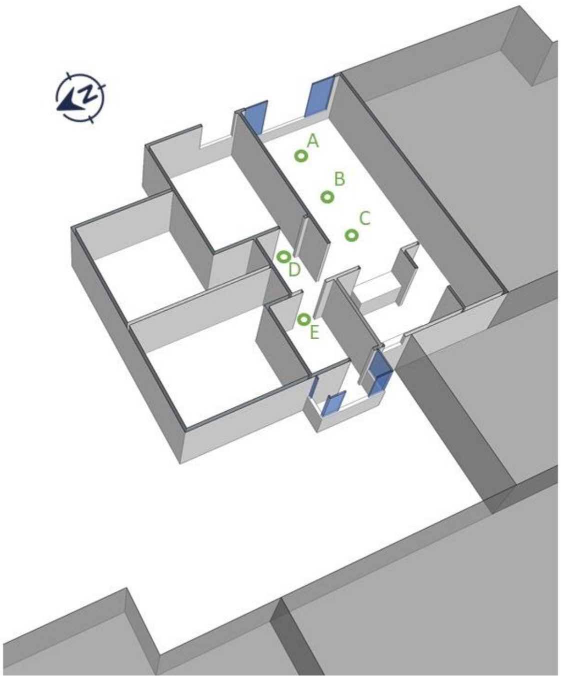


Figure 17.Anemometer used in the field measurements and the measurements locations

The field measurements toke place at two different configurations of window opening positions. In the first configuration, only the living room window was left open and all other windows and doors in the apartment were closed. In the second configuration, the doors and windows of the washroom and one bedroom were also left open. The measurements were taken only at locations A, B and C for configuration one while all six locations were measured in configuration Two.

The readings were taken in the presence of single occupant and absence of any heating activities such as cooking and ironing. There were no devices in operation during the measurement events and the lights were off in most of the instances, with exception to the night measurement events, however, the lights operated during that events were minimal, and they are LED efficient bulb. The single occupant is a male of age 28 years, and he was in standing position during the measurements events.

CFD simulations will be carried out for the two configurations and the results of the simulations will be compared against the respective field measurements. In the CFD simulations, the external wind speed will be assumed as 3.35 m/s according to the local weather information by ASHRAE (2017).

The validation results are presented in Chapter 5, with a detailed discussion on the findings

4.5.2 Simulation methodology

A total of Sixteen different geometries will be examined through the CFD modelling. Each geometry will be simulated twelve times at fifteen different boundary conditions, resulting a total of 192 simulations. The boundary conditions are elaboration section 4.4.3. The volumetric air flow rate will be measured at the plane of each ventilation opening.

As elaborated in Figure 18 The simulation process will be carried out on three stages. Stage one will start by simulating baseline 1 followed by the first four design cases. The results of each design case will be compared to baseline 1 and to each other, and the best performing design case will be considered as Baseline 2. Stage two includes the simulation of six design cases which represents six enhancement proposals to Baseline two. The results of the six cases will be compared and the best performing case will be considered as Baseline 3. Stage three includes the simulation of five design cases, which represents combinations of the six enhancements proposals simulated separately in stage two. The detailed description of all design cases is provided in section 3.3. As noted above each design case will be simulated twelve times for twelve different boundary conditions.

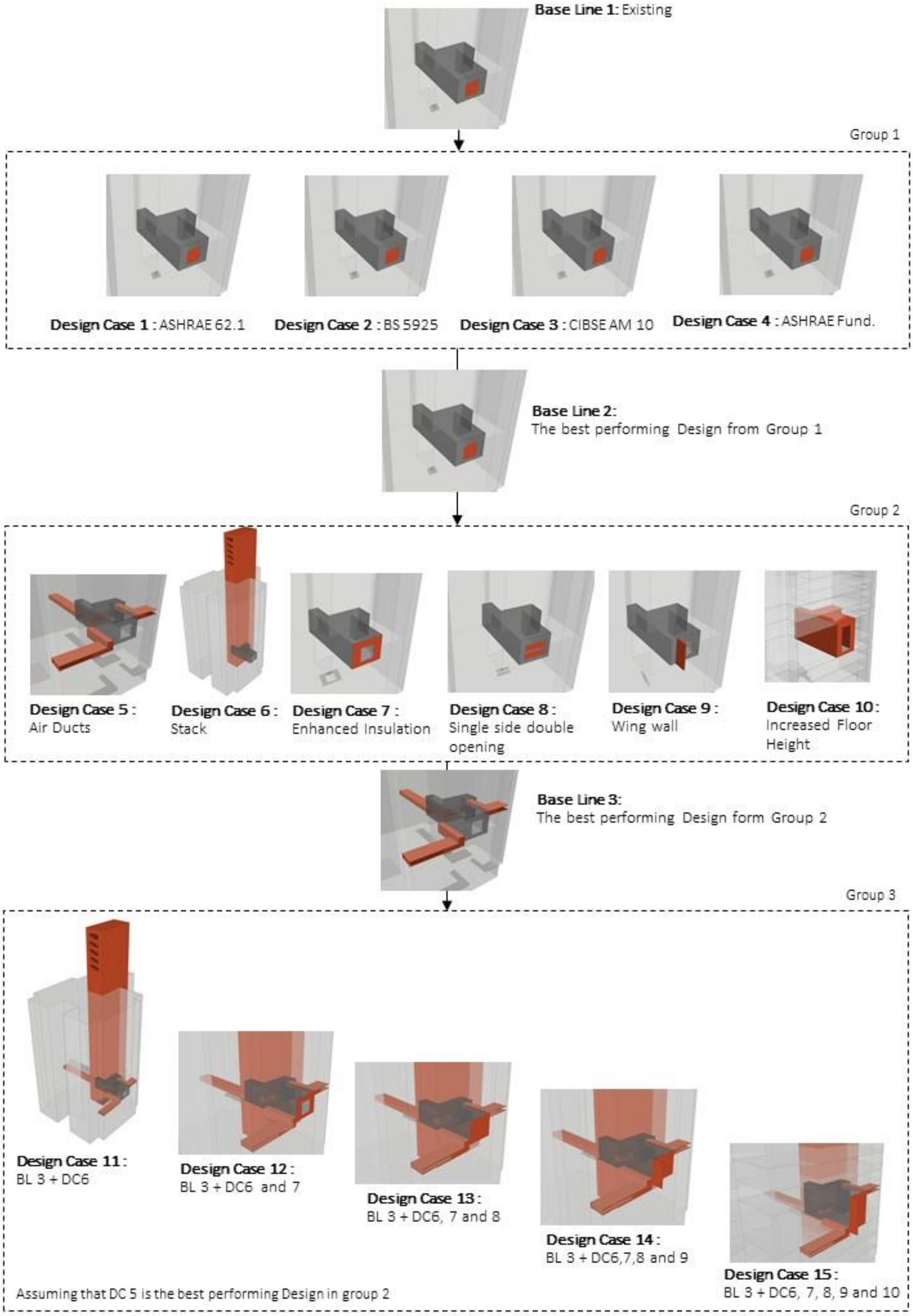


Figure 18. CFD Simulation Methodology

Source: Author

4.5.3 Boundary conditions

The values of the selected boundary conditions are presented in Table 36 and they cover the wind direction, outdoor temperature and Solar irradiance. The aim of simulating such variety in boundary conditions is to examine the performance of each design case under all possible weather conditions and extend the findings and recommendation of this study to inform the design of rooms with different orientations.

Table 36. Boundary Conditions
(Author)

	Wind direction	*Outdoor Temperature (°C)*	*Solar Irradiance (w)*
BC_1	No wind	34	793
BC_2	No wind	29	186
BC_3	No wind	24	0
BC_4	0	34	793
BC_5	0	29	186
BC_6	0	24	0
BC_7	90	34	793
BC_8	90	29	186
BC_9	90	24	0
BC_10	270	34	793
BC_11	270	29	186
BC_12	270	24	0

Boundary conditions number one, four, seven and ten represent a mid-day hour with peak outdoor temperature and solar irradiance intensity, tested at four different wind conditions as follows: absence of wind, presence of wind at an angle of zero degree to the window plane, 90 degrees and 270 degrees. Boundary conditions number two, five, eight and eleven represent an evening hour with moderate outdoor temperature and solar irradiance intensity, tested at the four wind conditions described above. Boundary conditions number three, six, nine and twelve represent a night hour with the lowest temperature and absence of the solar irradiance, tested at the four wind conditions described above.

All simulations were made for a summer day in August as being the hottest month across the year according to ASHRAE 90.1 (2016).

Chapter V.

Results and Discussions

The results of the CFD simulations and field measurements will be presented and discussed in this chapter, with a focus on the air flow performance in the simulated and measured cases. The calculations' results presented in the previous chapter for heat gains and ventilation rates will also be discussed and analyzed in this chapter, to understand the correlation between these numbers and the resultant air flows.

5.1 Heat gains

The calculated heat gains and indoor temperatures are presented in Chapter 4: Table 35, which shows the values of the total sensible heat gains as 37.34 w/m^2 and 45 w/m^2 for insulated and non-insulated scenarios respectively. These numbers confirm the applicability of the case study for natural ventilation according to CIBSE (2014) which states that a space can be naturally ventilated if the total heat gains are controlled below 40 w/m^2.

The temperature values presented in Table 35 shows that the façade insulation and shading have a minor reduction on the average temperature with a value of 1 °C, while it significantly reduces the peak temperature by a value of 5 °C. This is probably due to the fact that the solar gains which are controlled by the insulation and shading, are also having the biggest share in the temperature increase from average to peak values. Comparing the average internal temperature in Table 35 against the average outdoor temperature in Table 34, shows a delta T value of 3 °C approximately between indoor and outdoor temperatures, which agrees with the recommendations made by CIBSE (2014) to consider a value of 3 °C for delta T in the empirical calculations of sizing the ventilation openings.

5.2 Calculated Ventilation rates

The calculated ventilation rates are presented in table 34, which shows a comparison between the performance and the prescriptive values of ventilation rates for the study case room. The highest rate was a prescriptive rate by the Building Regulation Part F (2006) with a value of 40 l/s, and it was used in the calculations for sizing the openings. However it should be noted that during the field measurements activity in the study case apartment, it was noticed that the 40 l/s supply rate is insufficient to provide cooling effect under summer condition in such hot climate.

The calculated rate for Humidity control as per ASHRAE (2017) was found to be triple the rate calculated as per BSI (1995). This variance in results is mainly due the different Humidity sources considered by each standard. ASHRAE (2017) has considered the human respiration and the outdoor ventilation air while the BSI (1995) has considered the human respiration only.

5.3 Field measurements for CFD Validation

As described in section 4.4.1, the field measurements took place at two different configurations of openings' positions. In the first configuration, only the living room window was left open and all other windows and doors in the apartment were closed. The measurements taken for the first configurations were all close to zero and hence they were not considered representative readings that can be used to validate the software results. Accordingly, these readings were discarded, and no simulation runs were carried out for that configuration. In the second configuration, doors and windows of the washroom and one bedroom were also left open to create an air flow that helps in validating the software results. The measurements of the second configuration are presented in Table 37

The CFD simulation was repeated several times in order to understand the most accurate boundary conditions that lead to closest match with field measurements. The various trials have identified four main factors that affect the accuracy of the simulation. The first factor is the size of the domain used for simulation. Using small domains to save time has resulted into high mismatches with the field measurements, Hence the recommended size by Autodesk shall be followed. The second factor is the representation of the internal heat gains inside the space. Representing the heat gains of a specific element as being completely a point source is not an accurate approach, and it has resulted into mismatches with the field measurements. Whereas considering distributed heat gains have shown better match with the field measurements and from the other side it has also confirmed the assumptions made by Barnaby (2005) that some portions of heat gains get emitted to other surfaces inside the room and they get radiated gradually to the room's air node over the course of the day.

The third factor affecting the accuracy of the CFD modelling is the number of iterations that are allowed for each simulation run. Reducing the number of iterations to save time has resulted into big gap between the simulation results and field measurements. Hence, the recommendation of the Autodesk was followed, and the iterations were set for a high number to allow the software to reach convergence automatically. Lastly, the accuracy of the simulation is highly affected by the accuracy of the weather boundary conditions. Ignoring some elements such as the solar radiation or wind temperature have resulted into unrepresentative results. Hence, all weather conditions were considered in the final simulations.

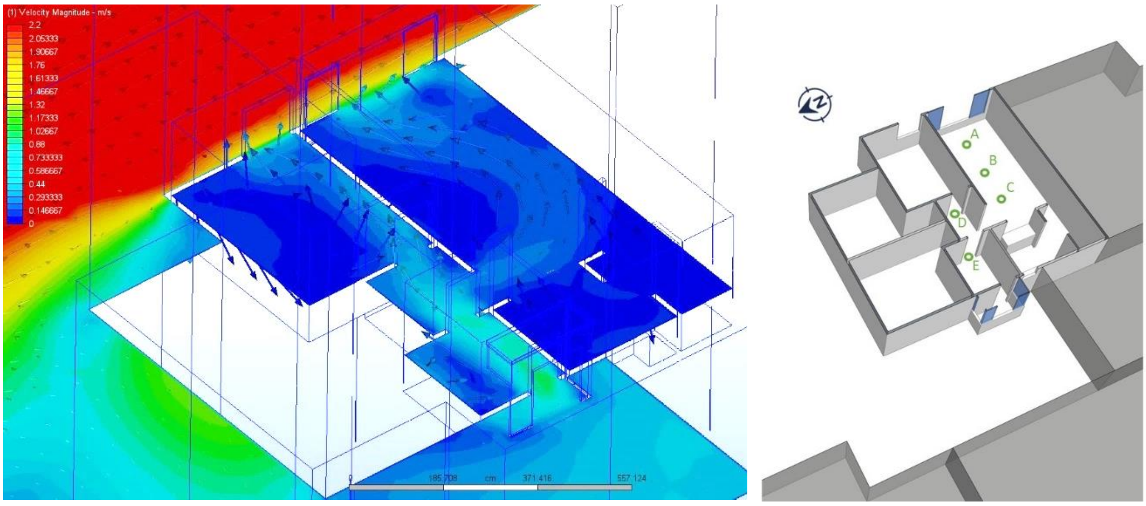


Figure 19 CFD Validation: a- Velocity contour lines by the CFD simulations (left), b- locations of measurement points (right)

(Author)

Table 37 A comparison between field measurements and the Simulation results

(Author)

Date / Time	Measured velocity (m/s)					Modelled velocity (m/s)				
	A	***B***	**C**	***D***	**E**	**A**	***B***	**C**	***D***	**E**
5 July 2018 6:25 am	0	0	0	0.5	1.4	0.29	0	0.19	0.3	1.0
20 July 2018 8:30pm	0	0	0	0.7	1.8	0.2	0	0.14	0.5	1.3
25 July 2018 10:50pm	0	0	0	0.6	1.7	0.15	0	0.10	0.4	1.2

Table 37 shows a comparison between the field measurements and the Simulation results at the six locations as marked in Figure 19 (b). The field measurements with values of zero were ignored in the validation comparison due to their high level of uncertainty. All simulation results below 0.3 m/s were also ignored due to the limitations of the anemometer device to measure velocities only above 0.3 m/s. Accordingly, the measurements taken at locations D and E were the only ones used for validation. Comparing the simulated and the measured values at these two locations concluded that the selected CFD software and boundary conditions can yield representative results at an accuracy level of 70% to 80% approximately. This margin is deemed acceptable according to Zhou, C (2014) and Gao, C.F. & Lee, W.. (2011), and it can be attributed to the software accuracy issues as well as the uncertainty of external wind speed, which was assumed as 3.35 m/s in the simulation, according to the local average wind speed by ASHRAE (2017).

The simulation has also indicated a good level of match with the field measurements in terms of air distribution and temperature inside the apartment. The only exception from that match is the temperature simulation results under buoyance conditions only (in absence of wind) for single opening schemes. These results will be ignored in this study as they are not directly relevant to the area of study which is air flow velocities and distribution.

5.4 Simulation results

The results of the CFD simulations will be discussed in this section, and the cases within each group will be compared against each other to understand the performance variations. The design details of each group are presented in Figure 19 and Table 36 in Chapter 4.

The section will be started with an overview on the general findings that applies to all groups, followed by separate subsections for each group, discussing the performance of the cases within that group. A graphical representation of the baseline results and the results of the best performing case will in each section. The graphical representation of all other cases is provided in Appendix A.

5.4.1 General Observations

The perpendicular winds have yielded the highest air flow through the openings only in the cross-ventilation schemes, while it did not show good performance in the single sided ventilation schemes. The reason behind such result is the fact that the perpendicular winds get disturbed by the opposite building across the street, which causes the wind to be scattered and redirected before reaching the study case window (Figure 20). In the cross-ventilation cases, the presences of other internal openings in the study case room acting as air outlets, created a negative pressure at the external opening, which assisted on pulling the scattered winds inside the space.

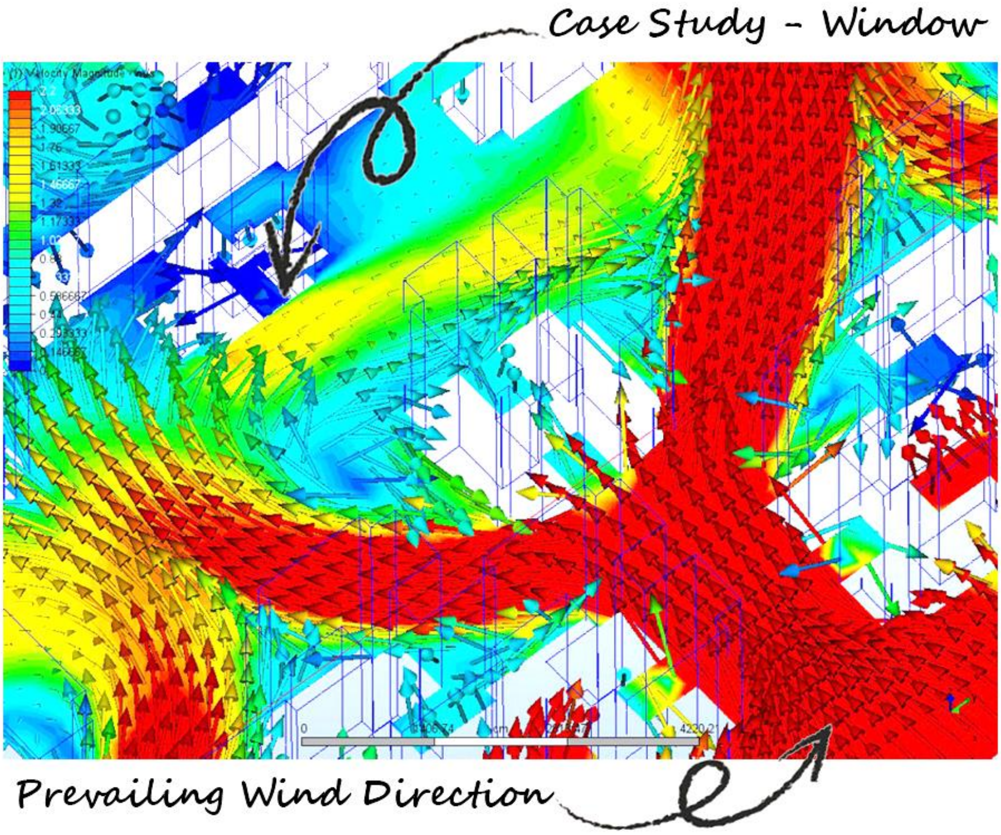


Figure 20. Perpendicular winds redirected to become lateral due to surroundings. *(Author)*

The simulation results of all Single opening cases under Buoyancy conditions only have shown an agreement with ASHRAE (2017) in regard to the location of the Neutral plane. The Neutral plane is a virtual plane that separates the air intake area from air discharge area and it is assumed by ASHRAE (2017) to be located at the centerline of the opening for single openings ventilation schemes. The arrows in Figure 21a show that the air enter the space at the lower portion of the openings and leaves the space from the upper portion. This assumption was validated only for the simulation under buoyancy conditions, whereas for simulations under wind conditions, this assumption was not valid due to the turbulence caused by the wind (Figure 21 b)

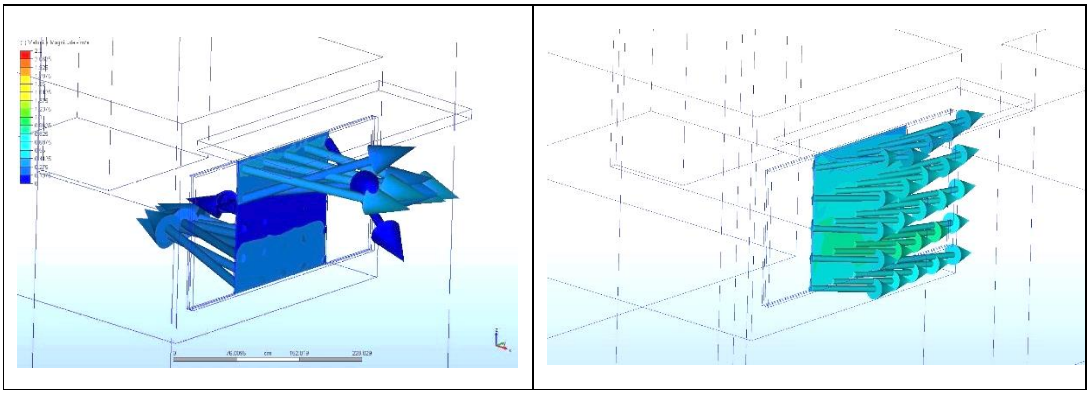


Figure 21. Neutral Plane location in single sided ventilation: a- under wind (right), b- under buoyancy Conditions (left)

(Author)

It was noticed that the air flow is directly proportional to the level of internal heat gains in absence to wind. Hence buoyancy will not drive air effectively in the well-insulated spaces.

All simulations made under peak outdoor temperature and solar irradiance have resulted into excessive indoor temperature above the acceptable level and hence a precooling strategy shall be coupled with the ventilation strategies to reduce the temperature, such as double screen façades or atriums. It was also noticed in most of the simulations that the increase in air flow is associated with minor decrease in the air temperature. Hence increasing the air flow rates can possibly be another mean of cooling the indoor space.

In terms of air distribution inside the space, it was noticed that the air induced by buoyancy only has the least penetration depth in the space where it reaches only few centimeters away from the opening. Whereas the air flow induced by external wind can reach up to one third of the room depth. This observation can be attributed to the lack of sufficient temperature differences to drive air by buoyancy. Figure 22 shows comparison between two cases where the air flow introduced in the space is induced by buoyancy in one case and wind on the other. In general, it was noticed that the depth of air penetration inside the room is directly proportional to the sizes of the opening.

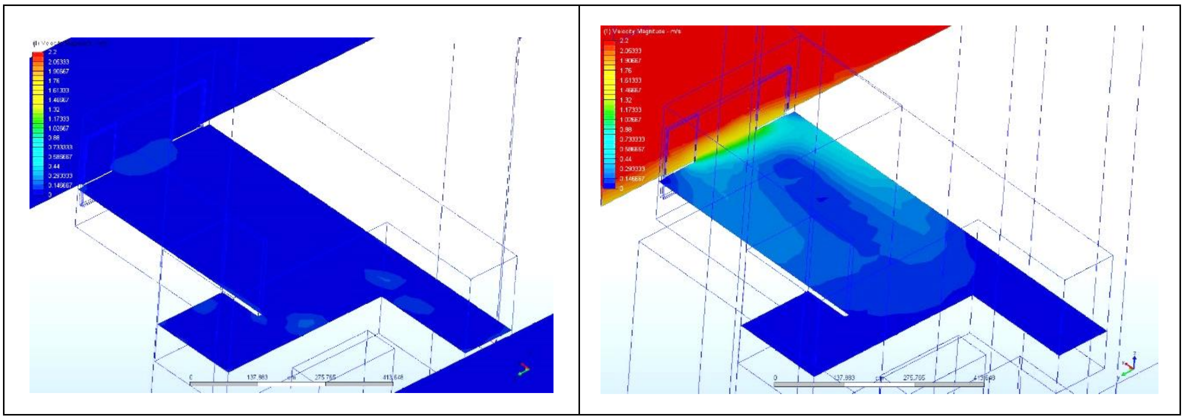


Figure 22. Extent of air penetration inside the room for single sided ventilation schemes under wind (right) and buoyancy Conditions (left)

(Author)

5.4.2 Group One Observations

As elaborated in Figure 23, Baseline number one represents the existing case study and Group one includes four design cases representing four design standards.

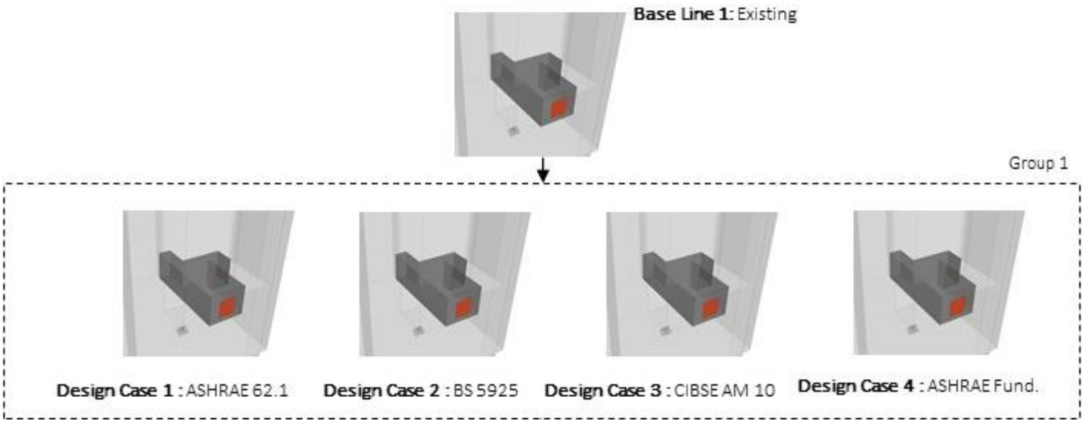


Figure 23. Group one Design cases

(Author)

The results presented in Table 38 show that the baseline one had the best performance compared to all other design cases. Among the four studied design cases, the BS 5925 (1995) design case has yield the best performance with a match level of 100% to 105% from the targeted air flow, but this high match level is only under the lateral wind conditions. For buoyancy and other wind conditions, the BS 5925 (1995) design case was also having the best performance but with lower match levels that ranges between 50% to 60% for wind conditions and 8% to 15% for Buoyancy. The BS 5925 (1995) design case is having the biggest opening area among the four other design cases, which might attributes to the high-performance results compared to other design cases. In general, it was noticed that the air flow rate is directly proportional to the size of the openings.

Table 38. Group One - Simulation tabulated results

(Author)

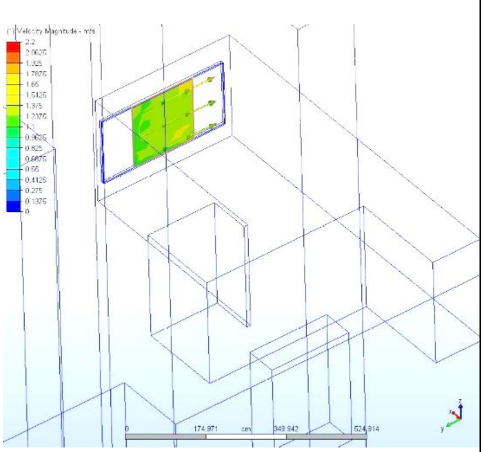
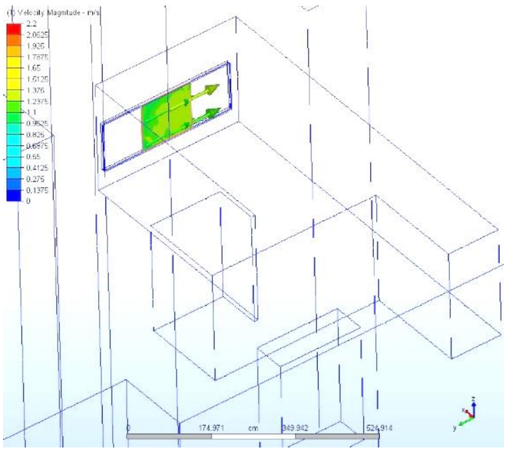
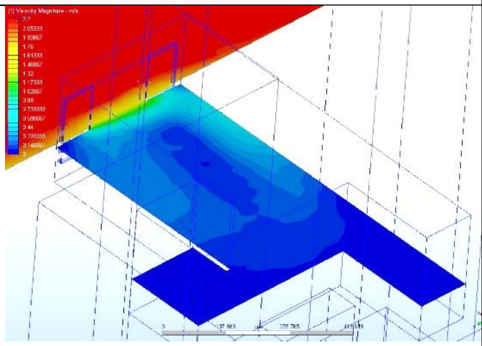
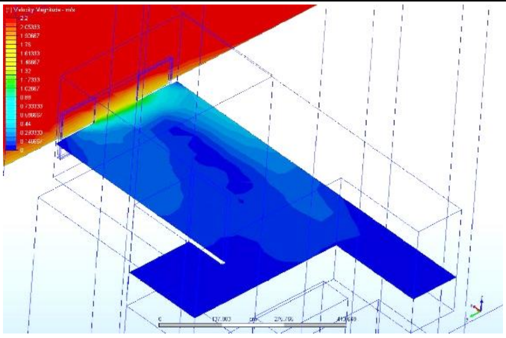
Boundary condition	Existing (Baseline)	ASHRAE 62.1	BS 5925	CIBSE AM10	ASHRAE FUNDAMENTALS
BC_1	**8.3 L/s**	5.3 L/s	6.1L/s	3.5 L/s	2.6 L/s
	-	-	-	-	-
BC_2	**8.7 L/s**	3.2 L/s	5.2 L/s	3.4 L/s	1.6 L/s
	-	-	-	-	-
BC_3	**5.8 L/s**	2.6 L/s	3.4 L/s	2 L/s	1.3 L/s
	-	-	-	-	-
BC_4	**44.3 L/s**	30.3 L/s	43.4 L/s	20.2 L/s	20.6 L/s
	34.7 °C	35.3 °C	35.2 °C	35.6 °C	35.7 °C
BC_5	**64 L/s**	27.5 L/s	43.3 L/s	20.2 L/s	20.4 L/s
	29.5 °C	29.7 °C	29.7 °C	35.6 °C	30.1 °C
BC_6	**64.7 L/s**	25 L/s	40.3 L/s	21 L/s	18 L/s
	24.1 °C	24.1 °C	24.2 °C	24.3 °C	24.6 °C
BC_7	**41 L/s**	17.4 L/s	22.2 L/s	17.9 L/s	14.3 L/s
	35 °C	35.9 °C	35.7 °C	36.2 °C	36.2 °C
BC_8	**39 L/s**	18 L/s	24.2 L/s	17.9 L/s	16 L/s
	29.6 °C	30 °C	29.8 °C	36.2 °C	30.4 °C
BC_9	**42 L/s**	19 L/s	26.1 L/s	18.5 L/s	16.3 L/s
	24.2 °C	24 °C	24.2 °C	24.3 °C	24.3 °C
BC_10	**36 L/s**	19.6 L/s	25.5 L/s	11.5 L/s	12 L/s
	35.6 °C	36.2 °C	36.1 °C	36.4 °C	36.5 °C
BC_11	**33.7 L/s**	18.2 L/s	23.7 L/s	11.5 L/s	11.5 L/s
	29.7 °C	30.2 °C	30 °C	36.4 °C	30.4 °C
BC_12	**28.6 L/s**	15 L/s	20.3 L/s	7.6 L/s	9.6 L/s
	24.2 °C	24.3 °C	24.1 °C	24.4 °C	24.3 °C

Comparing the air flow results of other design cases against the targeted air flow, it will be noticed that the ASHRAE 62.1 (2016) design case has resulted into a match level of 40% to 75% under the wind conditions and a match level of 6% to 13% under the buoyancy conditions, whereas the CIBSE AM10 (2014) and ASHRAE fundamentals (2017) design cases have resulted into a match level of 20% to 50% under the wind conditions and a match level of 3% to 8% under the buoyancy conditions

In terms of air distribution and air velocity inside the space, Baseline one and the BS 5925 (1995) design case are the only cases which have resulted into air penetration to full depth of the room. However, it has to be noted that the air velocity drops significantly after the first quarter of the room depth, resulting into an air speed less than 0.3 m/s which is insufficient to provide cooling effect in summer conditions.

Table 39 shows a graphical representation of the baseline results and the results of the BS 5925 design case as being the best performing case.

Table 39. Group One - Simulation graphical results of the highest two cases *(Author)*

	Baseline 1	BS 5925
Air Supply		
Air distribution		

5.4.3 Group Two observations

Baseline one from the previous group will now be considered as Baseline two since it has resulted into the highest performance among all design cases in group one. As elaborated in Figure 24, Group two includes six design cases that represents six enhancement proposals to the design cases in group one.

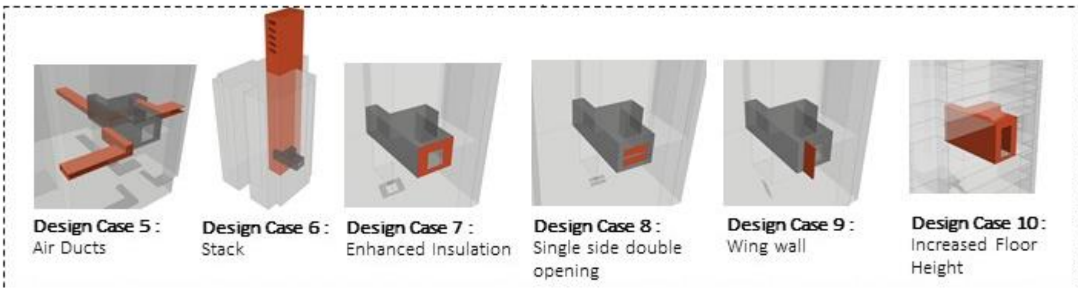


Figure 24. Group Two Design cases

(Author)

Two cross ventilation schemes and four single sided ventilation schemes were tested in this group. As elaborated in Table 40, the simulation results indicated a significant improvement in the air flow by cross ventilation schemes over the single sided schemes.

The two tested schemes for cross ventilation are the Air ducts and the stack ventilation schemes. The stack scheme has resulted into the best performance under the buoyancy and perpendicular (windward) wind conditions. The high performance under buoyancy can be attributed to the stack element which creates higher differences in temperature and consequently drives more air by buoyancy into the room, while the high performance under windward wind conditions can be attributed to the negative pressure caused by the stack at the external window, which assists on sucking the external air inside the room as elaborated in the general observations section. The air ducts scheme has resulted into the best performance under the lateral and leeward wind conditions as a result of the additional openings located at all building facades and connected to the study case room by ducts, which assist on collecting wind from all sides of the building and transporting it to the study case room.

Table 40. Group Two - Simulation Tabulated results
(Author)

Boundary condition	Existing (Baseline 2)	Air ducts	Stack	Insulation	SSD	Wing Wall	Increased Height
BC_1	**8.3 L/s**	361 L/s	750 L/s	1.8 L/s	7.5 L/s	6.7 L/s	10 L/s
	-	36 °C	34.8 °C	-	-	-	-
BC_2	**8.7 L/s**	586 L/s	1005 L/s	1.8 L/s	7.7 L/s	7 L/s	O L/s
	-	38 °C	29°C	-	-	-	-
BC_3	**5.8 L/s**	191 L/s	420 L/s	1.65 L/s	6.5 L/s	4.5 L/s	8.3 L/s
	-	24 °C	24.2°C	-	-	-	-
BC_4	**44.3 L/s**	1119 L/s	1050 L/s	44 L/s	33.3 L/s	O L/s	140 L/s
	34.7 °C	34.5 °C	34.7 °C	34.6°C	34.8°C	37.1°C	34.4°C
BC_5	**64 L/s**	1104 L/s	722 L/s	44 L/s	31.5 L/s	34.4 L/s	137 L/s
	29.5 °C	29.5 °C	29.4 °C	29.6°C	29.5°C	30.5°C	29.2°C
BC_6	**64.7 L/s**	1111 L/s	748 L/s	64.7 L/s	32.2 L/s	33.5 L/s	140 L/s
	24.1 °C	34.1 °C	24.5 °C	24.1 °C	24°C	24.4°C	24°C
BC_7	**41 L/s**	1470 L/s	2797 L/s	46 L/s	37.7 L/s	11.7 L/s	106 L/s
	35 °C	34.8 °C	34.4°C	35.4 °C	35.6°C	44°C	35°C
BC_8	**39 L/s**	1196 L/s	2670 L/s	46 L/s	40.2 L/s	11.2 L/s	105 L/s
	29.6 °C	29.2 °C	29.1 °C	29.3 °C	29.7°C	35.7°C	29.4°C
BC_9	**42 L/s**	789 L/s	2325 L/s	42 L/s	37.3 L/s	12 L/s	103 L/s
	24.2 °C	24.1°C	24 °C	24.2 °C	24.2°C	25°C	24°C
BC_10	**36 L/s**	3047 L/s	1431 L/s	32 L/s	27.7 L/s	27 L/s	71 L/s
	35.6 °C	35.5 °C	34.8°C	35.7 °C	35.7°C	35.6°C	35°C
BC_11	**33.7 L/s**	2974 L/s	1486 L/s	32 L/s	27.5 L/s	24.5 L/s	74.4 L/s
	29.7 °C	29.7 °C	29.3 °C	29.5 °C	29.7°C	29.7°C	29.2°C
BC_12	**28.6 L/s**	2793 L/s	1516 L/s	28.6 L/s	18.3 L/s	22.1 L/s	76.5 L/s
	24.2 °C	24.1 °C	24 °C	24.2 °C	24.4°C	24.2°C	24°C

The four tested schemes for single sided ventilation are the Single opening with wing wall, single sided double opening, single opening with increased internal space height and single opening with overhang and thermal insulation to external walls. Among these four schemes, Increasing the internal height of the space has resulted into the highest improvement under all wind conditions, with an improvement percentage of 15% to 140% against the baseline case. These results confirm the assumption made by the ASHRAE (2017) that increasing the internal clear height of the ventilated space shall result into a better air circulation and higher flow. The enhancement in air circulation and flow might be attributed to higher pressure differences that is created by increasing the internal height of the room.

The design cases with single opening and thermal insulation to external wall has resulted into a similar performance as of the baseline in most of the cases, which can be attributed to the extremely insignificant increase in outdoor/indoor temperature difference is caused by adding the insulation to such a small wall area. The SSD has resulted into air flow reduction under all boundary conditions.

Although the wing wall was expected to improve the air flow inside the room, at least under the lateral wind condition, the results of the simulation have indicated otherwise a reduction in air flow under all boundary conditions. The reduction in air flow under lateral wind condition can be attributed to the location of the window in respect to the wing wall, which was wrongly located in a dead corner at a low-pressure zone (Figure 25). Whereas the reduction in air flow under the leeward wind condition can be attributed to the fact that the leeward wind coming from the back side of the building, reaches the study case window at the front as lateral wing from the righthand side, which was obstructed by the wing wall wing wall.

