WIND LOADING ANALYSIS ON A RESIDENTIAL ROOF MOUNTED PHOTOVOLTAIC PANEL

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A report submitted
in fulfilment of the requirement for the Degree of
Bachelor of Mechanical Engineering

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DECLARATION

I declare that this project report entitled "Wind Loading Analysis on A Residential Roof Mounted Photovoltaic Panel" is the result of my own work except as cited in the references

Signature: ....

Name: ....

Date: ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the Degree of Bachelor of Mechanical Engineering

Signature : ....

Supervisor's Name : ....

Date : ....

DEDICATION

To my beloved father and mother for their understanding and support.

ABSTRACT

Solar is one of the renewable and alternative energy sources. Nowadays, solar PV is commonly installed at the rooftop of a residential house free of obstruction and highly efficient. There are a lot of factors need to be considered when installing the solar PV panel. One of the most important factors is the wind loading acting on the solar PV panel. Negligence to consider wind as potential risk can prove fatal to the structure of the rooftop and can even risk of injuring nearby people. This project was carried out to simulate the wind acting on the residential house's rooftop when installed with solar panels by varying the wind direction and tilt angle of panels. Through the wind flow field, pressure contour and pressure coefficients Cp result was predicted from simulation work. It was observed that the solar panel experienced lifting force that pulls the structure away from the rooftop and it became more obvious as the tilt angle increased from 20° to 30°. The same changes in pressure and wind flow field also occurred at different wind direction when increasing the panel tilt angle to 30°. The pressure acting on the panel is more varied in term of pressure contours and values especially at the bottom of the panel. The lifting force acted at bottom area of the panel increased as the tilt angle increased to 30°. Therefore, projected the influence of tilt angle and wind direction on wind loading on residential roof mounted solar photovoltaics panel. For future work, different type of roofs can be simulated to predict the geometrical influences to the wind loading on solar PV panels. The simulation work can be compared with experimental work for better result validation.

ABSTRAK

Tenaga solar adalah salah satu daripada sumber tenaga boleh diperbaharui. Masa kini, solar PV selalunya dipasang di atas bumbung rumah perumahan kerana bebas dari halangan dan bercekapan tinggi. Pelbagai faktor harus dipertimbangkan semasa pemasangan panel solar PV. Antara faktor yang penting ialah beban angin yang bertindak pada panel solar PV. Kecuaian untuk mempertimbangkan angin sebagai potensi risiko akan mendatangkan bahaya kepada struktur bumbung bahkan berisiko untuk mencederakan orang yang berdekatan. Projek ini dijalankan untuk mensimulasikan angin bertindak pada bumbung rumah perumahan apabila dipasang dengan panel solar dengan mempelbagaikan arah angin dan sudut kecondongan panel. Medan angin, kontur tekanan dan pekali tekanan, Cp telah diramalkan melalui kerja simulasi. Ia diperhatikan bahawa panel solar mengalami tenaga angkat yang menarik struktur dari bumbung dan ia menjadi semakin jelas semasa sudut kecondongan meningkat dari 20° ke 30°. Perubahan yang sama pada tekanan dan medan angin juga berlaku pada arah angin berbeza apabila sudut kecondongan panel ditingkatkan ke 30°. Tekanan yang bertindak pada panel lebih pelbagai dari segi kontur dan nilai tekanan terutamanya pada bawah panel. Daya angkat yang bertindak di bawah kawasan panel meningkat semasa sudut kecondongan meningkat kepada 30°. Justeru, menunjukkan pengaruh sudut kecondongan dan arah angin pada beban angin bertindak pada panel solar. Untuk kajian masa depan, bentuk bumbung yang berbeza boleh disimulasikan untuk menjangka pengaruh geometri pada beban angin. Kerja simulasi juga boleh dibandingkan dengan kerja eksperimen untuk pengesahan yang lebih baik.

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LIST OF SYMBOLS

m	meter
F	force
V	velocity
°	angle
°C	temperature (Celsius)
L	length
W	width
t	thickness
GW/h	power (10^9)
kW/h	power(10^3)
Cl	lift coefficient
Cd	drag coefficient
Cp	pressure coefficient
C_{PU}	pressure coefficient upper
C_{PL}	pressure coefficient bottom/lower
U_H	wind speed (m/s)
U_0	wind speed (m/s)
ρ	density
Po	free static stream pressure
P	pressure

LIST OF ABBREVIATIONS

RE	Renewable Energy
PV	Photovoltaic Panel
SEDA	Sustainable Energy Development Agency
CFD	Computational Fluid Dynamics
AC	Alternating current
DC	Direct current
WTT	Wind tunnel testing
WOW	Wall of Wind
RANS	Reynold Average Navier Stokes
SST	Shear Stress Transport
APA	American Psychological Association

CHAPTER 1

INTRODUCTION

1.1 Background

Renewable energy (RE) is one of the best alternatives to the conventional electrical generator. Since the discovery of electricity, human's life benefit greatly from it. Electricity power for an example can be produced in a power plant through multiple processes before being distributed to residential and industrial area. With the fast-growing electricity power consumption and the concern for the increasing greenhouse gas emission that caused climate change have started the sustainable policies development in regarding the renewable energy had been introduced. The renewable energy provided better and cleaner environment while providing humanities with electricity through greener method.

One of the types of renewable energy is solar energy. The irradiance from the sun is collected via solar panel or solar photovoltaics panel which can then be processed into electricity power. Malaysia is a country that relies on non-renewable resources such as fuel and gas to generate energy. Located on equator, Malaysia is blessed with temperature average ranging from 25°C to 40°C throughout the year. [32] Due to this, Malaysia is suitable to implement solar energy as one of its renewable energy.

Based on a report by Sustainable Energy Development Authority (SEDA), 2017 shows an increase of solar PV application by the year 2017. Solar PV panel hold 26.95% of the type of renewable energy being practiced in Malaysia with almost 9000 applications. This is due to faster installation and the price going much cheaper over the year. In term of energy generation, solar PV shows increment over the year by generating 330.03 GW/h compared to 272.44 GW/h in 2015.

When designing solar PV panel for installation, there are several parameters that need to be considered to achieve the best operating condition. The significant parameter is type of roof, tilt angle of the solar panel, dimension of solar panel, exposure hours, solar PV facing direction and dust accumulation [27]. In this study, the critical parameter that affect the wind loading on the photovoltaic panels has been investigated.

1.2 Problem Statement

There is a very important factor that need to be considered when designing solar panel system before installation is made to the buildings which is the wind loading force on solar photovoltaic panel. Improper design when installing is done can causes the improper pressure distribution on PV panel and structural damage to the system and even worse to the roof. At certain zones of the roof, there's a possibility of air pressure drop on top of the panel. The difference in pressure between below and above surface of the roof creates uplift forces that causes failure of panel and roof. Hence, the effect of tilt angle of the PV panel, PV panel geometrical scales, roof type, clearance height and wind direction are significant to investigate the flow distribution near the roof.

1.3 Objectives

1. To determine the parameter affecting the wind force impacted on the photovoltaic panel.
2. To obtain the wind flow field, pressure contour and pressure coefficients acting on the roof top.

1.4 Scopes

1. The simulation is to simulate the wind flow on PV panel roof mounted on low rise buildings (residential house) only.
2. The wind speed to use is the highest average wind speed 4.5 m/s in Malaysia.
3. The tilt angle is parallel, parallel + 10° to test the influence of tilt angle on wind loading on PV panel.

1.5 Methodology

The aim of the project is to simulate the wind passing through the PV array and find the wind loading acting on the PV arrays. Figure 1.1 shows the steps in carrying out the study

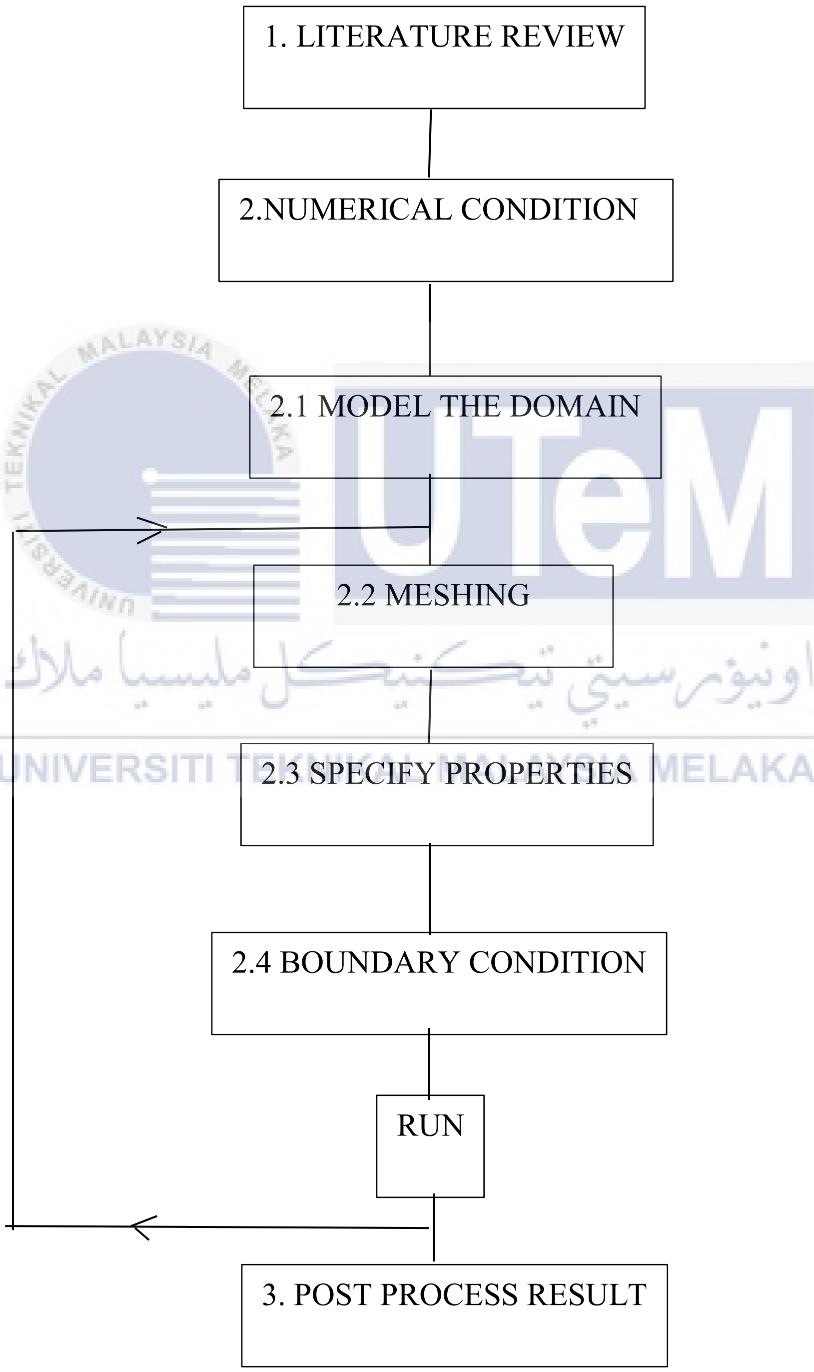


Figure 1.1 Flowchart of simulation steps

In order to understand the aim and concept of the simulation, multiple journal and research taken as references. From the journal, the wind loading on PV panel or arrays are critically influenced by the tilt angle of the panel and the wind direction acting on the panel. Others influences are presence such as the gap between the module however the effect is to be minimal and not significant [1]. The type of the roof also critical parameter. However, this simulation only will be focusing on simple gable roof.

For numerical modelling of the simulation, a 3D model is created. The model of house has the dimension of 6 m length x 21 m width with 2.1 m height to the roof. The roof dimension is to be 8 m length and 21 m width with a 20° pitch. The dimension of the individual solar panel is 0.814 m length x 1.6 m width x 0.04 m thickness. The array consisted of 5 modules in a row with size of 4 m length and 8 m width. The arrays are kept near the edge and centre of the roof. This is the standard gap left for installation and maintenance. The PV arrays are kept to parallel inclination while facing north and south. [27]. The inclination angle is chosen based on optimum power output at place with latitude of 4°.

The CFD simulation is performed for two different wind direction. A study of wind loading analysis on PV panel differs with types of roof and tilt angle is done by Naeiji, A. et. al [1]. The arrays of solar PV are mounted on hip roof. Models are subjected to different wind direction 0°, 90°, 180° and 270°. Based on result, wind force coefficient for hip roof are affected by the wind direction and tilt angle. The critical values are noted at 180° and 0° wind direction.

The computational domain is set at 70 m length x 105 width and 12 m height. At the domain inlet, the model is subjected to a constant wind speed at 4.5 m/s [31]. The wind speed is the highest wind speed at 10 m height of each month in Malaysia averaged from year 1993 to 2016.

In order to analyse fluid flows, the flow domain is split into smaller subdomains made up of hexahedra or tetrahedra in 3D. The governing equation is then solved inside each of the subdomains. Then, the next step is to set the flow inlets and flow outlets of the domain. The sides and top of computational domain are set as slip wall. A velocity inlet is used at the upwind boundary while a pressure outlet boundary is used at the downwind boundary. The bottom wall of the domain will be specified as no slip wall to simulate the effect of surface roughness.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The main focus of the project is to investigate the wind loading on roof mounted photovoltaic panel. The chapter analyses the wind loading on PV panel situated on the ground and above the roof and the parameter that affect the wind loading on the panel. The chapter begins with brief introduction of solar PV and the factors that affect the PV panels.

2.2 Solar Photovoltaic Panel

Photovoltaic panel as shown in Figure 2.1 is semi-conductor panel that convert irradiance from the sun rays to electricity. The panel is normally made from crystalline silicone. Differentiate with solar collector, the panel needs the amount of irradiance from the sun not the heat from the sun itself.