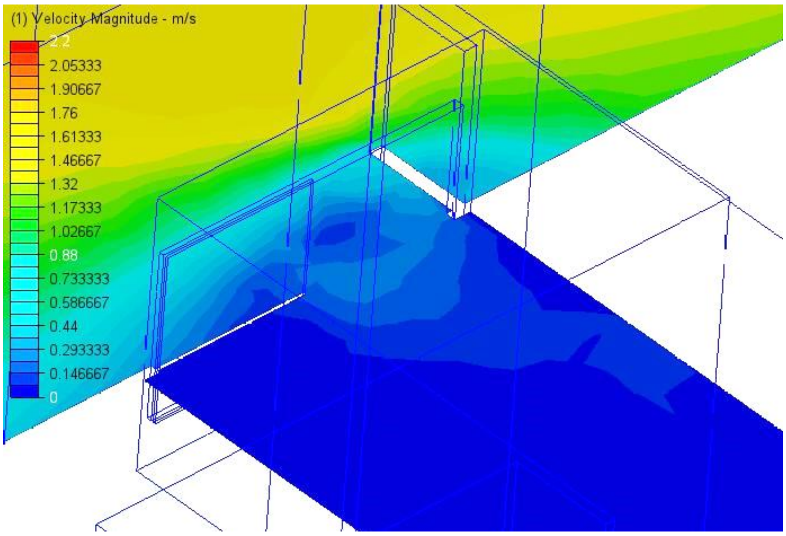


Figure 25. Low pressure zone caused by wing wall

(Author)

The simulation results of the stack under buoyancy conditions were not in line with the findings documented by Alex (2001) about the minimum temperature difference requirements for Buoyancy driven air flow to be created. Alex (2001) noted that the buoyance cannot drive a proper air flow inside a space if the temperature difference is less than 23 °C. The observation elaborated in Figure 26 indicates that the buoyant air flow was possibly induced under temperature difference of 13 °C approximately. However, the argument made by Alex (2001) is still valid about that the impracticality of expecting a buoyancy air flow in the single sided ventilation scheme.

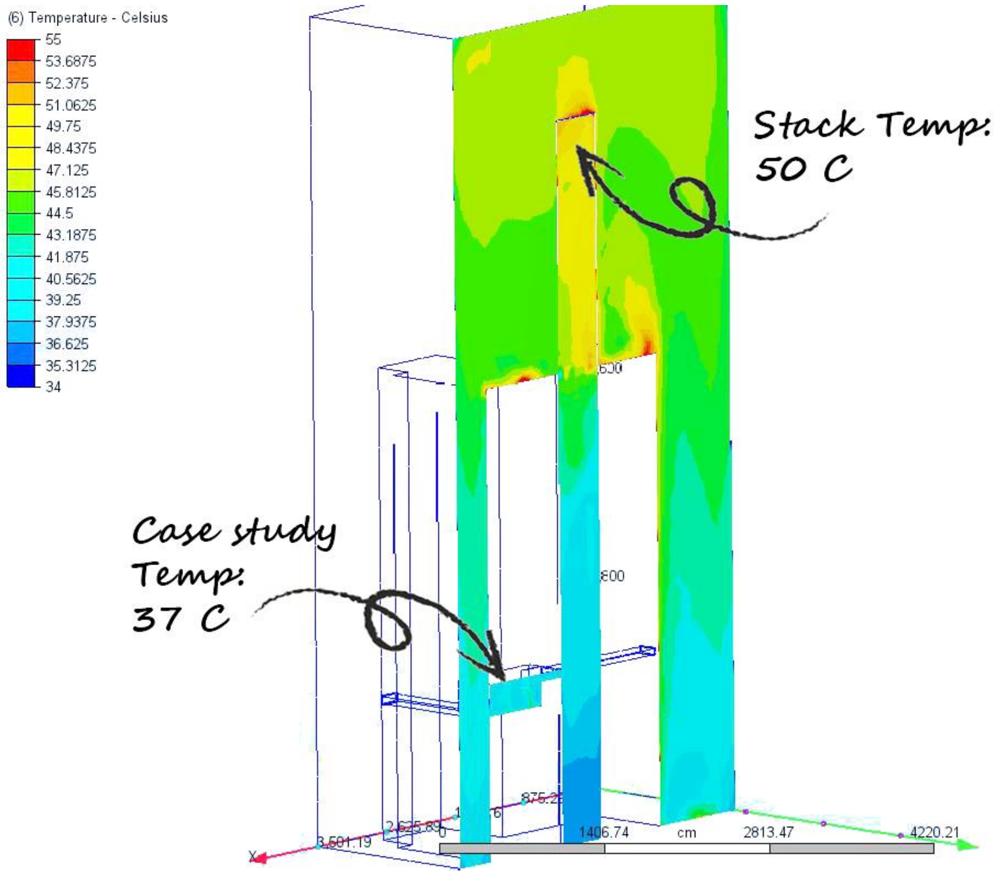


Figure 26. Stack temperature difference driving air flow

(Author)

In terms of air distributions, the cross-ventilation schemes have resulted into extremely better distribution than the single sided ventilation. This can be attributed to the presence of separate air inlets and outlets in the cross-ventilation scheme located at opposite rooms side for better distribution. Whereas, in the single sided ventilation scheme the air enters and leaves the space from the same opening, which results into air circulation only at the close proximity to the window plane. The extent of air penetration in each case is elaborated in Figures 27b and 27a respectively.

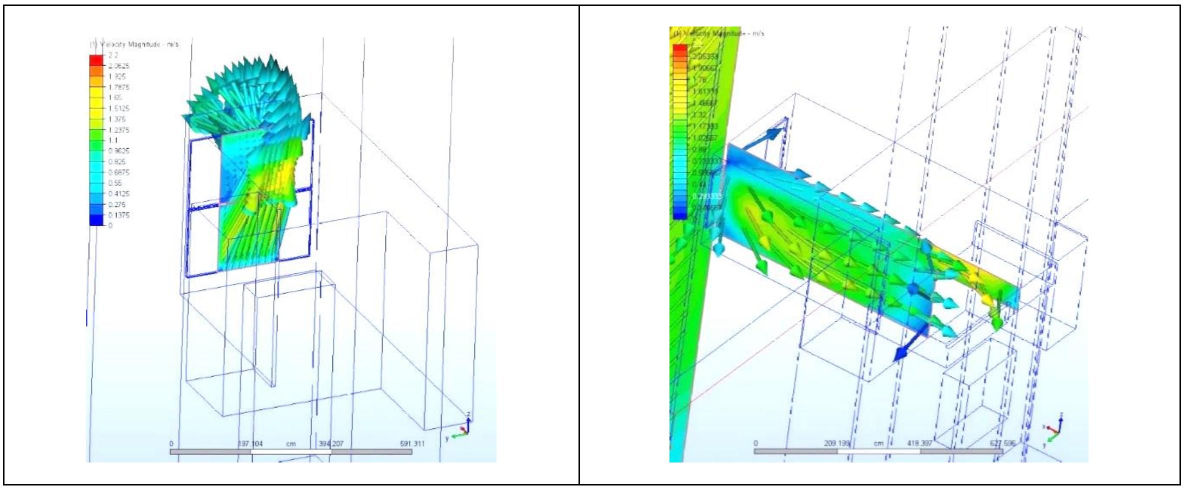
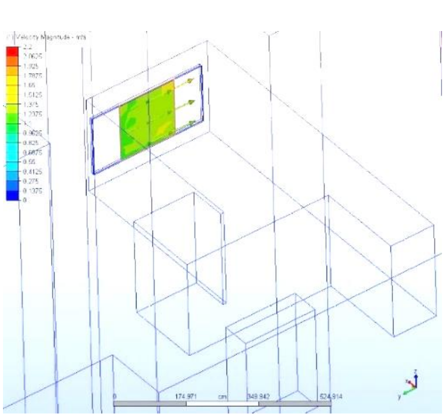
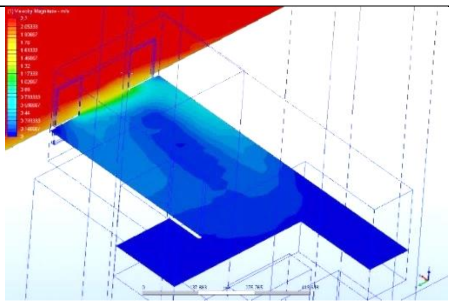
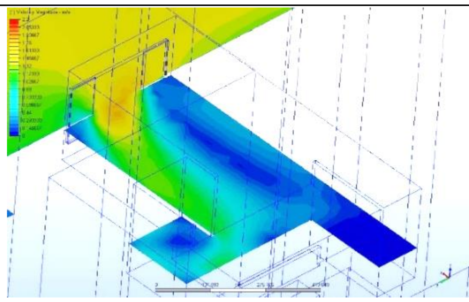


Figure 27. Extent of air penetration inside the room for single sided ventilation schemes (left-a) and cross ventilation (right-b)

(Author)

Table 41. Group Two - Simulation graphical results of the baseline two and the stack design case as being the heist performing design case

(Author)

	Baseline 2	Stack
Air Supply		
Air distribution		

5.4.4 Group Three observations

Although the stack and Air ducts design cases were both having good results in the previous group, the stack design case was selected as the baseline for this Group ‘Group three’ due to its the enhanced air distribution results inside the study case room. As elaborated in Figure 28, Group three includes five design cases that represent incremental combination of the six proposals tested individually in group two.

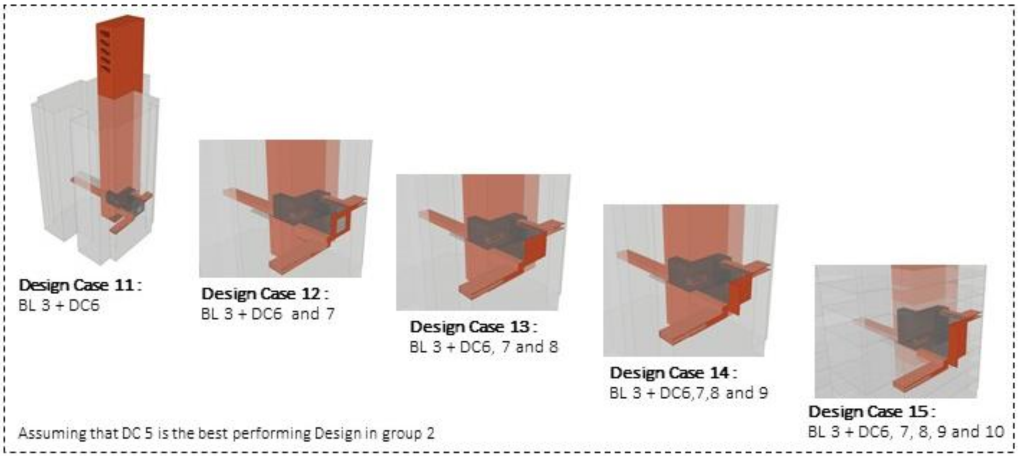


Figure 28.Group Two Design cases

(Author)

Adding the enhancement proposals incrementally one on top of the other has resulted into incremental increase in air flow under all wind boundary conditions, with exception to the wing wall and the Single sided double opening elements, which have increased the air flow under the lateral wind conditions only and reduced the flow under all other boundary conditions. Whereas the buoyancy simulations of all design cases have indicated an incremental increase in air flow only for two cases which are the addition of air ducts and increasing the space height cases.

The maximum incremental increase in air flow was caused by the air ducts addition to stack under the lateral wind condition, which have resulted into an increase of 110%

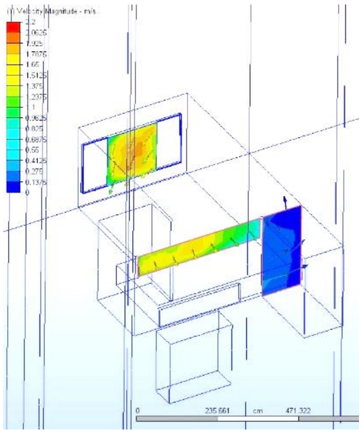
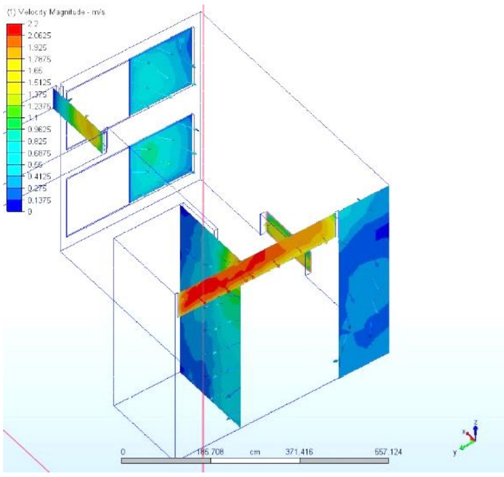
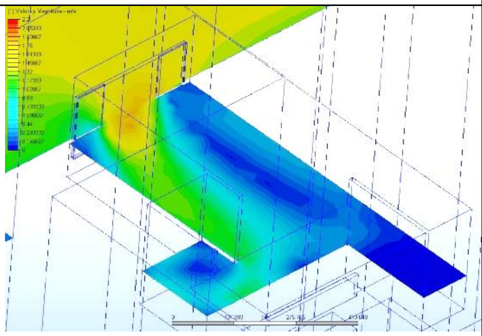
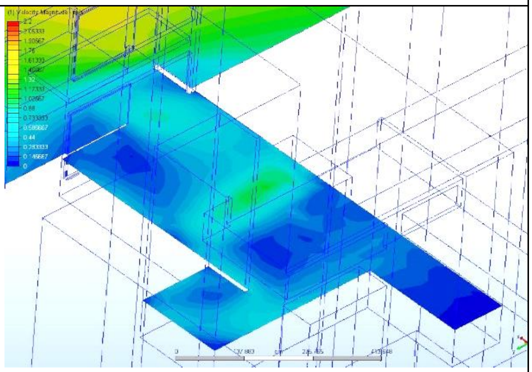
approximately in air flow. The only proposal that have yield a consistent increase under all conditions is the increased internal height proposal.

Combining the air ducts with the stack have resulted into improvements under all boundary conditions except the buoyancy conditions. This is probably due to the air short circuiting effect that toke place as a result of connecting the air duct to the same planum box to which the stack is connected. Connecting the two elements to the same planum box have resulted into air short circuiting from the air duct into the stack without entering the room.

Table 42 Group Three- Simulation Tabulated results
(Author)

Boundary condition	Stack (Baseline 2)	Design case 11	Design case 12	Design case 13	Design case 14	Design case 15
BC_1	750 L/s	376 L/s	657 L/s	460 L/s	440 L/s	753.6 L/s
	34.8 °C	40 °C	40.5°C	40°C	40°C	41°C
BC_2	1005 L/s	618 L/s	655 L/s	462 L/s	438 L/s	753.6 L/s
	29°C	30 °C	30.5 °C	30.4 °C	30.8 °C	31 °C
BC_3	420 L/s	351 L/s	366 L/s	395 L/s	370 L/s	448.2 L/s
	24.2°C	24.3 °C	24.2°C	24.2°C	24.3°C	24.4°C
BC_4	1050 L/s	1521 L/s	1561 L/s	1587 L/s	2036 L/s	2580 L/s
	34.7 °C	34.7°C	35°C	34.8°C	34.7°C	34.6°C
BC_5	722 L/s	1520 L/s	1558 L/s	1560 L/s	2028 L/s	2580 L/s
	29.4 °C	29.3 °C	29.5 °C	29.4 °C	29.3 °C	29.4 °C
BC_6	748 L/s	1540 L/s	1540 L/s	1598 L/s	2038 L/s	2272 L/s
	24.5 °C	24 °C	24 °C	24°C	24°C	24°C
BC_7	2797 L/s	4506 L/s	4525 L/s	4426 L/s	4348 L/s	4805 L/s
	34.4°C	34.6 °C	34.7 °C	34.6°C	34.6°C	34.6°C
BC_8	2670 L/s	4105 L/s	4520 L/s	4429 L/s	4353 L/s	4813 L/s
	29.1 °C	29.1 °C	29.2 °C	29.3 °C	29.5 °C	29.1 °C
BC_9	2325 L/s	2919 L/s	2907 L/s	2847 L/s	2697 L/s	2910 L/s
	24 °C	24 °C	24 °C	24°C	24°C	24°C
BC_10	1431 L/s	1850 L/s	2118 L/s	2078 L/s	1876 L/s	2091 L/s
	34.8°C	36.5 °C	35.2 °C	36 °C	35.8°C	36.3°C
BC_11	1486 L/s	2180 L/s	2125 L/s	2086 L/s	1868L/s	2080 L/s
	29.3 °C	29.8 °C	29.7 °C	30 °C	29.8 °C	29.5 °C
BC_12	1516 L/s	1998 L/s	1987 L/s	1699 L/s	1384 L/s	1976 L/s
	24 °C	24.1 °C	24.2°C	35°C	24.5°C	24.1°C

Table 43. Group three - Simulation graphical results of the baseline three and the combined enhancement strategies design case as being the heist performing design case *(Author)*

	Baseline 3	All enhancement strategies combined
Air Supply		
Air distribution		

Chapter VI.

Conclusion

Four natural ventilations design standards were investigated in this study to understand their reliability for designing an effective Natural ventilation system in hot climates. Two design standards out of the four were performance-based methods and the other two were prescriptive based methods. The air flow requirements for healthy environments were calculated multiple times according to various performance and prescriptive methods, and the highest rate was used as an input in the sizing calculations of the ventilation openings. The investigation was coupled with CFD simulations to validate the resultant designs. The CFD simulation was validated through experiential field measurements. The validation findings concluded a great match in terms of air distribution and a level of match of 70-80% in terms of air velocities. Hence, the results of the CFD simulation of all tested study cases can be considered highly matching the reality in terms of air distribution and representing the real velocities with a level of accuracy of 70-80%

5.1 General Conclusions

The results of the simulations indicated that only one design method out of the four was able to achieve the targeted air flow, which is the BS 5925 performance Method. However, the targeted air flow was achieved only at the window location and it was insufficient to achieve thermal comfort inside the room beyond 1.5 m from the window. The general findings and observations can be summarized as follows:

- The prescriptive procedure of the Building Regulation Part F 2006's (2006) for minimum ventilation rate calculation has resulted into the highest rate among five other procedures with a value of 40 l/s. This value was inserted as an input in two different performance procedures to calculate the size of the ventilation opening., however the largest resultant openings among the two procedures did not achieve air penetration inside the room beyond 1.5 m from the window according to the CFD simulation. Inserting higher ventilation rate in the sizing calculations would have yielded larger ventilation opening and consequently better air flow inside the room. The conservative ventilation rate results are maybe due to the fact that these ventilation calculation procedures are originally established for the sizing purposes of mechanical ventilation systems which rely on consistent air supply rather than the intermittent supply in the case of a natural ventilation.

- The empirical and analytical equations established by ASHRAE Fundamentals (2017) and CIBSE AM 10 (2014) for sizing of the ventilation openings were found not to be precisely applicable for hot climates. Appling these calculations on the case study have resulted into ventilation rate of 30% to 50% of the targeted rate. This is maybe due to the fact that these procedures were originally established for the use in cold and warm climates rather than hot climates.
- The room depth limits established by ASHARE 62.1 (2016) and CIBSE AM10 (2014) for single sided ventilation schemes did not result into sufficient air distribution inside the space for thermal comfort. The air decayed right after the window and it did not penetrate into the space.
- The single sided ventilation schemes that were proposed to enhance the existing baseline did not yield any improvement with the exception to one scheme only which is the increased internal height of the ventilated space. This scheme has proved that increasing the internal space height from 2.7 m to 5.0 m can lead to an improvement of 15% to 140% in air flow compared to the baseline (existing). This improvement is due to the internal pressure differences created by increasing the internal height.

- Orienting the window towards the prevailing direction does not grant a proper air flow inside the space by default, especially in heavily developed neighborhoods. This is because the fact that such perpendicular wind gets scattered and reoriented by the opposite buildings. For instance, the simulations of the single sided schemes under lateral wind conditions have yield 50% improvement in air flow compared to same scheme simulations under windward conditions.
- It is possible to achieve high ventilation rates if the natural ventilation system design is optimized. The cross-ventilation schemes which were tested as potential means of enhancement to the existing system performance have yield significant improvement of 4000% to 8000% in the volume of air flow and air distribution inside the room. This is due to increasing the opening's discharge coefficient to be 0.6 as opposing to 0.25 for the single sided schemes according to CIBSE (2014)
- Combining systems together to increase air flow does not necessarily achieve the end target as they might adversely ruin the performance of each other. The simulations have indicated a degradation of 40% to the stack system after being combined with the air duct system under specific boundary conditions. That was due to connecting the two systems to one plenum which lead to the short circuiting of air (coming into the plenum from one system and leaving the plenum through the other system) without going in the room. The wing wall has obstructed the air rather redirecting it to inside the room and caused a decrease in air flow of 6% to 265% under different boundary conditions.
- Performance methods are not necessarily more accurate than the prescriptive methods. The prescriptive methods have yielded an average match level of 85% comparted to the targeted air flow, whereas the performance methods have yield an average match level of 20% compared to the targeted air flow. This is maybe due the

huge amount of variables and factors considered in the performance procedures which increase its level of sensitivity to inaccurate inputs or misunderstanding the scientific terminologies.

5.2 Recommendations

The above findings and observations suggested the following:

- Natural ventilations design codes and standards should not be limited to sizing the ventilation openings only. It should cover the holistic design parameters, at least: Spaces height, opening sizes, openings' locations and configurations, sizes of other components of the systems (ex. stack, air ducts, atrium …etc), guidance on the façade design at leeward and lateral wind orientations
- A climate specific design standard should be developed for hot climates. This standard should set out firm criteria for the selection of the appropriate natural ventilation scheme that is to be adopted in each specific room based on its size and orientations.
- The proposed design standard shall establish minimum flow rates' thresholds that are higher than the rates used for mechanical ventilation. This is to cater for such inconsistency in air flow. It shall also establish minimum requirements for air distribution inside the space.
- The new design standard should be comprehensive in terms of providing all information required by the designer to complete the design through one reference. This is to avoid obtaining misleading information from various sources. It should also avoid scientific terminologies, and where necessary used, it should provide a simplified description.

- The maximum room depth limits for single sided ventilation schemes shall be revisited in the hot climate design standard.
- The discharge coefficient which accounts for the backflow in the mathematical equations of sizing the opening shall be reviewed to ensure that it correctly capture the back-flow effect and avoid under estimating the size of the opening.
- Single opening schemes are not recommended for hot climates, however, In case it is necessary to be used, the window opening and the internal clear height should be maximized.
- When combining stack and air ducts systems together in a single space, attention should be given not to connect the two systems to a single planum, this is to avoid air short circuiting before going into the room space.
- Wing walls should be dealt with carefully in the design as it might adversely obstruct the air from entering the space.

5.3 Further research

Further research is required to cover the following items:

- Control measures should be studied to address the Safety, privacy, acoustic, dust and insects control concerns associated with the natural ventilation systems and the impacts of these measures on the effectiveness of the natural ventilation system
- Means of precooling the warm (outdoor) air before being introduced into the indoor space shall be further investigated. This can potentially be achieved by adding a shaded zone ahead the inlet such as double screen or stack.
- All windows of other apartments in the building and adjacent buildings were closed during the simulation. Opening these windows should not result into significant variations in the result of the study, expect in the Stack design cases.
- Advantageous ventilation through cracks were not considered in the study. This ventilation is expected to result into minor enhancement if considered in design.

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Appendix A.

CFD Simulation report

A.1 Group 1 Results

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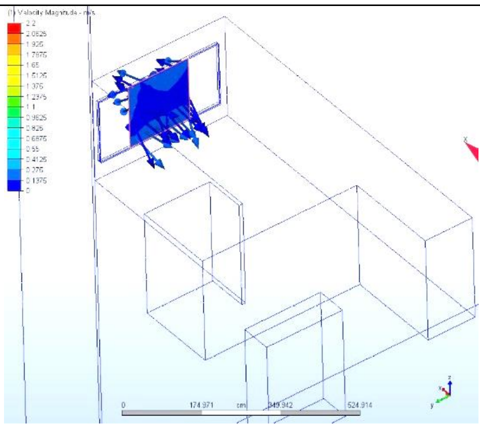
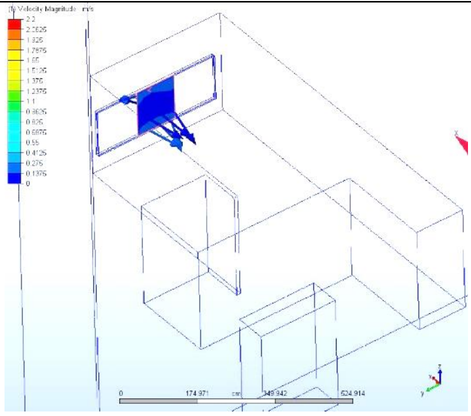
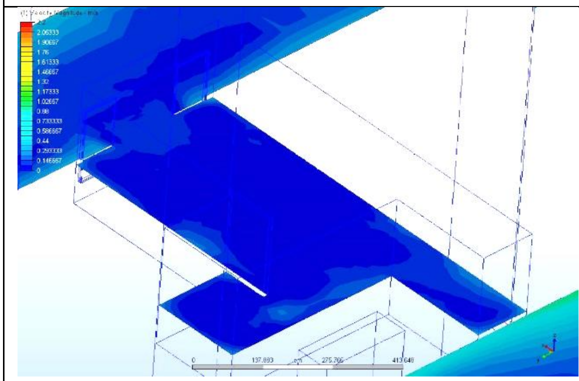
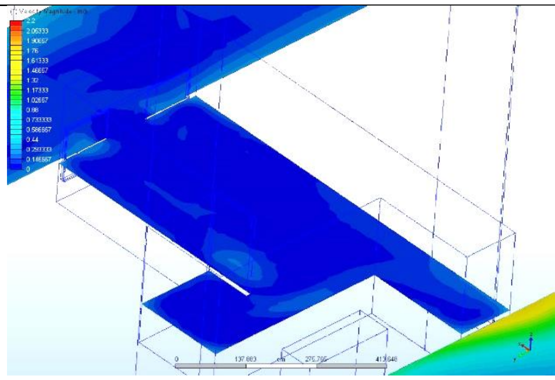
Boundary Condition **#BC_1**		
		
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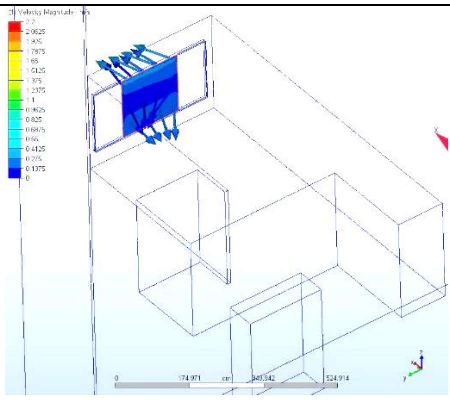
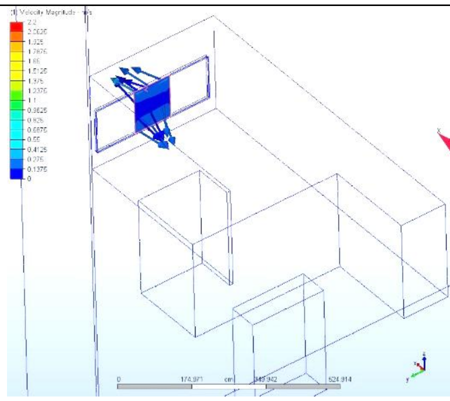
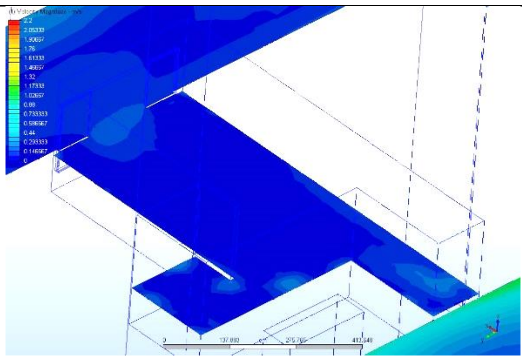
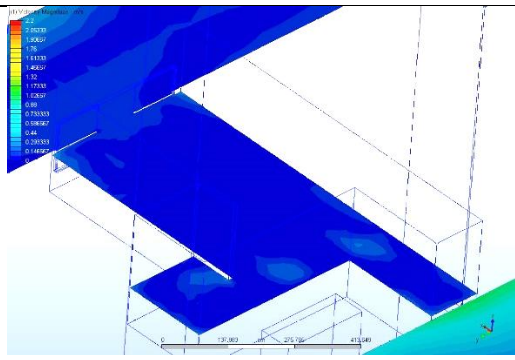
Boundary Condition **#BC_2**		
		

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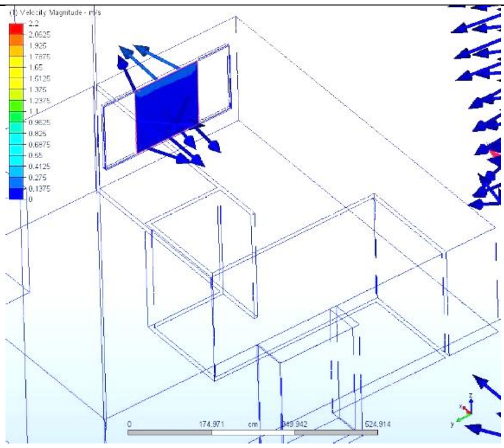
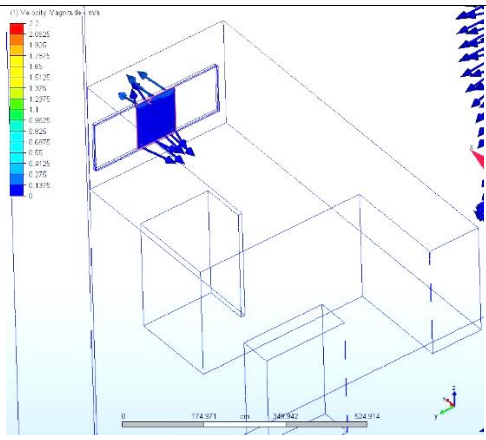
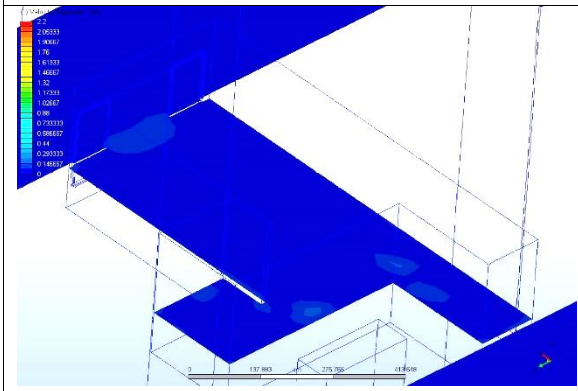
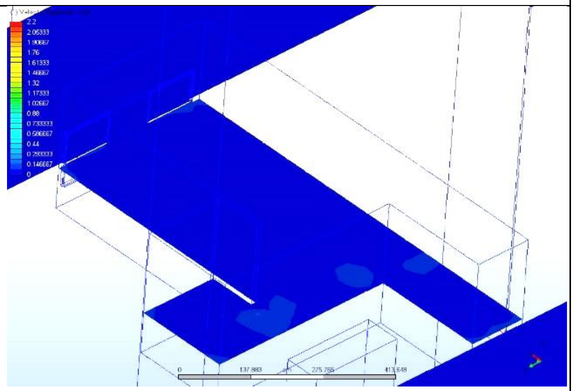
Boundary Condition **#BC_3**		
		
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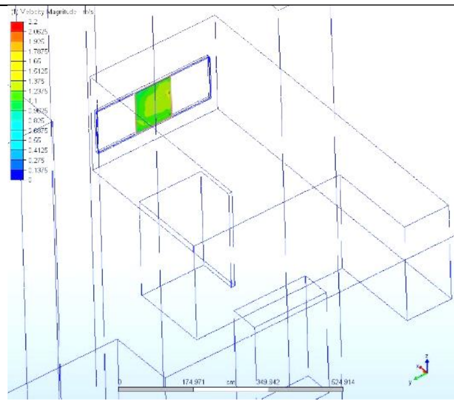
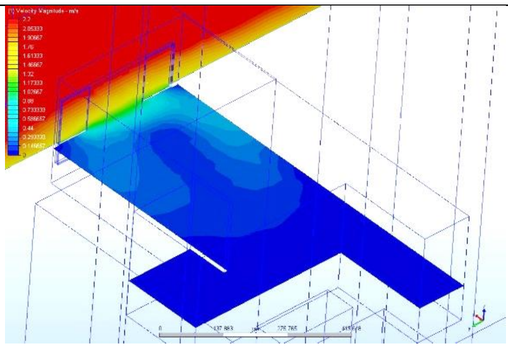
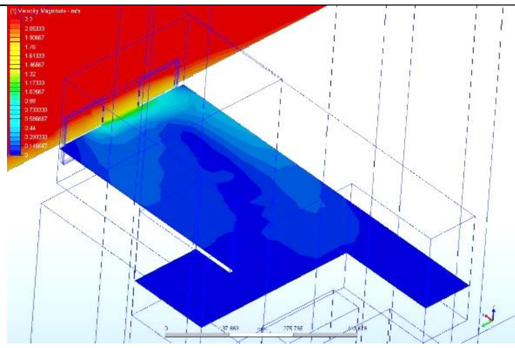
Boundary Condition **#BC_4**		
		

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	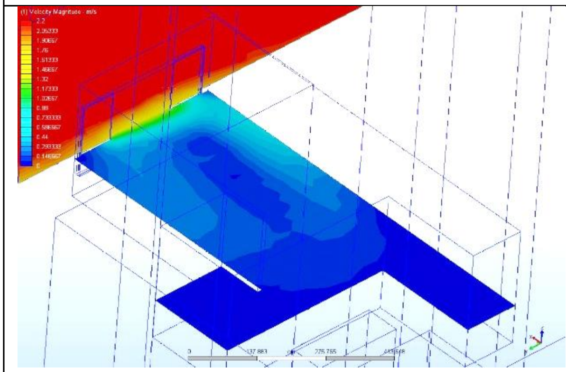	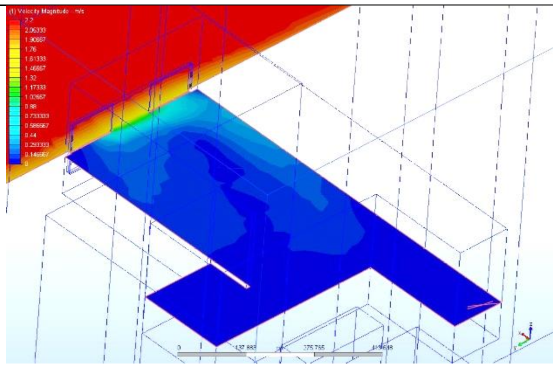
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	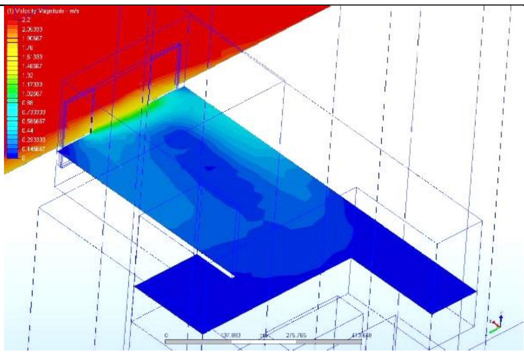	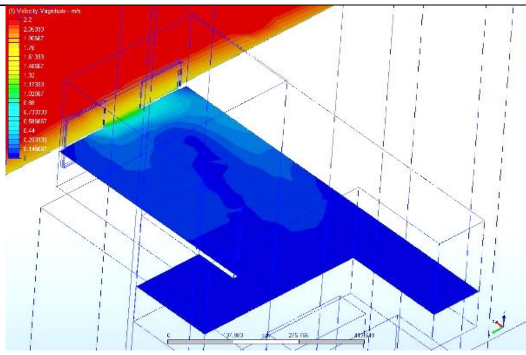

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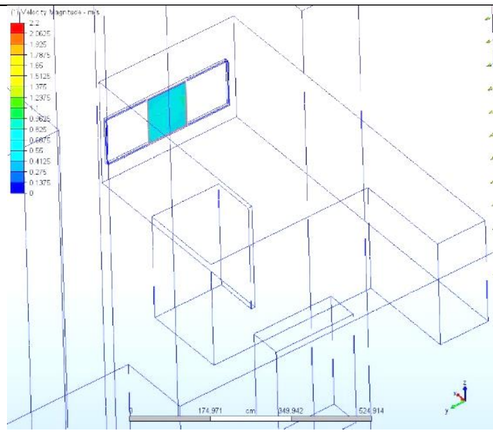
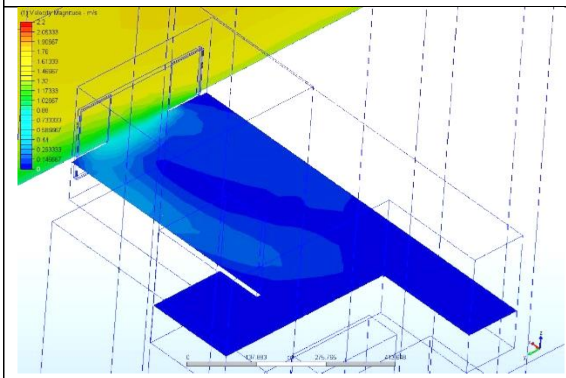
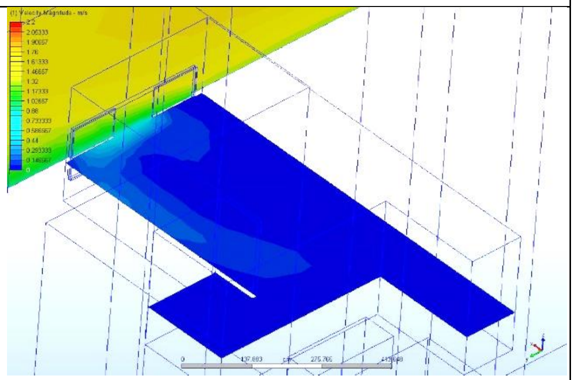
Boundary Condition **#BC_7**		
		
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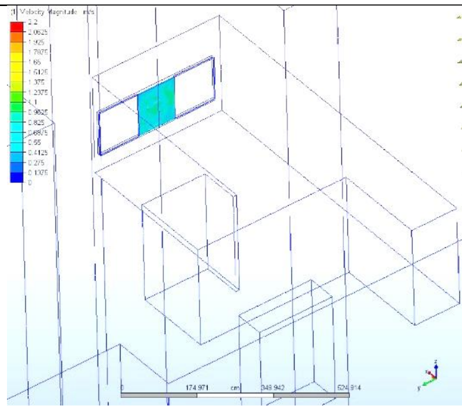
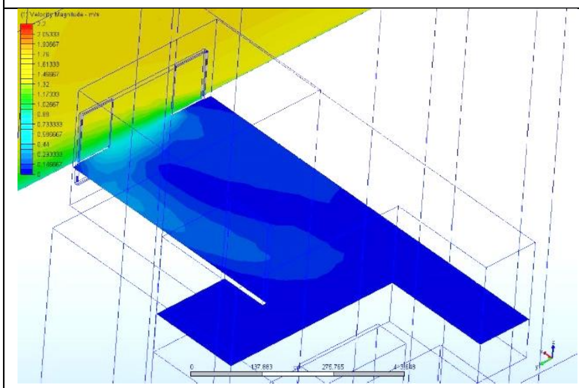
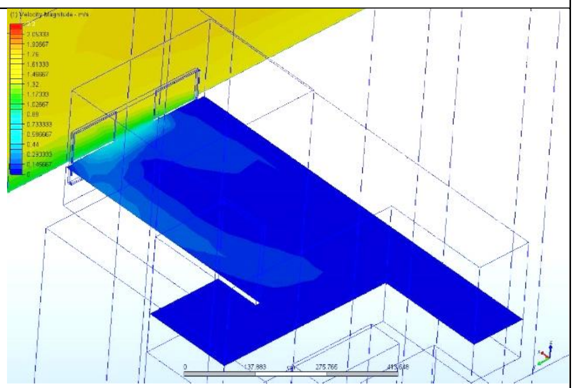
Boundary Condition **#BC_8**		
		

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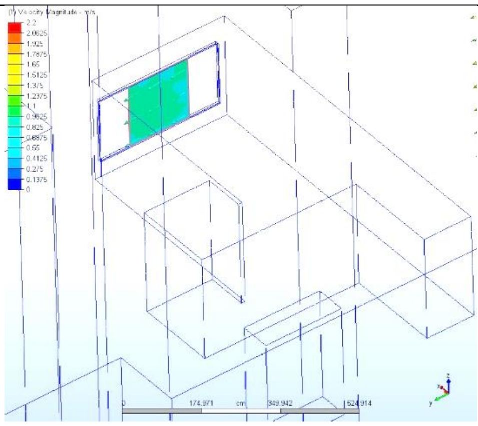
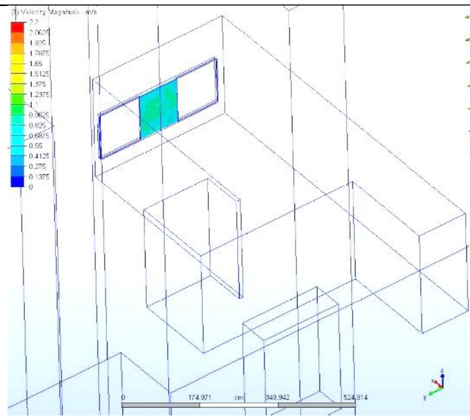
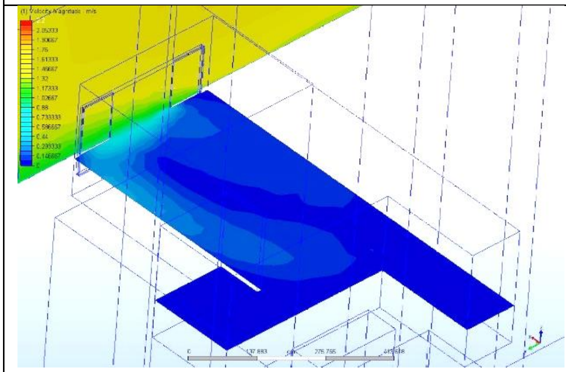
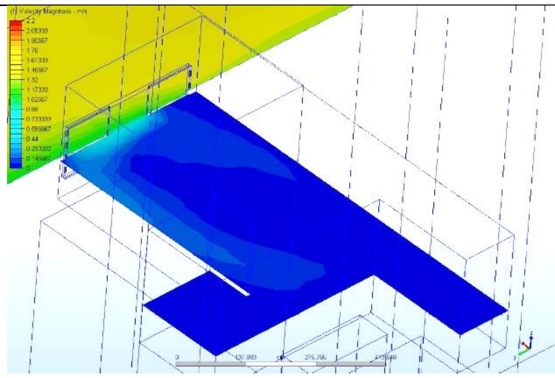
Boundary Condition **#BC_9**		
		
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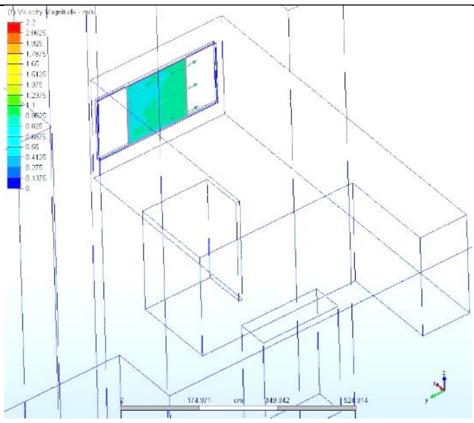
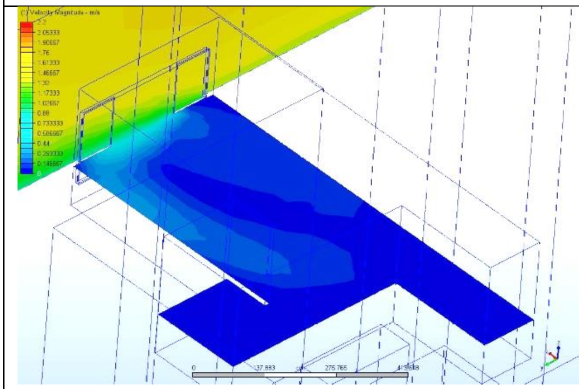
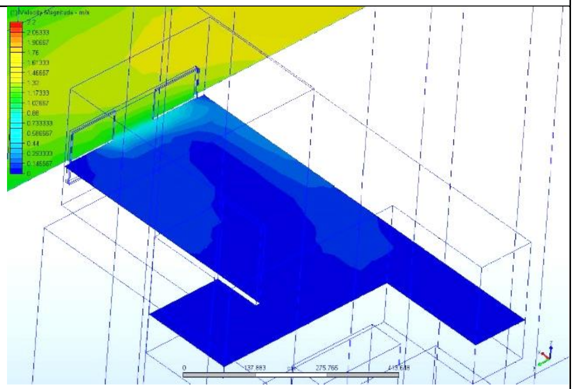
Boundary Condition **#BC_10**		
		

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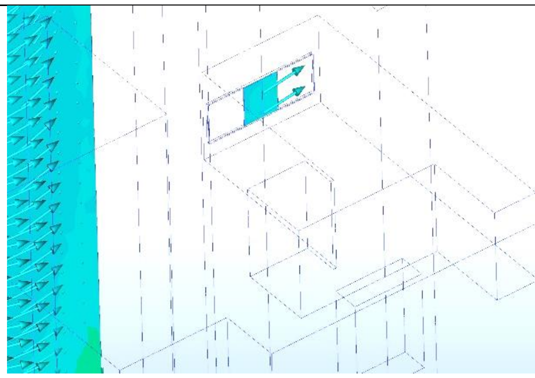
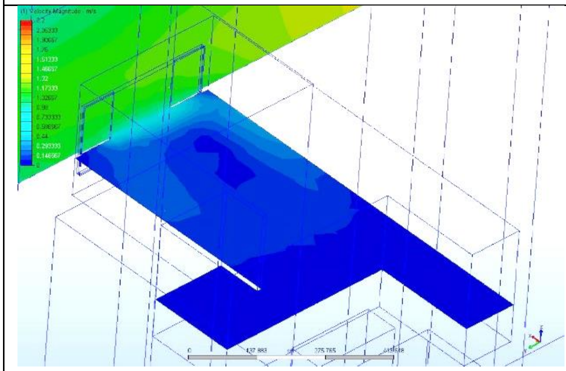
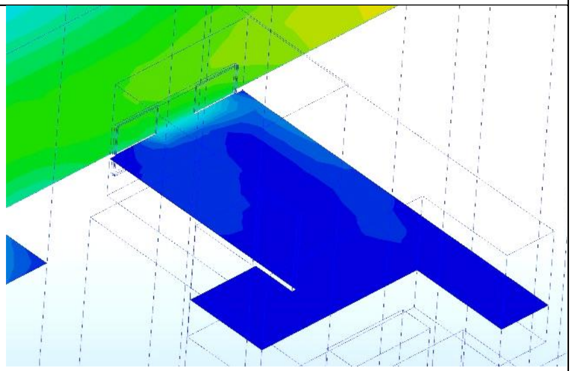
Boundary Condition **#BC_11**		
		
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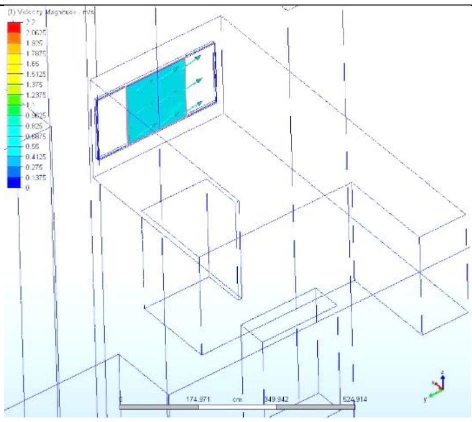
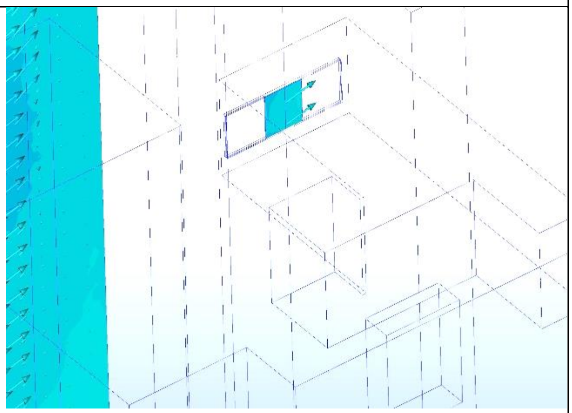
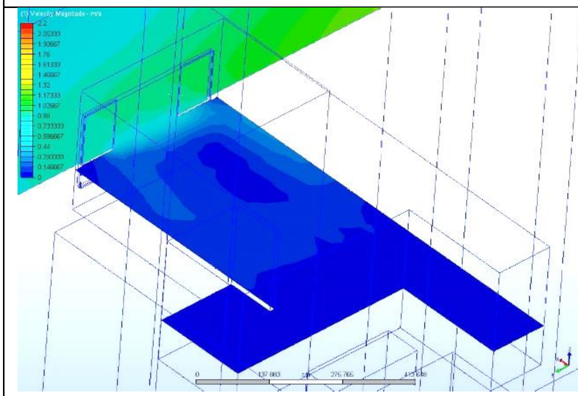
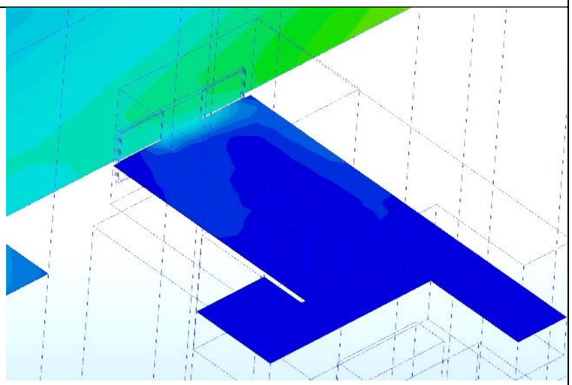
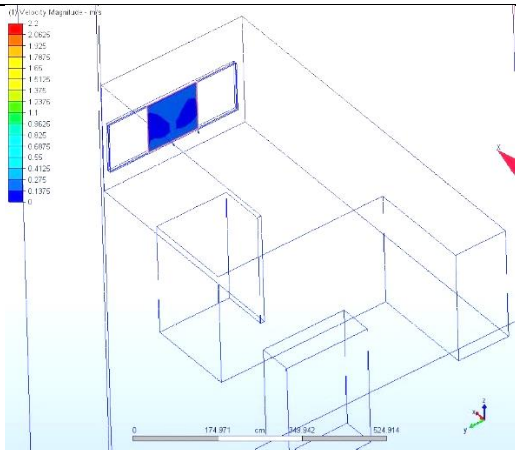
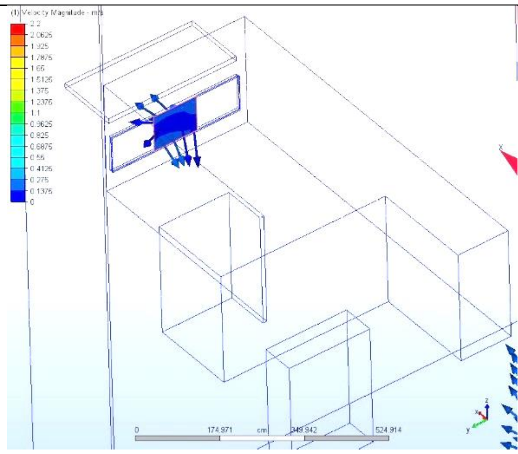
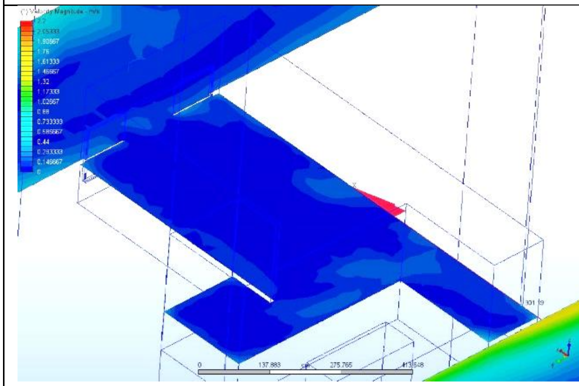
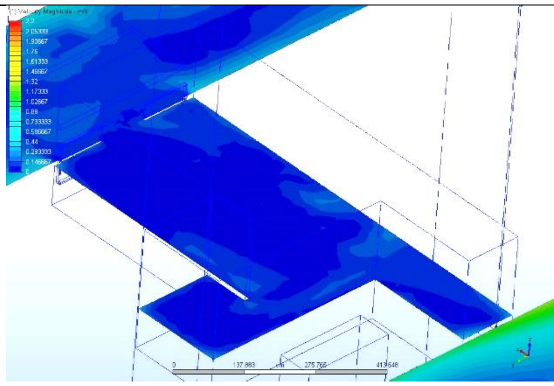
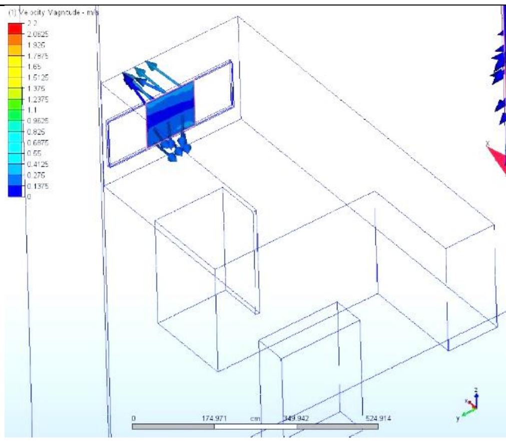
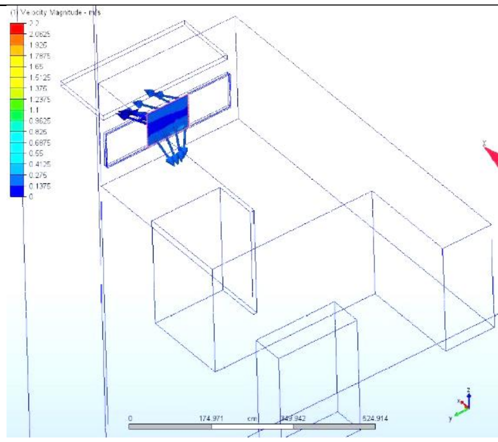
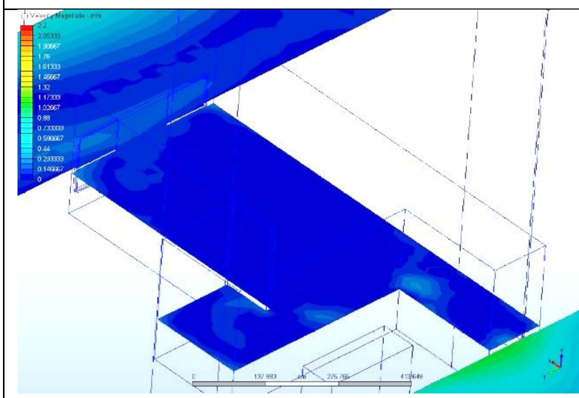
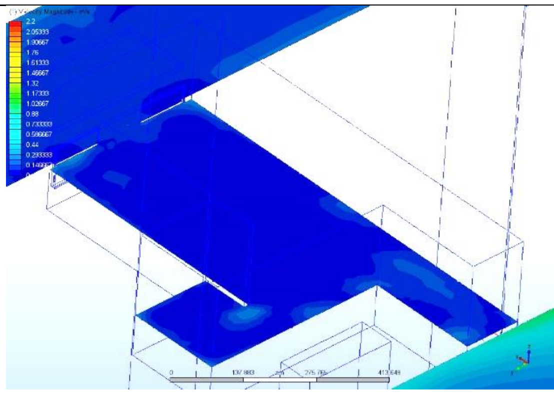
Boundary Condition **#BC_12**		
		

	BS 5925	CIBSE AM10
Boundary Condition **#BC_1**		
		
	BS 5925	CIBSE AM10
Boundary Condition **#BC_2**		
		

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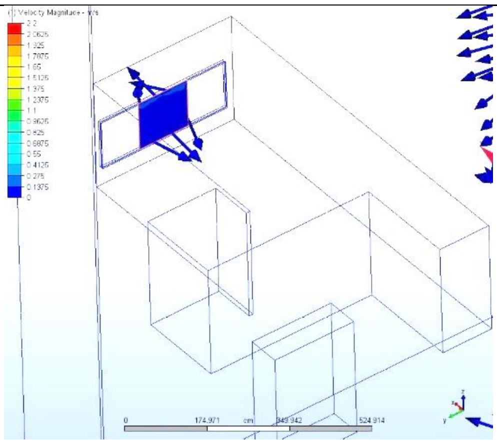
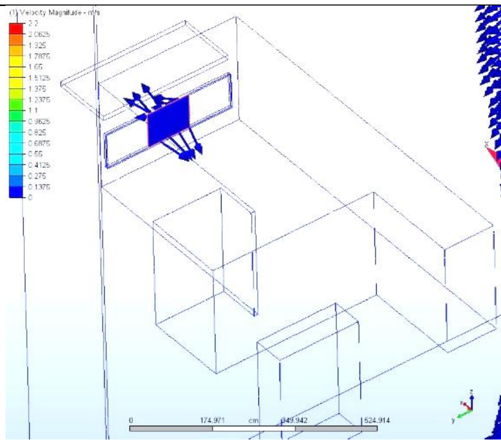
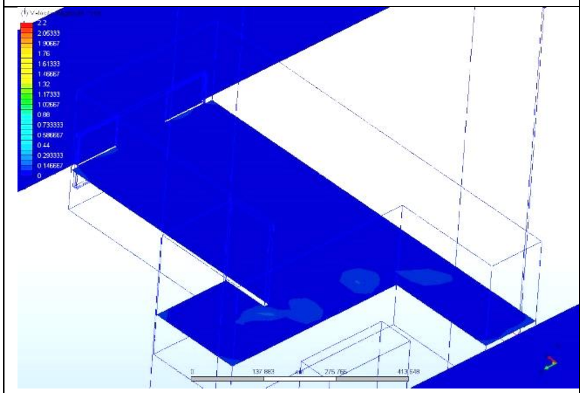
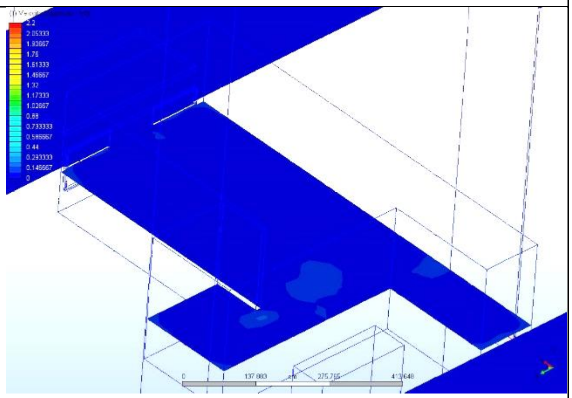
Boundary Condition **#BC_3**		
		
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	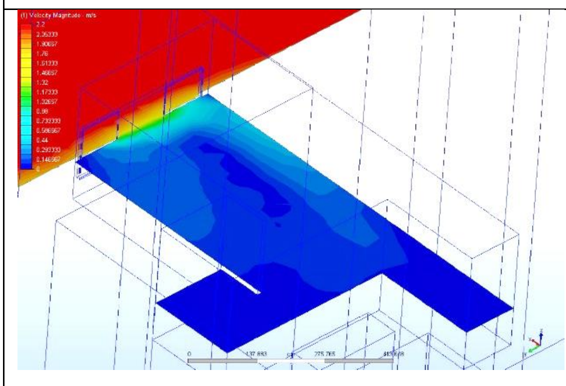	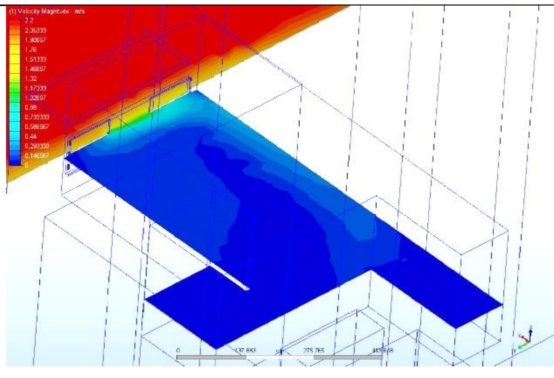

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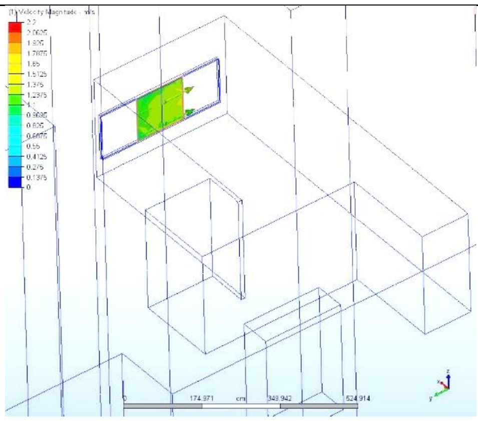
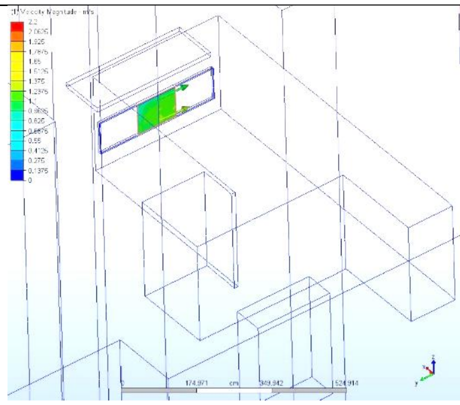
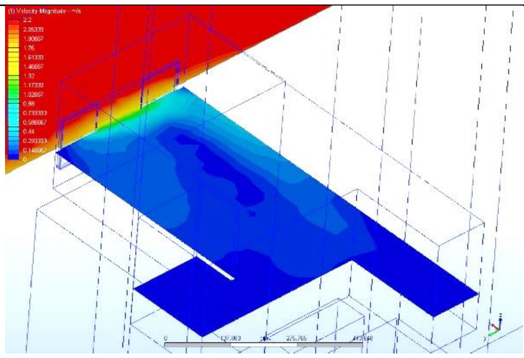
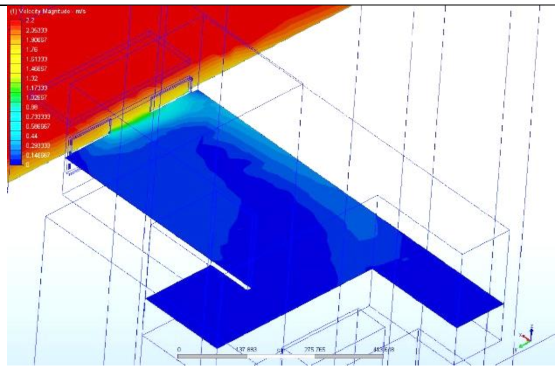
Boundary Condition **#BC_5**		
		
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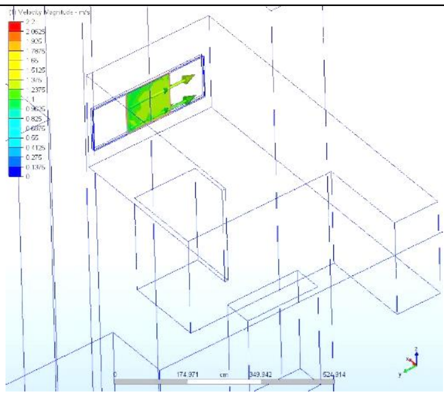
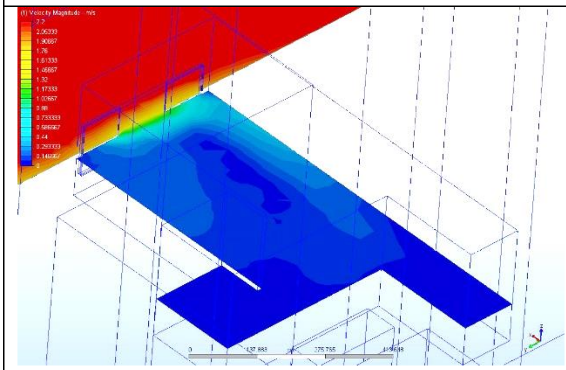
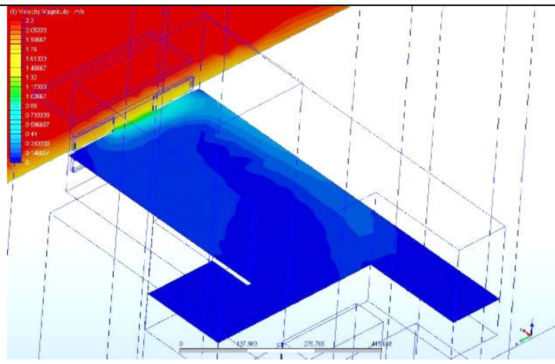
Boundary Condition **#BC_6**		
		

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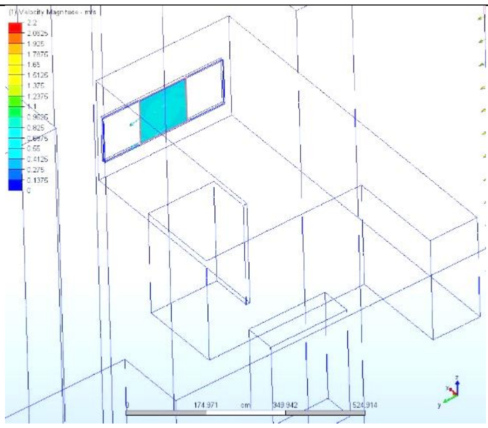
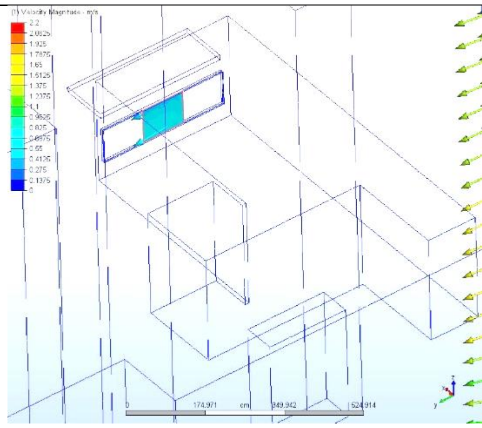
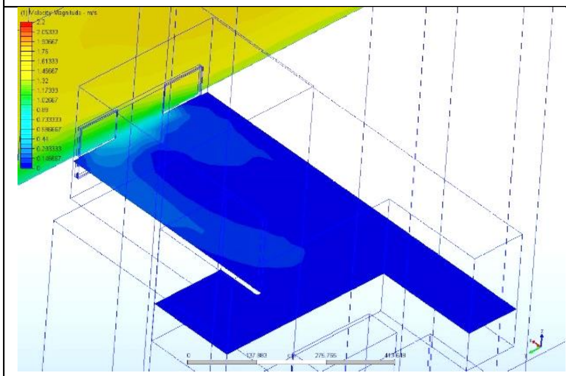
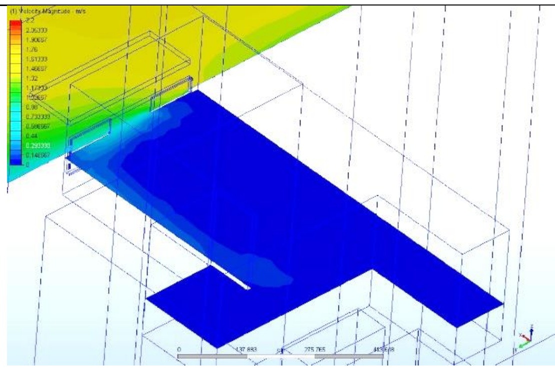
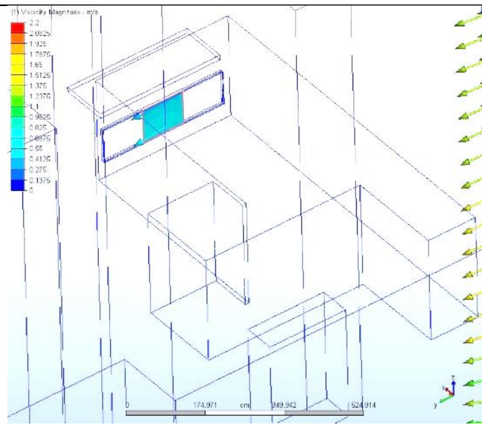
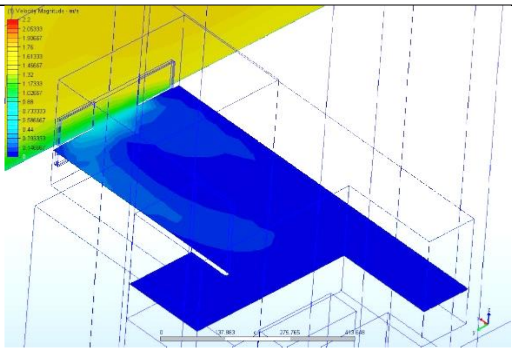
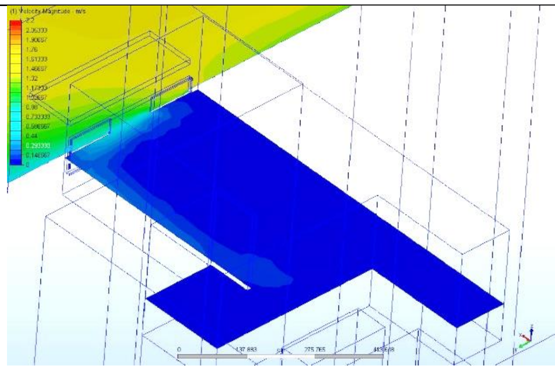
Boundary Condition **#BC_7**		
		
	BS 5925	CIBSE AM10
Boundary Condition **#BC_8**		
		

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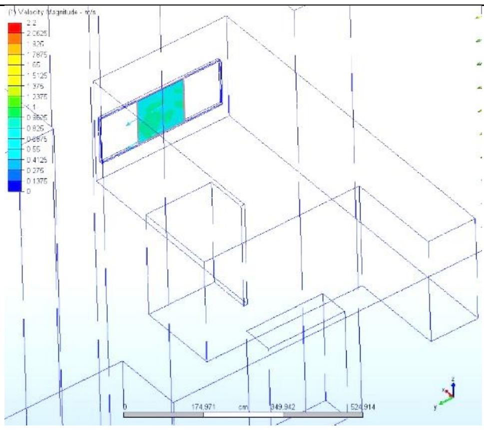
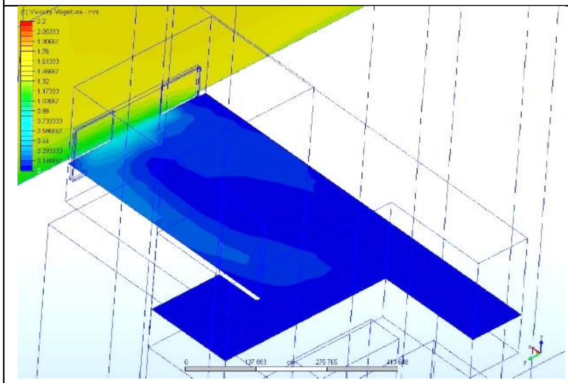
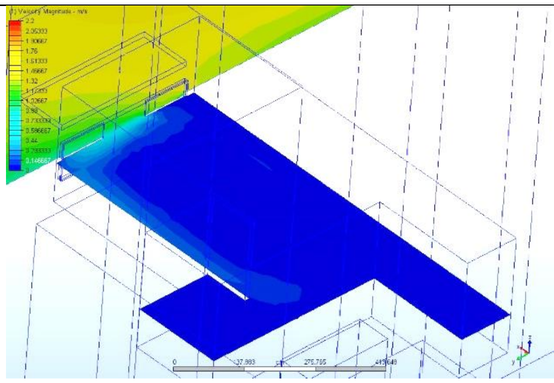
Boundary Condition **#BC_9**		
		
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	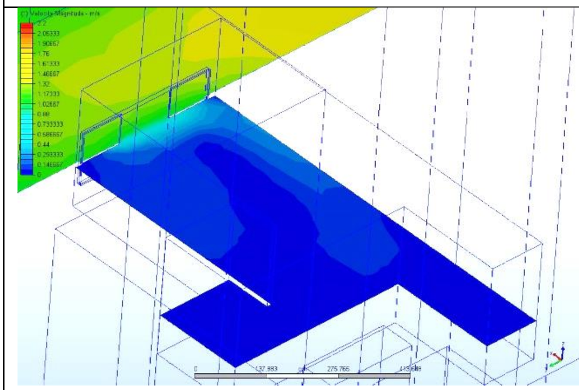	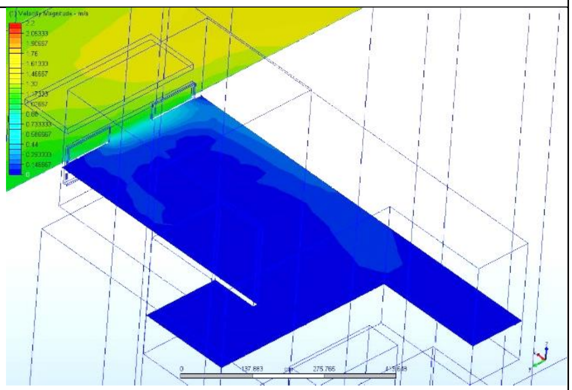

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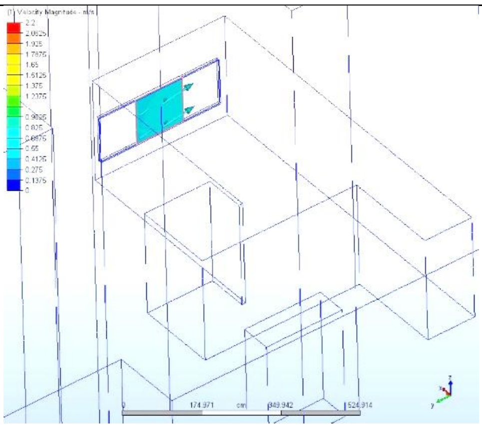
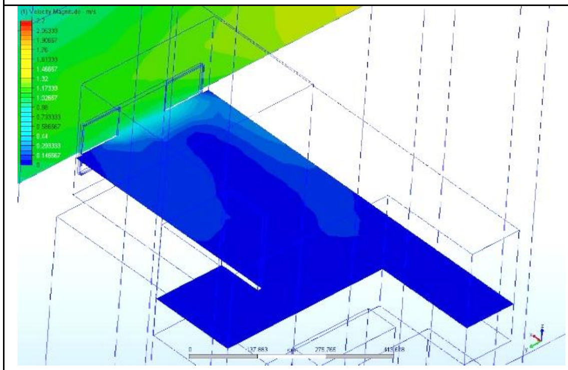
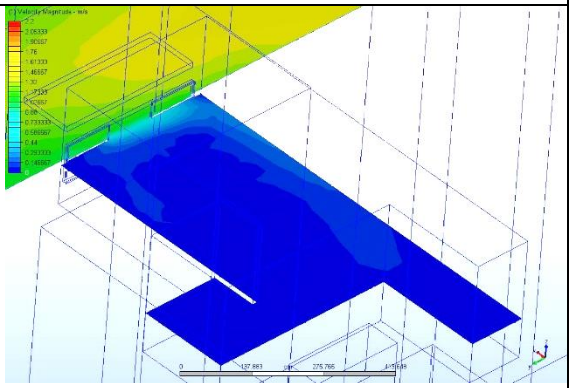
Boundary Condition **#BC_11**		
		