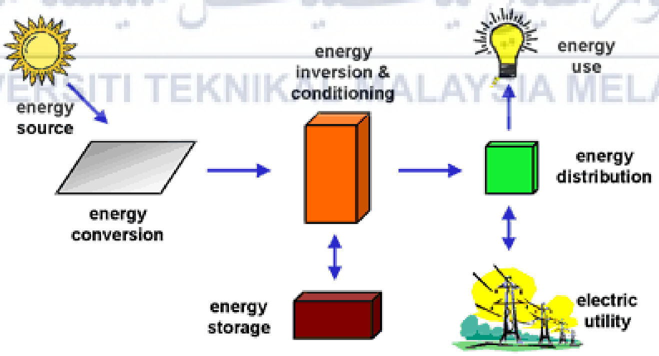


Figure 2.1: Basic PV operation (Source: Florida Solar Energy Center)

Solar panel works by allowing light to move electron from atom that can generate a flow of electricity. The electricity flow is then converted from AC to DC current by inverter before it is stored or used for electricity utility.

2.3 Solar Pv Panel Installation Design

When designing solar PV panel for installation, there are several parameters that need to be considered to achieve the best condition and performance. Such parameter is type of roof, tilt angle of the solar panel, dimension of solar panel, shading, solar PV facing direction and dust accumulation.

2.3.1 Roof type

In PV power generation, type of roof plays an important part. Generally, solar panel is work best without the influence of shade. This is because the shade is blocking the panel causing the productivity of power generation to be slow. There is different type of roofs that varies with surface area and ° of pitch. However, the most essential is the roof is in good condition to be able to withstand panel load and homogenous surface. Examples of roof type commonly associated with solar panels are gable, flat and hip roof [7] as shown in Figure 2.2

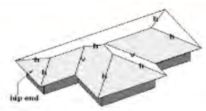
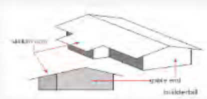
Name	Description	Diagram
Hip roof	The classic roof type has two slopes that meet at a high point in the centre of the roof to form a kind of triangle shape. Very common in Australia.	
Skillion roof	A Skillion roof has a single flat surface that slopes down from one side of the house to the other.	
Flat roof	Should be self explanatory really, flat roofs are roofs that are flat.	

Figure 2.2.: Example of roof types.

An experiment was done by [27] in 2014 to test the efficiency of solar PV in residential areas with different type of roof. A few houses in Shah Alam, Malaysia are selected to determine the energy generated after a lengthy amount of exposure hours. The result shows an adequate amount of energy collected through the exposure hour with average of 20-30 kw/h. The inconsistent average of energy generated was due to type of roof and direction face as shown in Figure 2.3

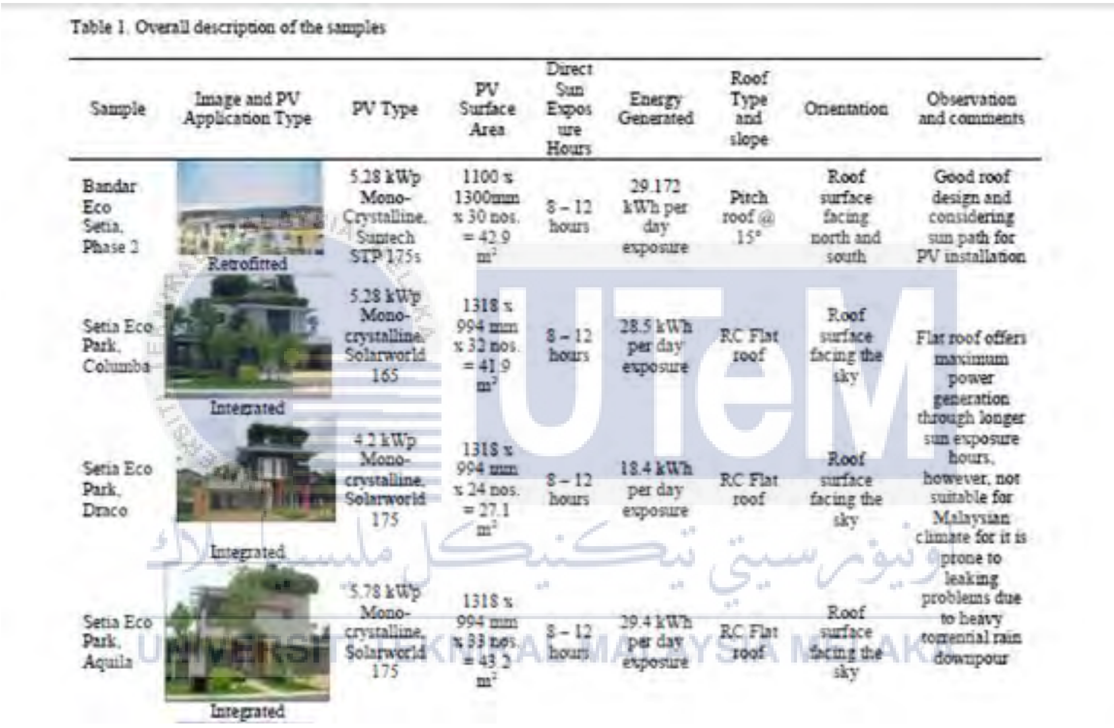


Table 1. Overall description of the samples

Sample	Image and PV Application Type	PV Type	PV Surface Area	Direct Sun Exposure Hours	Energy Generated	Roof Type and slope	Orientation	Observation and comments
Bandar Eco Setia, Phase 2	Retrofitted	5.28 kWp Mono-Crystalline, Suntech STP 175s	1100 x 1300mm x 30 nos. = 42.9 m²	8 – 12 hours	29.172 kWh per day exposure	Pitch roof @ 15°	Roof surface facing north and south	Good roof design and considering sun path for PV installation
Setia Eco Park, Columba	Integrated	5.28 kWp Mono-crystalline, Solarworld 165	1318 x 994 mm x 32 nos. = 41.9 m²	8 – 12 hours	28.5 kWh per day exposure	RC Flat roof	Roof surface facing the sky	Flat roof offers maximum power generation through longer sun exposure hours, however, not suitable for Malaysian climate for it is prone to leaking problems due to heavy torrential rain downpour
Setia Eco Park, Draco	Integrated	4.2 kWp Mono-crystalline, Solarworld 175	1318 x 994 mm x 24 nos. = 27.1 m²	8 – 12 hours	18.4 kWh per day exposure	RC Flat roof	Roof surface facing the sky	
Setia Eco Park, Aquila	Integrated	5.78 kWp Mono-crystalline, Solarworld 175	1318 x 994 mm x 33 nos. = 43.2 m²	8 – 12 hours	29.4 kWh per day exposure	RC Flat roof	Roof surface facing the sky	

Figure 2.3: Samples from the experiment done in Shah Alam, Malaysia [27]

2.3.2 Tilt angle

For the panel to have maximum power generation it must be placed perpendicular to the sun. The panel must face to the north or south depending on the installation location's latitude as shown in the Figure 2.4. Normally, the tilt angle of the panel as shown in Figure 2.5 is within the range of 10° but it depends on the latitude too. In some area, the tilt angle is increased for self-cleaning due to dust accumulation. If two same type of roof installed solar panel with different tilt angle, there will be difference in power generation.

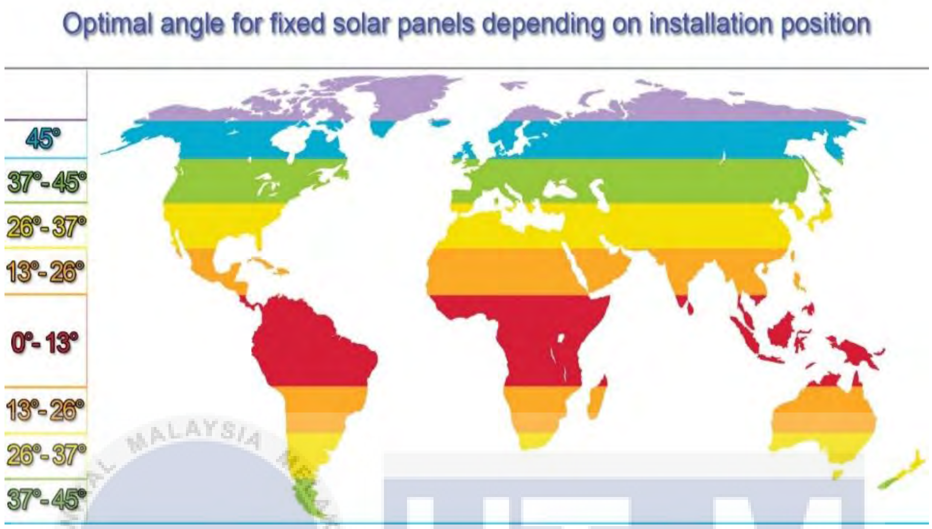


Figure 2.4: Optimum tilt angle based on hemisphere.

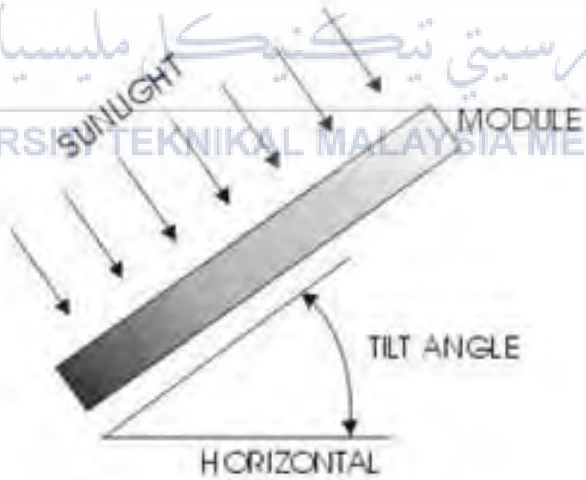


Figure 2.5: Tilt angle’s principle.

2.3.3 Shading

The amount of power generated is influenced by the exposure period to the sun without the obstacle from any shading. There are several factors that contribute to shade such as the panel location and also the orientation and roof form.

The solar panel location can contribute to the lesser power generation if it is installed near within area that has trees, pole or any obstruction to the sunlight as shown in Figure 2.7. When the panel are blocked by the shade, the exposure to the sun rays is lessen. The shade affects the current flow in the whole panel and shaded cells contributed to performance losses [14]. The shade can also come from the orientation and the roof form or types. The experiment done at Shah Alam highlighted the estimated sun exposure hours in different residential areas. [7] The flat and roof with low tilt angle experienced more exposure hours. When the tilt angle is higher, it could be under shaded by the roof structure.

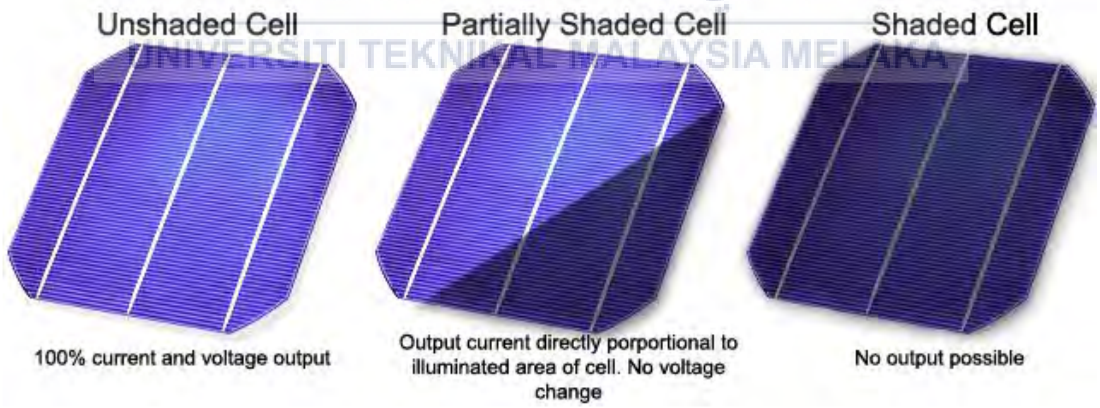


Figure 2.6: PV panel performance related to shading [14]

	Trees - solar panels are shaded by the trees surrounding the area of the installation. Can decrease performance down to zero performance.
	Soiling - particles like dust and sand. Normally happened in dusty area such as desert. Problem mostly occurred in Middle East.
	Roof structure -Structure such as roof can block the solar panel due to the sun path that changes with time.
	Bird dropping -Problem occurred at solar panel installed on the roof top. The problem can become severe if left unclean as it will block the solar panel almost completely.

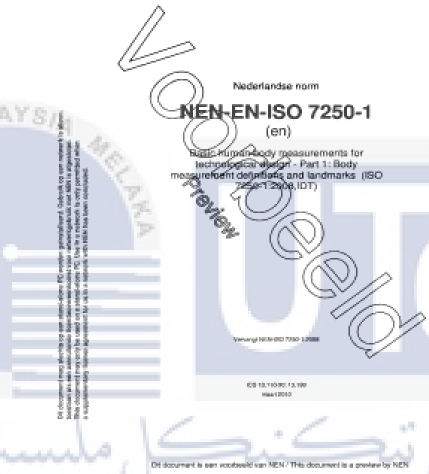
Figure 2.7: PV panel shaded by various obstacles [14]

2.4 Wind Loading on Photovoltaics Panel

Improper design when installing can impact the pressure distributed on PV panel and can cause structural damage to the system and even worse to the roof. [1] The concern of design is PV panel is always vulnerable to uncertain and high turbulent of wind. In certain zones of the roof, there’s a possibility of air pressure drop on top of the panel. The difference in pressure between below and above surface can create uplift forces that may cause failure of panel and roof as shown in the. The wind distribution is also affected by several parameter that can contribute to higher wind load such as tilt angle of the PV panel, PV panel geometrical scales, roof type, clearance height and building height.