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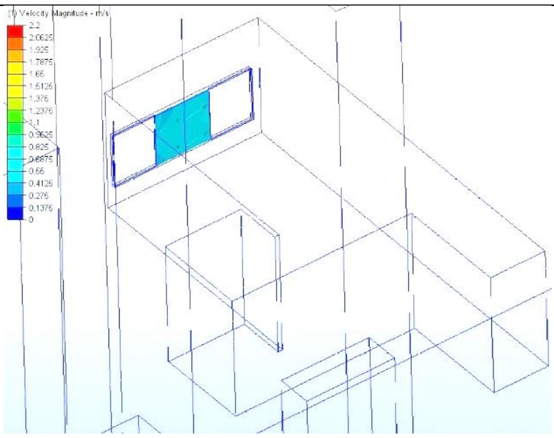
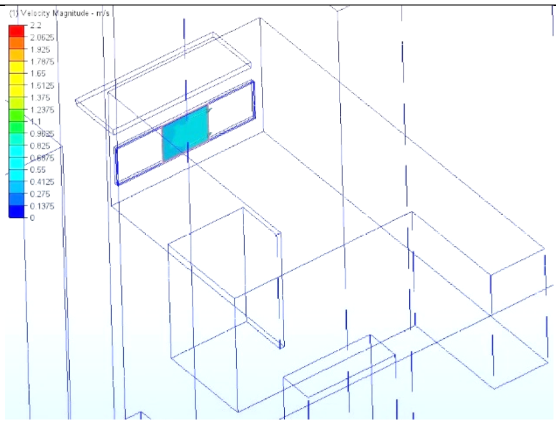
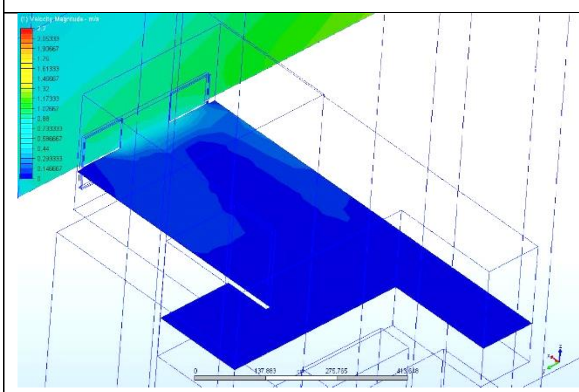
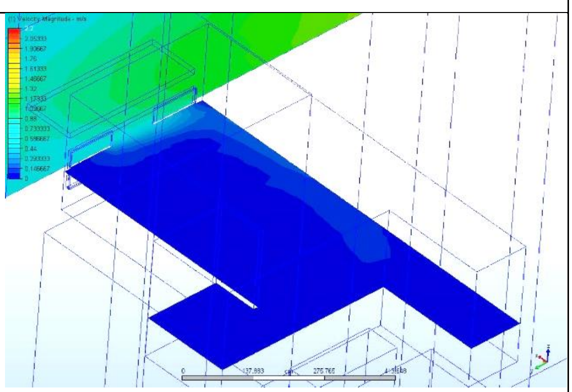
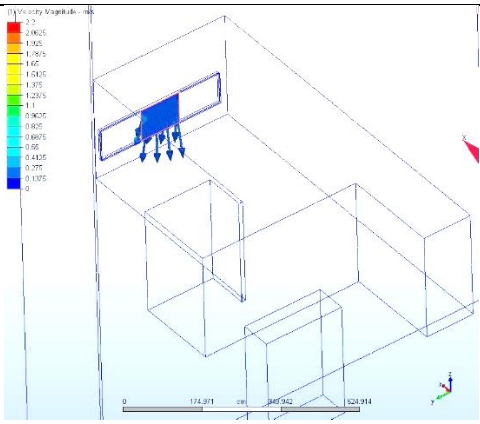
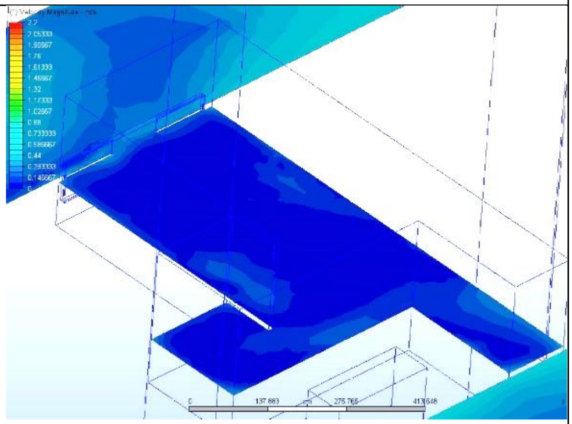
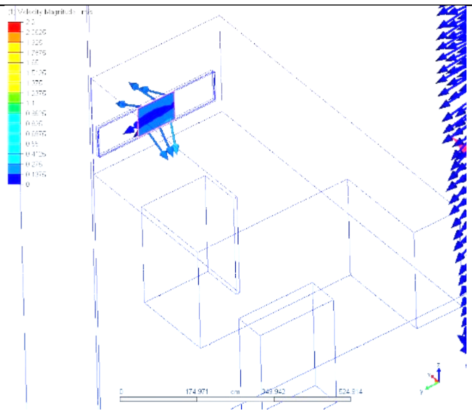
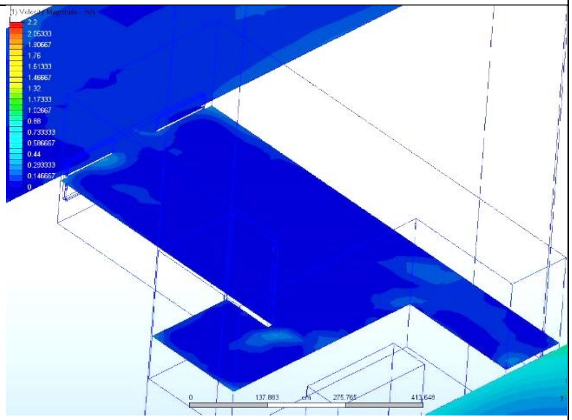
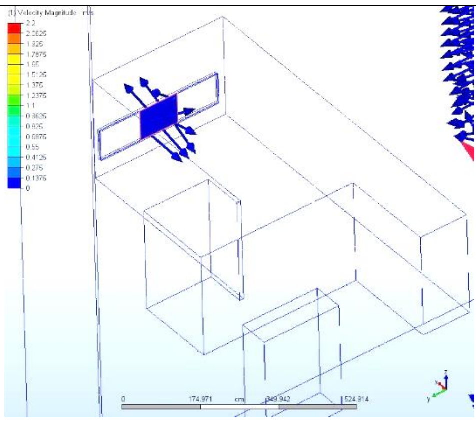
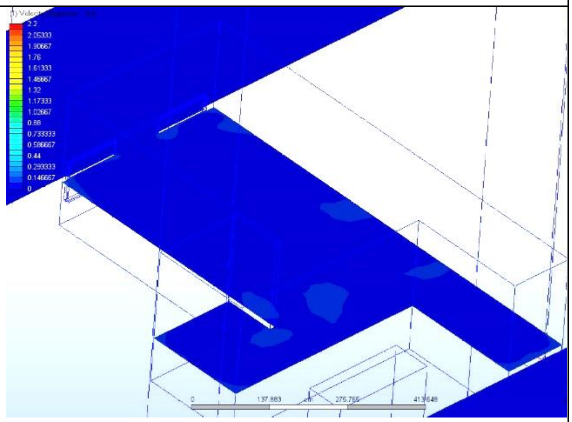
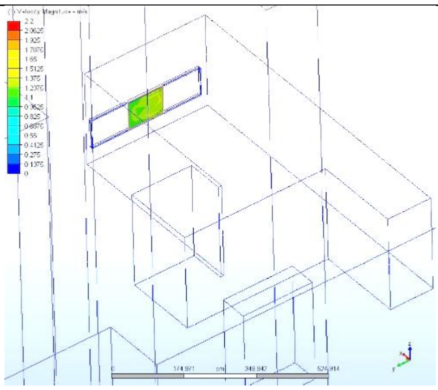
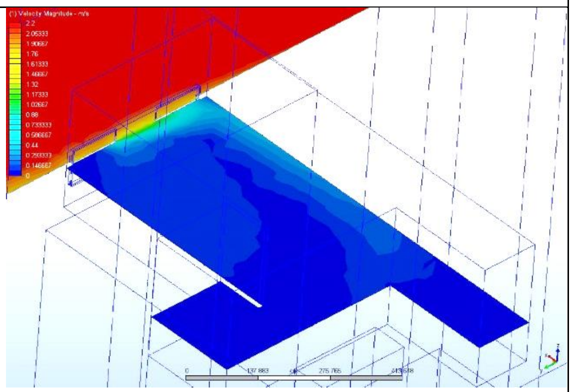
Boundary Condition **#BC_12**		
		

	ASHRAE Fundamentals	
Boundary Condition **#BC_1**		
Boundary Condition **#BC_2**		
	ASHRAE Fundamentals	
Boundary Condition **#BC_3**		
Boundary Condition **#BC_4**		

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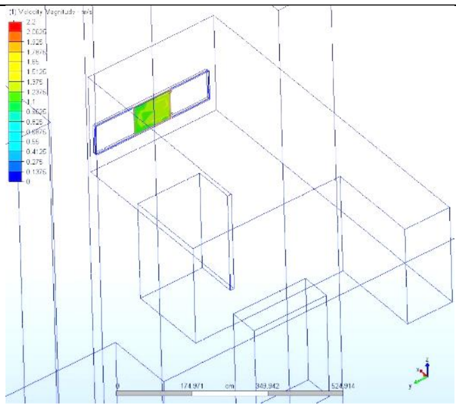
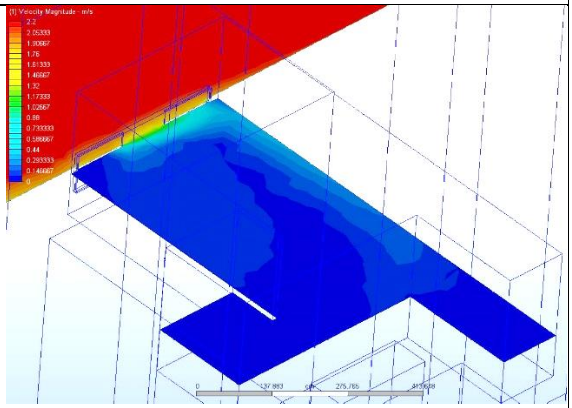
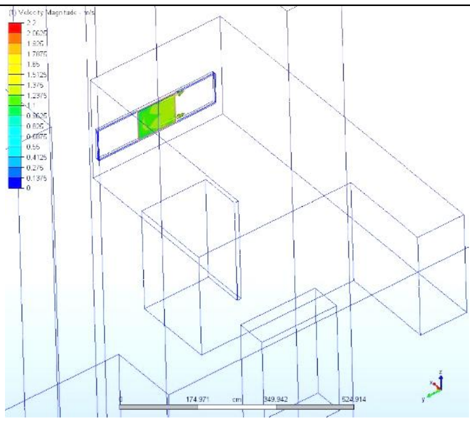
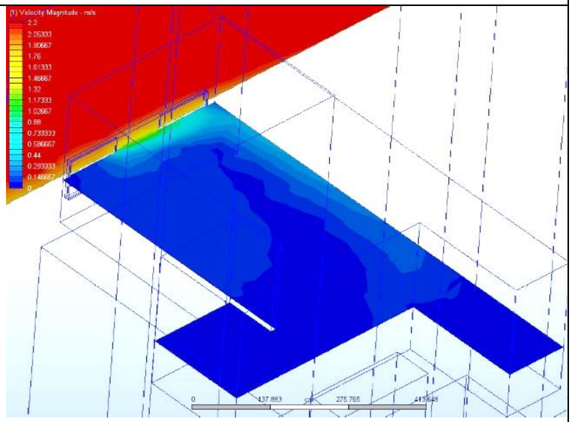
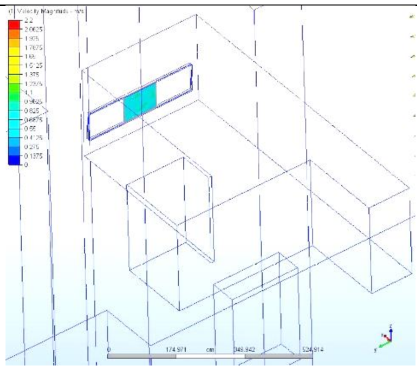
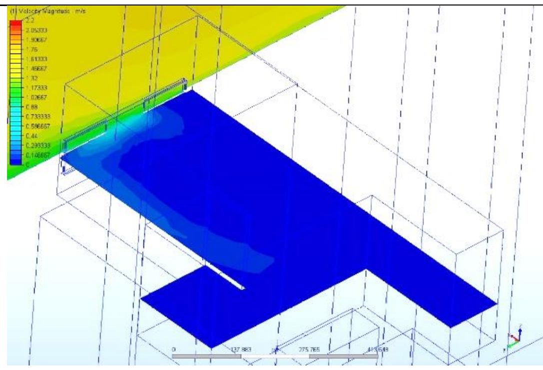
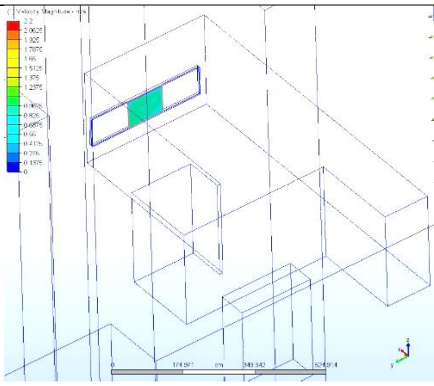
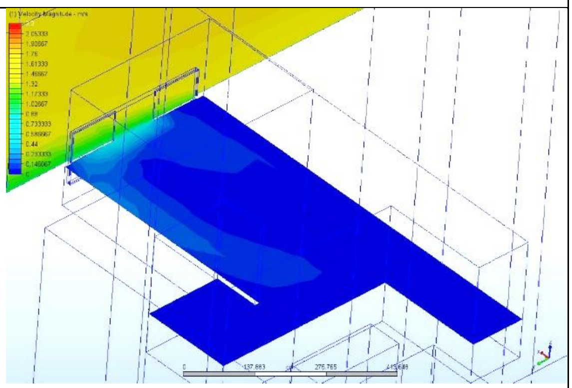
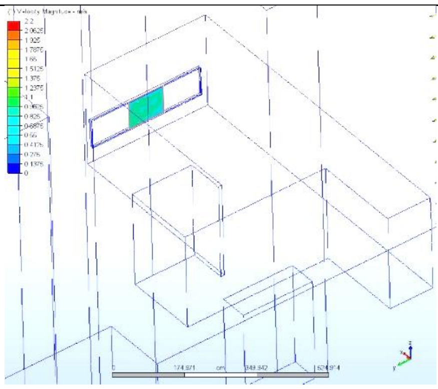
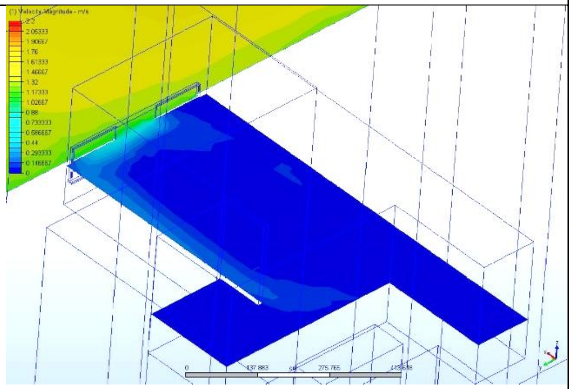
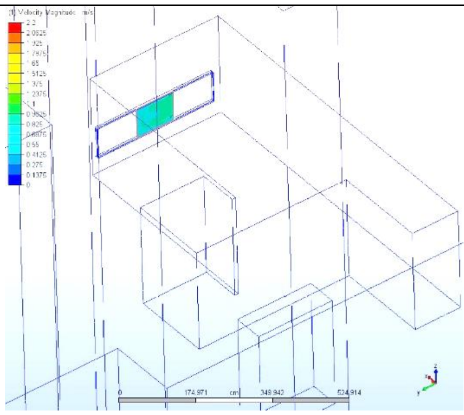
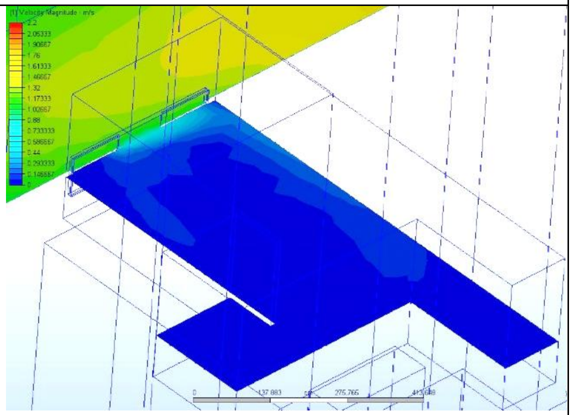
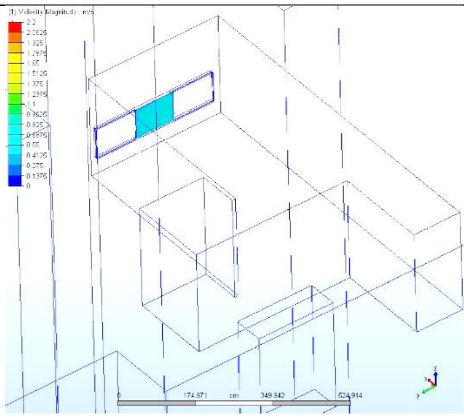
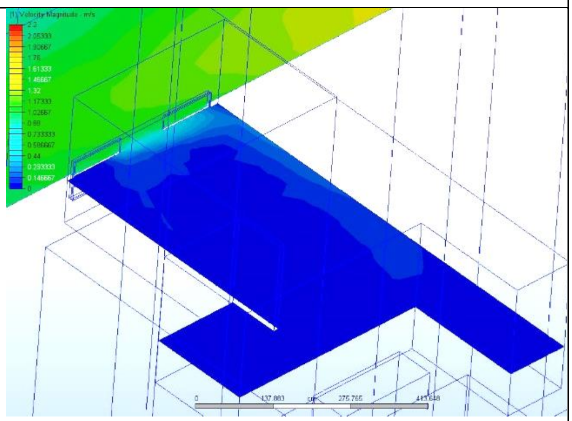
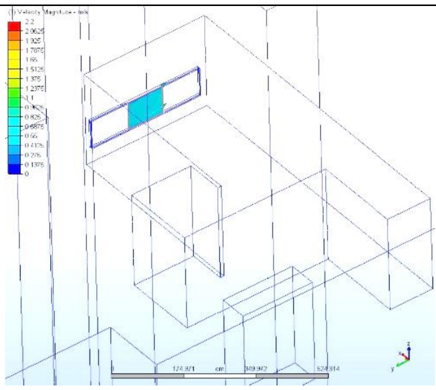
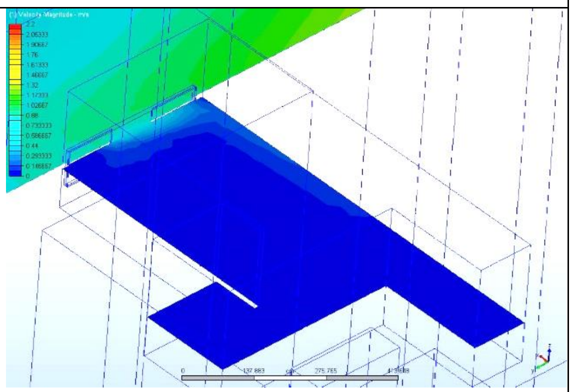
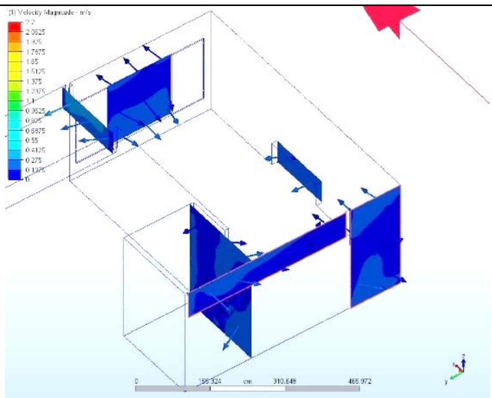
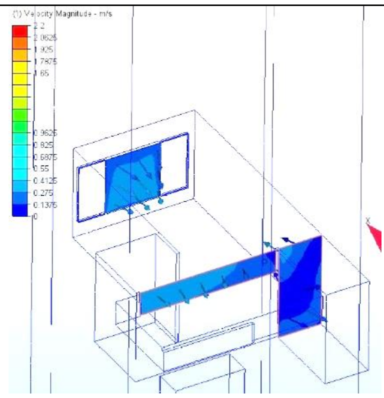
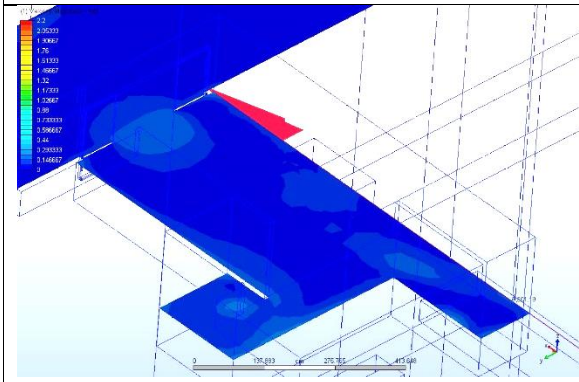
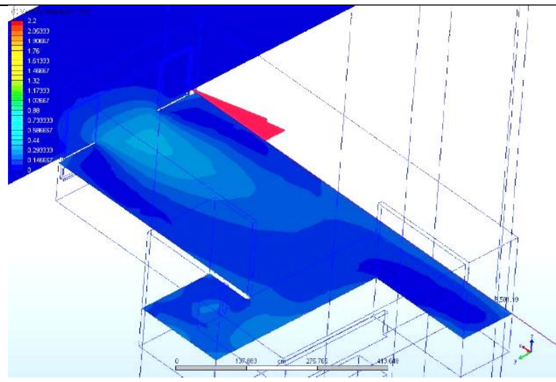
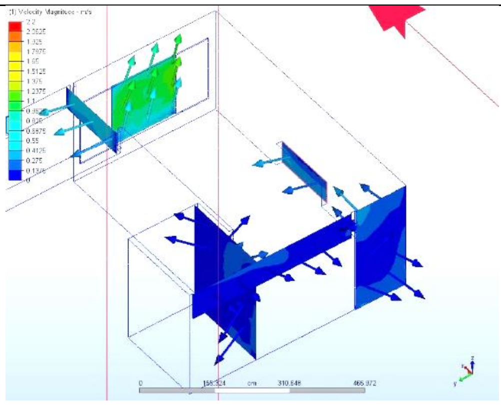
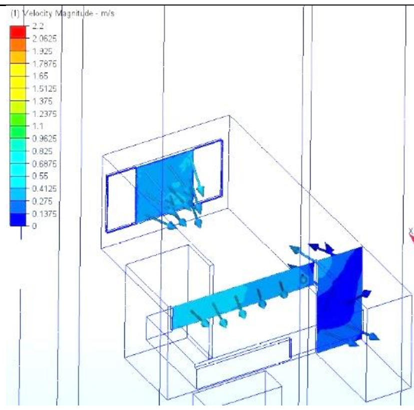
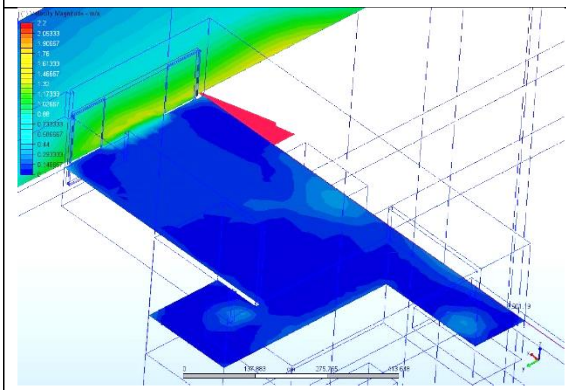
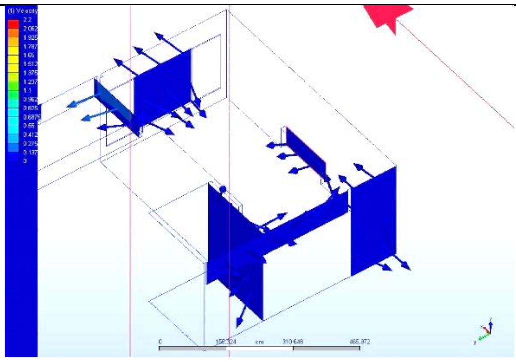
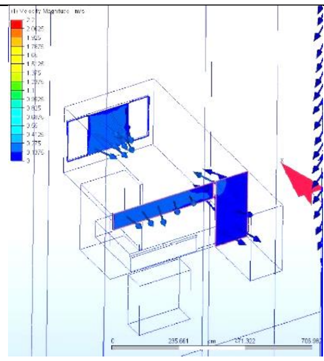
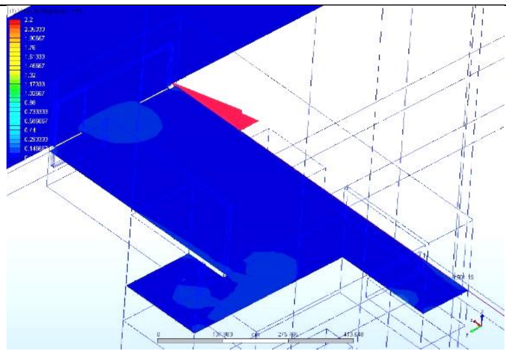
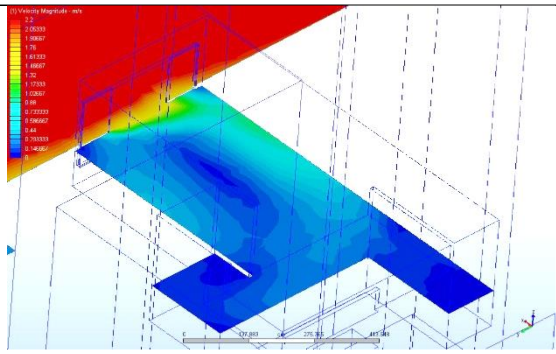
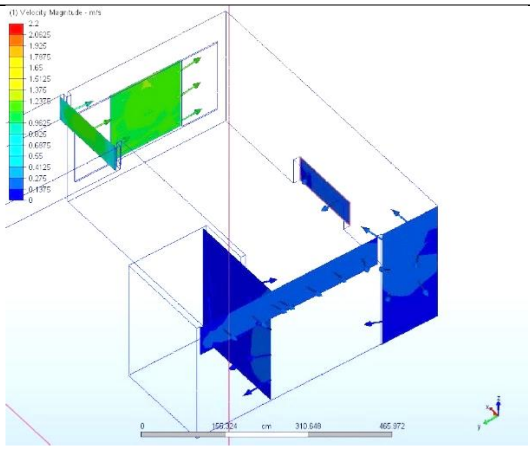
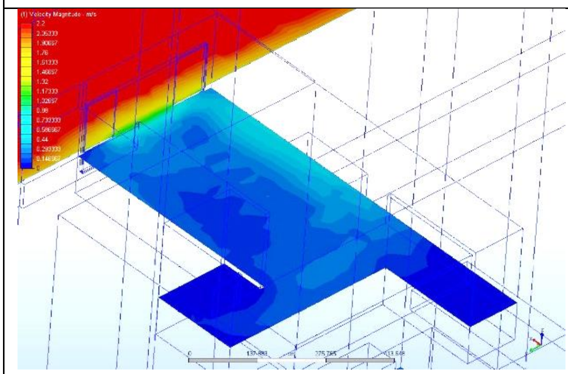
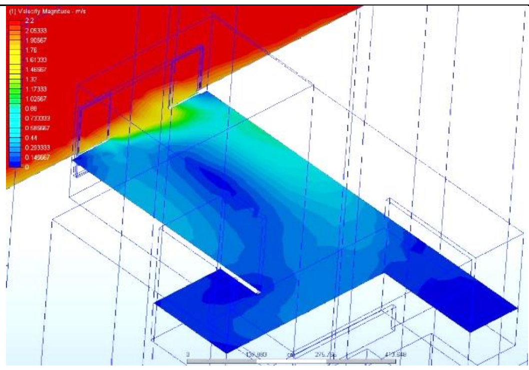
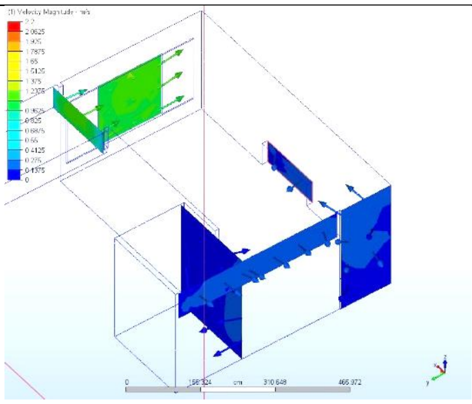
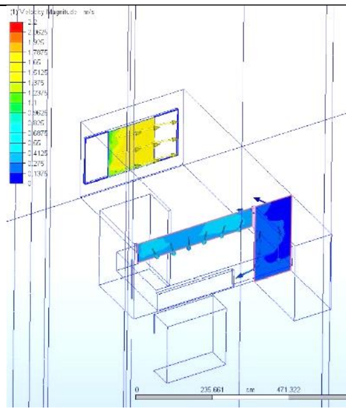
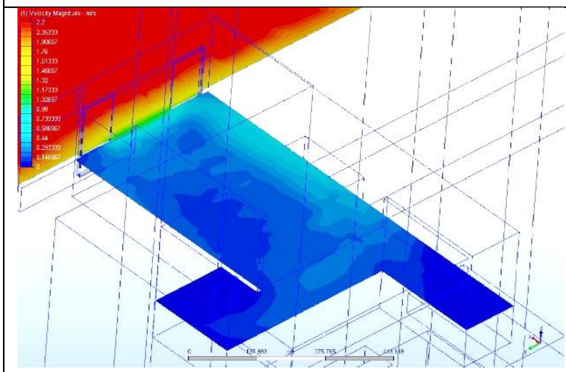
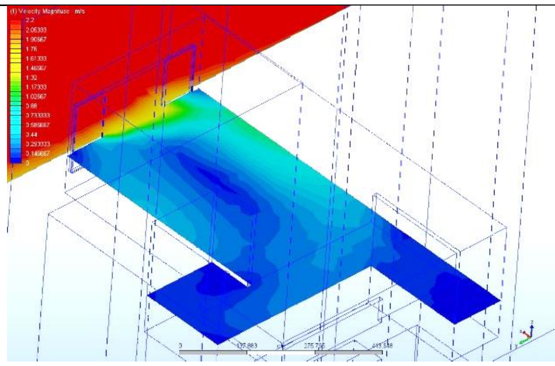
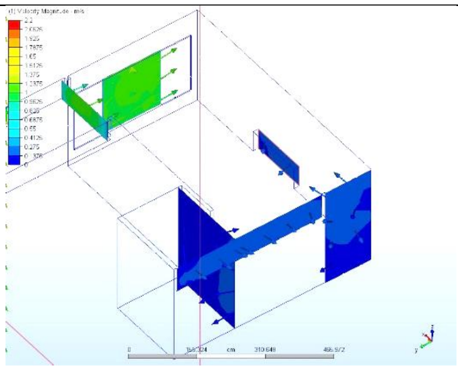
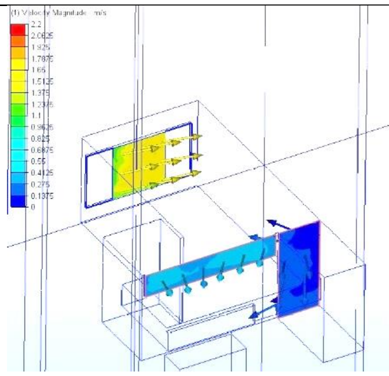
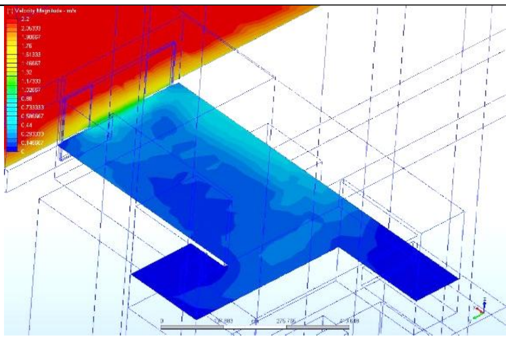
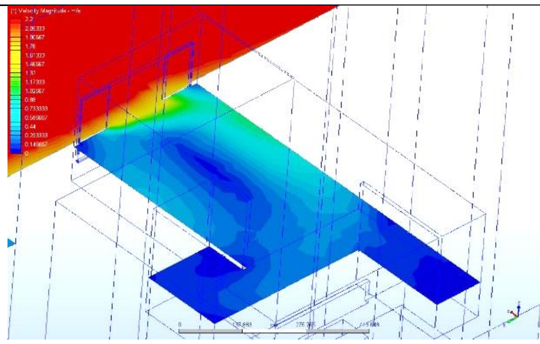
Boundary Condition **#BC_5**		
Boundary Condition **#BC_6**		
	ASHRAE Fundamentals	
Boundary Condition **#BC_7**		
Boundary Condition **#BC_8**		

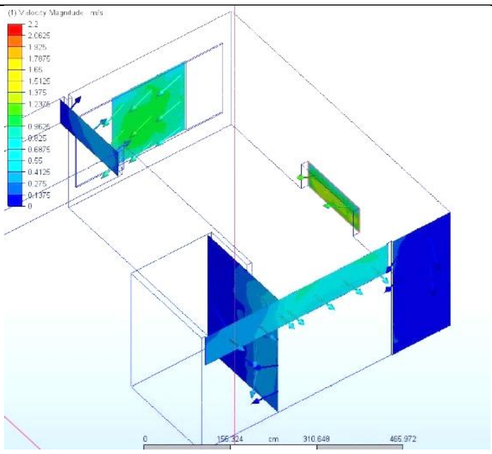
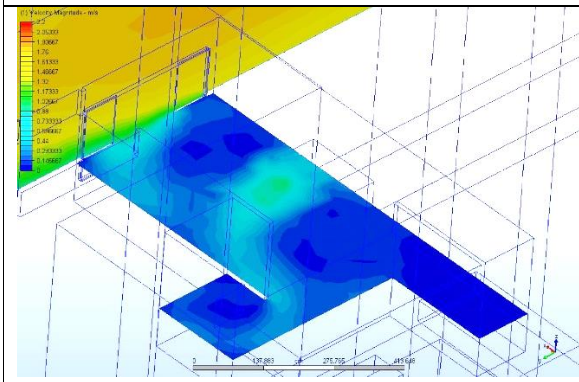
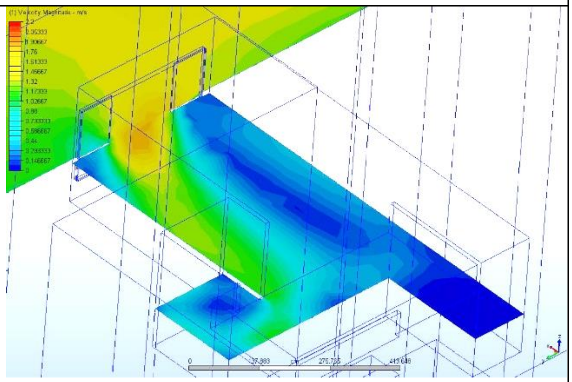
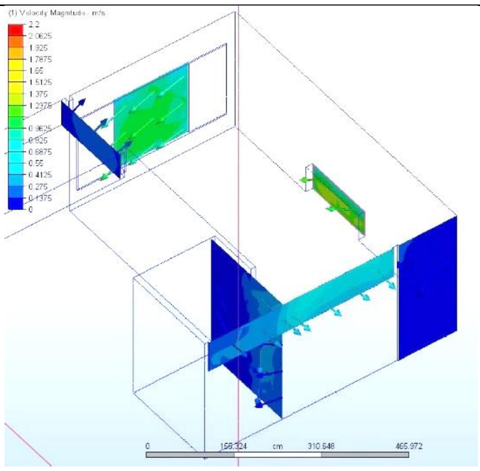
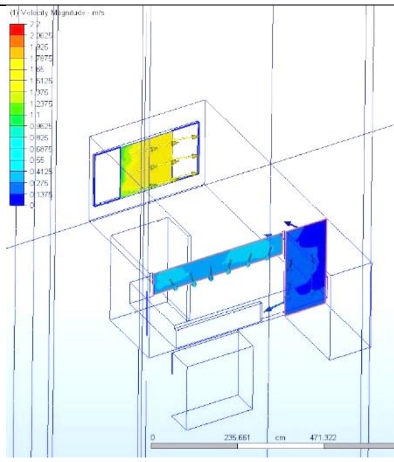
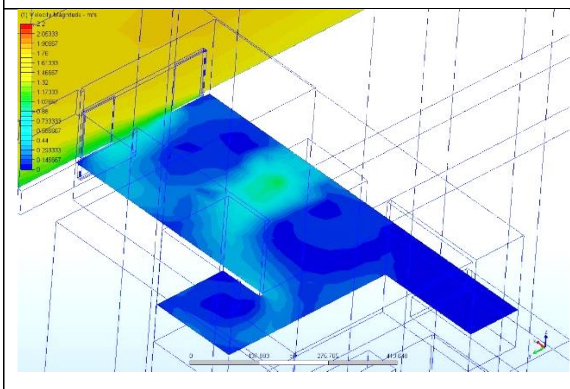
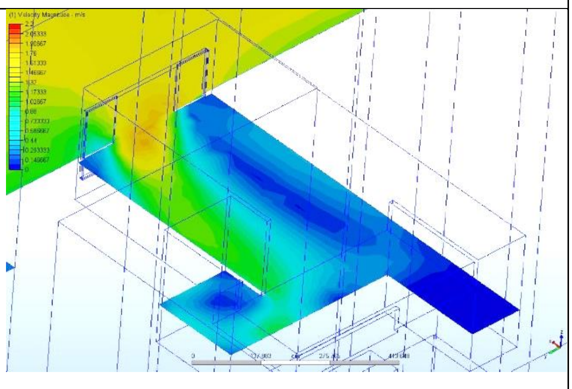
	ASHRAE Fundamentals	
Boundary Condition **#BC_9**		
Boundary Condition **#BC_10**		
	ASHRAE Fundamentals	
Boundary Condition **#BC_11**		
Boundary Condition **#BC_12**		