Figure 2.8: PV panels displaced by wind forces. (Source: Renewable Energy World. com)

Normally the solar panel installation comes with a guideline as shown in Figure 2.9. The tilt angle, distance between panel and ground or roof, placed pitch or flat roof all has been provided inside the guidelines. Since the discovery of solar energy as potential, the technology and installation method has become mature in term of handling the wind load acting on the panel. This is due to various past researches and investigation done by the engineers and researchers.


Nederlandse norm

NEN-EN-ISO 7250-1
(en)

Basic human body measurements for technological design - Part 1: Body measurement definitions and landmarks (ISO 7250-1:2008,IDT)

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Figure 2.9: NEN 7250 2007 Guideline

There are many experiment and simulation that study the parameter that affect the wind loading on PV panel done by researchers. Generally, solar panel are usually mounted on the ground or the rooftop after considering few factors that can become an obstacle to the panel arrays. Such obstacles are shades from the building or from the trees and limited installation area. Below are some of the wind loading study that related to the ground mounted solar panels and roof mounted solar panels.

2.4.1 Ground Mounted PV Panel

Several studies have investigated the wind load on ground mounted PV panels. A numerical simulation of sun tracking ground mounted solar array is done by [10] to investigate the mean wind loading on the arrays. Each of the 2m chord length, 1.2m width and 0.007m thickness panels were inclined to various angle with respect of oncoming wind direction. Wind with velocity of 26 m/s as velocity reference. It was found out that there is net pressure coefficient at the upper and lower surface of the panel. Other studies [11] investigated the effect of spacing parameter on ground and also roof mounted panel. The wind tunnel experiment showed that the peak and moment coefficient increased with longitudinal spacing between panels. Despite that, the moment coefficient was highly reduced due to the sheltering effect by the other panel in the arrays. It could be noted that the first row of the arrays received more wind loading than the second row. While the spacing parameter between PV panel regarding the wind load was found to be minimal.

2.4.2 Roof Mounted PV Panel

There are many studies involving roof mounted PV panel. With the decreasing cost of PV installation, the topics of wind loadings were aggressively debated and investigated especially mounted PV on low and high-rise buildings. Generally, roof is subjected to higher wind loading due to higher elevation. The wind speed is subjected to surface friction and higher air density. The higher the height means the higher wind speed. The roof is designed to withstand wind load up to a certain point. If the roof is subjected to much higher wind than it was designed, there is possibility for suction force to loosen and lift roof sheathing and coverings that causes damaging to the roof and surrounding. With the addition of PV panel, a proper installation design is needed to be made.

An investigation of wind loading on roof mounted PV had been done [4] on a sloped roof type, focusing on the geometry of the array. The wind tunnel experimentation highlighted that external wind load depended on the gap of module and arrays to the roof surface. Large peak suction occurred on the upper surface of the module when the space between arrays and roof surface was higher but the wind load on lower surface of the module was lower due to reduced flow resistance. The wind load of gap between module was relatively small.

2.5 Wind Loading Parameters

2.5.1 Tilt angle

An investigation of wind loading analysis on PV panel differed with types of roof and tilt angle [7]. The arrays of solar PV were mounted on different types of roof that were flat, gable and hip. The tilt angles were changed to investigate the force coefficient value. Models were subjected to four different wind direction such as 0°, 90°, 180° and 270°. Based on the result, wind force coefficient for flat roof was not significantly affected by the change of tilt angle. Gable and hip roof however were affected by the increases of tilt angle as the average force coefficient also increased. It can be noted that low tilt angle less than 10° didn't affect much on force coefficient. When the tilt angle was more than 10°, there was aggressive increment in the wind loading.

The difference between gable and hip roof wind force coefficient was due to the design of the roof which could contributed to larger wind loading. Tilt angle of solar PV panel could also affect the critical wind direction by changing the positive and negative values of wind coefficient. Inclination angle is important for critical wind direction [6]

2.5.2 Space between the panel and the roof

Solar PV panel are occasionally installed with a gap between the panel and surface, regardless of roof surface or ground surface for easier maintenance. However, the gaps have an effect towards the wind loading on the PV panel. An experiment on stand-off PV systems on pitched roofs is conducted to investigate the effect of distance between panel and roof surface. From the result, the peak pressure on the upper surfaces of PV module as the height of the module increased but the effect is small. The module was reduced the wind loads on the roof beneath the module. The net pressure coefficient was smaller than the values recommended for use in solar PV design guidance. [3]

Another wind tunnel experiment of wind loads on 28 modules of photovoltaic arrays was mounted to 30° sloped roof on low rise buildings was to investigate the effect of distance between module and the mounting height above the roof surface. It could be found that the space between the roof and panel yielded low net wind loads. The lower surface of the panel pressure decreased slightly when the height of the panel was increased due to the reduced flow resistance and more uniform underside pressure [4] As conclusion, the distance between the panel and roof influenced the wind loading but the effect was relatively small and not critical.

2.5.3 Roof Type

Solar PV panel is commonly installed on a roof surface. There are many types of roof but the most commonly are flat, gable and hip roof. Different type of roofs has different structure that can influence air flow on the roof. The coefficient of force acting on PV panel installed on each type of roof is different from each other.

There is wind tunnel experiment that focuses on the wind loading on PV panels on three types of roof. [7] The roof is flat, gable and hip while the factors evaluated such as building height, tilt angle, roof and panel clearance and area averaging effect. For review, only the tilt angle parameter to be taken and compared with roof types. The tilt angle tested on flat roof was 20°, 30° and 40° while the gable and hip are both parallel to the slope and parallel + 14°. Based on the result, the wind loading on PV panel at the flat roof was not affected by tilt angle when it is greater than 10°.

For gable and hip roof type, increasing the tilt angle from parallel to + 14° had increased the wind load. This is because increasing tilt angle can generate turbulence. In comparison, for flat roof, coefficient of force is considerably lower than gable and hip roof types.

2.5.4 Wind speed

Wind speed is one of the parameters that affect the wind loading on solar photovoltaic panel regardless of the panel mounting location. Wind speed are depended on the location, height and also the weather. During installation of solar PV, the designers have to consider a certain amount of wind speed that the solar PV can withstand. Failure and neglect of wind speed influence in the panel installation design can result in contributing to the damage of the panel and the area around it.

It can be stated that the wind increased as the height increased. There are multiple reasons for this. One of the reasons was wind speed is less on the ground due to the surface friction. Objects such as trees, buildings and rocks can act as an obstacle as the wind collides into them. As the height increased, there is less obstacle thus less the friction. Hence the wind speed increased with height.

The other reason is due to the lower air density. The density of air is highest at the surface and decreases as the height increases. This is because a dense air requires a higher force to move it at the same speed as less dense air. With air density decreasing with height the less dense air is easier to move at higher speed.

Wind speed varies with location and weather. Windy weather has high wind speed than normal day. With location, wind speeds can vary with time. A research of reliability of wind speed from satellite altimeter in 2017 highlighted the differences of wind speed in time of month in Malaysia from the year 1996 until 2016 [31] as shown in Figure 2.10. The country received strong wind during Northeast Monsoon from November to February. During Monsoon transition on March to April and September to October, the country experienced slower wind speed.

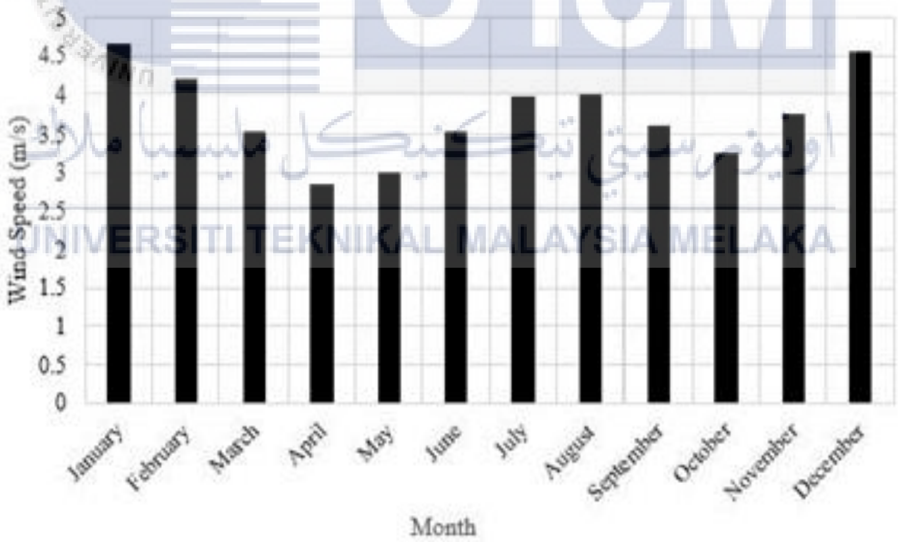


Figure 2.10: Wind speed each month average from 1996 until 2016 [31]

2.5.5 Wind direction

Wind comes into contact with solar panel from all directions. Depending on the direction, the pressure acting on the roof structure can vary. Roof structure can withstand or experiences high uplifting force and high pressure that pulls the roof away from the structure. In case of solar panel, the panel can experience uplift on its surfaces. This parameter is studied and discussed [26]. A model of house was created for three cases; house without panel, house with panel no gap and house with panel with gap. All of the model was subjected to same constant wind speed and tested with multiple wind directions.

It was observed that varying the wind direction changing the aerodynamics load acting on the solar panel and roof structure. At 0° wind direction, the whole structure was under negative pressure which the uplift forces were high. The perturbation of solar panel caused changes to local flow field that influence the flow field. At 90° degree wind direction, the pressure contour changed completely. The front roof experienced high pressure due to flow separation while the back roof experienced negative pressure due to flow separation at the ridge and recirculation forming at the area. Therefore, wind direction affects the wind loading on the rooftop.

2.6 Analysis Method

There are two method that can be used in order to study the wind loading on solar PV panel. The methods are by experimenting using wind tunnel and simulations using computational fluid dynamics. In terms of wind analysis on the panel, there are many researches that has been done using wind tunnel [1][2][3][4][5] and CFD simulations [8] [10] [12] [13] [17]. Both methods are different and has their own advantages and disadvantages. Nevertheless, it is both equivalently appropriate and effective.

2.6.1 Wind tunnel testing

Wind Tunnel Testing (WTT) is an experiment that is done physically within a certain size of an area to test the effects of wind and flow moving past a solid object. It is also used to determine the aerodynamics resistance forces, stability and controllability. The wind is generated and controlled by rotating fans. For large wind tunnels, the wind tunnel is usually equipped with multiple rotating fans that are used in parallel to provide sufficient airflow. Special instruments are often used to measure the force of air on object.

Wind tunnel consists of five basic sections; the settling chamber, contraction cone, test section, diffuser and drive section as shown in Figure 2.11.

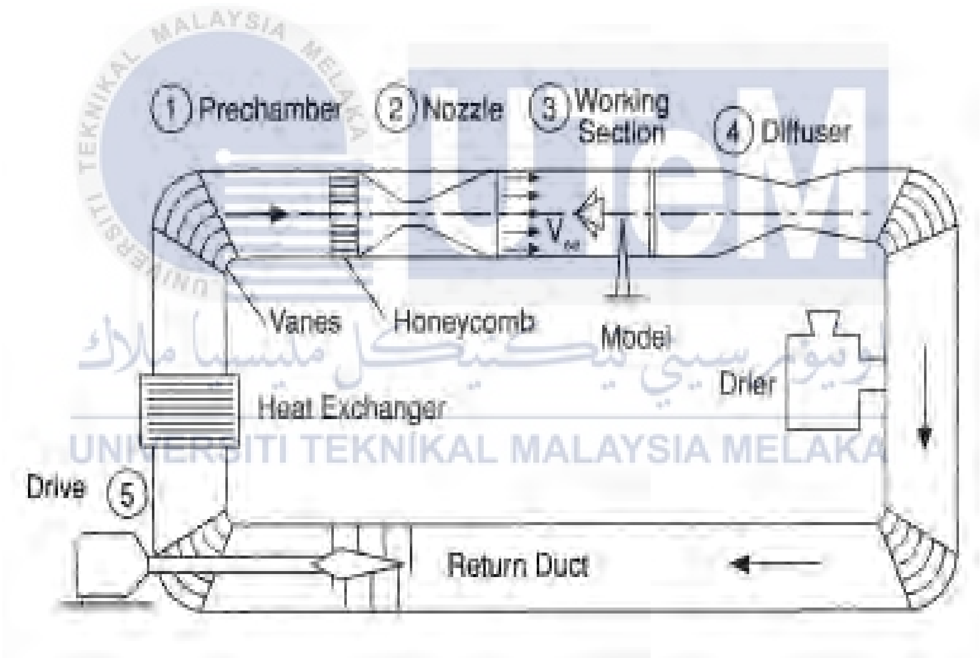


Figure 2.11: Basic component in wind tunnel

Component		Description
1	Settling chamber/ prechamber	• Settling and strengthening the air through the honeycomb shaped holes and series of screens.
2	Contraction cone/ area	• Flow uniform • Increases the flow at test section.
3	Test section	• Area to place the test objects. • Sensors function to record data • Provide visual observations.
4	Diffuser	• Reduce the air velocity without causing turbulence in the test section.
5	Drive section	• Housing the rotating fans that creates high speed airflow. • Fan always placed at the downstream at the end of the tunnel to pull air into smooth stream.