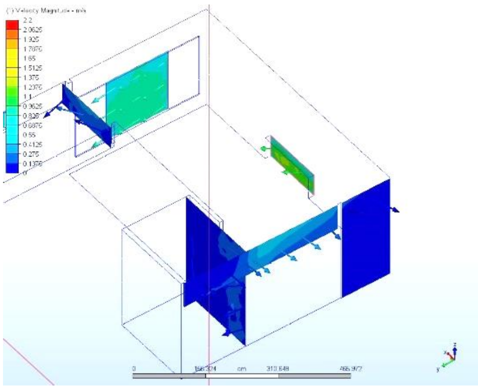
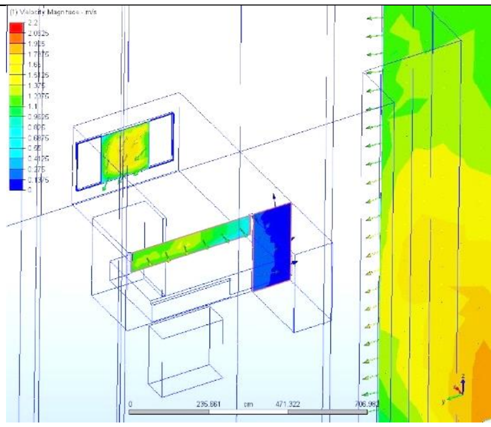
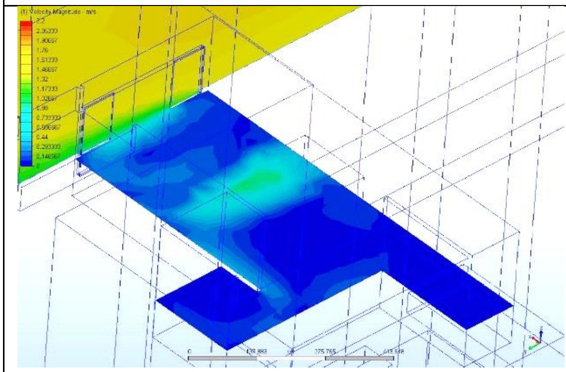
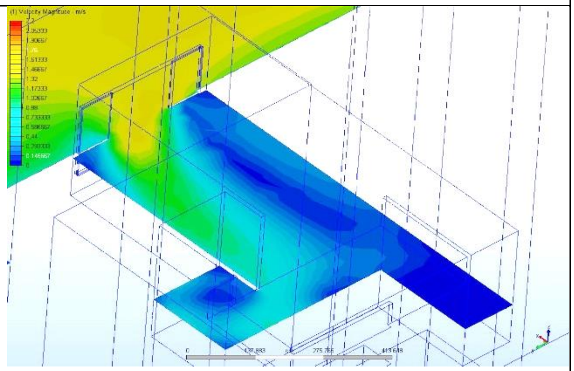
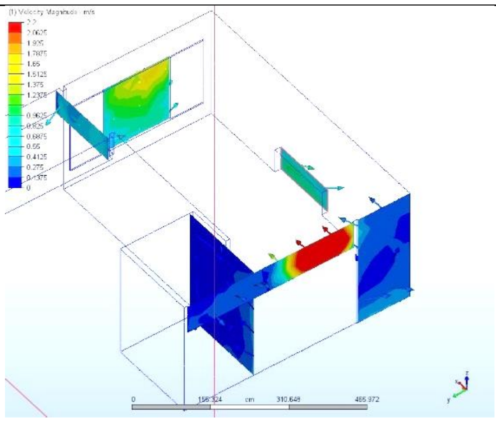
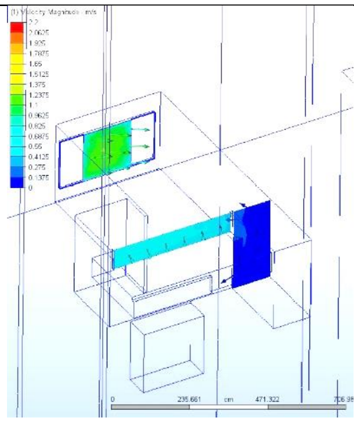
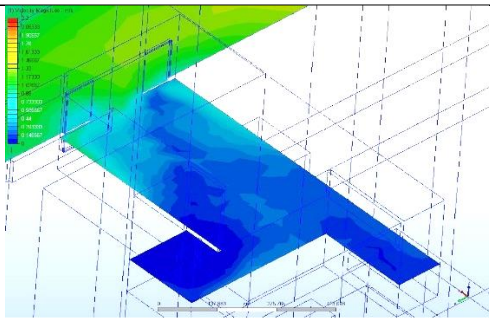
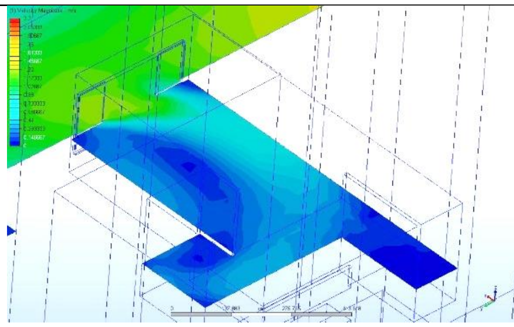
A.2 Group 2 Results

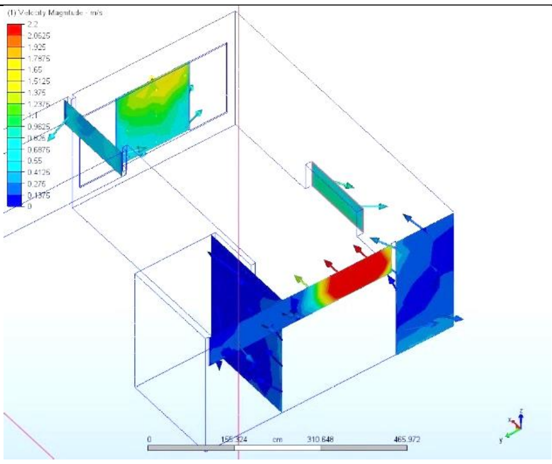
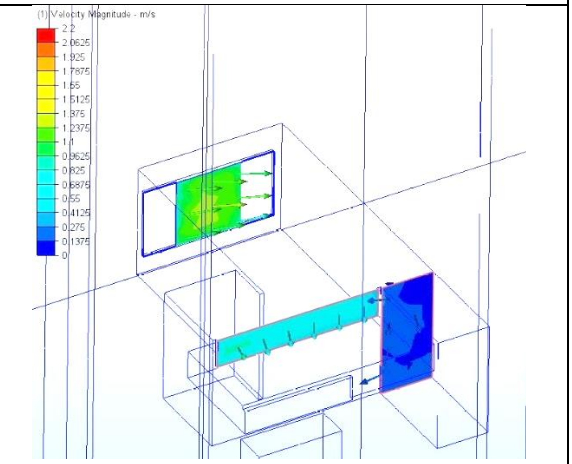
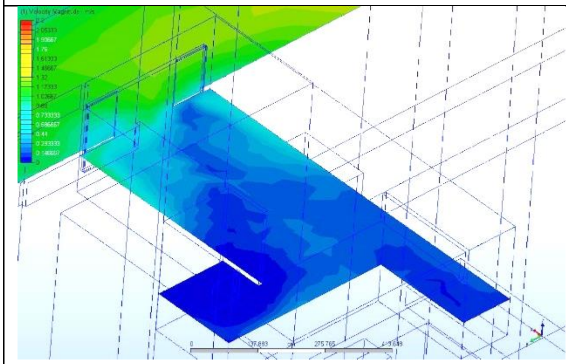
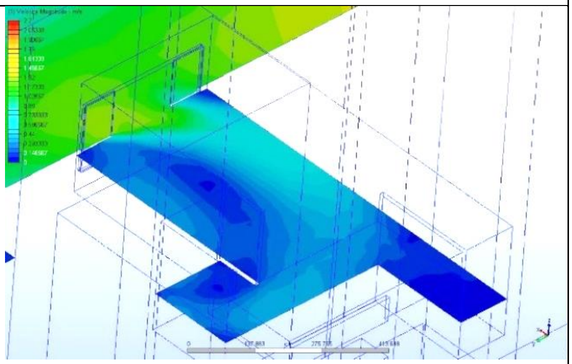
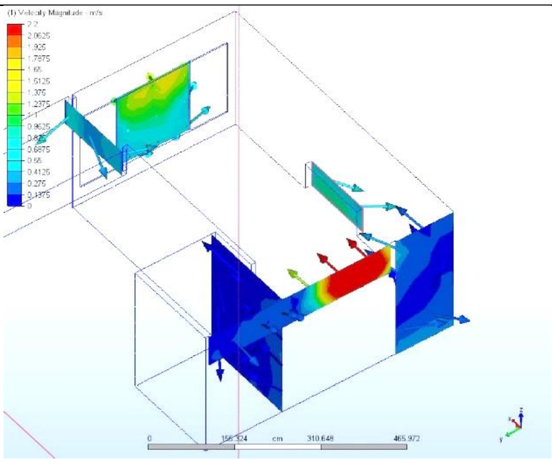
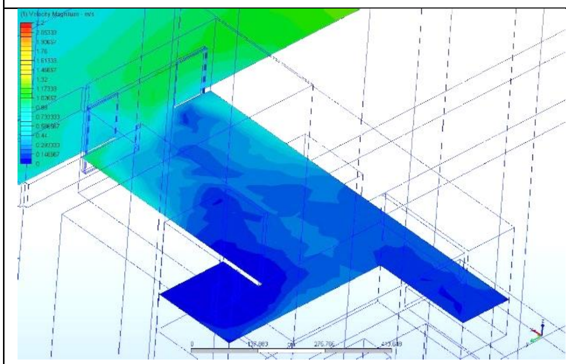
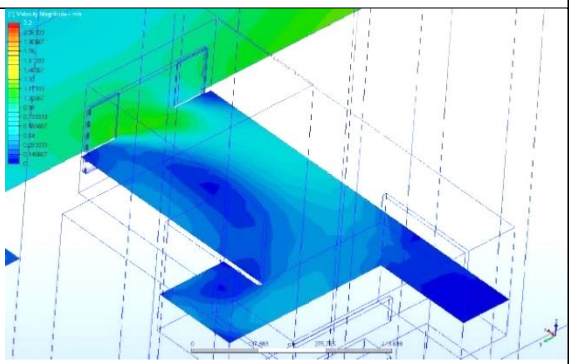
	Air Ducts	Stack
Boundary Condition **#BC_1**		
		
	Air Ducts	Stack
Boundary Condition **#BC_2**		
		

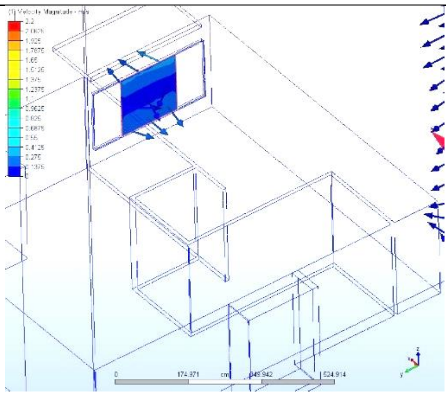
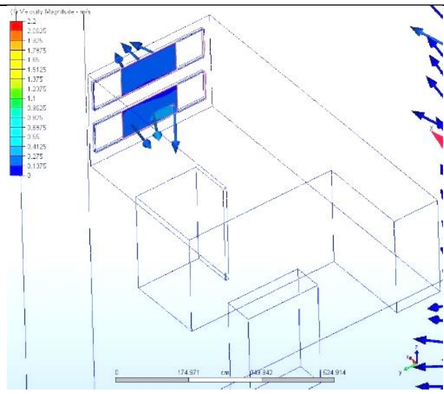
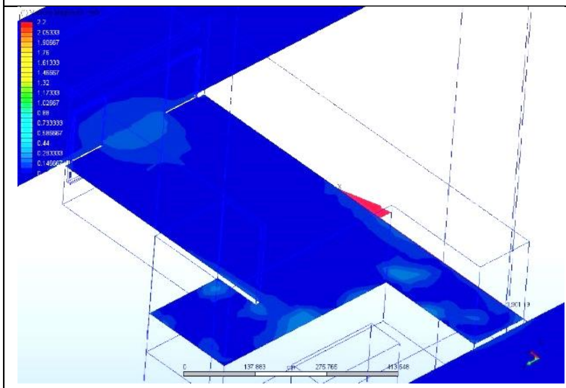
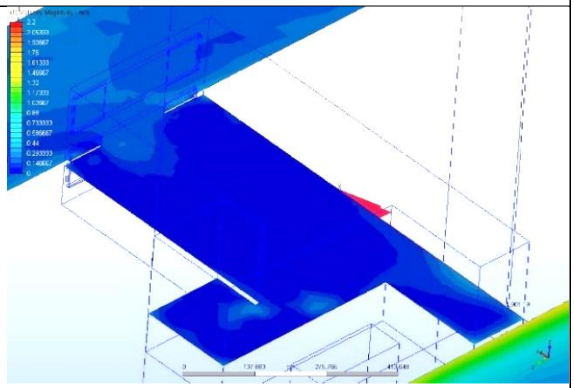
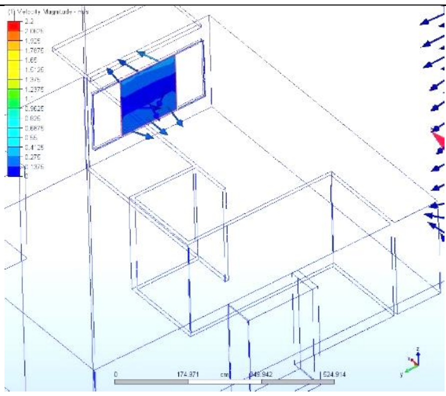
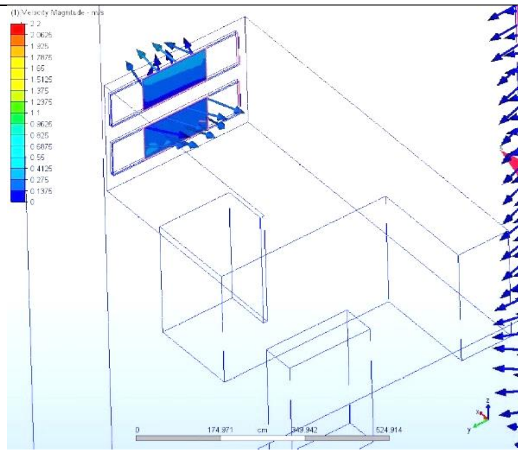
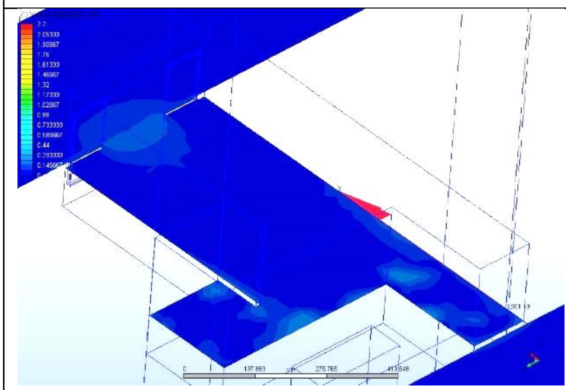
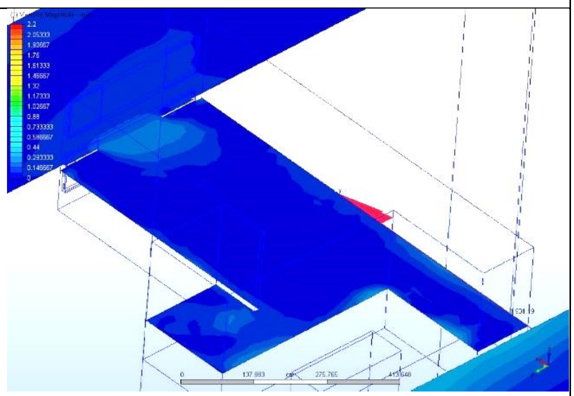
	Air Ducts	Stack
Boundary Condition **#BC_3**		
		
	Air Ducts	Stack
Boundary Condition **#BC_4**		
		

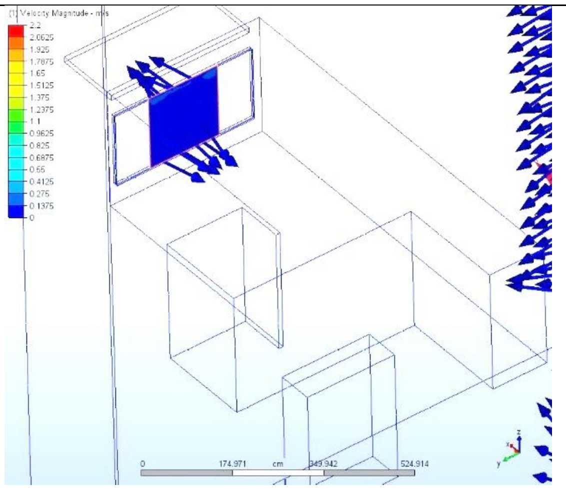
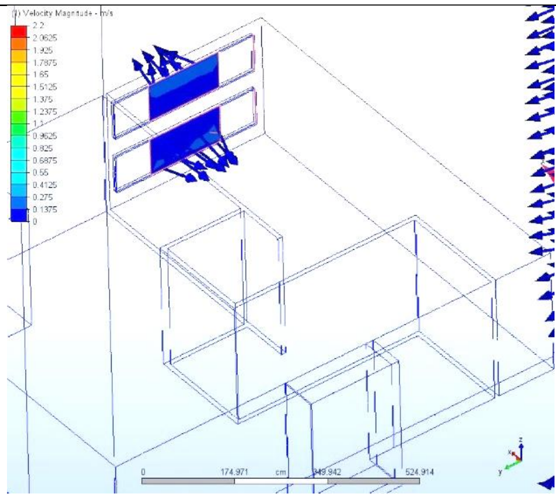
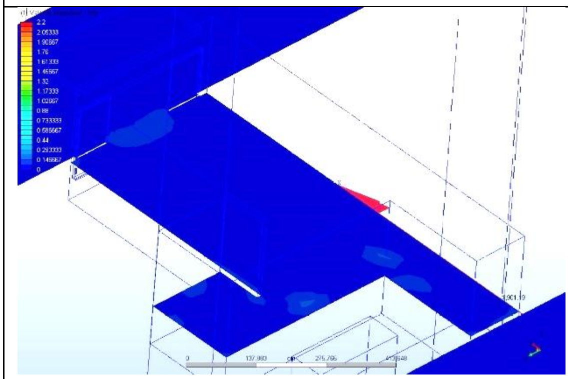
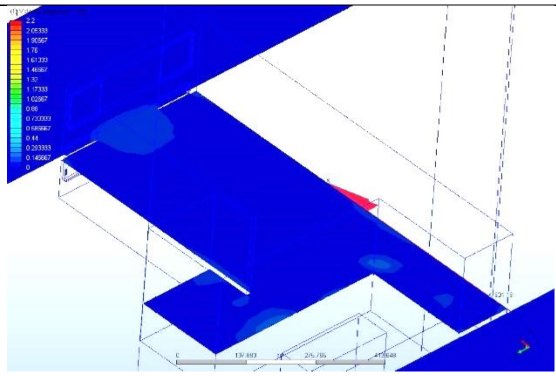
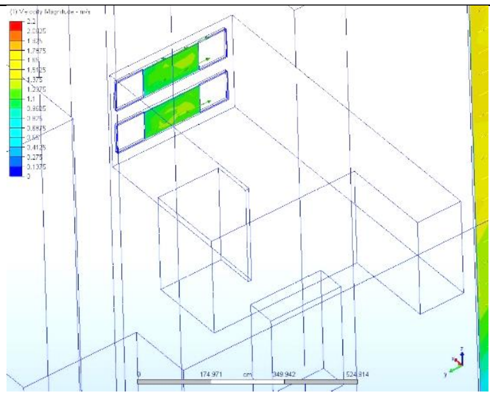
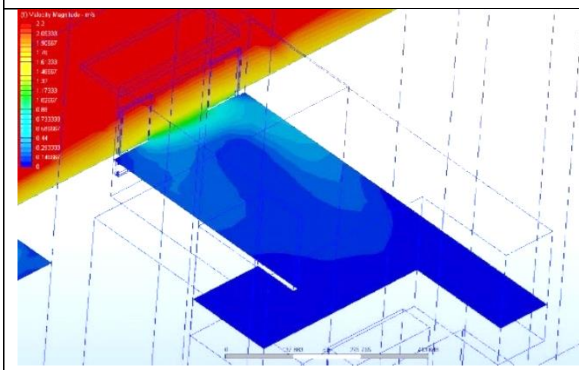
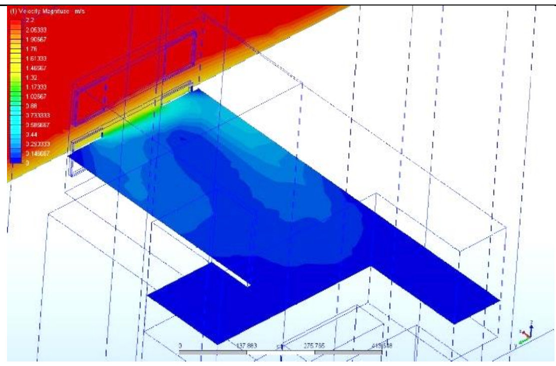
	Air Ducts	Stack
Boundary Condition **#BC_5**		
		
	Air Ducts	Stack
Boundary Condition **#BC_6**		
		

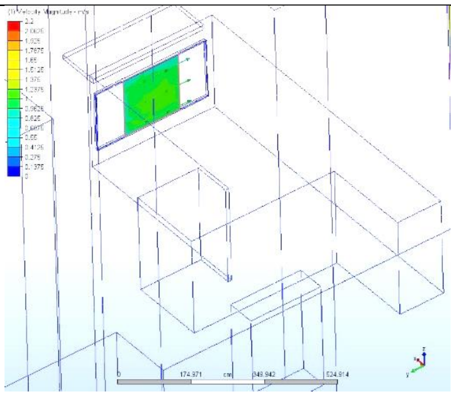
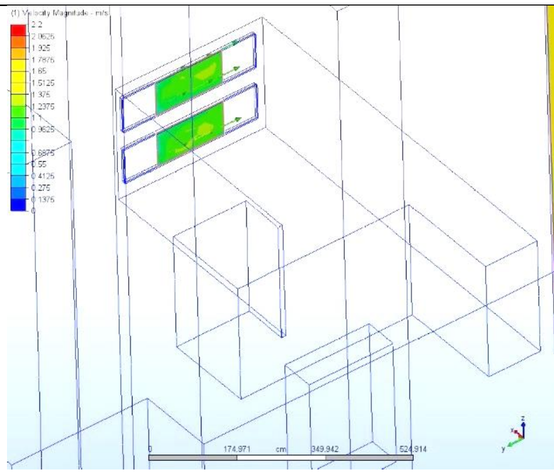
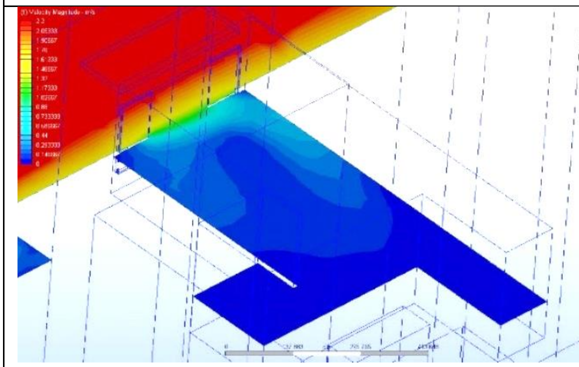
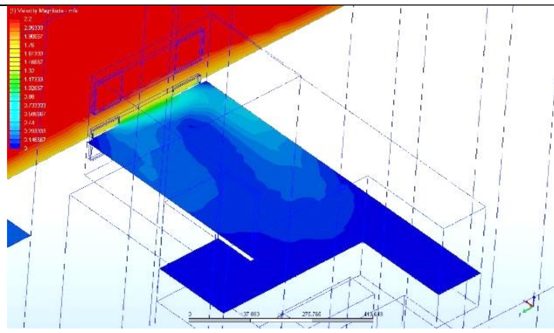
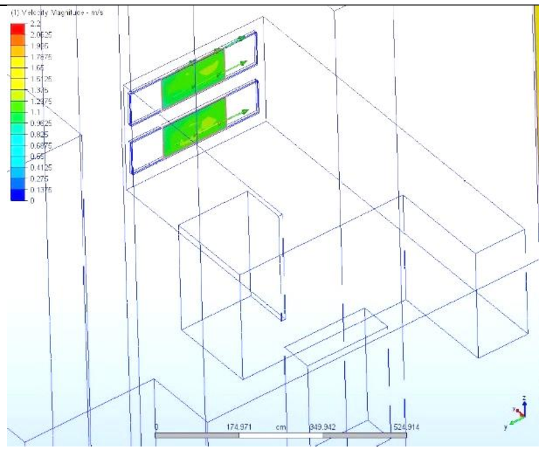
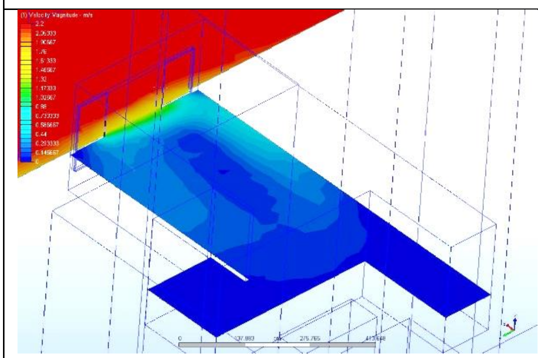
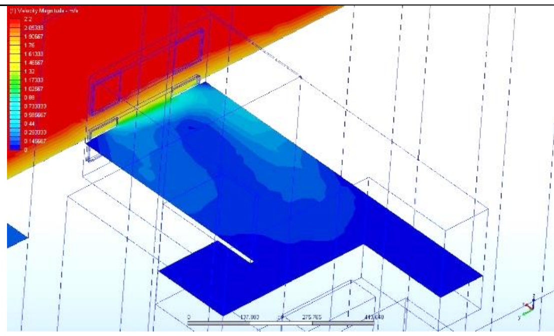
	Air Ducts	Stack
Boundary Condition **#BC_7**		
		
	Air Ducts	Stack
Boundary Condition **#BC_8**		
		

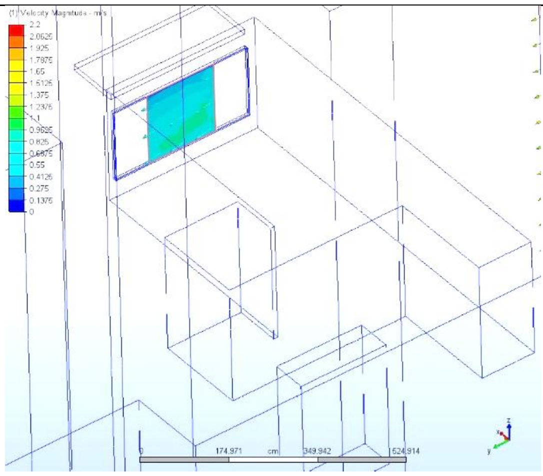
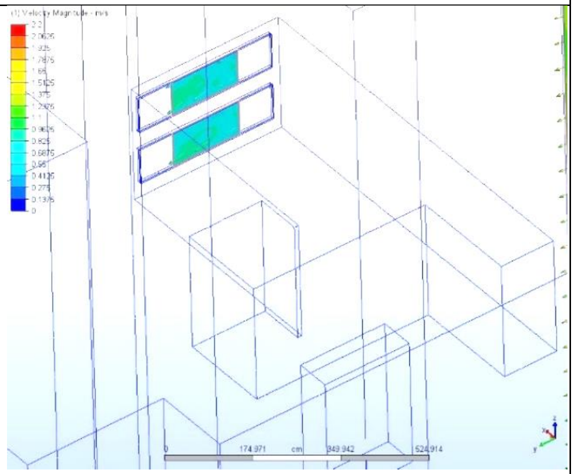
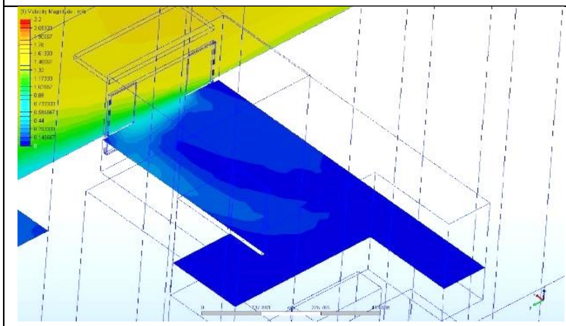
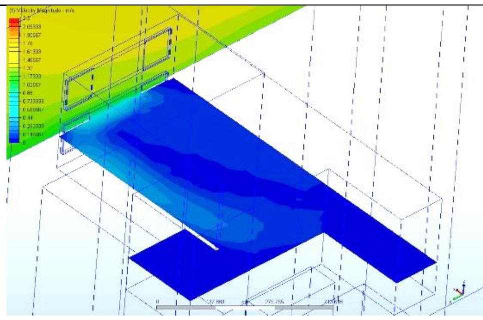
	Air Ducts	Stack
Boundary Condition **#BC_9**		
		
	Air Ducts	Stack
Boundary Condition **#BC_10**		
		

	Air Ducts	Stack
Boundary Condition **#BC_11**		
		
	Air Ducts	Stack
Boundary Condition **#BC_12**		
		

	Insulation	SSD
Boundary Condition **#BC_1**		
		
	Insulation	SSD
Boundary Condition **#BC_2**		
		

	Insulation	SSD
Boundary Condition **#BC_3**		
		
	Insulation	SSD
Boundary Condition **#BC_4**		
		

	Insulation	SSD
Boundary Condition **#BC_5**		
		
	Insulation	SSD
Boundary Condition **#BC_6**		
		

	Insulation	SSD
Boundary Condition #**BC_7**		
		
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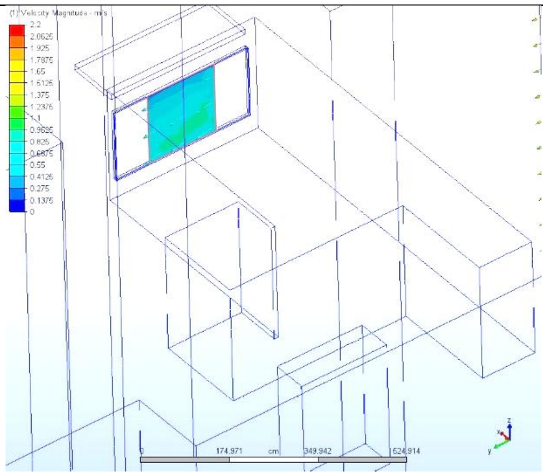
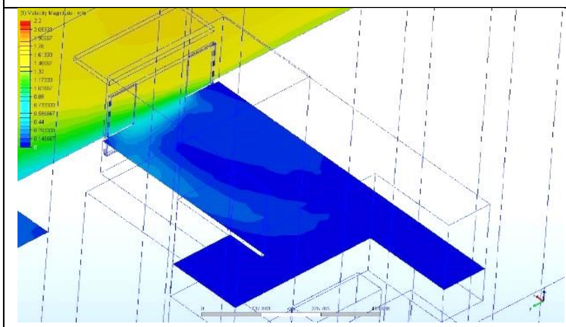
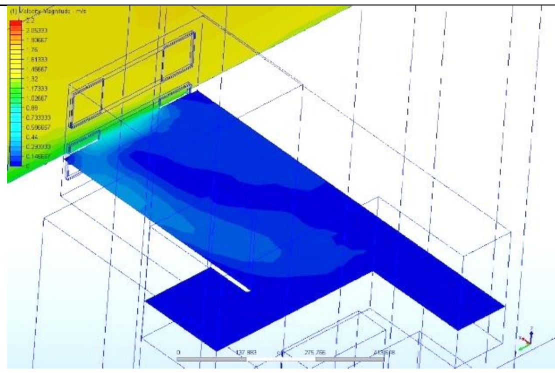
Boundary Condition #**BC_8**		
		

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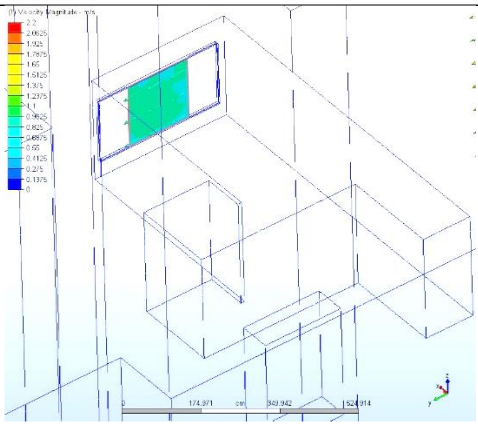
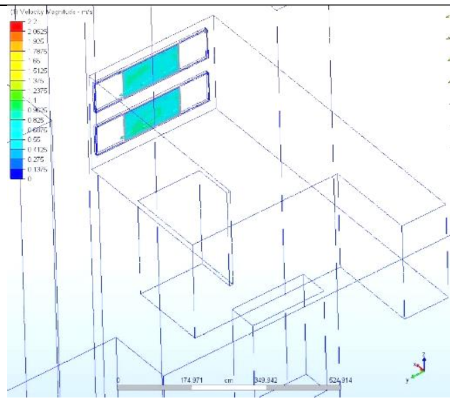
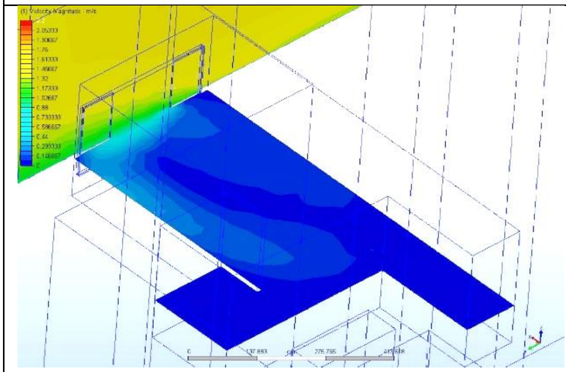
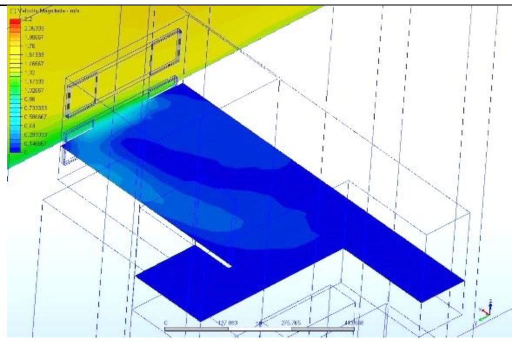
Boundary Condition **#BC_9**		
		
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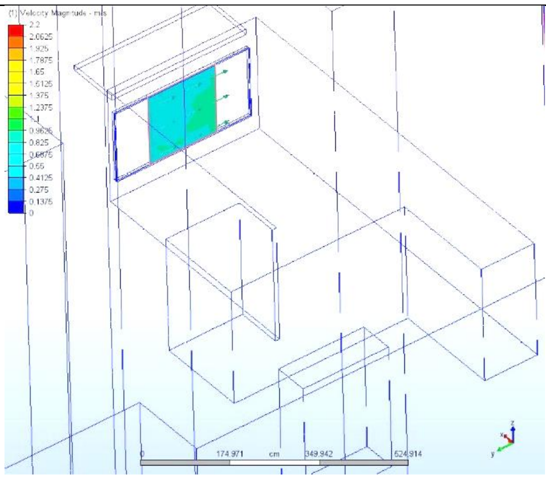
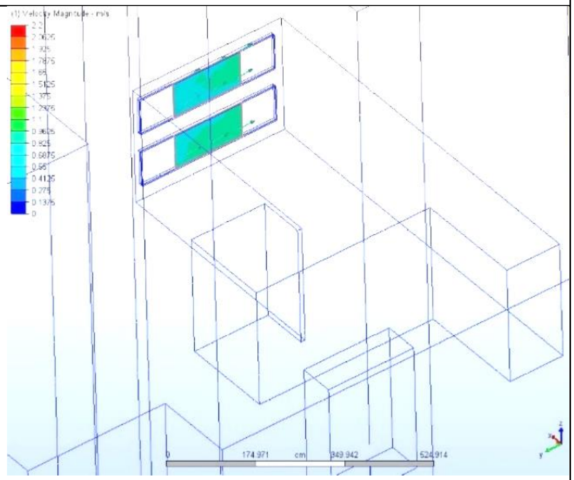
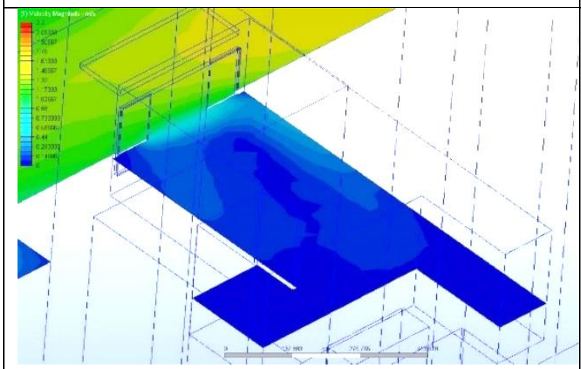
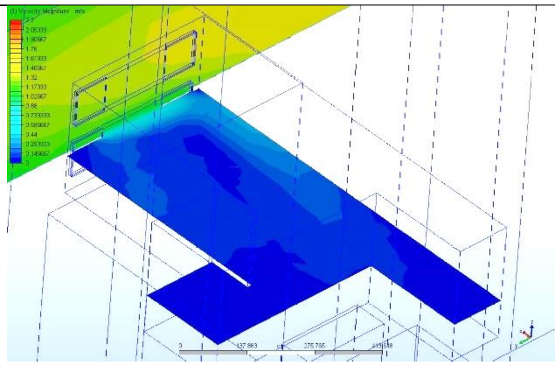
Boundary Condition **#BC_10**		
		