Figure 2.12: Description of wind tunnel sections

A wind tunnel test is done by Amir Naeiji, 2017 [1] to analyse the parameter such as geometric properties, tilt angle, clearance height, building height and roof type that can damage the solar PV panels. Large scale models are test inside wind tunnel facilities. The models have different roof types such as flat, gable and hips as shown in Figure 2.13. All models had dimension of 9.1 m width and 13.7 m length in full scale. To simulate the effect of building height on wind loading, the roofs are built with mean roof height of 6.55 m and 10.59 m for flat roof and 11.6 m for gable and hip roof respectively. The panel size is 2 m (L), 1 m (W) and 0.15 m (t). The clearance distances are 0.3 m and 0.45 m. The tilt angle for flat roofs are 20, 30° and 40° while gable and hip roof are parallel and parallel + 14°. Each model is tested at multiple wind directions.

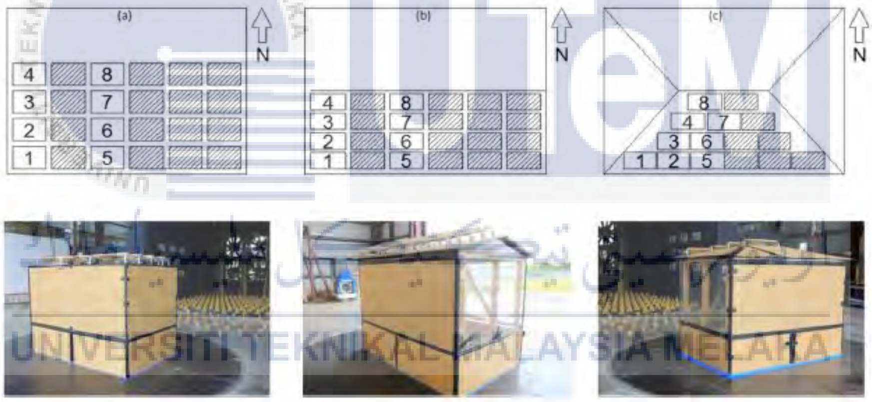


Figure 2.13: Model of flat, gable and hip roof with array configuration [1]

It can be seen in the result that the tilt angle and roof type are the critical parameter that effect the wind loading on solar PV panels. For flat roofs, increasing the tilt angle increased the maximum and minimum net force coefficient. The coefficient was observed at 40°. The increased in tilt angle had led to higher suction at bottom surface while the force at top surface increased about almost double. For gable and hip roof, changing the tilt angle did not changed the force coefficient much. It can be noted that the panel located at the edge of the roofs are immediately affected by the wind load.

Another wind tunnel experiment was done to investigate the difference of values between full scale and small-scale test of wind loading testing on solar PV panels. [25] The full-scale model was a simplified with flat roof. The solar panel is 157.1 cm length x 95.1 cm width x 4.1 cm thickness. The clearance between panel and the roof surface is 7.6 cm as minimum recommended clearance for roof mounted PV. The tilt angle tested are 0°, -15°, -45°, 15° and 45° .The model was exposed to wind using 6 fans in Wall of Wind facilities while the small-scale model test is conducted inside wind tunnel. The setting was the same as the full-scale model.

Table 2.1: Peak normal force coefficient.[25]

angle	CFn, Wall of Wind	CFn, Wind Tunnel
0	1.32	0.62
-15	1.63	0.91
-45	2.53	3.52
15	1.44	0.97
45	-2.07	-2.47

It can be seen in the result shown in Table 2.1 that the force coefficient between WOW test and wind tunnel test are different. It was concluded that dynamic effects of full-scale testing are the reason why the result between those two tests are different even though the experimental settings are the same. A solution was suggested by developing mechanical admittance functions to modify the wind tunnel to get the same force coefficient with the WOW test. The study also highlighted the importance of vibrations when conducting full scale test to which the panel was subjected higher wind load and extreme wind speed during windstorms.

2.6.2 CFD Simulations

Computational Fluid Dynamics (CFD) is qualitative prediction of fluid flows by using mathematical modelling, numerical methods and software tools. These mean enables engineers to conduct experiment virtually to determine aerodynamics, airflow and many more. Modern engineering problems is impossible to solve with the use of CFD. It also offers easier modification and portable. There are currently multiple CFD software available to be use such as:

Table 2.2: Example of CFD software

ANSYS CFX	OPEN FOAM
ALTAIR	STAR CD
FEMLAB	ANSYS FLUENT
FEATFLOW	AUTODESK
SOLIDWORK	SIMSCALE

Physical aspects of fluid flow are associated with three fundamental principles. The Newton second law where force is equal to mass times with acceleration. Mass is conserved and energy is conserved. These principles are expressed in terms of basic mathematical equations (integral or partial differential equations). CFD replaces these equations into discretized algebraic forms which are solved. To solve these equation, CFD software requires the repetitive manipulations that can reach millions of numbers which is impossible for human. Hence, CFD is chose for its mathematical solutions ability.

A lot of wind loading analysis on solar photovoltaics panel are done using wind tunnel testing. However, recently engineers and researchers took interest in using CFD software in simulating the flow on the solar panels. Such examples can be seen in a simulation done by Chowdhury Mohammad Jubayer et al (2016) [12] to simulate wind loading on solar arrays mounted on the ground. The aerodynamics load on solar arrays were investigated using Reynold-Average Navier Stokes approach.

A model was built using the 3D modelling software as shown in Figure 2.14. The dimension for solar panel module is 1.2 m length x 0.6 m width x 0.007 m thickness. About 24 of the modules was arranged in 4 x 6 arrangement with 25° inclination angle to simulate a stand-alone system. The array configuration used was 5 rows of panels with 3 stand-alone system side by side in each row. The distance between the support legs was 3.05 m with the end legs having distance of 0.24 m from the edge of the arrays. Two domains are created for 4 wind direction. 3D dimensional, RANS simulation was carried out using unsteady solver OpenFoam and transient solver that applies Pressure Implicit Splitting Operators algorithm were used to solve Navier Stokes equation and SST k omega turbulence model was used. Boundary conditions were set accordingly such as no slip wall at surface and panel.

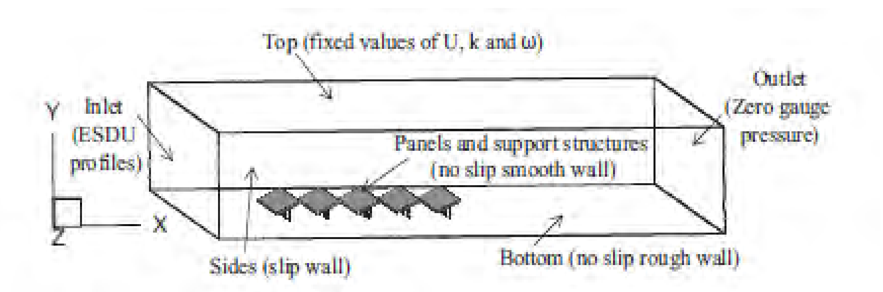


Figure 2.14: Boundary condition of the model.[12]

From the result, row 2 until 5 of the solar arrays were completely in the wake of the first windward flow at 0° and 180° wind direction. Row 1 experienced maximum wind load (drag and lift) for all four wind directions. Maximum uplift occurred at row 1 was observed at 180° wind direction as maximum drag at 0° wind direction. The drag and lift force for row 2 until 5 as shown in Figure 2.15 was higher in 45° and 135° wind direction rather than straight line 0° and 180° wind direction. The maximum overturning moment was found at 45 and 135 wind direction as all row shows similar coefficient at the wind direction unlike 0° and 180°.

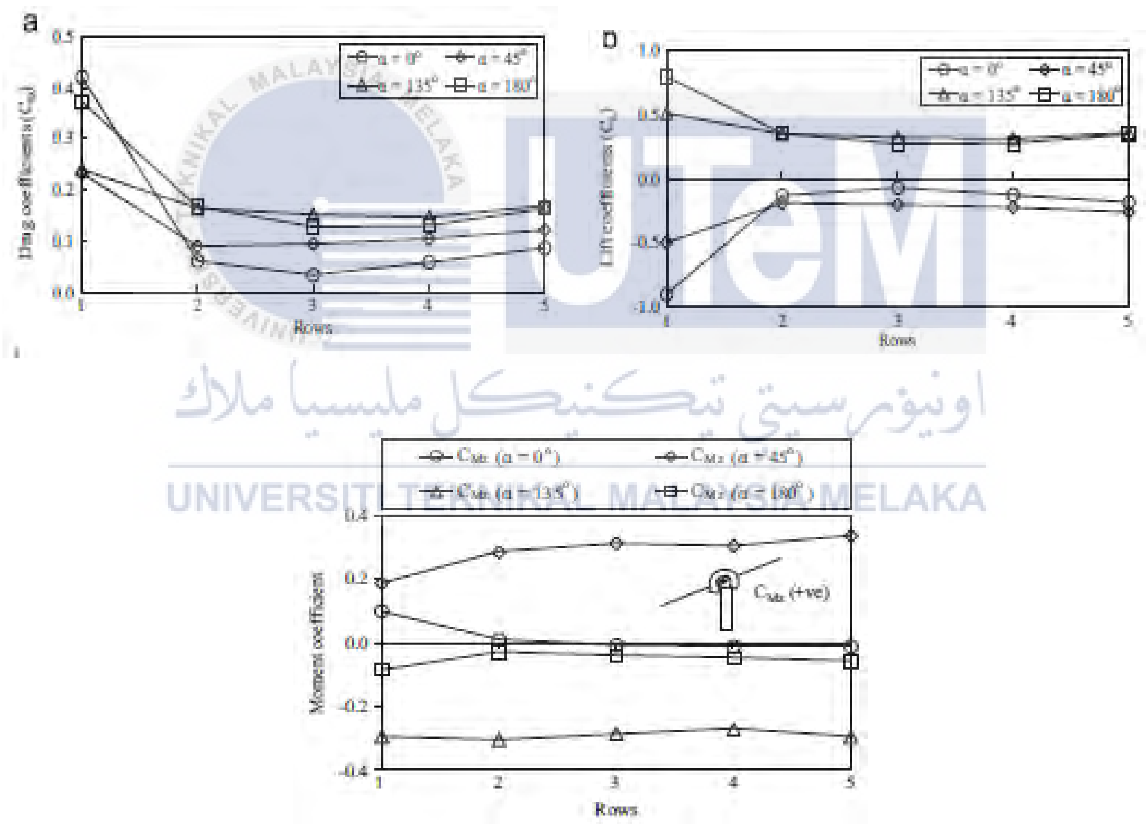


Figure 2.15: Lift, drag and moment coefficient of the analysis [12]

2.6.3 Wind tunnel and CFD difference

Regarding the wind loading on solar PV panel, wind tunnel testing provides fully developed turbulence which can be used to test high rise buildings due to the long test section with roughness element. The pre-chamber or settling chamber that consist of honeycomb shaped holes allow for smooth flow at the entrance. However, the testing of small size structure such as low-rise buildings was difficult if the geometric scales are large. This is because it is impossible to produce turbulence in the wind tunnel at large scale [3].

In comparison, CFD was faster and multi-purpose. It provided more realistic in term of simulating control volume of atmospheric boundary layer surrounding a real structure. The virtual wind tunnel has similar boundary condition to the experimental wind tunnel. It only if the boundary conditions and the surroundings objects were properly simulated. There are few problems related in using CFD such as increased time and computational resources needed to be able to simulate correctly. It also required high computing capabilities for longer simulations. The license to use CFD is also expensive which was another obstacle in researching the wind loads. [2]

2.7 INFORMATION AND DATA SEARCH

In order to understand the aim and concept of the simulation, multiple journal and research taken as references. The searching is emphasized on wind load analysis on photovoltaic panel. The references are taken in regardless of the mounting located on the ground or mounted on the rooftop. As the references increases, it becomes hard to keep track or differentiate the journal from another. Hence an approach is taken by creating a references table using Microsoft Excel. The tables enhance information searching and make it easier to differentiate each journal while at the same times discard the needs to open every journal every time.

Table 2.3: References table

	PROBLEM	STUDY PARAMETER	CRITICAL PARAMETER	RESULT	IMPORTANT REMARKS
1	the distributed pressures on PV panels' surface can lead to considerable structural damage which can result in partial or total loss of the PV array as well as potential damage to nearby properties	Different geometrical properties, including panel tilt angle, clearance height, building height and roof type,	tilt angle and roof type	tilt angle and roof type are the most important parameters that affect the wind forces on roof mounted PV panels, while the effect of clearance distance and building height was not significant.	angle 315, 337.5 -0 ,247.5 ,180
2	Traditionally design wind loads for buildings and other structures are obtained using building codes and standards.no complete guidance ready for codification of wind loads on these types of structures	Wind loads on solar panels depend on wind speed, terrain characteristics, shape, which includes inclination angle, and installation type,the geometric scale and the inflow turbulence characteristics	the geometric scales	Mean pressure coefficients are not significantly affected by the model size while peak pressures are alerted by both geometric scale and inflow turbulence	tilt angle of 40 and leg height of 24 in. (0.61m) at
3	The results from previous wind analysis are very conservative, uneconomic in many cases and do not cover the situation occur nowadays	distance between panel and roof	The effect of distance between PV system and roof surface	loads can be expected that are substantially lower than the external loads on the roof surface,as given in wind loading standards	The distribution of the loads with respect to th differs in fullscale and wind tunnel ex
4	large uplift forces on low-rise building roofs,but also the flow environment for roof-mounted equipment	gaps between the panels and the roof surface	gap between modules	larger gaps between modules, G, and smaller gaps between the panels and the roof surface, H, were found to yield lower net wind loads	roof slope of 30 degree
5	the existing literature has less than comprehensive data for the evaluation of wind loads on solar panels resulting in either conservative designs that overestimate the wind loads or unsafe structures	roof slope and the panel's location, vertical distance, horizontal gap between the solar panels	roof slope and the panel's location	Solar panels mounted in zone 1 are locally subjected to higher suction at their outer edges	gable roof with a slope of 22.6 degre roof with a slope of 14 degree. impor avoiding corner and edge zones of the roof to loads on the individual modules

The table created in Excel is divided into several sections. References comparison, references APA and important note and symbol. For references comparison, it is consisting of problem statement, study parameter, critical parameter, result, important remarks and researching method.