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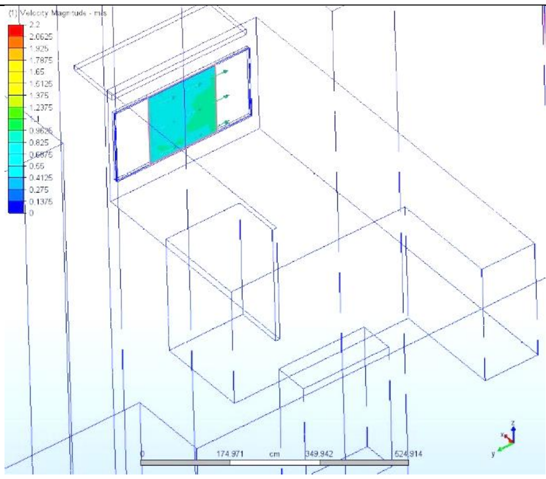
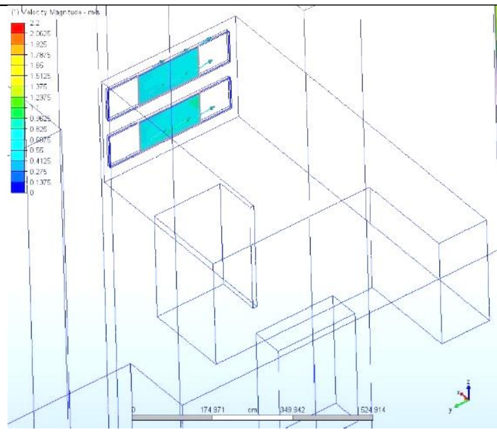
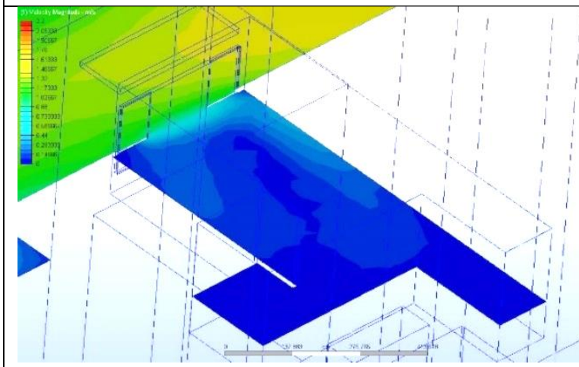
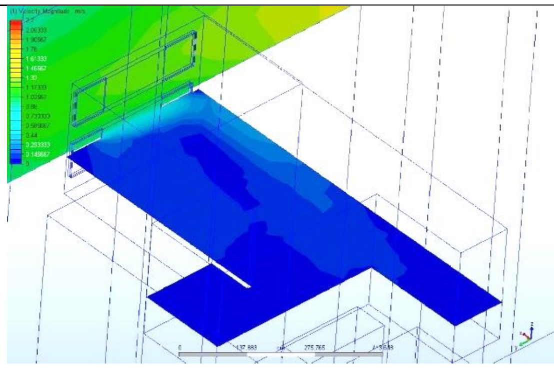
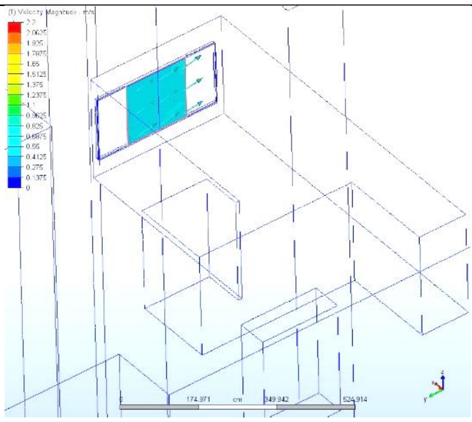
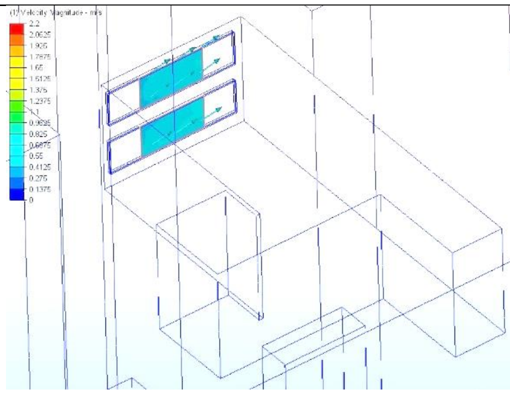
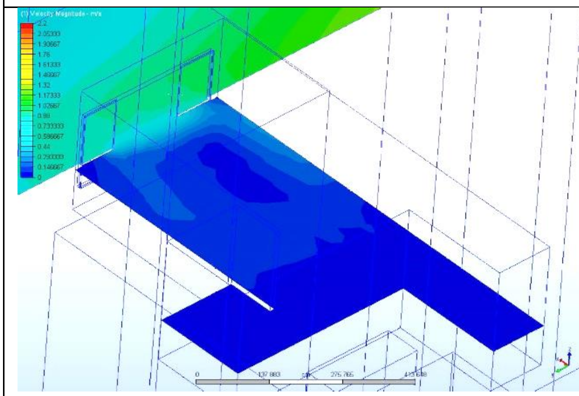
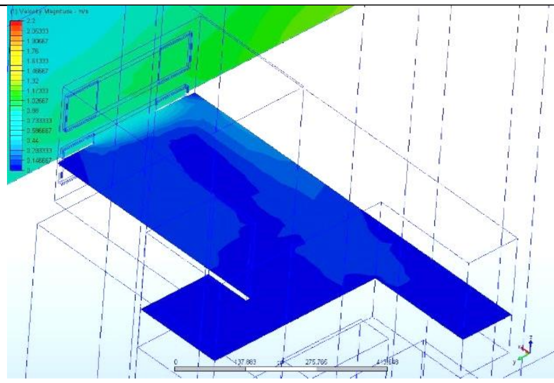
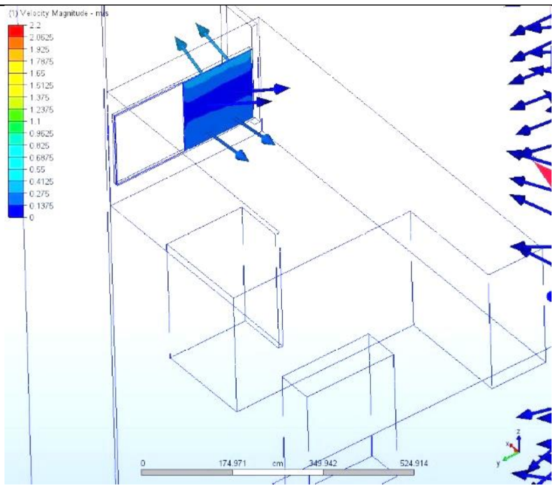
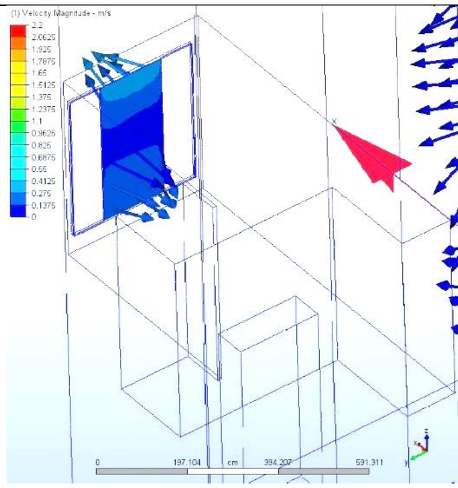
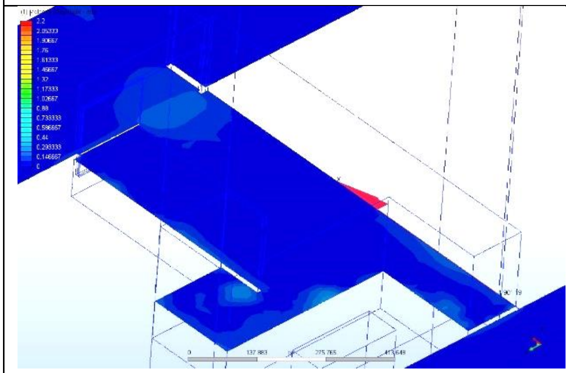
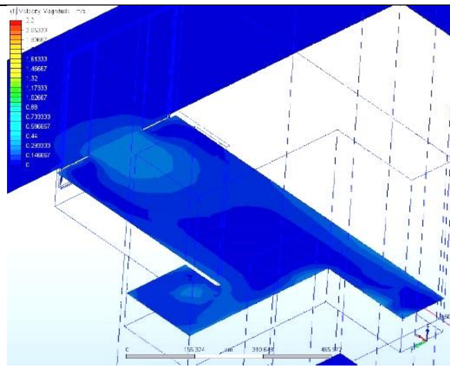
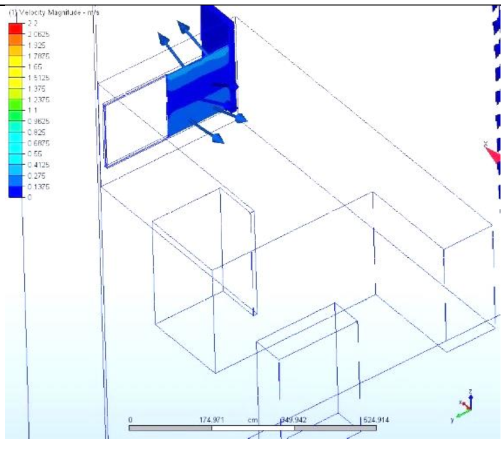
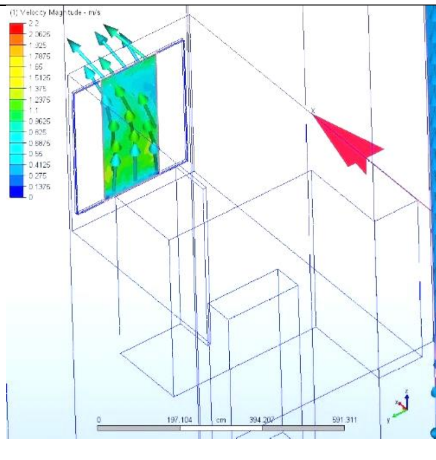
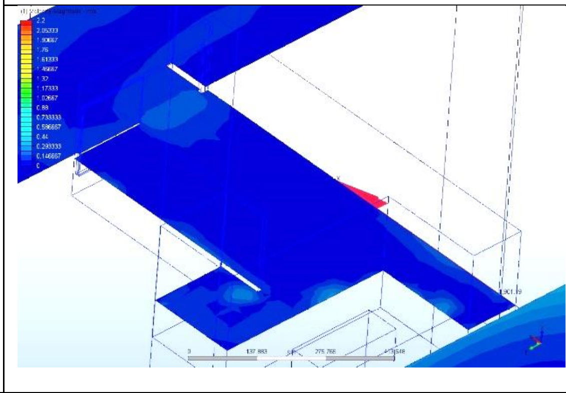
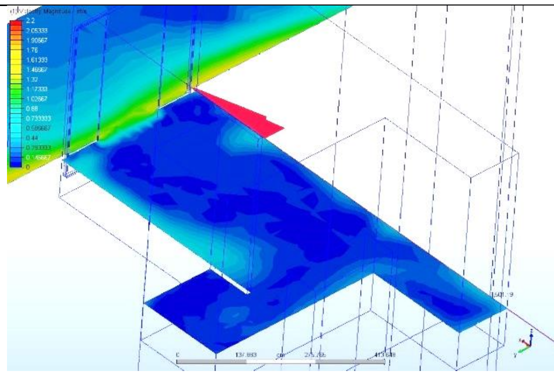
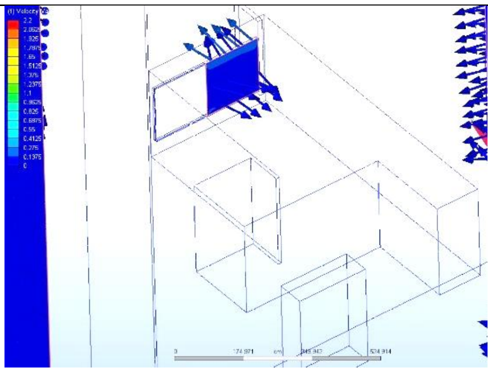
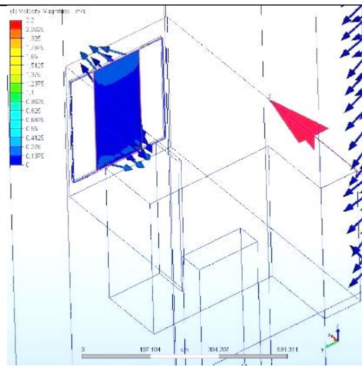
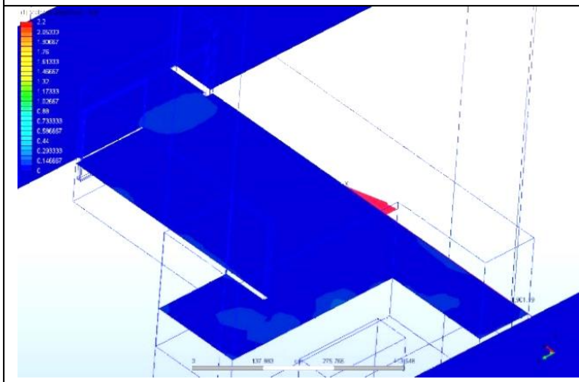
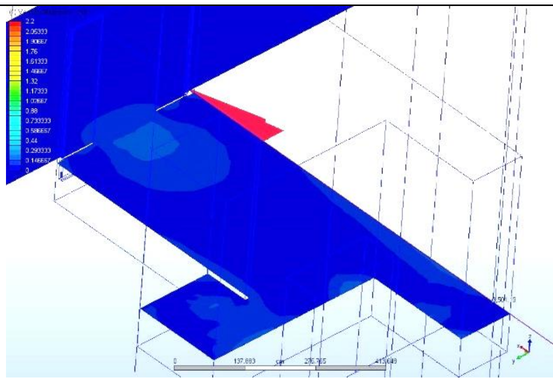
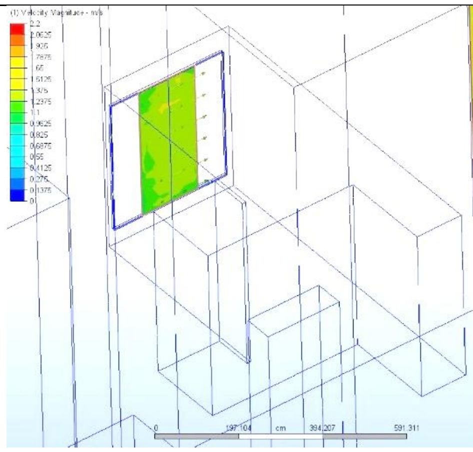
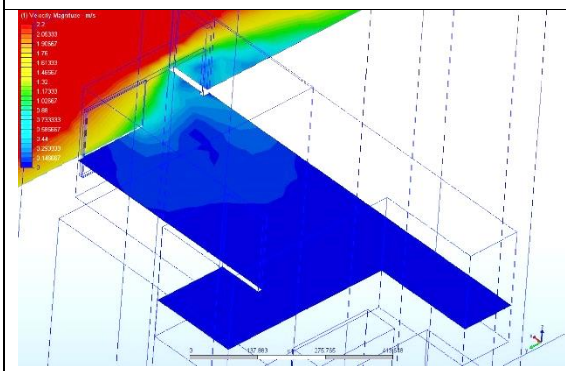
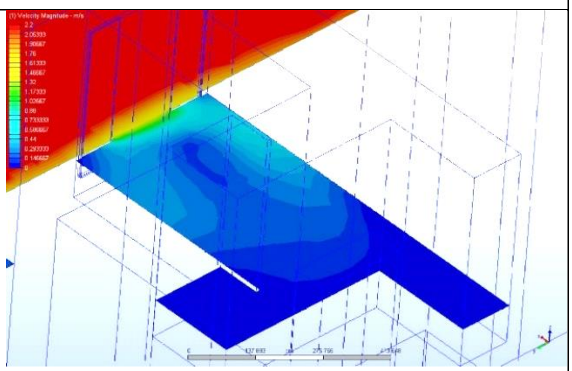
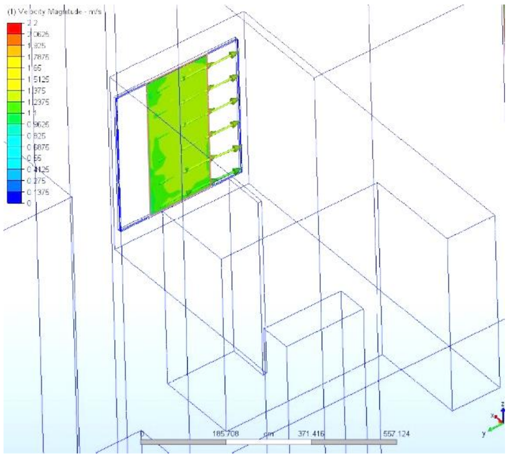
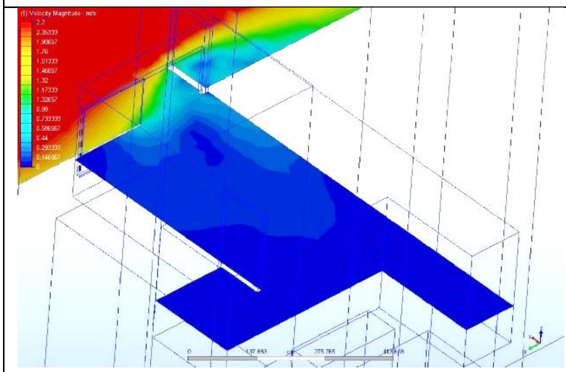
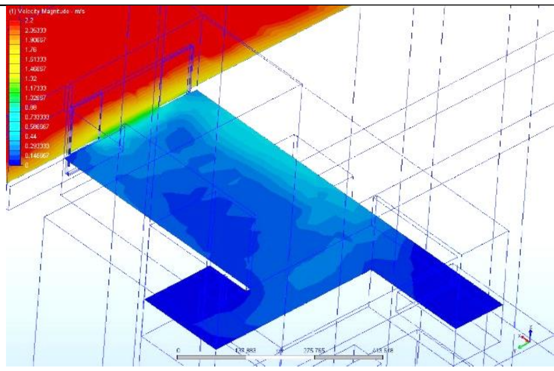
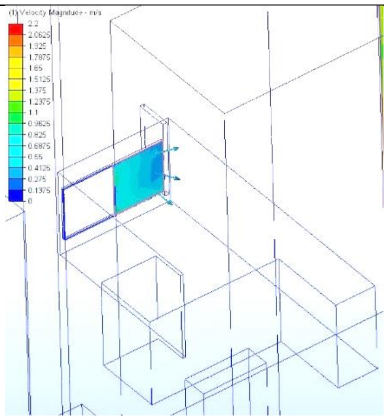
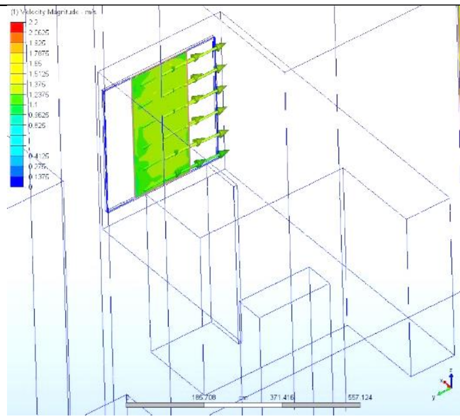
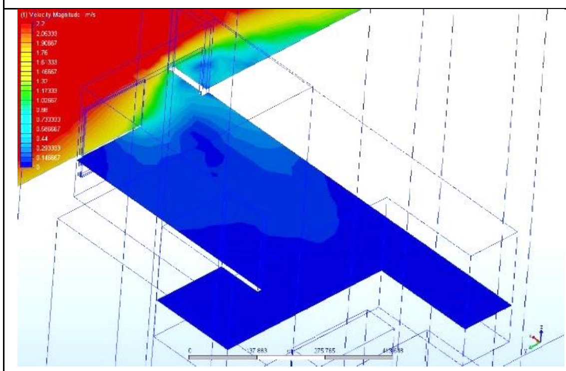
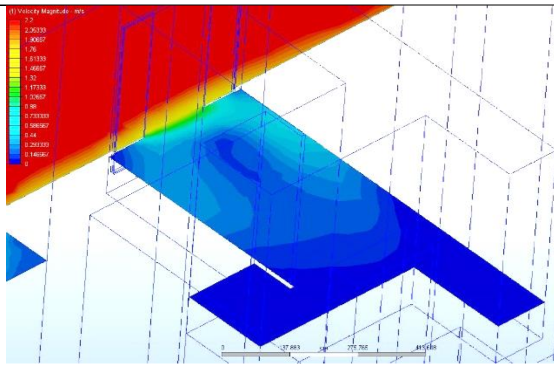
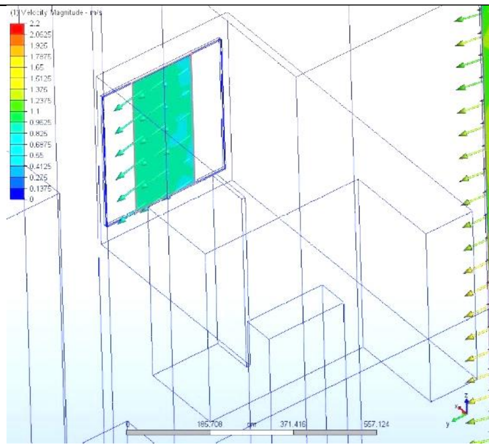
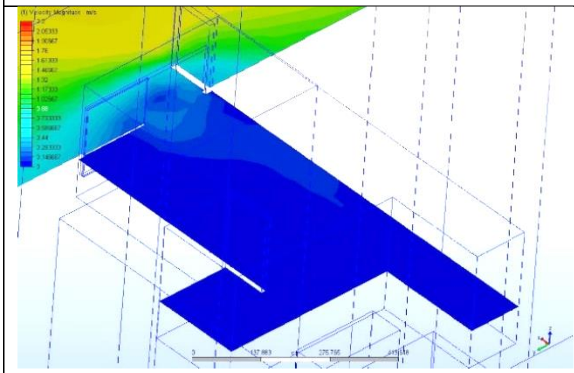
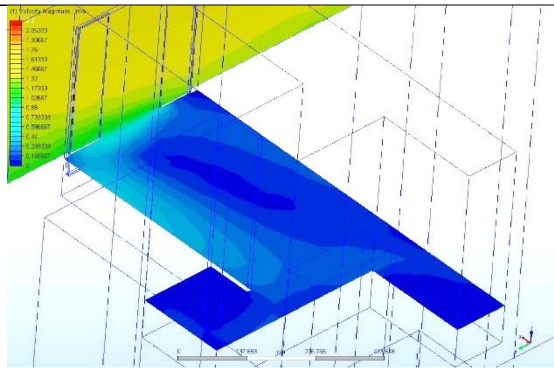
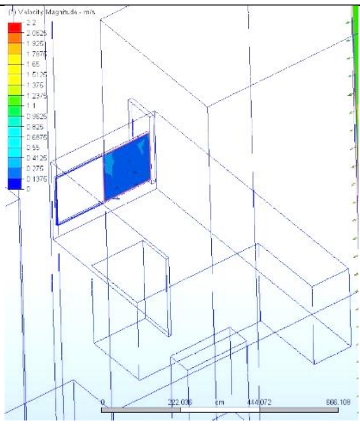
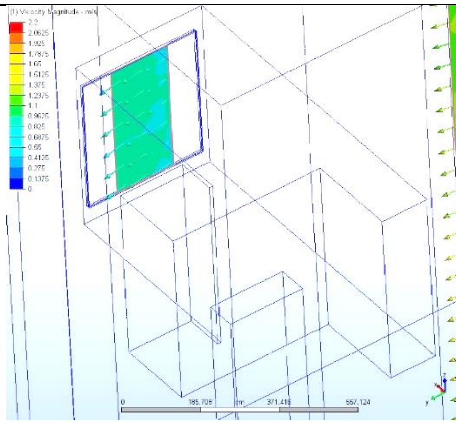
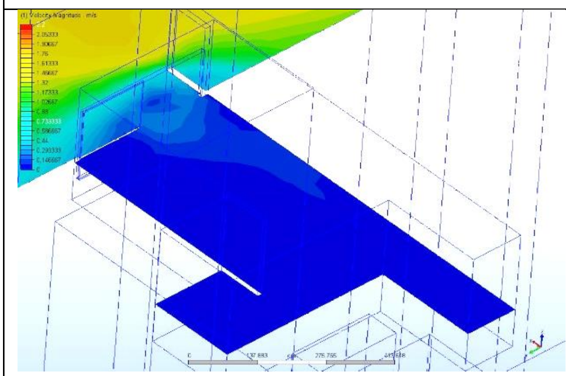
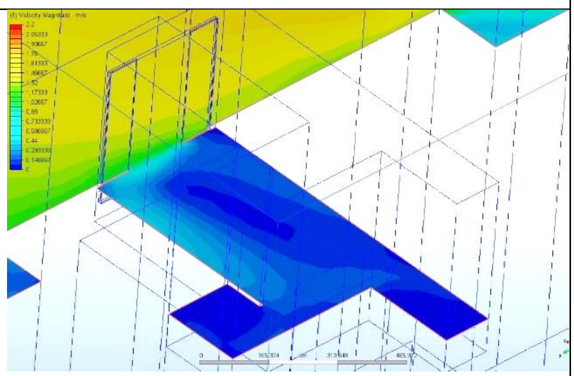
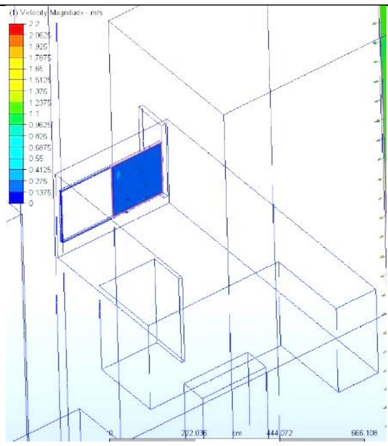
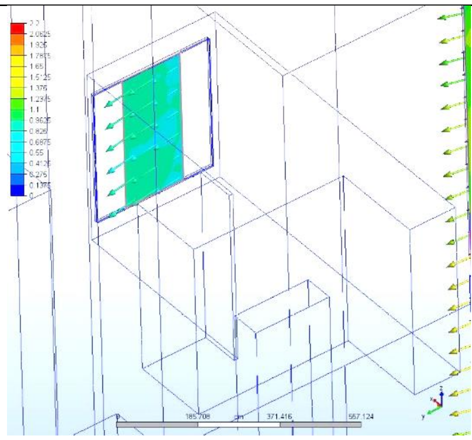
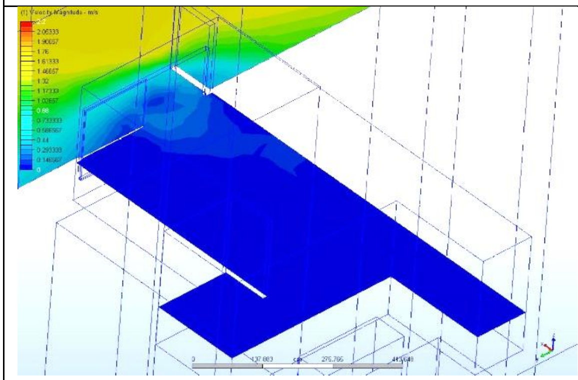
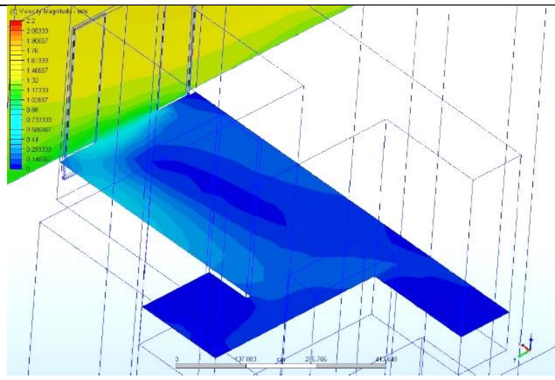
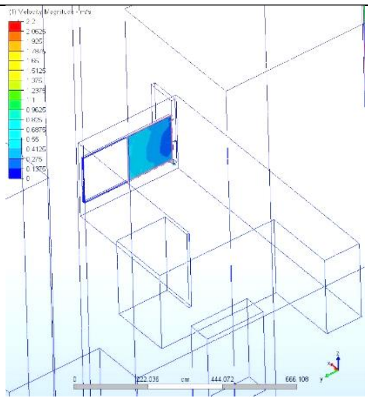
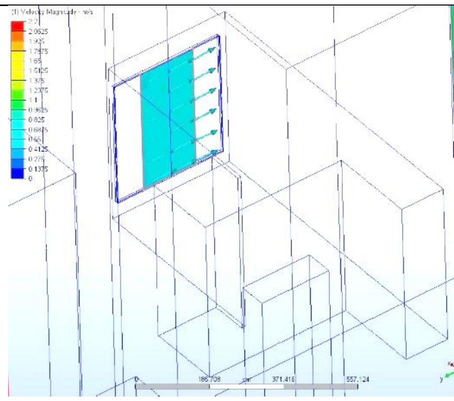
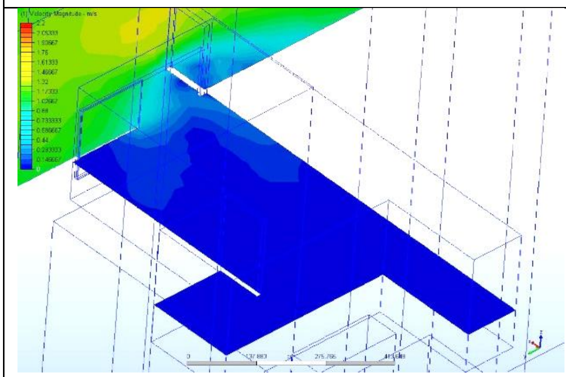
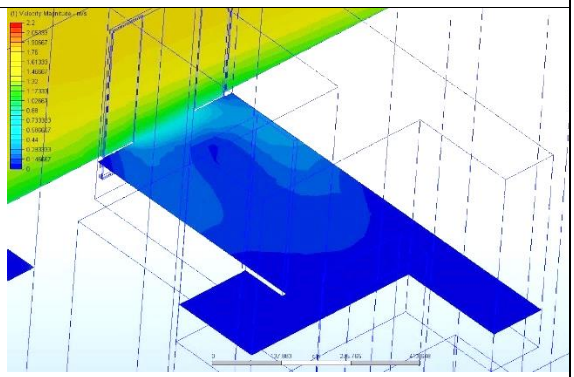
Boundary Condition **#BC_11**		
		
	Insulation	SSD
Boundary Condition **#BC_12**		
		

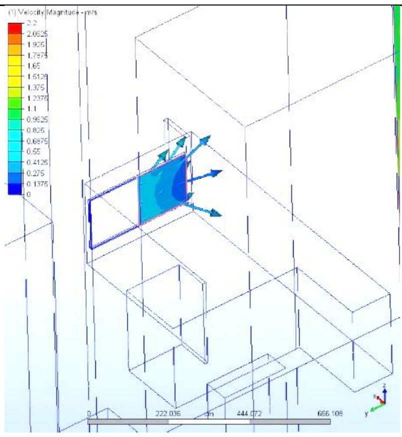
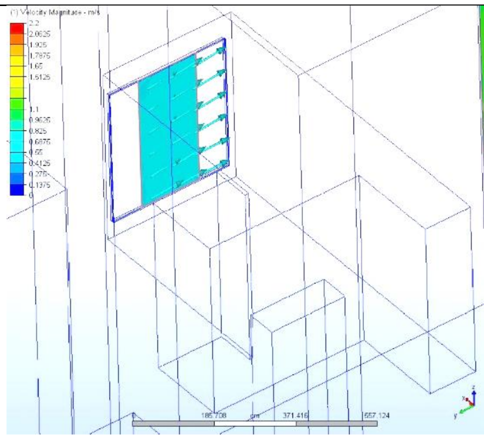
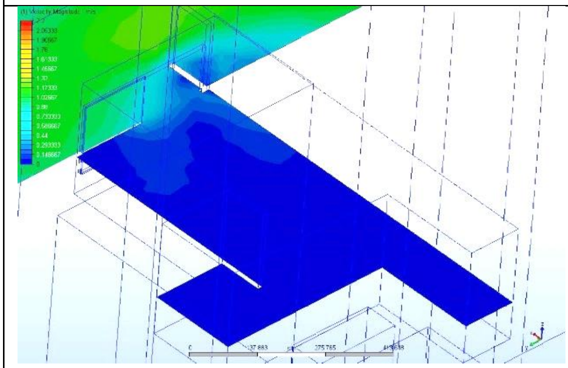
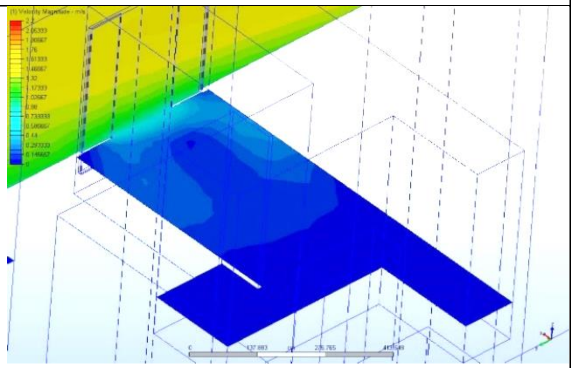
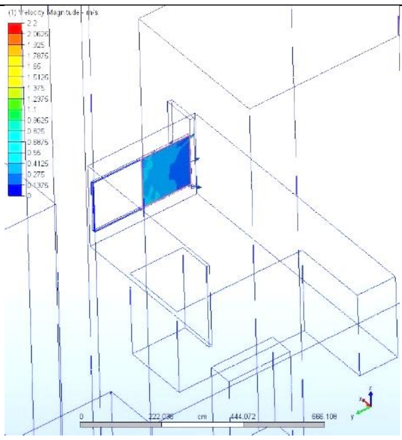
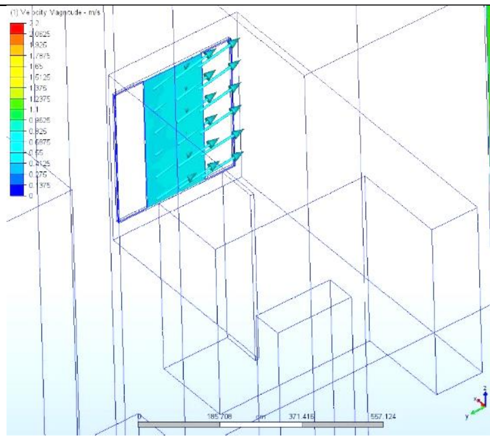
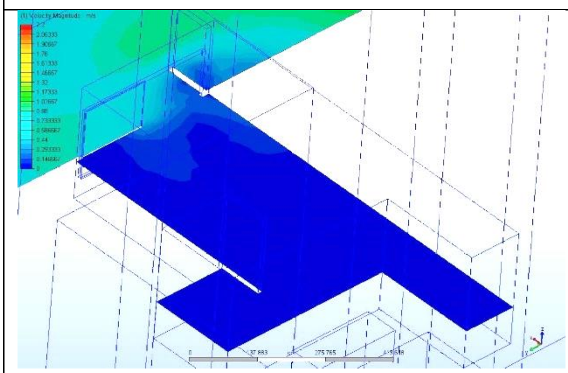
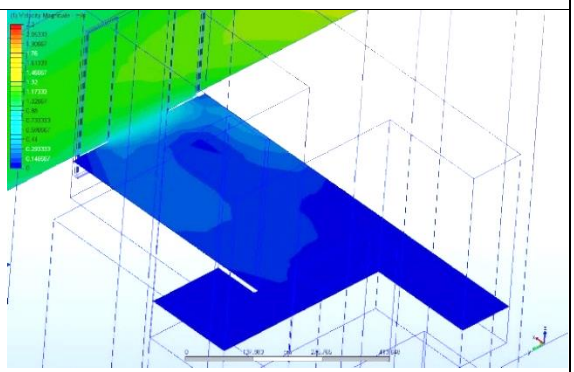
	Wing Wall	Increased Height
Boundary Condition **#BC_1**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_2**		
		

	Wing Wall	Increased Height
Boundary Condition **#BC_3**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_4**		
		

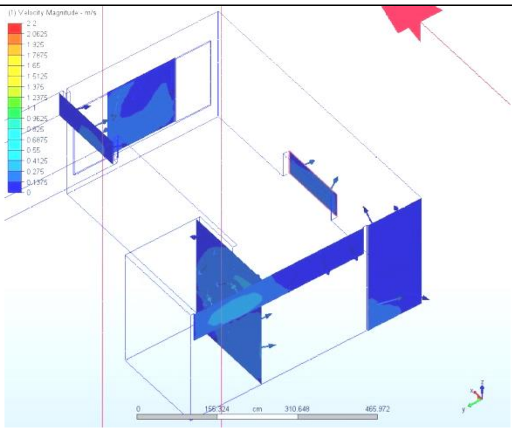
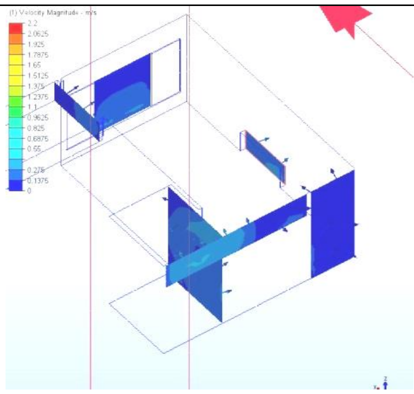
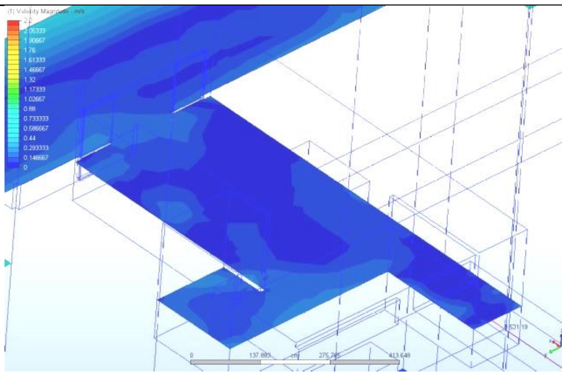
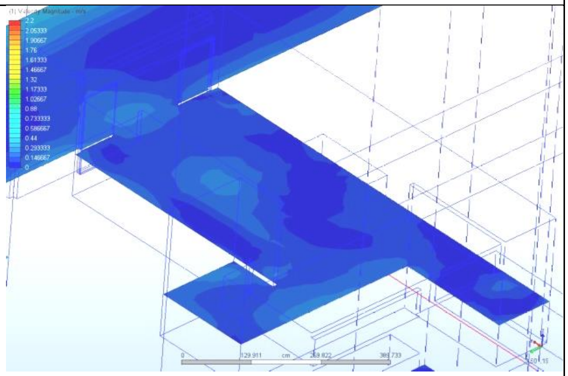
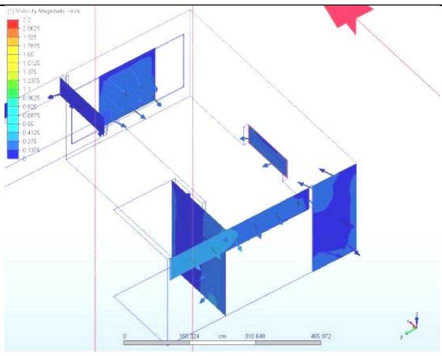
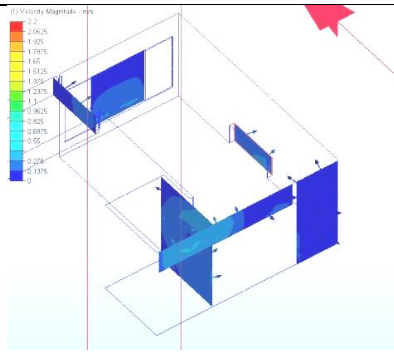
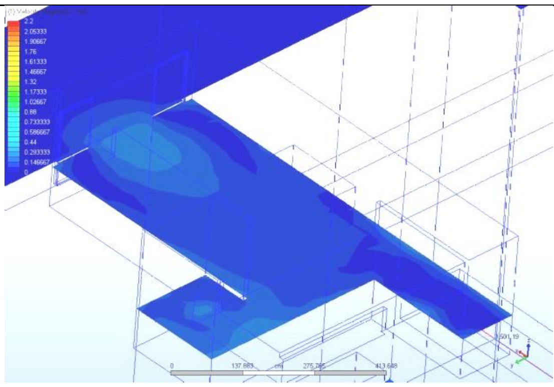
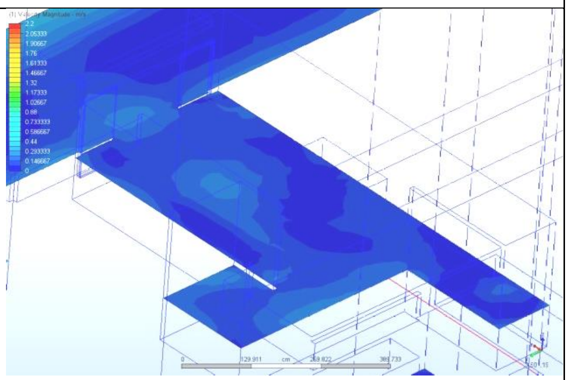
	Wing Wall	Increased Height
Boundary Condition **#BC_5**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_6**		
		