The problem statement is reasons of study and issue addressed that related to the research topic. Then, the study parameter is taken. It is variables or conditions that may or may not have impact on the test subject and outcome results. Critical parameter is the variables or conditions that confirmed to have impact on the outcome and main causes of the result. Result is the outcome and conclusion while some notes is written at important remarks. Lastly the method used to investigate the problem.

As summary after a collective number of journals, it can be concluded that the wind loading on PV panel or arrays are critically influenced by the tilt angle of the panel. The wind load at angle of 10° is constant but increases as tilt angle increased. [7] The gap between the module however the effect is to be minimal and not significant [4]. The type of the roof also critical parameter. The wind load on flat roofs is higher as tilt angle increased but for gable and hip roofs the wind load increased but almost similar between other tilt angle. The space between the panel and the roof surface also contributed to the critical wind load if the gap is larger. [1] The parapet height can cause the uplift loads to reach worst case values. [24]

For analysis, two critical parameters are taken and to be study. The parameters are tilt angle and wind direction. Tilt angle is to be kept parallel to the roof and parallel + 10°. The array dimension, gap of the roof and panel and other parameters are standardized and kept constant. 3D unsteady RANS simulations are chosen to calculate and solve the wind load on the panel.

CHAPTER 3

METHODOLOGY

3.1.1 Introduction

The aim of the simulation is to investigate the parametric studies on wind force loading on the photovoltaic panel and determine the wind effect on the panel. To achieve the result, each step had been planned and presented in a flow chart. The progress of the project had been timed in the Gantt chart so that the plan had been followed. The critical parameters of wind loading analysis had been taken based on multiple references. The 3D modelling had been created using Ansys Fluent design modeler. The models were setup to specify the settings and the boundary conditions. The result was obtained after the simulations were finished.

3.2 Numerical Modelling

The idea is to simulate the wind flow on top of the roof mounting a solar panel. For numerical modelling of the simulation, a 3D model was made. The model of house has the dimension of 6 m length x 21 m width with 2.1 m height to the roof. The roof dimension is to be 8 m length and 21 m width with a 20° pitch.

The dimension of the individual solar panel is 0.814 m length x 1.6 m width x 0.04 m thickness. The panel dimension is taken based on dimension of solar module Powermax Ultra/ Plus - c manufactured by Shell as shown in Figure 3.1

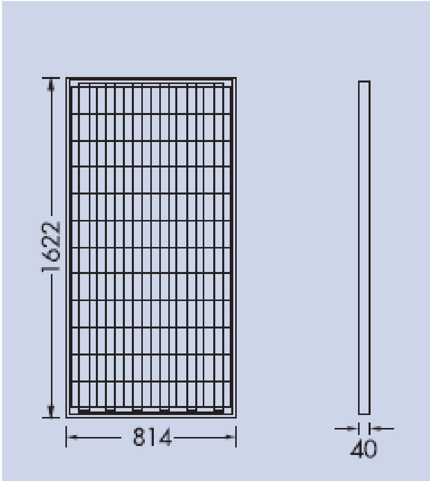


Figure 3.1: Solar PV dimensions

The array consisted of 5 modules in a row. Hence making the array size to 4 m length and 8 m width. The array was kept near the edge and centre of the roof with small gap as shown in Figure 3.2. This is the standard gap left for installation and maintenance. The PV array was kept to parallel inclination while facing north and south.

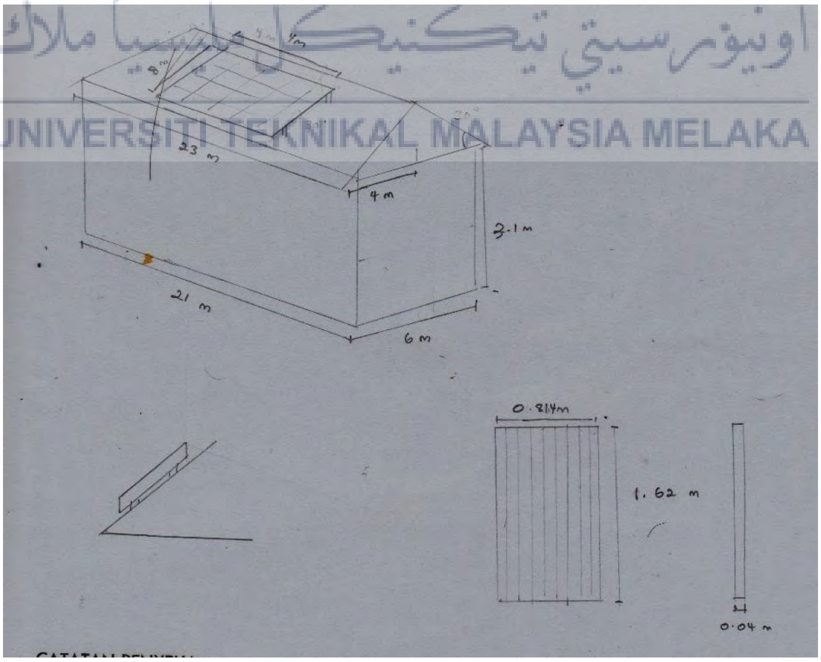


Figure 3.2: Sketch of house with dimensions.

Based on the sketching, the idea was presented via computer modelling. The software used for modelling was Ansys Fluent. There was total of three volume created. A rectangle with dimension of 21 m x 6 m x 3.1 m (house body), a triangle with 20° slopes extrude to the edge of the rectangle (roof) and a rectangle with dimension of 4 m x 8 m (panel). Boolean function was used to extract the model of the house from the domain. This was to simulate the wind flow inside the domain.

The computational domain was set at 70 m length x 105 width and 12 m height. The computational domain must be large enough to include all relevant features while minimizing the effects from field boundary conditions on the flow field in the region of interest [26]. Hence the size should be enough for accurate simulation of the flow field.

3.3 Meshing

In order to analyse fluid flows, the flow domain is split into smaller subdomains made up of hexahedra or tetrahedra in 3D. The governing equation then was solved inside each of the subdomains. After constructing the model and the boundary domain, next step was meshing. The meshing element of the body of the house and roof was to be detailed because of area of study. The meshing for boundary domain contained less element than body of the house and roof.

Quality of the meshing had to be maintained to get accurate result. There are two condition that need to be fulfilled so that the meshing quality is good. The conditions were aspect ratio and skewness. Aspect ratio of the mesh has to be below 16 while the skewness has to be in the range of 0.8 to 0.98.

3.4 BOUNDARY CONDITION

The sides and top of computational domain was set as slip wall. A velocity inlet was used at upwind boundary while a pressure outlet boundary was used at downwind boundary. The bottom wall of the domain was specified as no slip wall to simulate the effect of surface roughness. The body of the house, the roof and the panel were set at no slip wall. The sides of the domain are slip wall. Atmospheric boundary layer is SST k-epsilon turbulence closure was chosen because it is suitable for flow around inclined plate. There is no temperature involved in the simulation.

At the domain velocity inlet, the model was subjected to a constant wind speed. The wind speed was the highest wind speeds at 10 m height of each month in Malaysia averaged from 1993 to 2016. The wind speed is 4.5 m/s.

The pressure-velocity coupling used for the simulation was SIMPLE scheme along with the Green Gauss Cell Based gradient in spatial discretization. The solution to be standard initialized and compute from the inlet where the velocity will be depended on the wind direction set during meshing.

CHAPTER 4

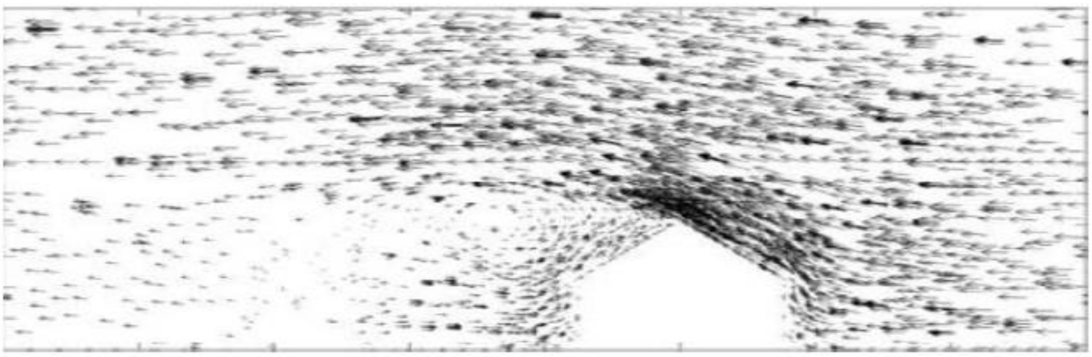
RESULT AND DISCUSSION

4.1 Introduction

The aim of the section to find the wind direction and tilt angle effects on the wind loading acting on the panel. The simulation was used for finding the flow fields of the wind. the maximum and minimum value of pressure coefficient Cp acting on the roof also has been obtained. Model with no panel was created first for wind characteristics comparison. The result after the simulation was to be compared with the expected result based on other simulation [26].

4.2 Validation

In order to validate the result, the simulation result is compared to the result obtained from previous work as shown in Figure 4.1. Residential house without panel is chosen to be compared because it is easier to analyse since the wind flows smoothly over the roof due to the absence of solar panel. Velocity field and pressure contour were compared and analysed. The dimension of the house, domain and wind speed is the setting difference between both results.



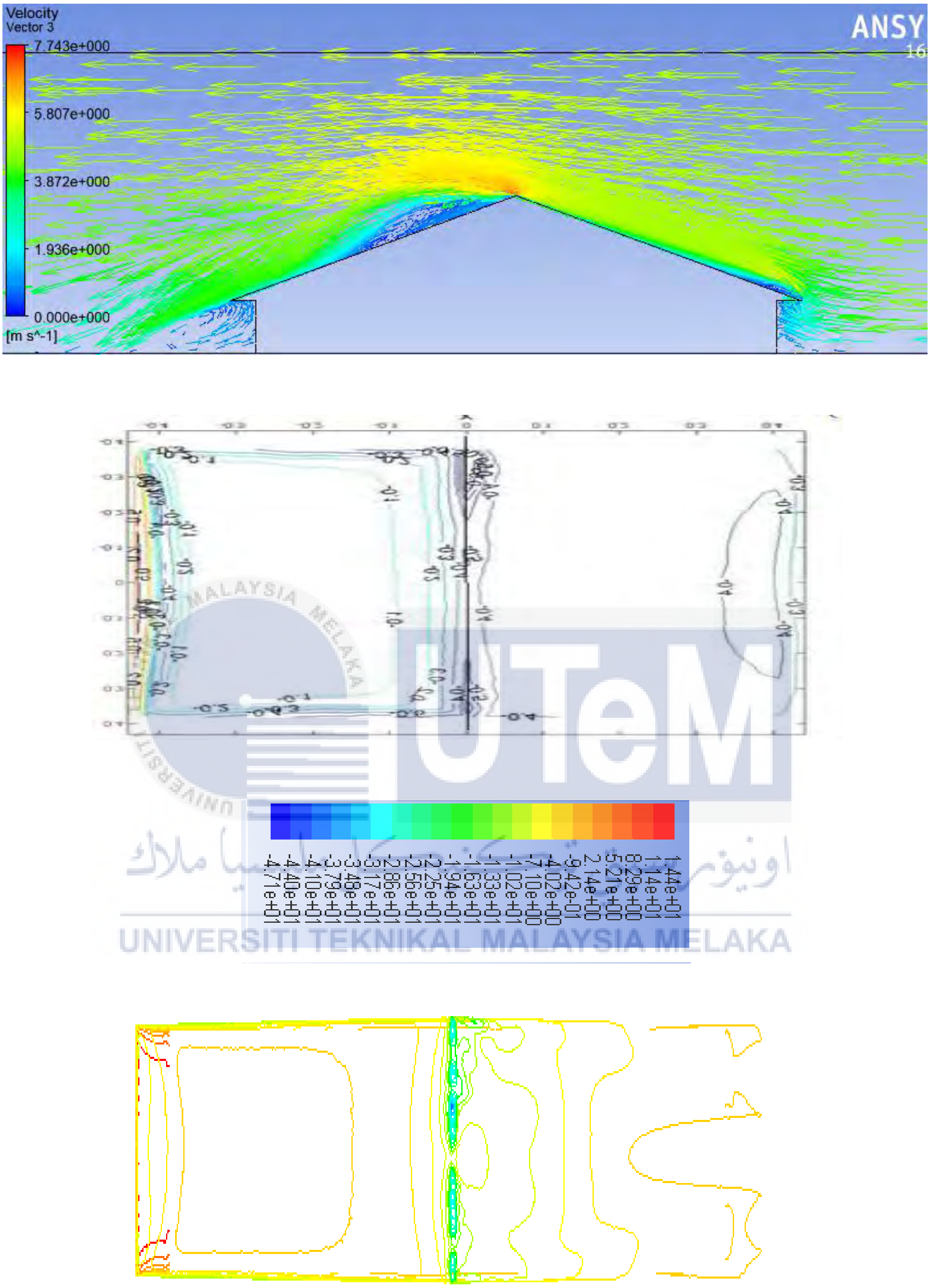


Figure 4.1: Residential house without panel expected and simulation comparison. a) velocity field b) pressure contour profile

Table 4.1: Boundary condition comparison between expected result and simulation result

Boundary condition	Expected model	Simulation model
a) Velocity Inlet	velocity magnitude	velocity magnitude
b) Pressure Outlet	Normal to boundary	Normal to boundary
c) Slip wall	Stationary wall, specified shear, shear stress magnitude components 0 (upper, left and right boundaries)	Stationary wall, specified shear, shear stress magnitude components 0 (upper, left and right boundaries)
d) No slip wall	Stationary wall (ground)	Stationary wall (ground)

As seen from velocity field of expected and simulation result from Figure 4.1, the wind flow was similar when flowing over the rooftop and separating at the ridge. The small recirculation at the overhang and flow merging were presenced at the simulation. The recirculation expected at the leeward side of the roof (back of the roof) was observed in the velocity field for the simulation. The wind that separated at the ridge and flowing downstream creating a recirculation at the leeward side. This was correspondent to the flow on the rooftop because when the front roof experienced pressure, the back roof will be experiencing lifting and suction due to flow recirculation as stated in the numerical simulation [26].

For the pressure contour, there are similarity between simulation and expected result. Due to the front roof that experiencing wind first, the pressure was much higher than the back roof. Symmetrical value at the middle shows the smooth flow from the edge at the front roof to the ridge. Variance in pressure magnitude at the area where panel supposed to be located is similar to the expected result.

4.3 Simulation Setup

The model with no solar panel as shown in Figure 4.2 was selected and built first because it is to be used for wind flow field and pressure contour comparison. The dimension of the model and boundary domain without solar is the same. Before proceeding to the setup, the model and boundary domain were meshed first as shown in Figure 4.3. Aspect ratio and skewness were controlled to ensure good mesh quality.

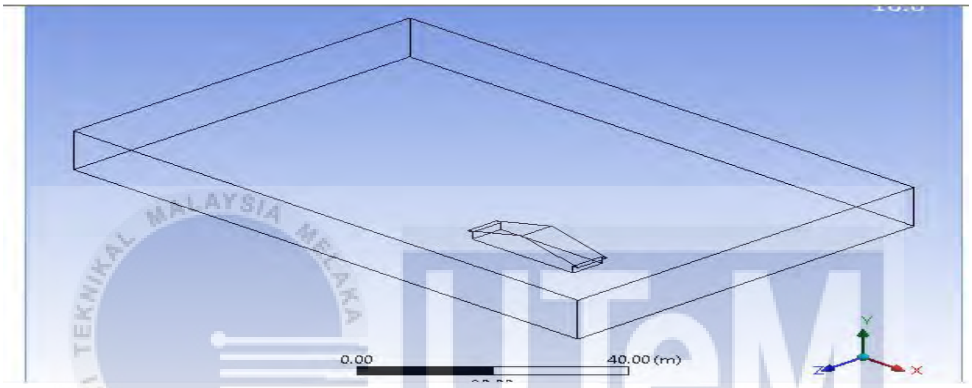


Figure 4.2: The model without solar panel before meshing

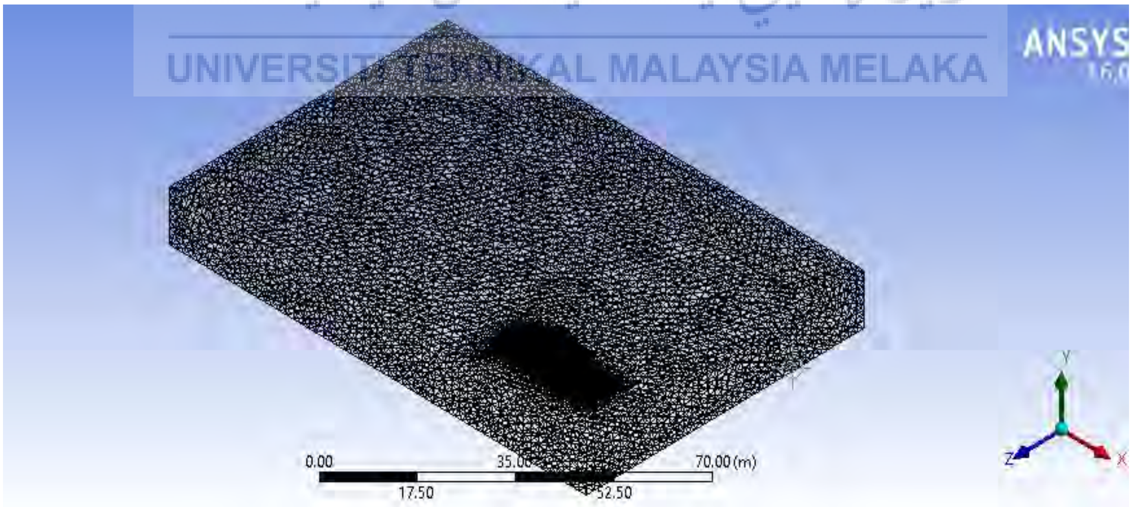


Figure 4.3: The model without solar panel after meshing

The specified boundary conditions were inlet velocity, pressure outlet, slip wall at the sides and top of domain, no slip wall at model body and roof, no slip wall at bottom surface of domain. Once the model, value of boundary conditions and solution method have been set, the simulation is run for 1000 iteration.

4.4 Expected Result

Wind loading analysis on roof mounted photovoltaics panel using CFD simulation were already done by several researchers. For this simulation, the result obtained from a numerical study by Aklilu T. G. Giorges [26] was used for comparison. The simulation done was suitable and can be used for guidance to complete the objective of this project.

The numerical study analyzed wind loading on a house model with 1:12 scale of a real house dimension. The roof type is gable and inclined by 26.5°. The panel arrays were geometrically similar to the actual house model as shown in Figure 4.4. The model was tested with different wind direction and a constant 50 m/s wind speed. The flow was simulated using Navier Stokes equation and k-ε turbulent model.

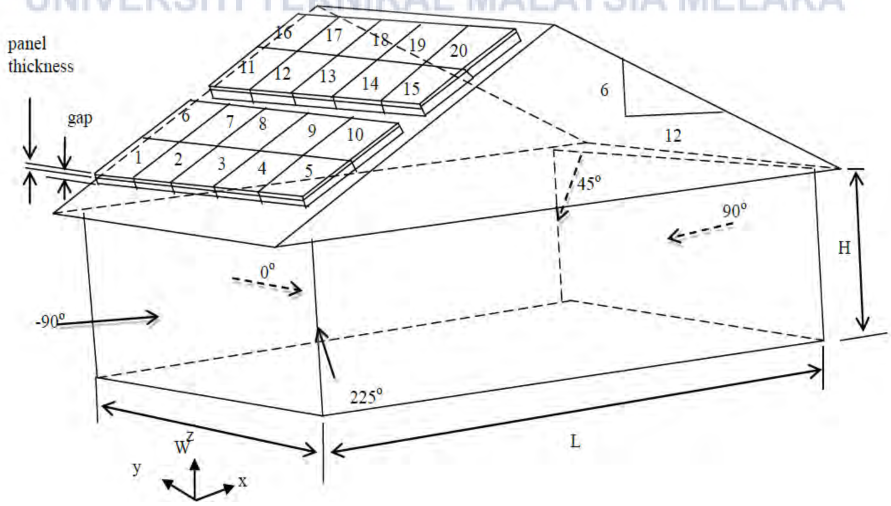


Figure 4.4: Residential structure schematic [26]

4.4.1 Wind Flow Field

The addition of solar panel on the roof can changed the local flow field as shown in Figure 4.5 and Figure 4.6. The flow field was altered due to the propagations of local perturbations. The gap between the panel and the roof influenced the surrounding flow because the surface area interacted with the flow increased. Due to the simulation will have two difference wind direction, the difference in wind flow field is expected.

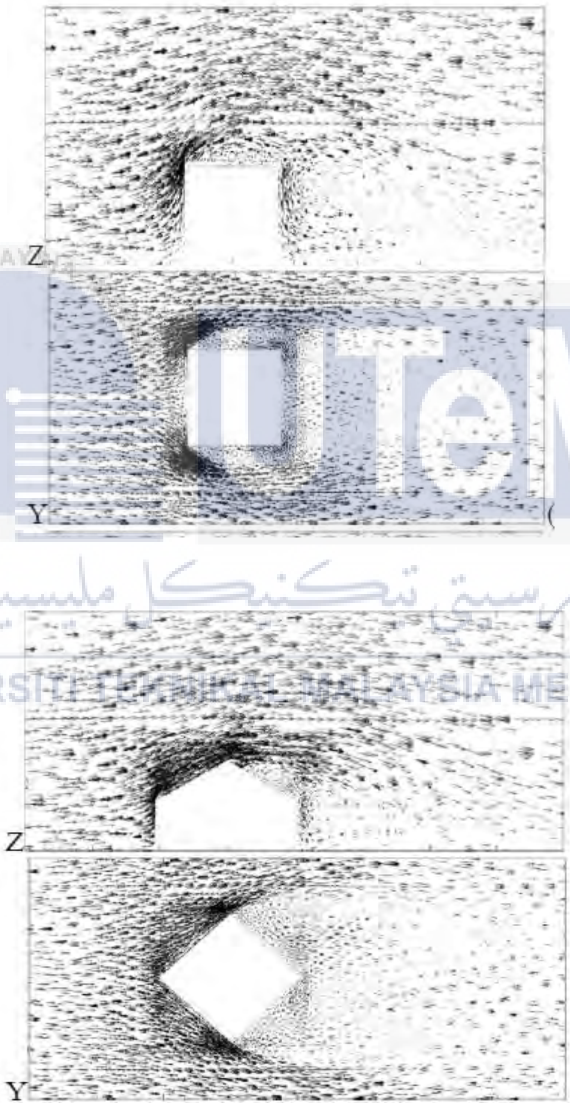


Figure 4.5: Wind flow profile for model without panel at 0° and 45°

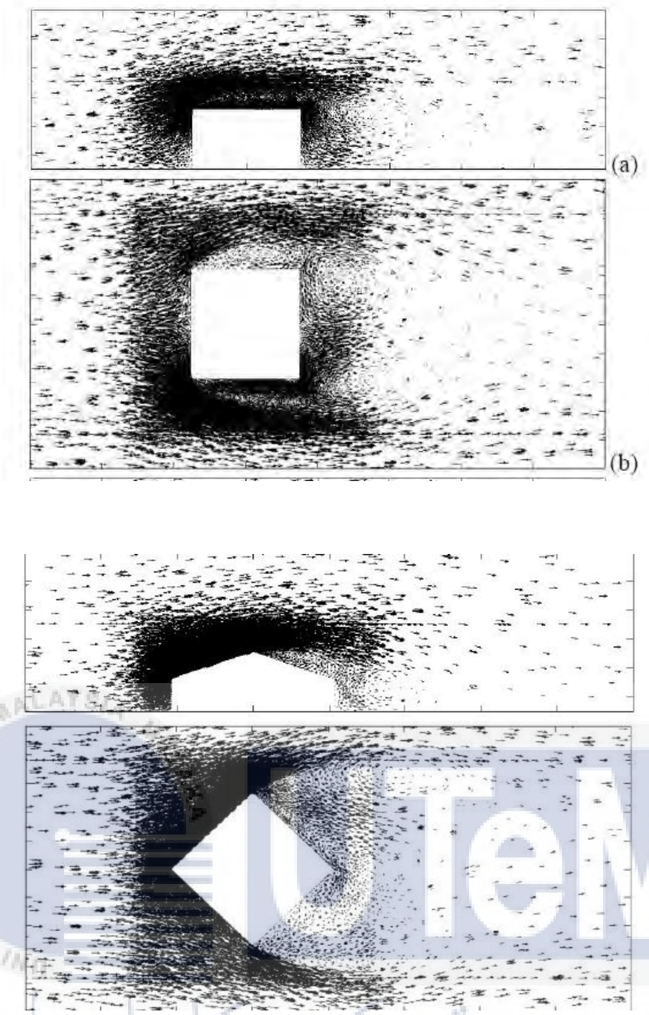


Figure 4.6: Flow field profile for roof with panel with wind angle of 0° and 225°

4.4.2 Pressure contour

Wind direction affects the wind flow and pressure contour. The pressure contour is varied depending on the which part of the roof is hit by the wind first, recirculation, windward and leeward side of the roof.

Figure 4.7 shows the roof pressure contour profile when the wind direction is 90°. The pressure contour was symmetry in the middle while the edge of the roof experienced down lift. The symmetry was due to the wind direction that flow smoothly from the overhang to over the roof. It is shown where the pressure at the middle (ridge) is lower than windward side and leeward side. The roof at the leeward side displayed variable pressure magnitude and range. It can be observed that front roof received experiencing high torsion load. The back roof experiencing less load (negative pressure) because of the sheltering effect from the windward side and also due to the flow separation at the ridge. The back roof experienced up lift while front roof experienced down lift. Hence the contour is expected to be obtained during simulation at wind direction 0°.