	Wing Wall	Increased Height
Boundary Condition **#BC_7**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_8**		
		

	Wing Wall	Increased Height
Boundary Condition **#BC_9**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_10**		
		

	Wing Wall	Increased Height
Boundary Condition **#BC_11**		
		
	Wing Wall	Increased Height
Boundary Condition **#BC_12**		
		

A.3 Group 3 Results

	DC11	DC12
Boundary Condition **#BC_1**		
		
	DC11	DC12
Boundary Condition **#BC_2**		
		

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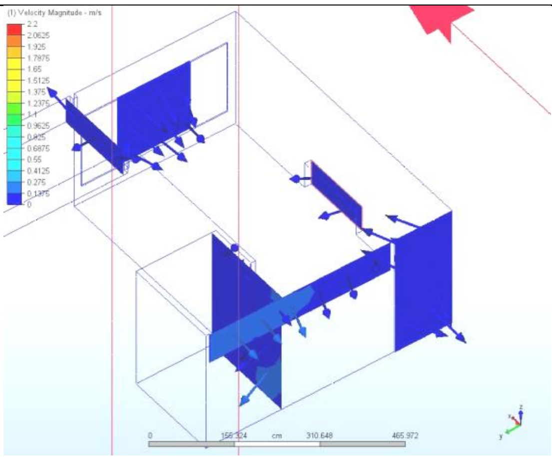
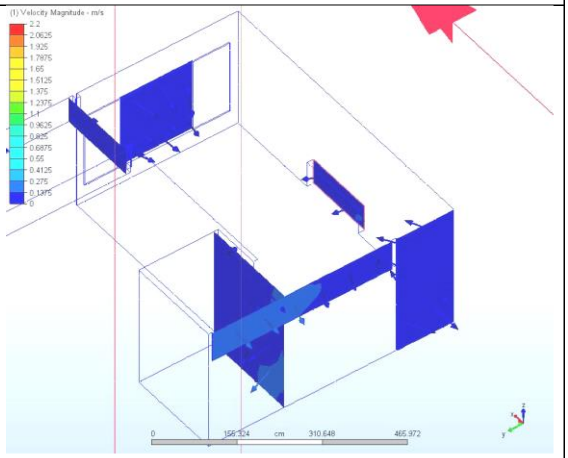
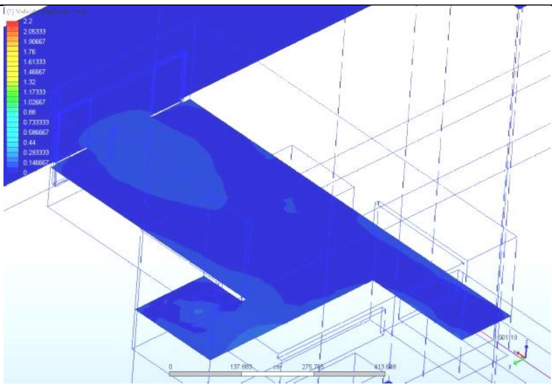
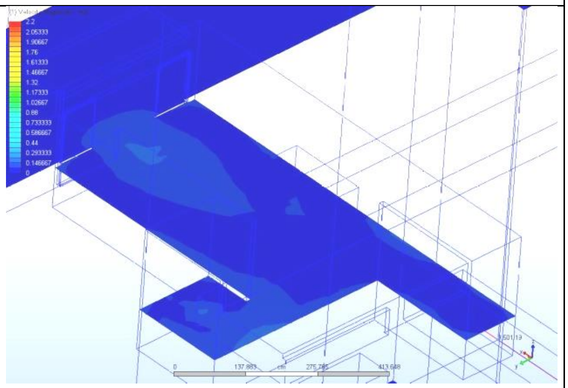
Boundary Condition **#BC_3**		
		
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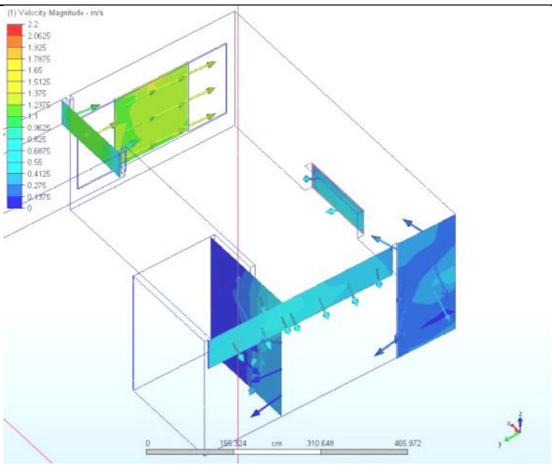
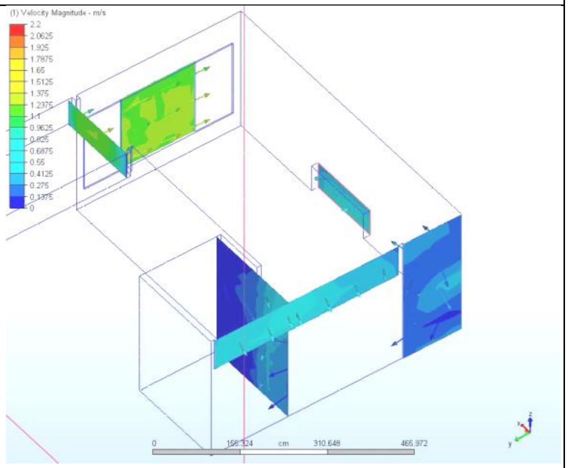
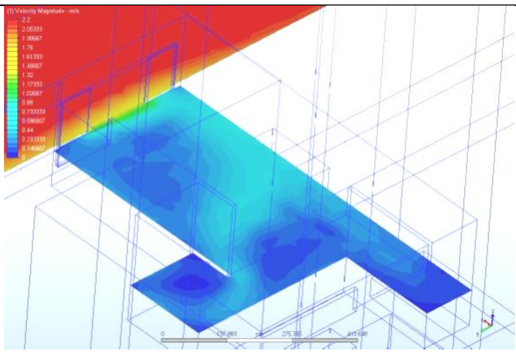
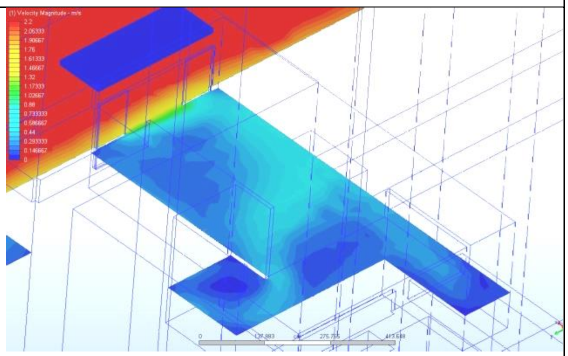
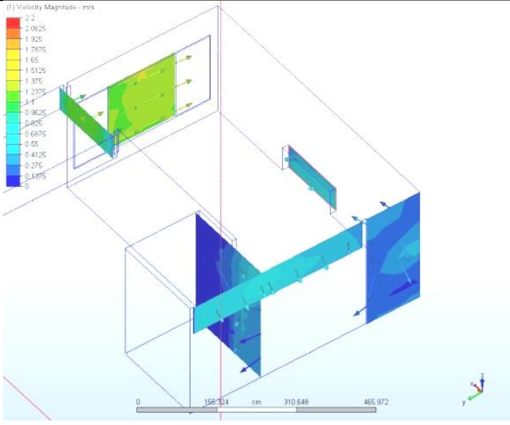
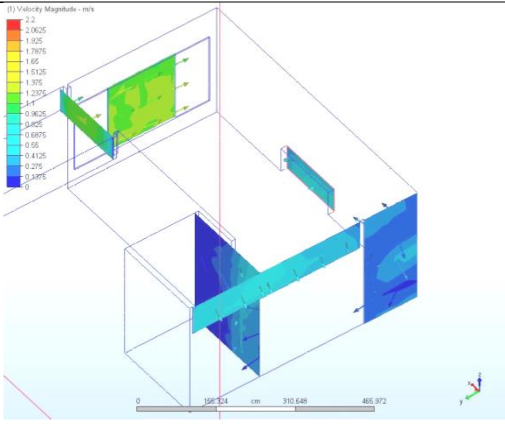
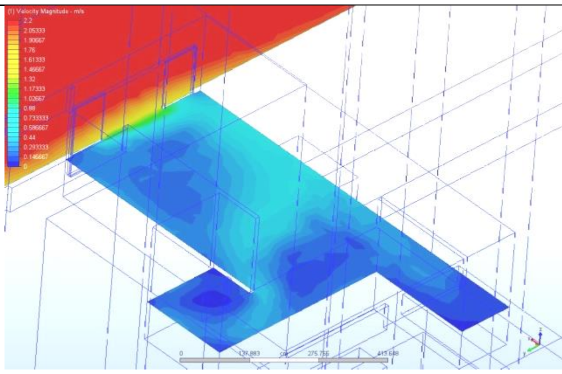
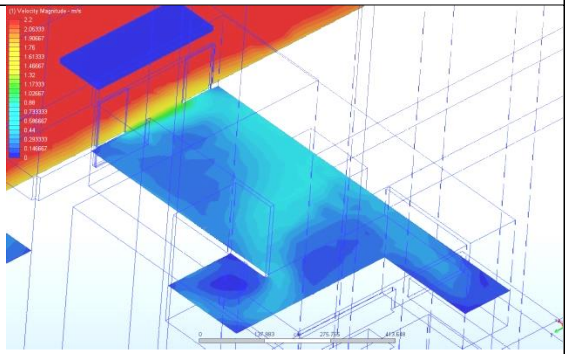
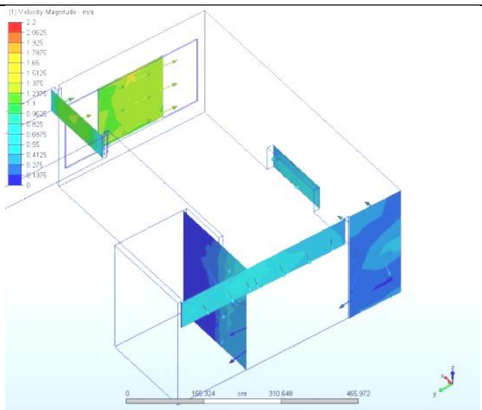
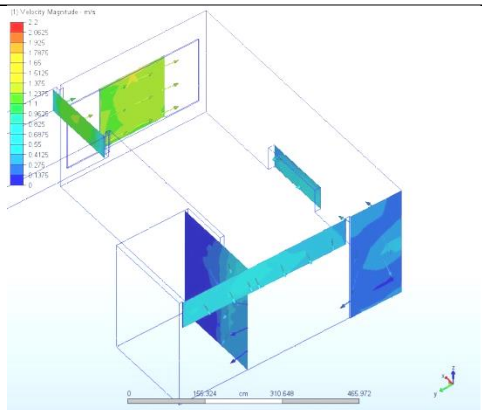
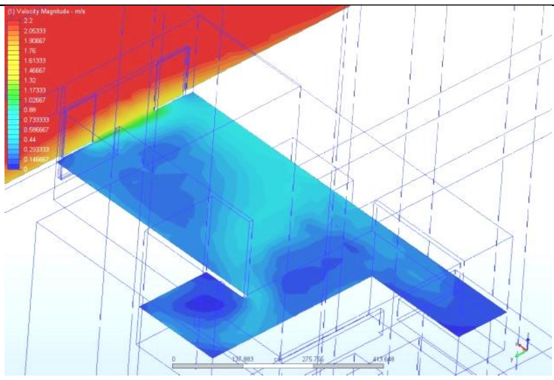
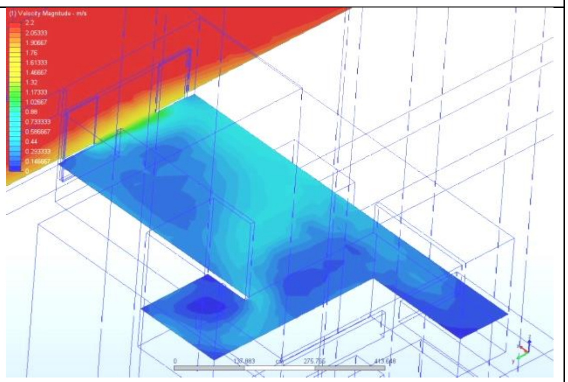
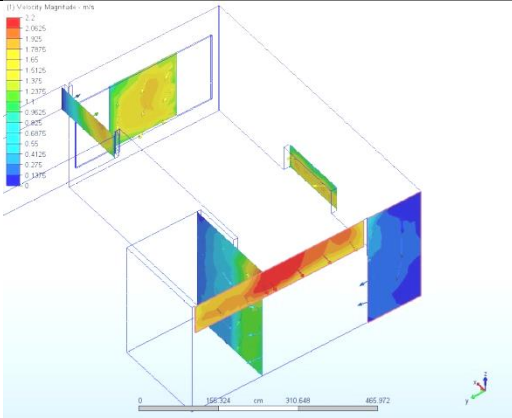
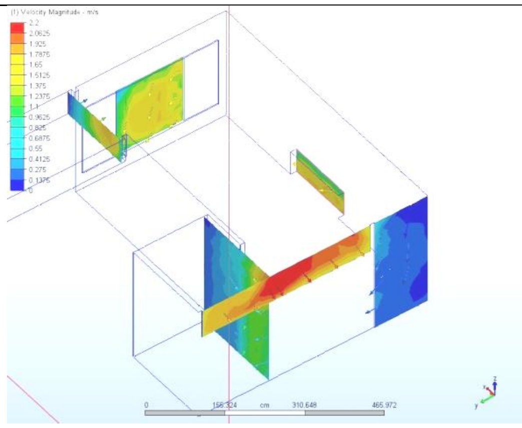
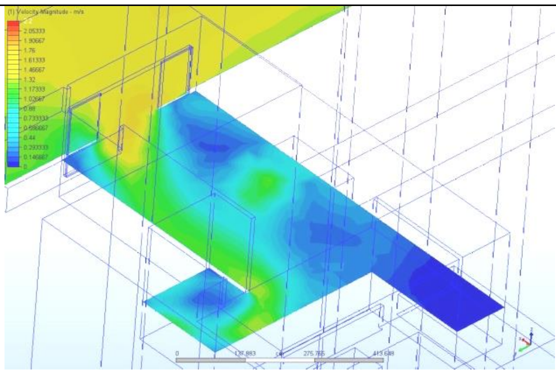
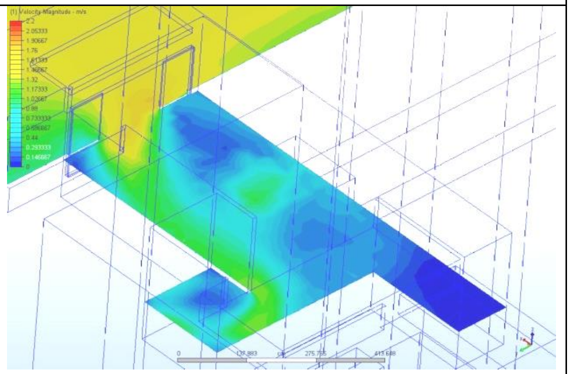
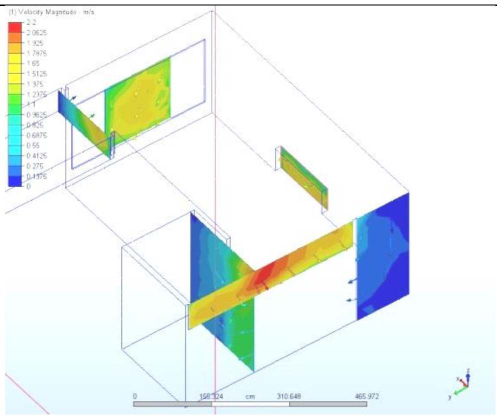
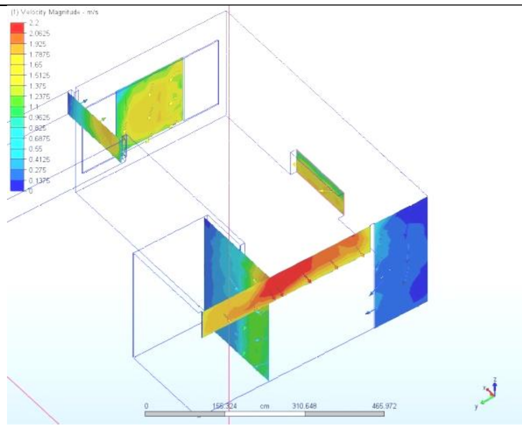
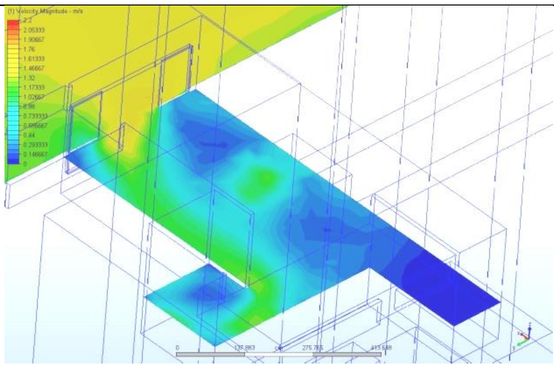
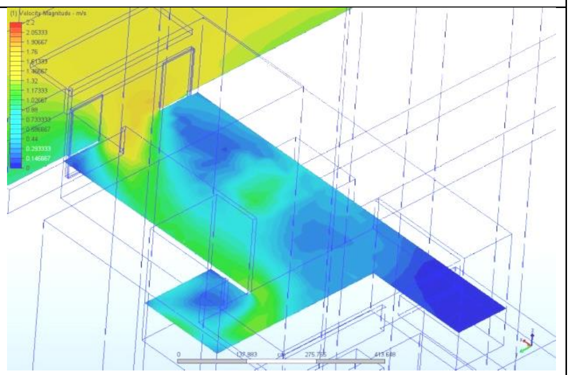
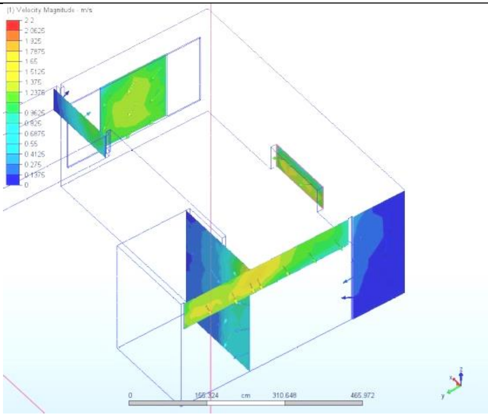
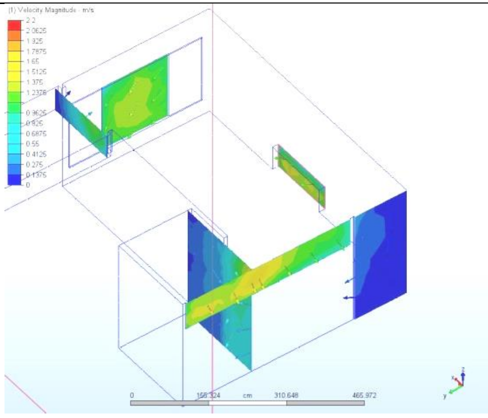
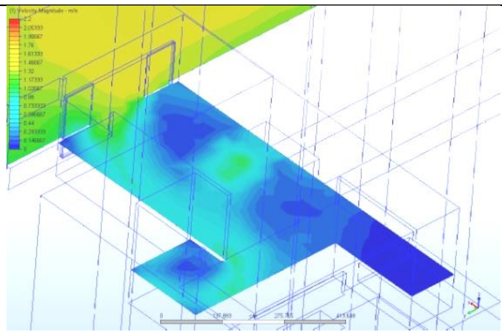
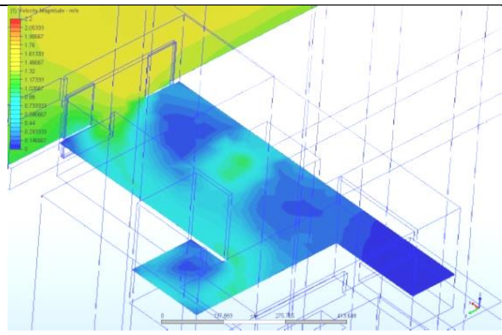
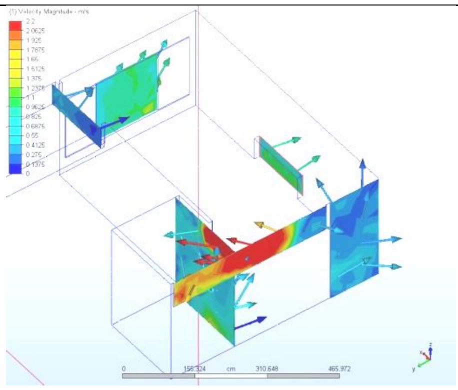
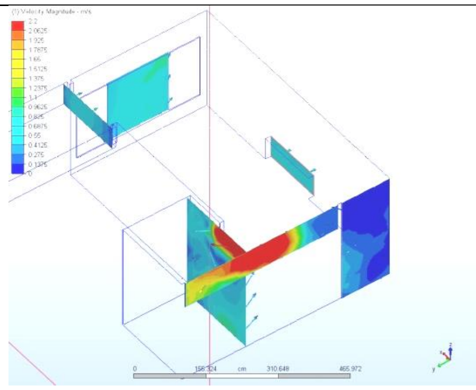
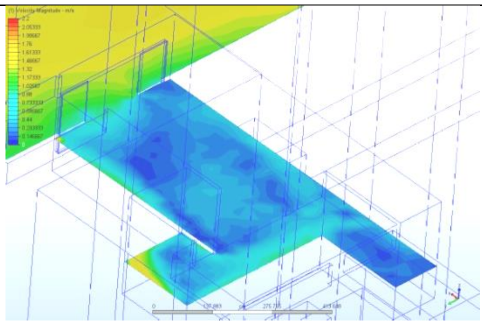
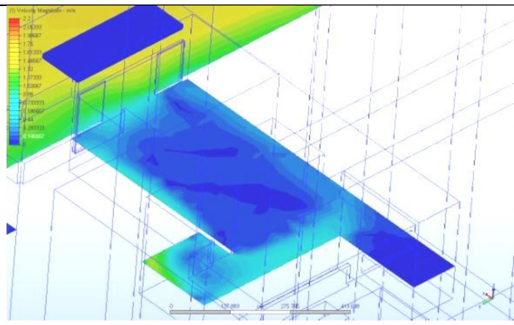
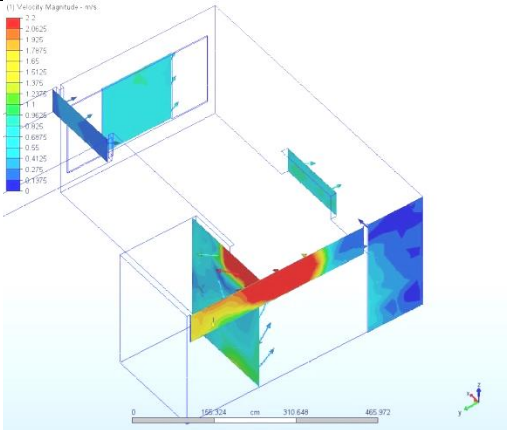
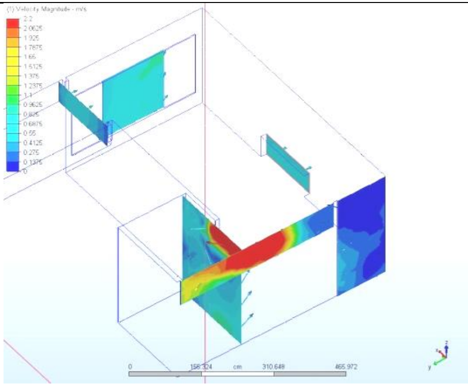
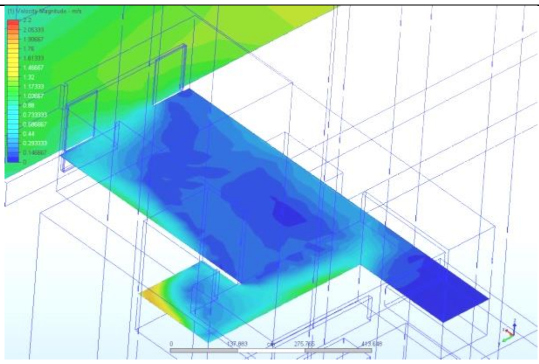
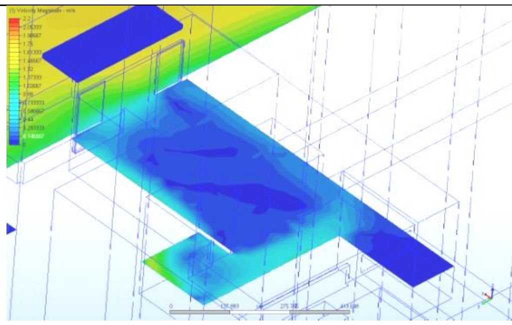
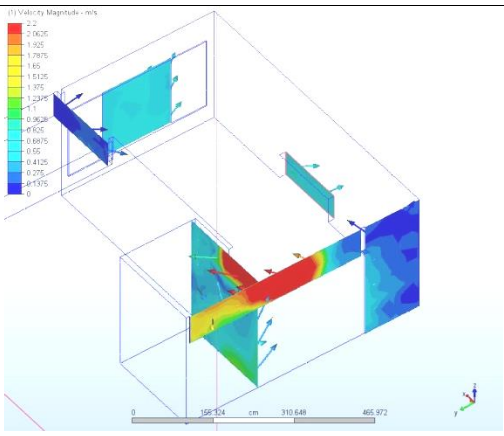
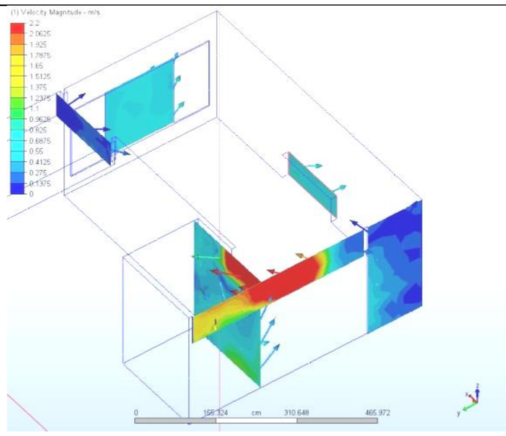
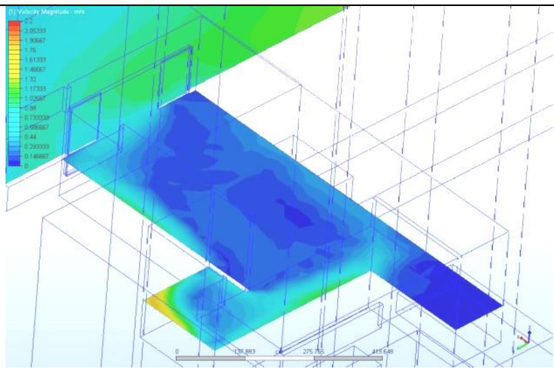
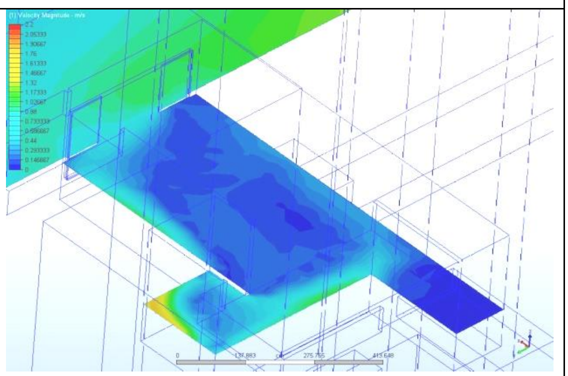
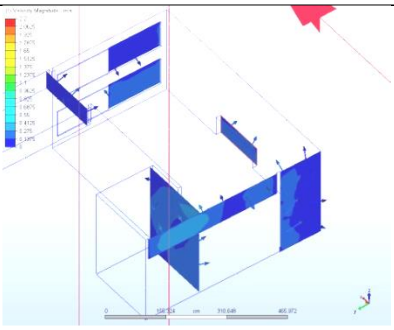
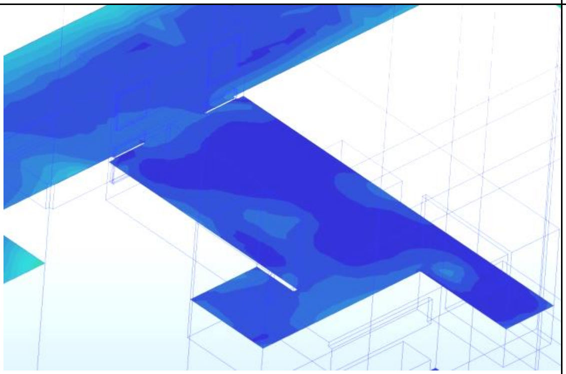
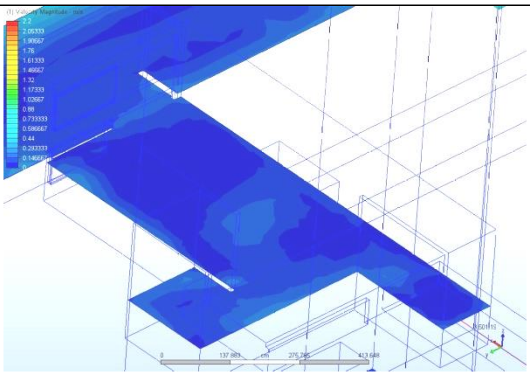
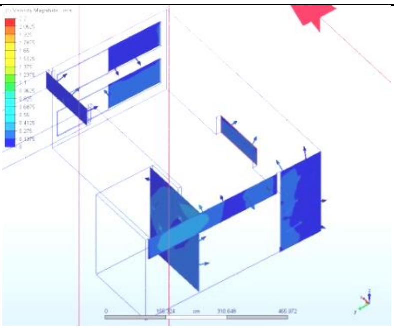
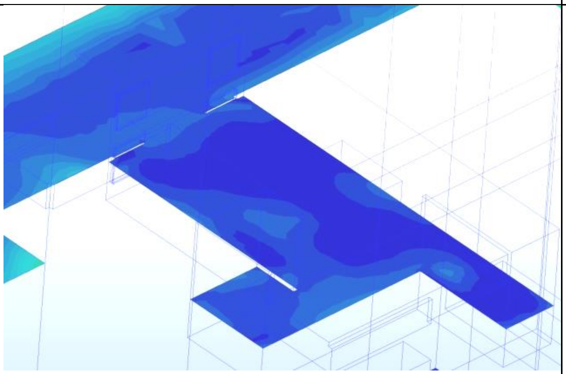
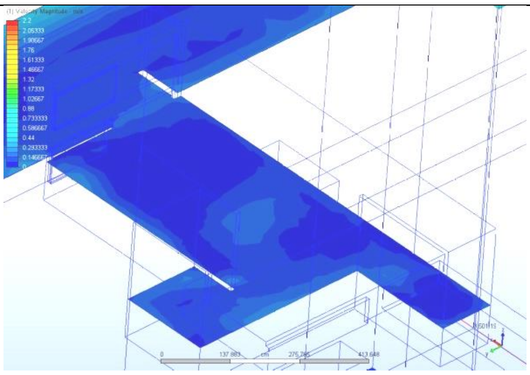
Boundary Condition **#BC_4**		
		

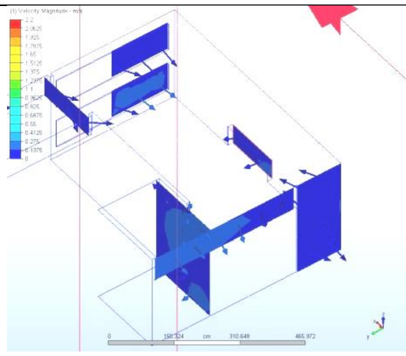
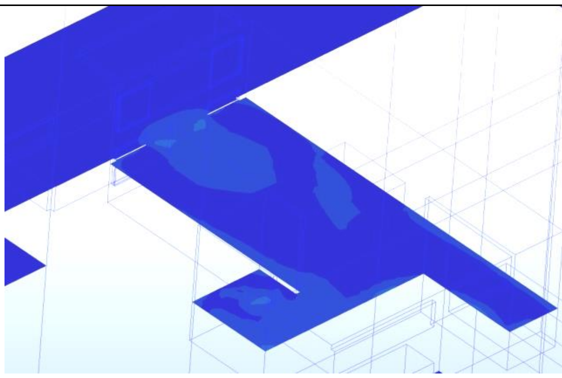
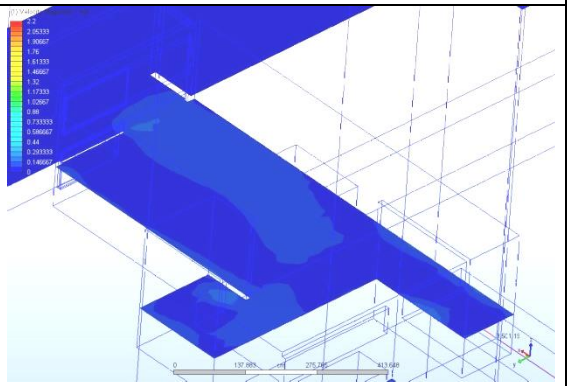
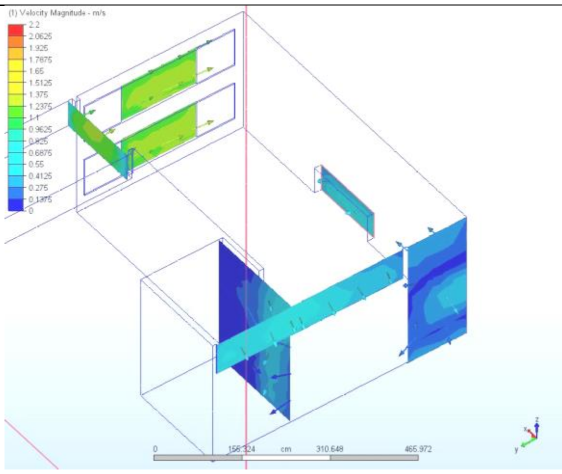
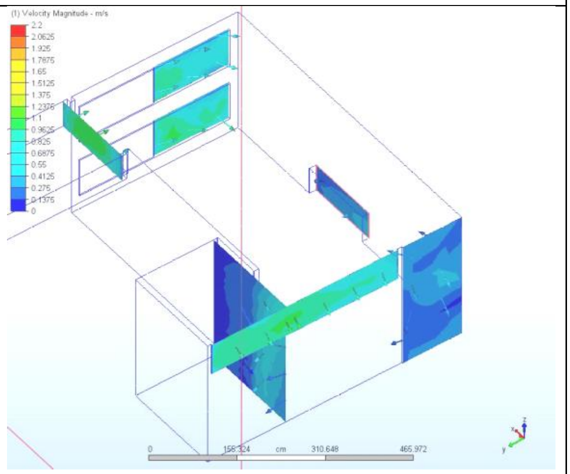
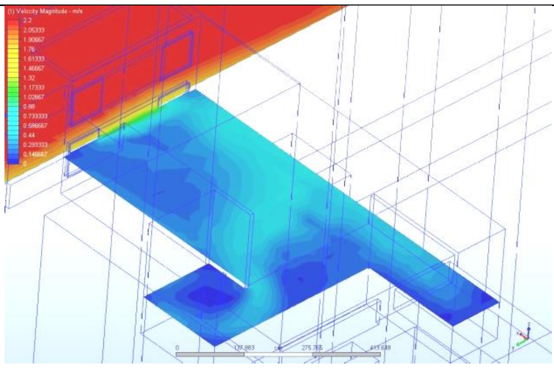
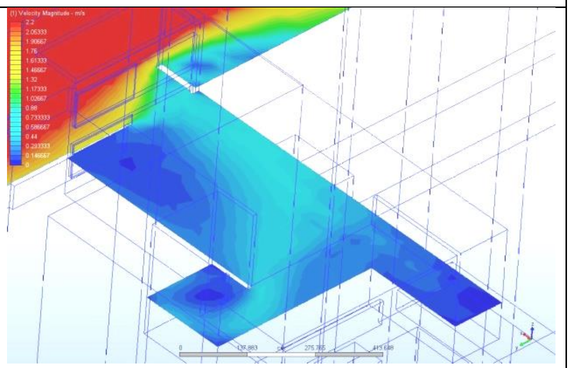
	DC11	DC12
Boundary Condition **#BC_5**		
		