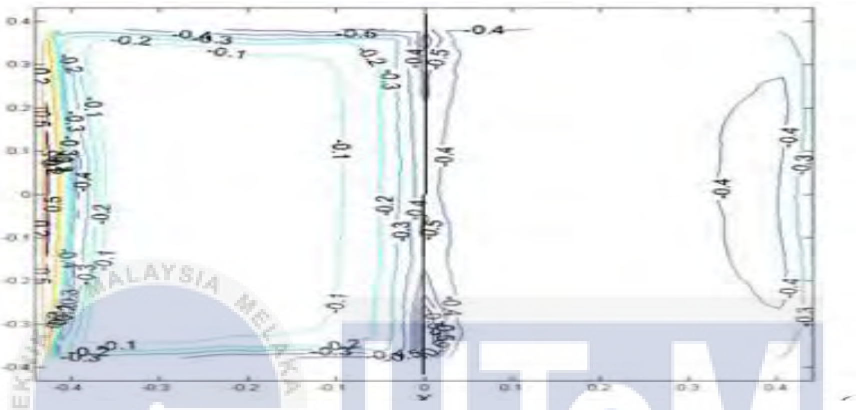


Figure 4.7: Pressure contour of house without panel under 90 ° wind direction

4.4.3 Pressure coefficient Cp

Pressure coefficient, Cp was obtained to observed the value near the surfaces of the panel. The average coefficient Cp for roof without panel and with panel no gap was expected to be slightly difference. This is due to the local field perturbation that changed the flow field. As stated in the numerical simulation, the Cp of roof with panel that has gap was higher because the flow at bottom of the panel translates to pressure equalization and pressure exerted on bottom surface. The pressure at top and bottom of the panels combined to impart net pressure coefficient. In this simulation work, the Cp to be compared are panel with parallel and parallel + 10°. Since tilt angle will affect the force coefficient, the Cp will be different as the Cp when changing to different wind direction.

$$C_p = \frac{P - P_0}{\frac{1}{2}\rho u_0^{\ 2}} \qquad (4.1)$$

According to eq 4.1, pressure coefficient, Cp formula where P is pressure at point of interest, Po is free stream static pressure.ρ is density of air and u_0 is the wind speed. The net pressure coefficient is the difference between pressure coefficient at upper and pressure coefficient at lower Net pressure formula is;

$$Cp_{net}(t) = Cp_{upper}(t) - Cp_{lower}(t). \qquad (4.2)$$

$$C_{pu} = \frac{p_u}{1/2\rho U_H^2}$$

$$C_{pl} = \frac{p_l}{1/2\rho U_H^2} \qquad (4.3)$$

In eq 4.3, where C_{PU} is pressure coefficient upper while C_{PL} is pressure coefficient lower/bottom of the solar panel. U_H is wind speed in m/s. Although the pressure coefficient can be gained through calculation, the pressure coefficient for the simulation is obtained straight from simulation result only.

4.5 Simulation Result

The aim of the section is to simulate the wind load on roof mounted photovoltaic panel through CFD analysis. The simulation was done using commercial Ansys Fluent. Model of house without panel, house with panel angle parallel to rooftop (20°) and +10 to rooftop (30°) are simulated with a constant wind speed of 4.5 m/s. The simulation is done for two wind direction, 0 ° (-X velocity) and 90 ° (-Z velocity) The result is studied then compared to the expected result obtained from previous work. Numerical simulation done by previous researcher [17,26,30.] are used for simulation guidance.

4.5.1 Wind loading on residential house without panel

i) 0° Wind direction

Wind load on house without panel was simulated and analysed. The air inlet was at 0° direction where the rooftop faced the wind directly from the front. The vector field, pressure contour and maximum pressure coefficient are obtained after the iteration of the simulation is complete. The flow field of the wind around the residential house is shown in Figure 4.8.

The wind flow evenly from the inlet collided with the house structure, forcing the wind to flow over the rooftop and around the wall. The collision causing change in flow field as seen below. The collision caused a small recirculation which located at the wall top of the roof overhang, indicated by Figure 4.10. As the wind flow over the rooftop, it flows smoothly due to the 20° slope of the roof. The slope of the roof preventing the flow from separating. The flow only separated as it reaches the ridge (the middle of the rooftop) where portion of the wind descended down the roof.

The velocity field vector shows development of recirculation region at the back of the rooftop and behind of the house near the overhang. It could also be seen the flow interaction and merging among all separated flows at the back of the house shown in Figure 4.9

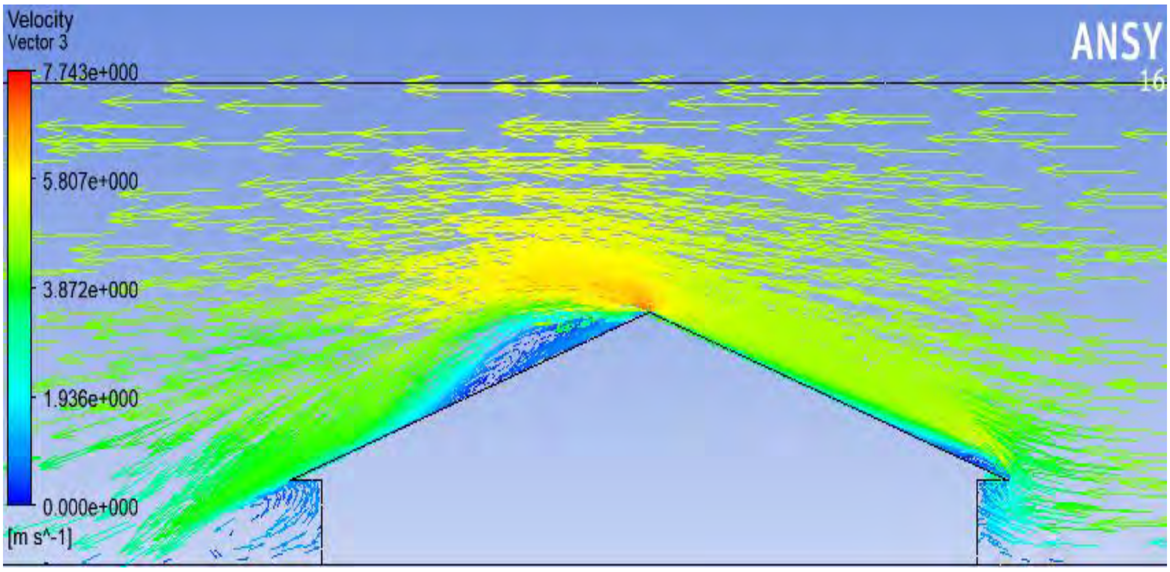


Figure 4.8: The velocity field for house without solar panel under 0 °wind direction from front view

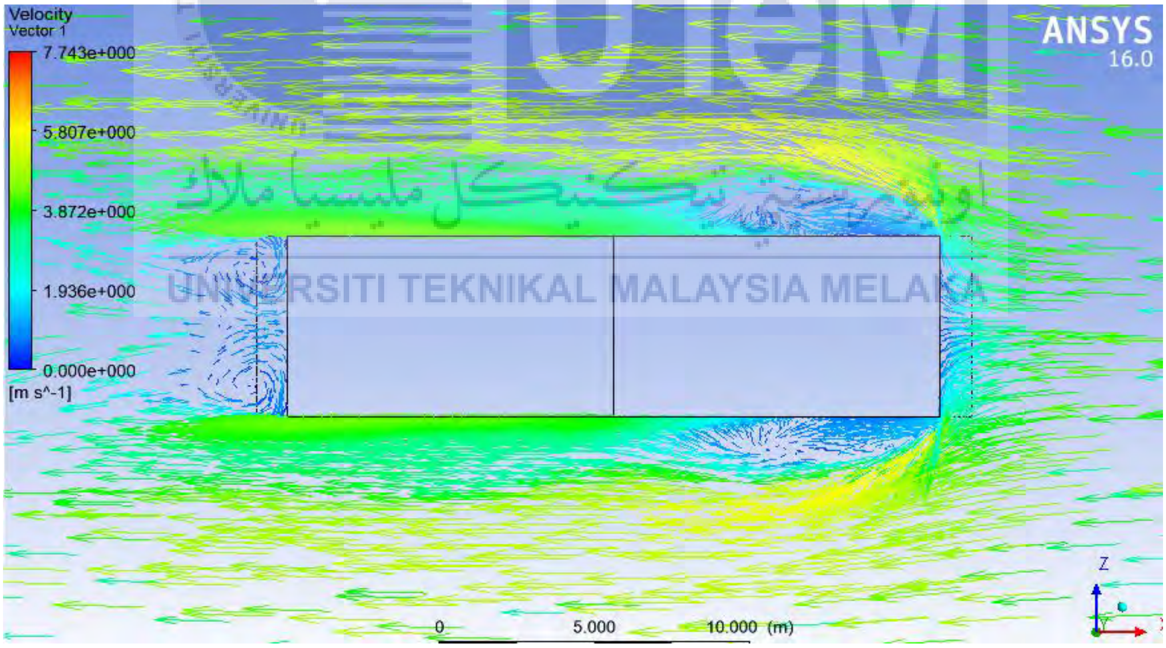
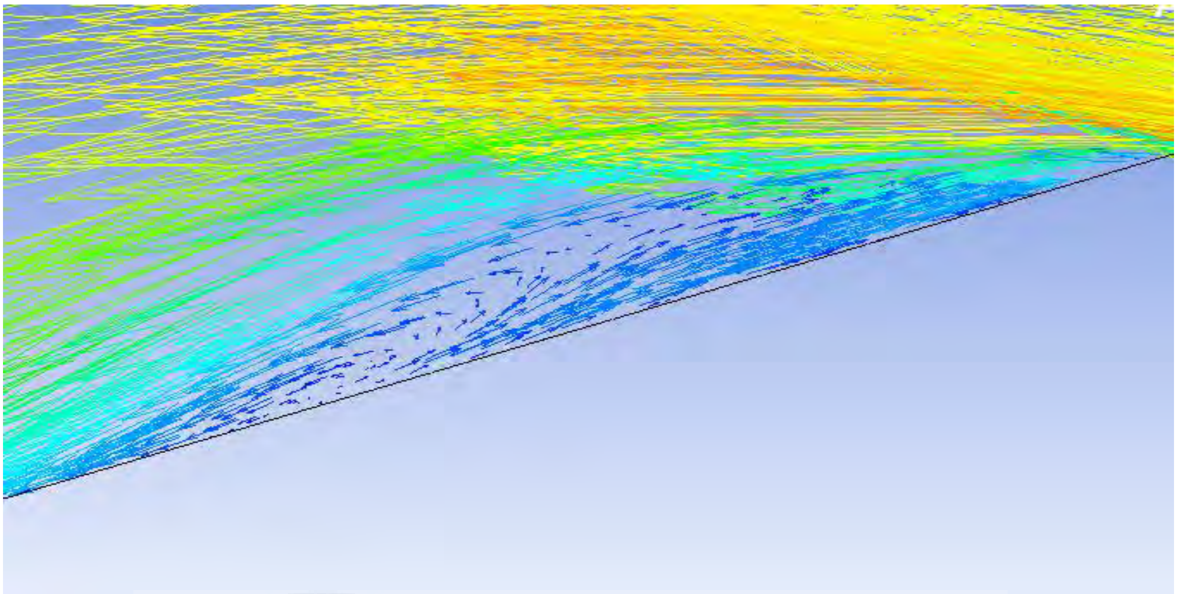


Figure 4.9: The velocity field for house without solar panel under 0 ° wind direction from top view

a)



b)

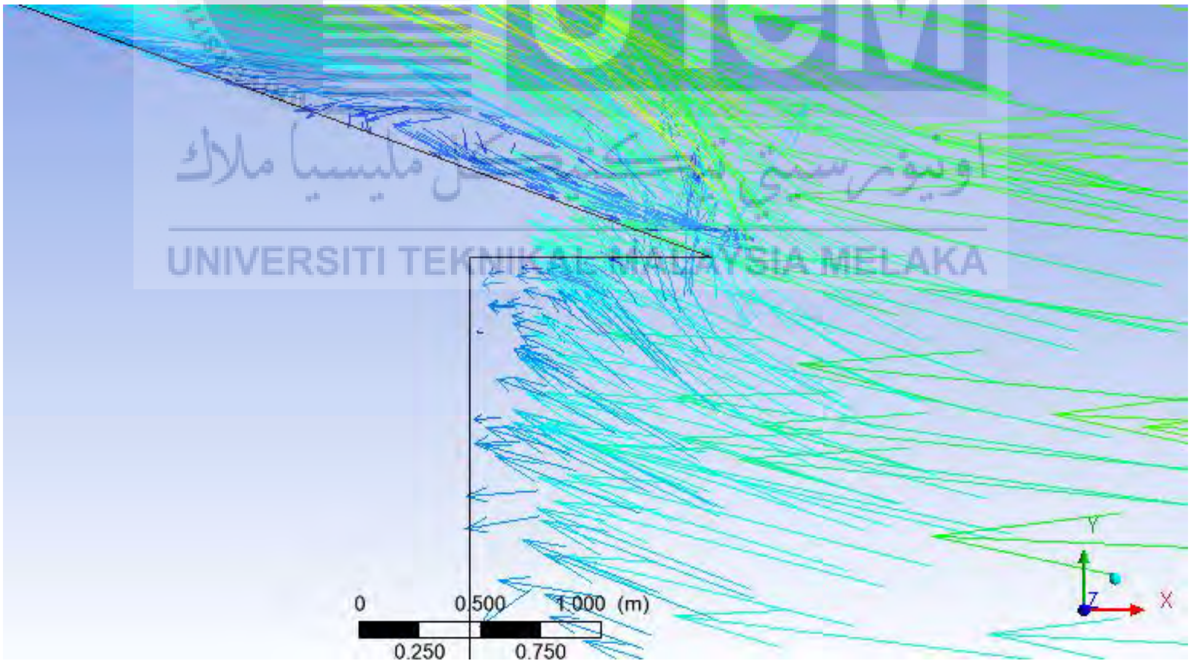
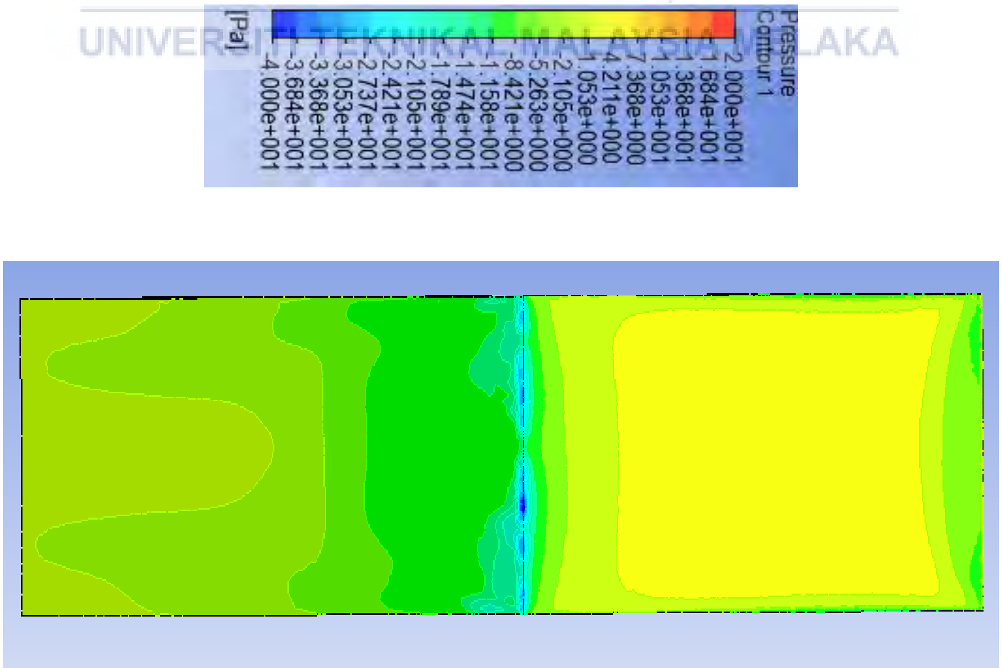