	DC11	DC12
Boundary Condition **#BC_6**		
		

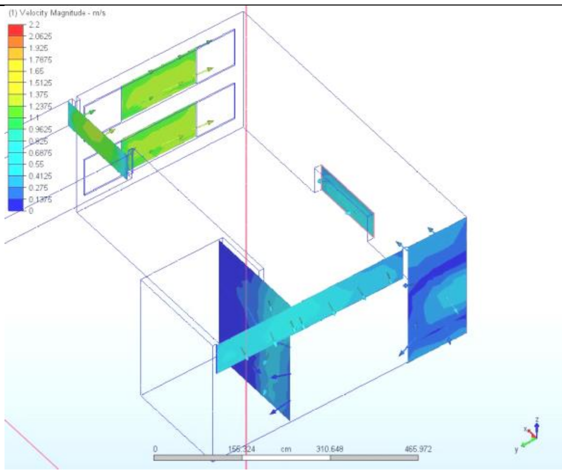
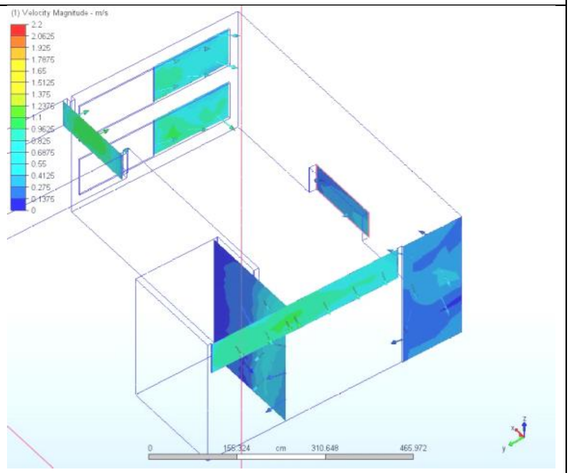
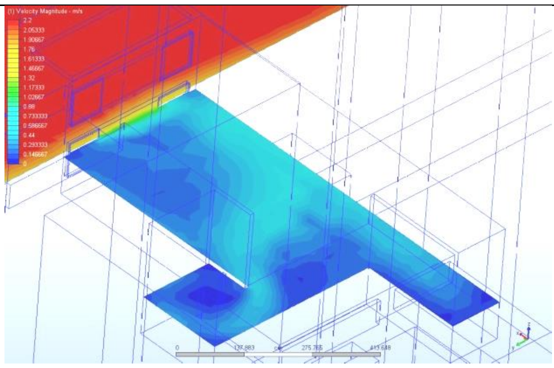
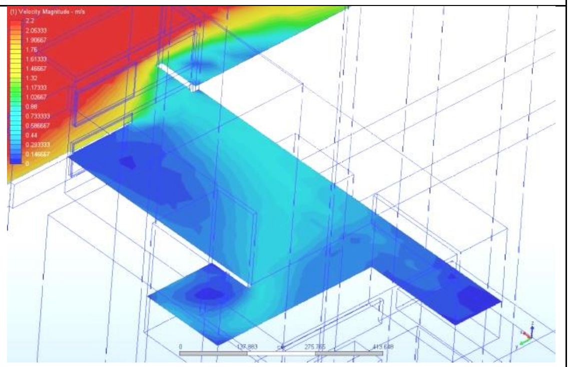
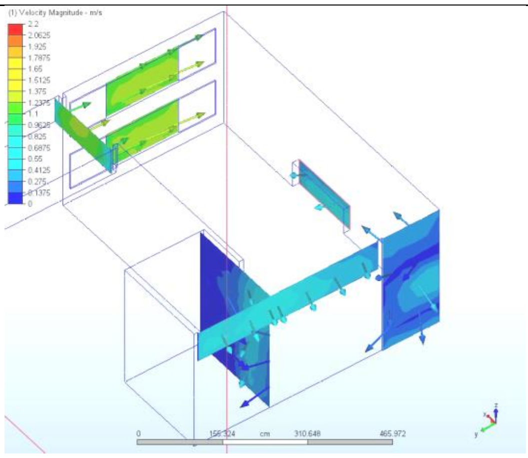
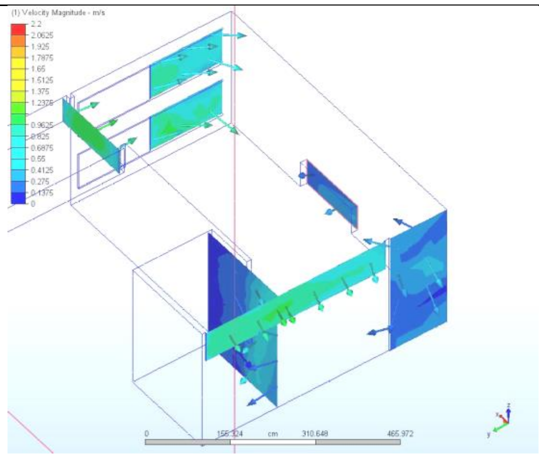
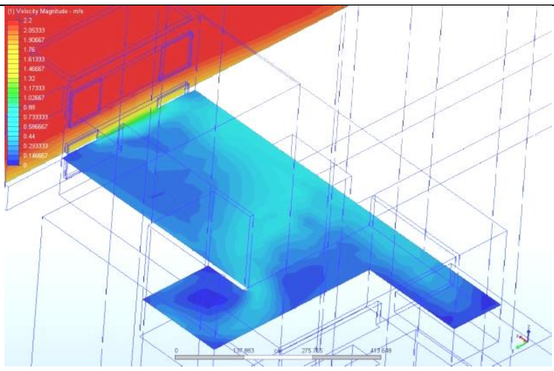
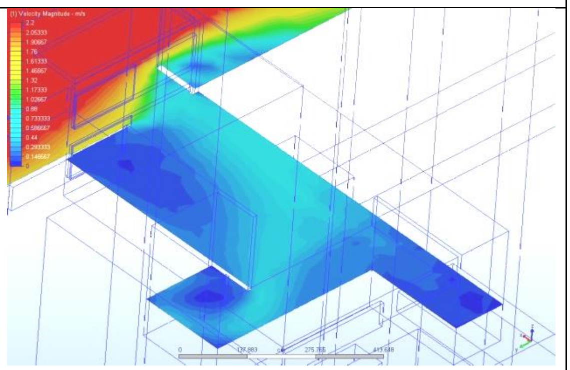
	DC11	DC12
Boundary Condition **#BC_7**		
		
	DC11	DC12
Boundary Condition **#BC_8**		
		

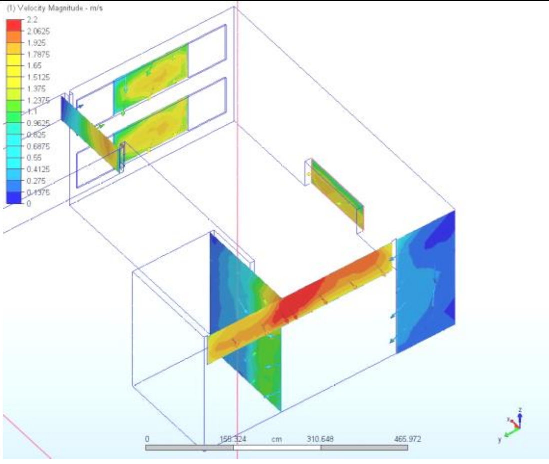
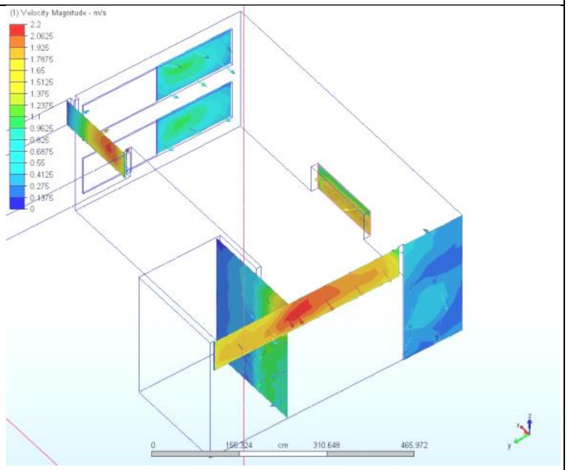
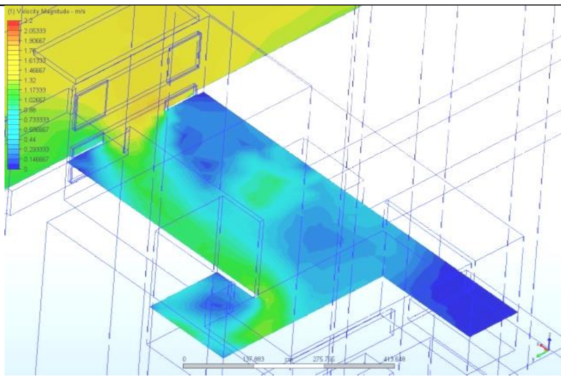
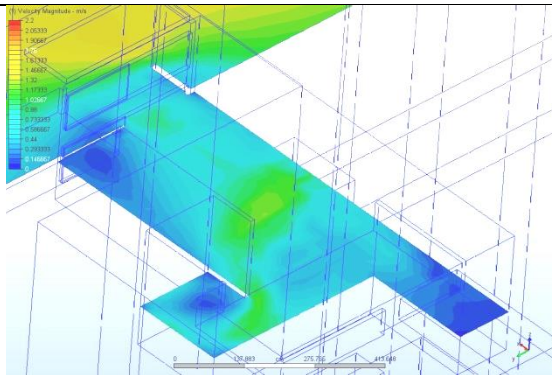
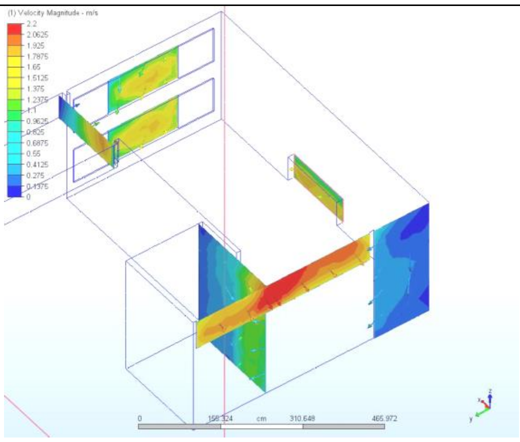
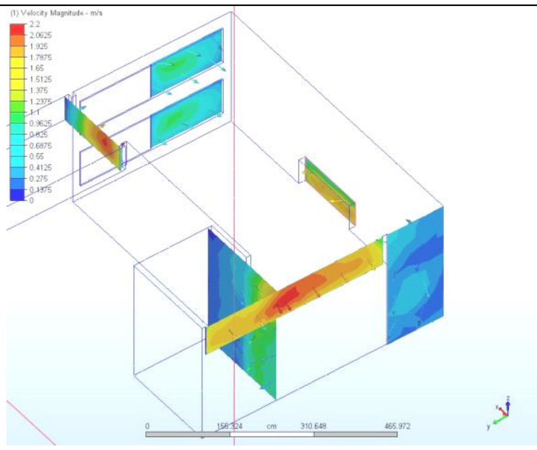
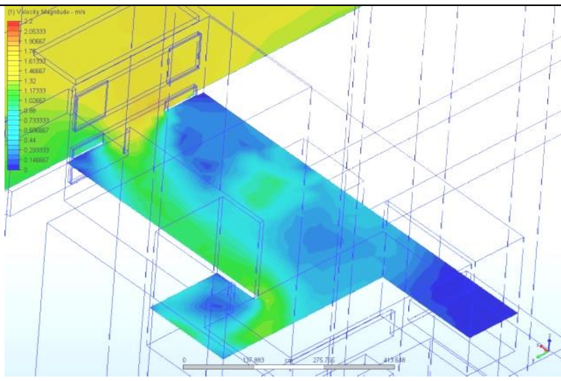
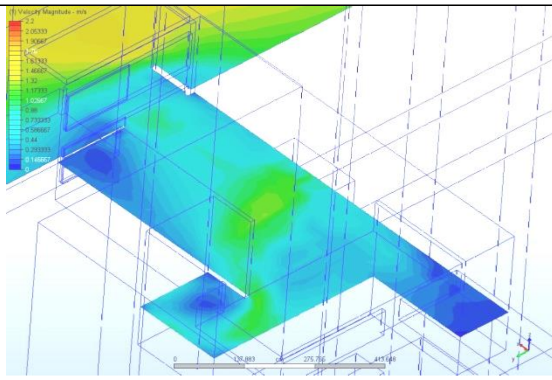
	DC11	DC12
Boundary Condition **#BC_9**		
		
	DC11	DC12
Boundary Condition **#BC_10**		
		

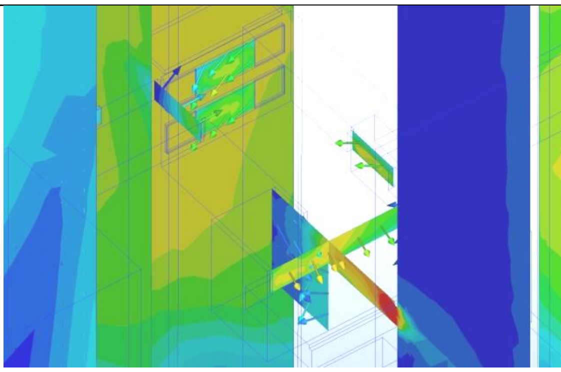
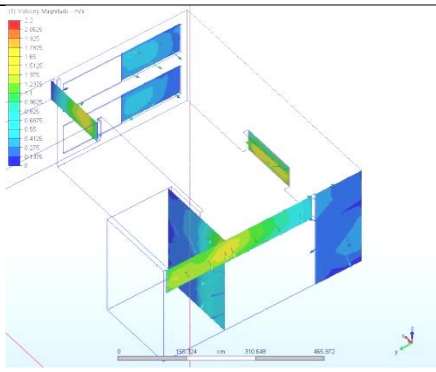
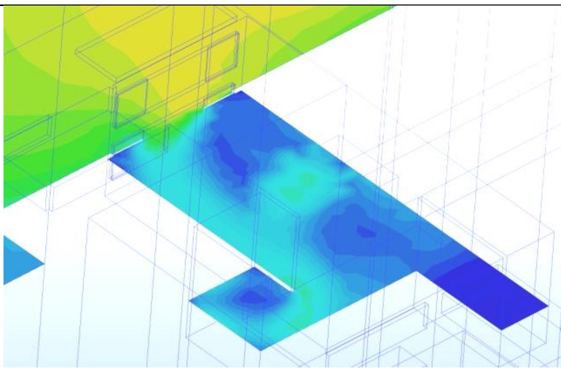
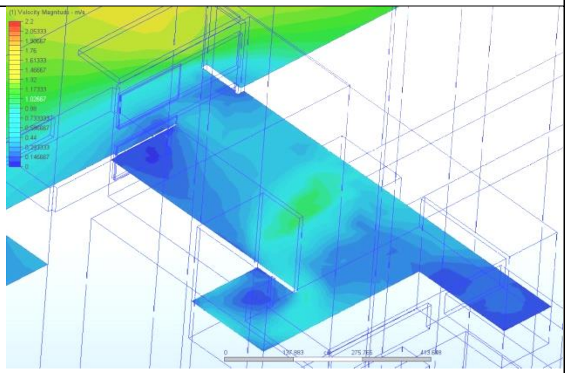
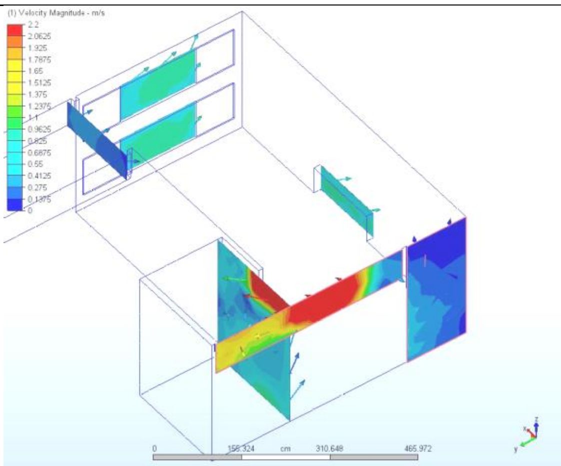
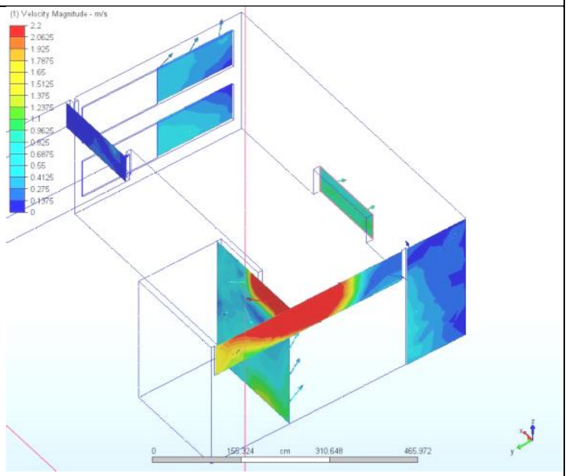
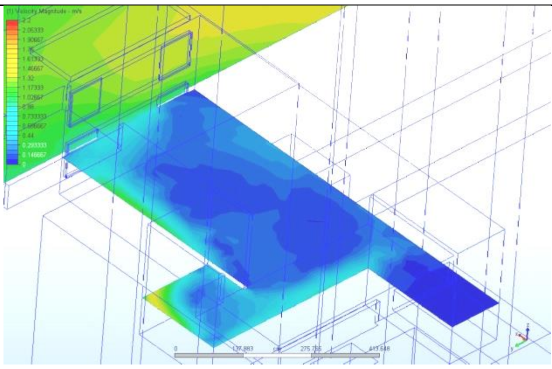
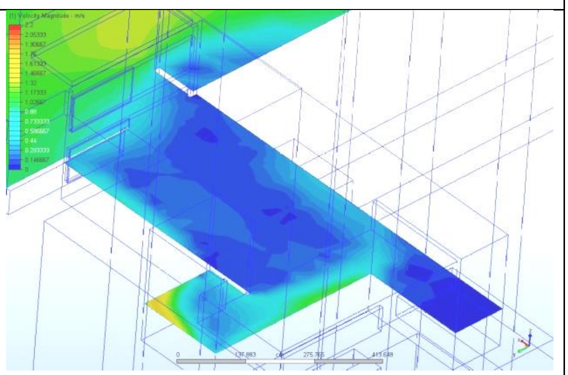
	DC11	DC12
Boundary Condition **#BC_11**		
		
	DC11	DC12
Boundary Condition **#BC_12**		
		

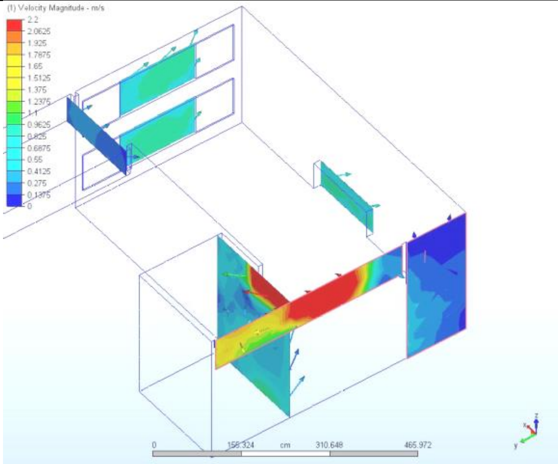
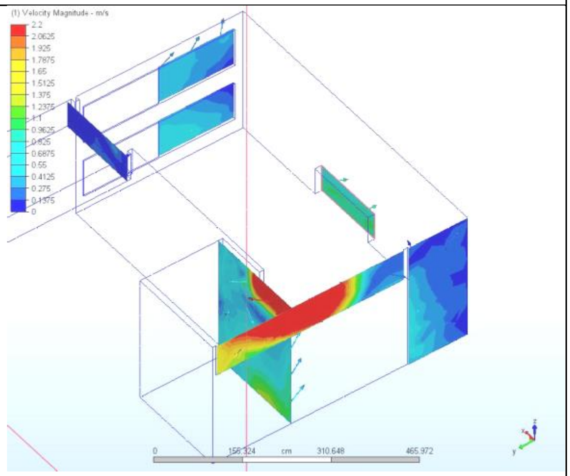
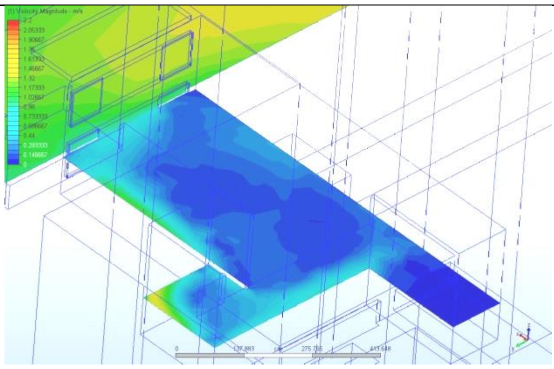
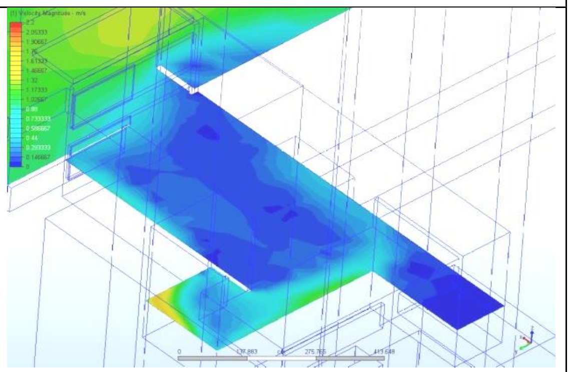
	DC13	DC14
Boundary Condition **#BC_1**		
		
	DC13	DC14
Boundary Condition **#BC_2**		
		

	DC13	DC14
Boundary Condition #**BC_3**		
		
	DC13	DC14
Boundary Condition #**BC_4**		
		

	DC13	DC14
Boundary Condition **#BC_5**		
		
	DC13	DC14
Boundary Condition **#BC_6**		
		

	DC13	DC14
Boundary Condition **#BC_7**		
		
	DC13	DC14
Boundary Condition **#BC_8**		
		

	DC13	DC14
Boundary Condition **#BC_9**		
		
	DC13	DC14
Boundary Condition **#BC_10**		
		

	DC13	DC14
Boundary Condition **#BC_11**		
		
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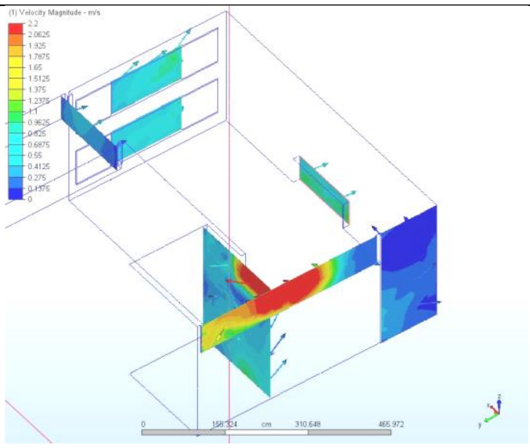
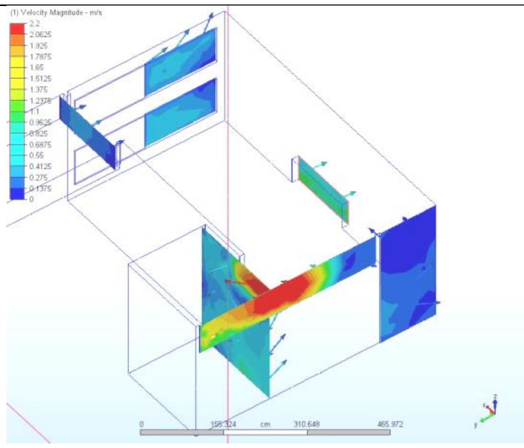
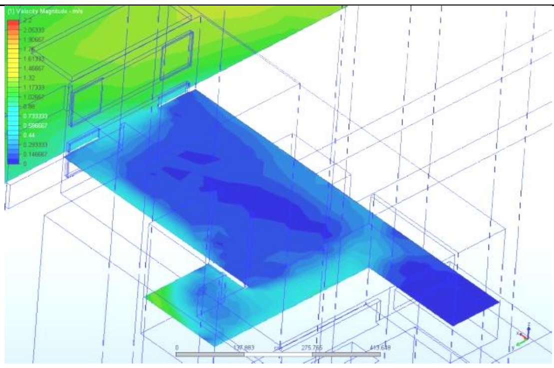
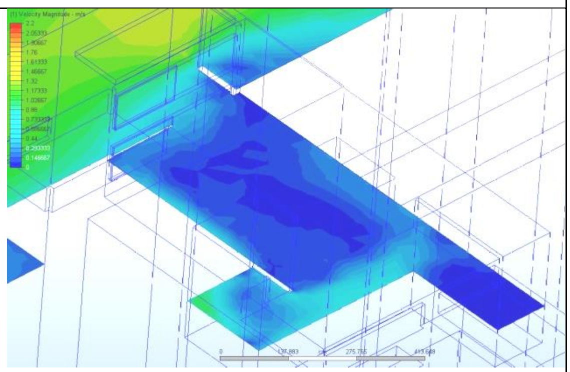
Boundary Condition **#BC_12**		
		

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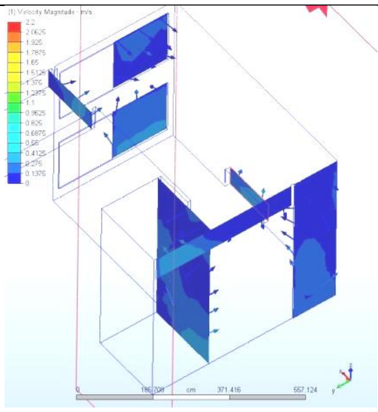
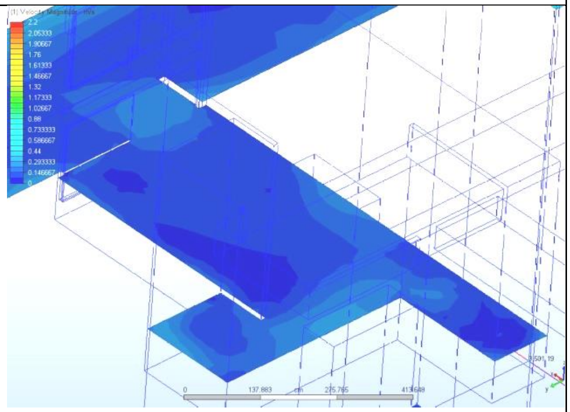
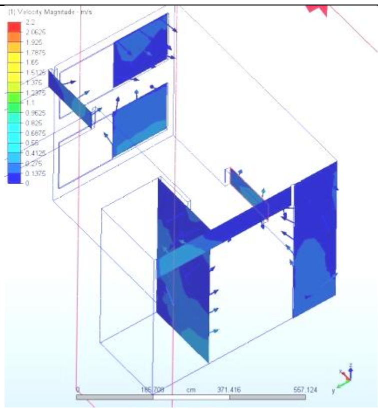
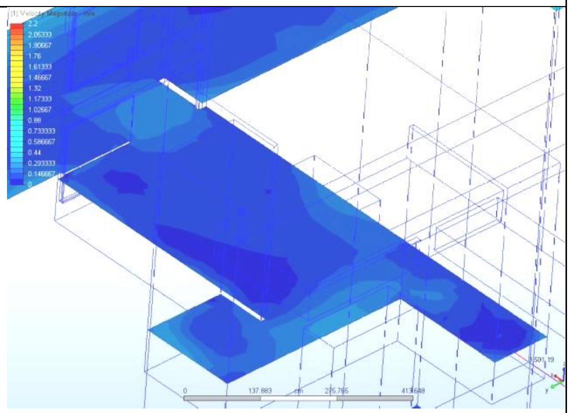
Boundary Condition **#BC_1**		
Boundary Condition **#BC_2**		

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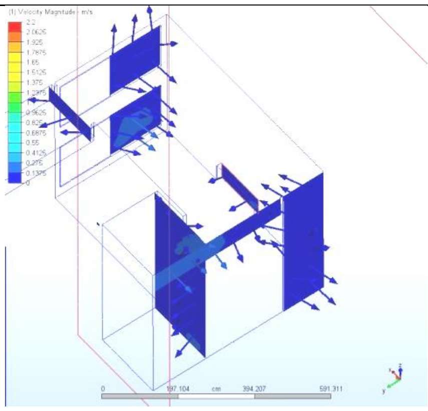
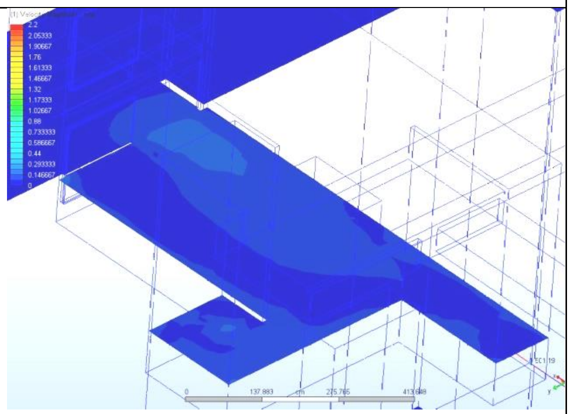
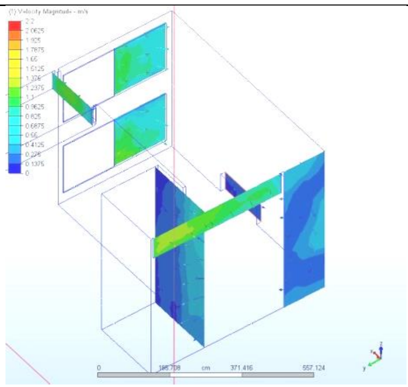
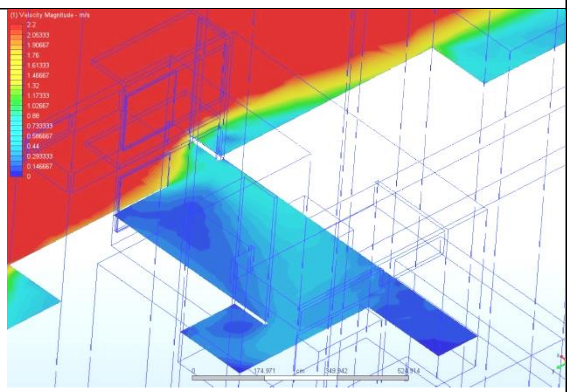
Boundary Condition **#BC_3**		
Boundary Condition **#BC_4**		

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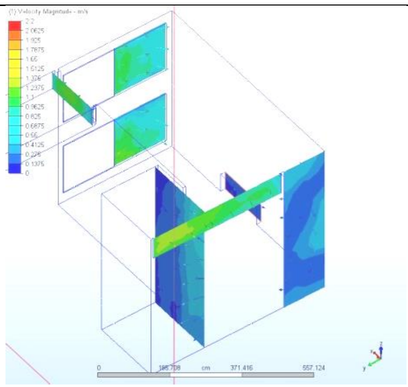
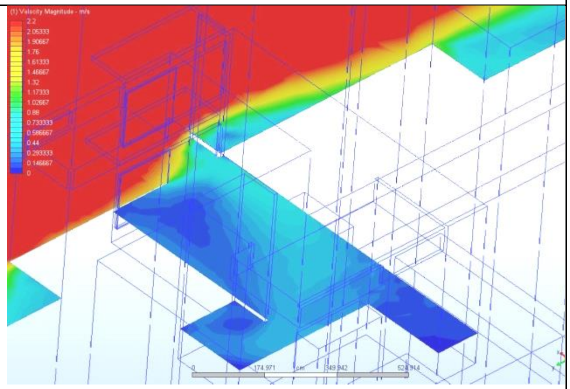
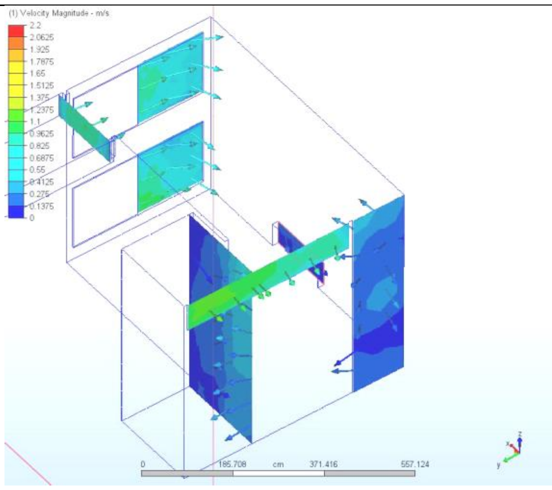
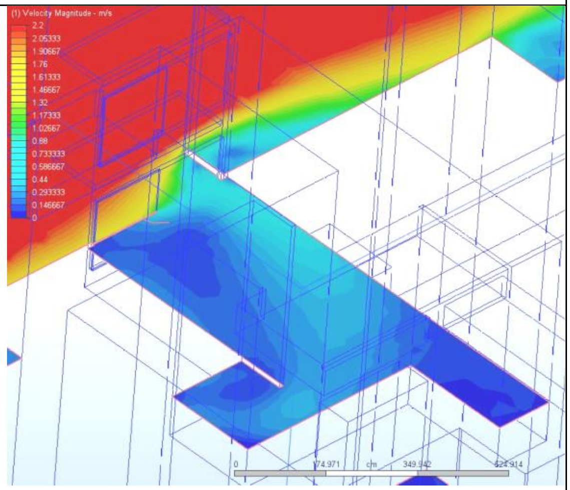
Boundary Condition **#BC_5**		
Boundary Condition **#BC_6**		
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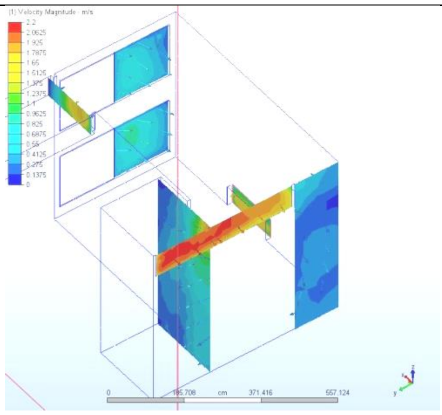
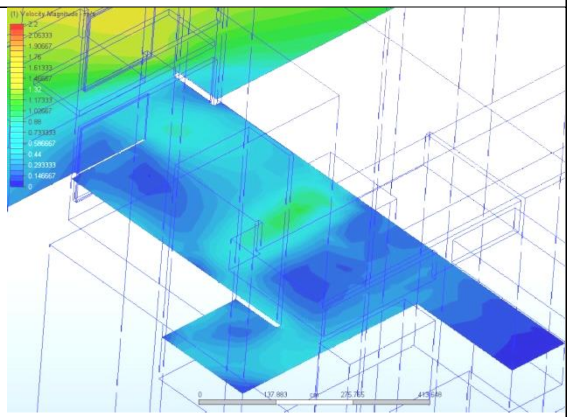
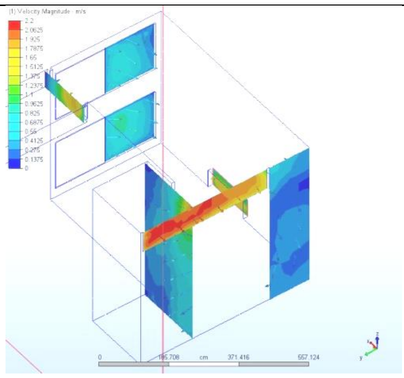
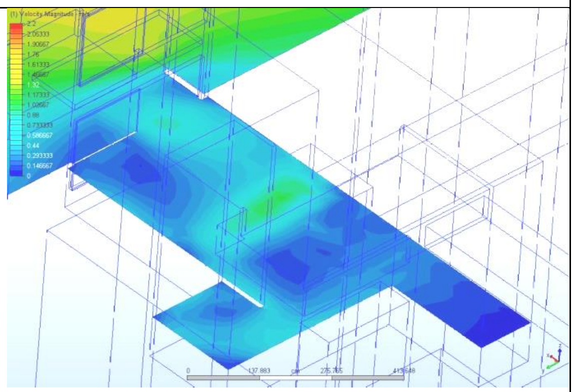
Boundary Condition **#BC_7**		
Boundary Condition **#BC_8**		

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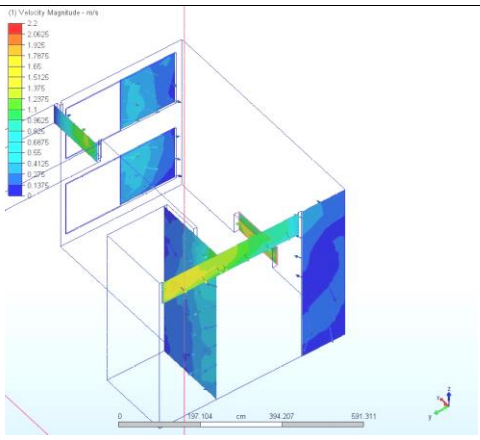
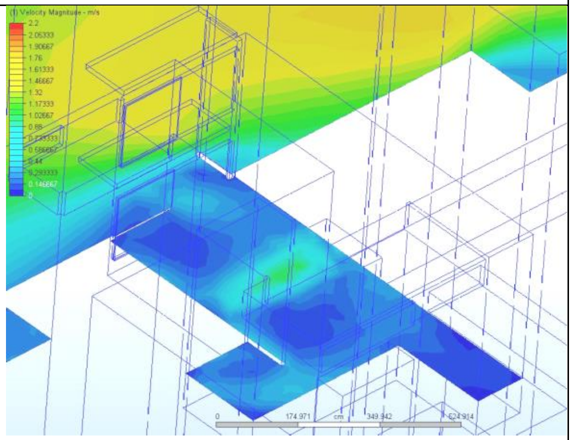
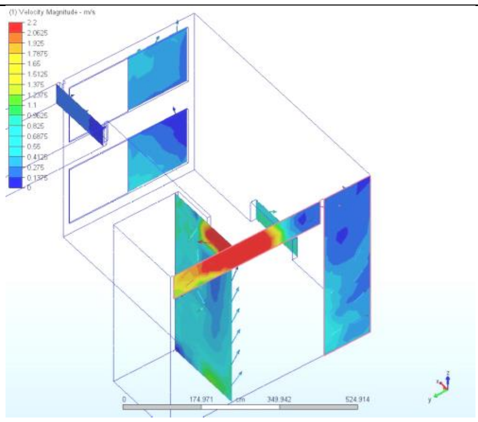
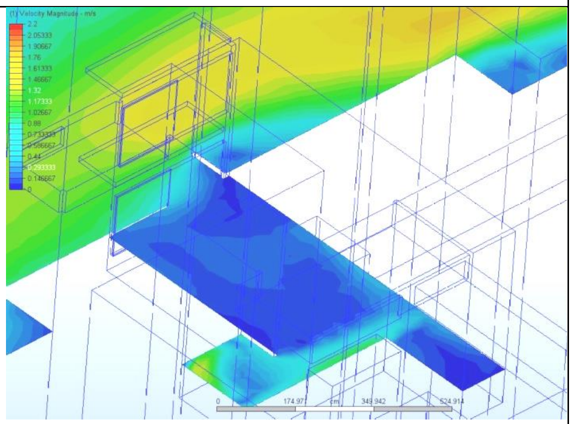
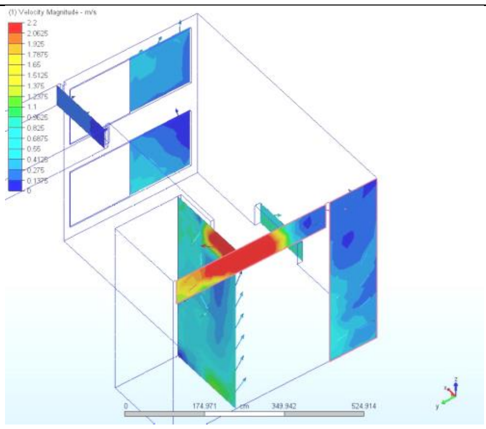
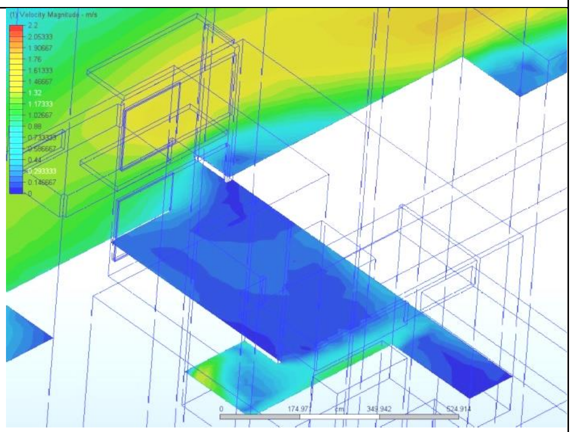
Boundary Condition **#BC_9**		
Boundary Condition **#BC_10**		
	DC15	
Boundary Condition **#BC_11**		
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