Figure 4.10: Wind flow recirculation a) at the back of the rooftop b) top of the roof overhang

Figure 4.11 shows the roof pressure contour when the wind direction is 0°. The pressure contour was symmetry in the middle with exception the edge of the roof. The symmetry was due to the high velocity flow collides with the middle of the roof. The pressure was positive at the middle but the edge of the front roof was in negative pressure due to recirculation and edge effect. It can be observed that front roof experiencing high torsion load. It is shown where the pressure at the middle (ridge) is lower than windward side and leeward side. This is due to flow separation at the ridge.

The roof at the back displayed variable pressure magnitude and range. The back roof experiencing less load (negative pressure) because of the sheltering effect from the windward side and also due to the flow separation at the ridge shown in Figure 4.12. The back roof experienced up lift while front roof experienced down lift. This is evidence from the wind flow field where the area with negative pressure experienced recirculation. The recirculation created suction force to the rooftop causing the area to experience up lift. The same situation also occurred at the top of the overhang.



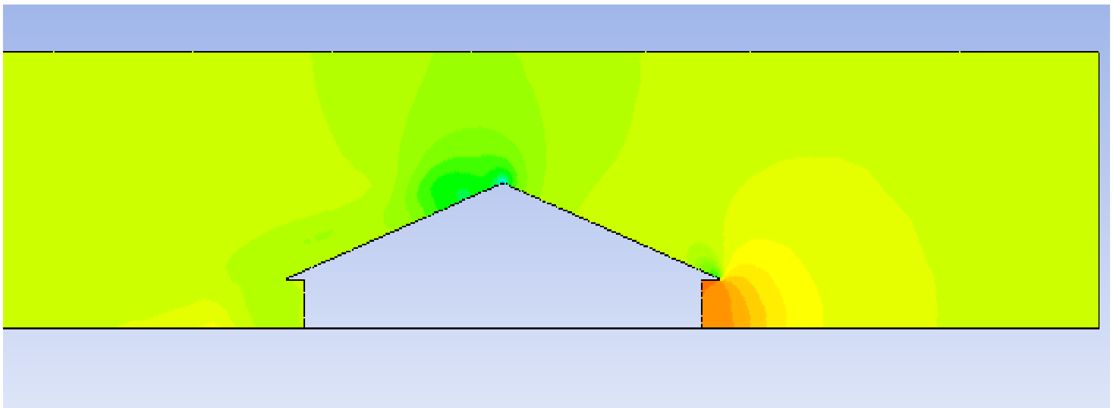
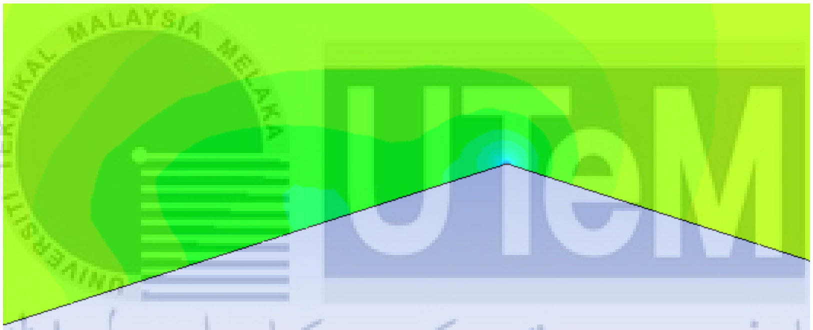


Figure 4.11: Pressure contour of house without panel under 0 ° wind direction. a) at rooftop b) from side view

a)



b)

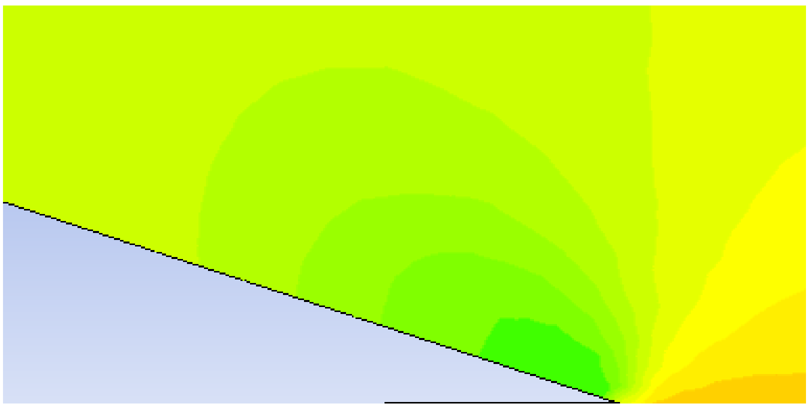


Figure 4.12: Area of the rooftop experienced negative pressure due to recirculation a) back of the rooftop b) top of the overhang

Pressure coefficients, Cp is obtained to further analyze the pressure value and to gain better idea of the effect of panels on the pressure field. Two 2 m line were created at the front roof labelled top and bottom 1.6 m of the line belong to solar panel area while 0.4 m was free stream or non-panel area as shown in Figure 4.13. For house without panel, the Cp value was taken at where the location of the panel was supposed to be for each individual panel.

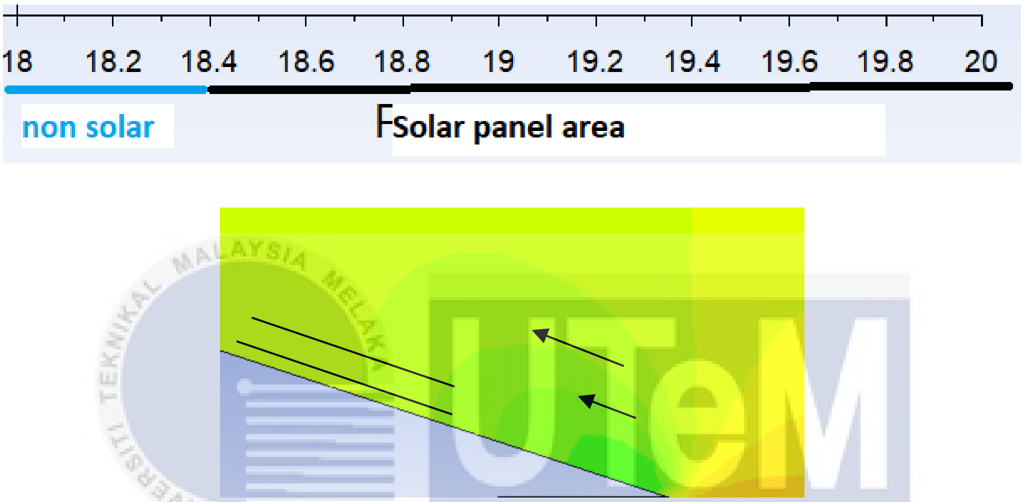
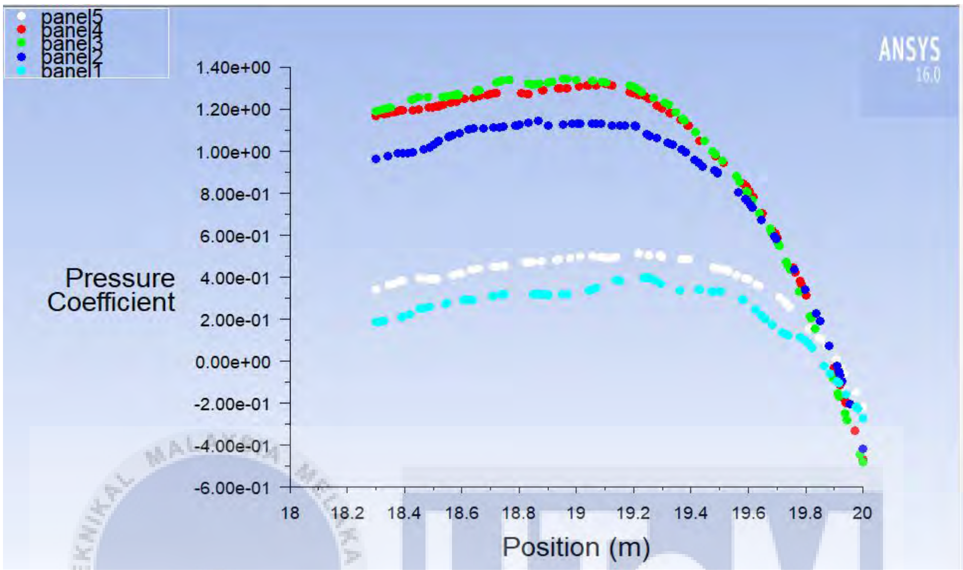


Figure 4.13: The location of the line at solar panel area.

The graph in Figure 4.14 shows the relationship between distance and pressure coefficient. The value of Cp was reflected by flow field and pressure contour at that position. At 20 m roof surfaces are the closest to the air inlet while at 18 m the roof surfaces are the farthest. From velocity flow field and pressure contour, it was established that the front roof experiences recirculation at the overhang top. Hence the negative value of Cp. As flow travels, Cp gradually increased to positive pressure. The Cp at panel number 2,3 and 4 location are almost similar with each other with the exception of panel 1 and 5 location. This is because of edge effect significant where panel 1 and 2 are located at the edge of the array Since there was no presence of solar panel, the value of top and bottom of the solar panel area is almost similar.

a)



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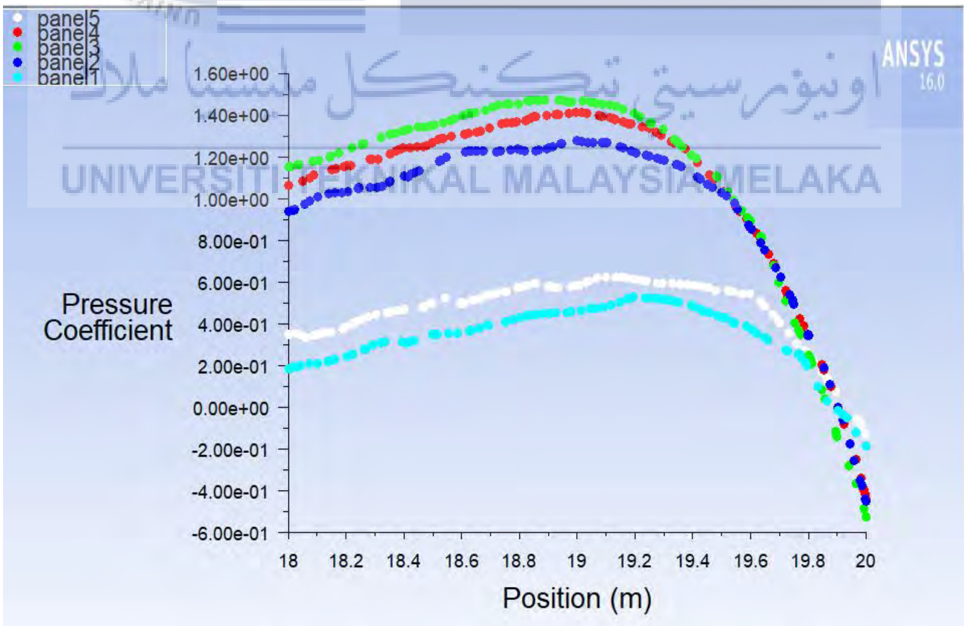


Figure 4.14: Pressure coefficient for roof without solar panel under 0 ° wind direction a) top location of solar panel b) bottom location of solar panel

ii) 90° Wind direction

The wind flow evenly from the inlet collided with the house structure, forcing the wind to flow over the rooftop and around the wall. The collision causing changes in flow field as seen in Figure 4.15 below. The wind did not flow smoothly as the wind direction from 0°. Instead of smooth flow, the wind separated at the edge ridge of the roof. The separation created a recirculation between the separated flow and ridge. A similar pattern can also be seen at the sides of the wall as well. It could also be seen the flow interaction slowly merging among all separated flows at the far back of the house.

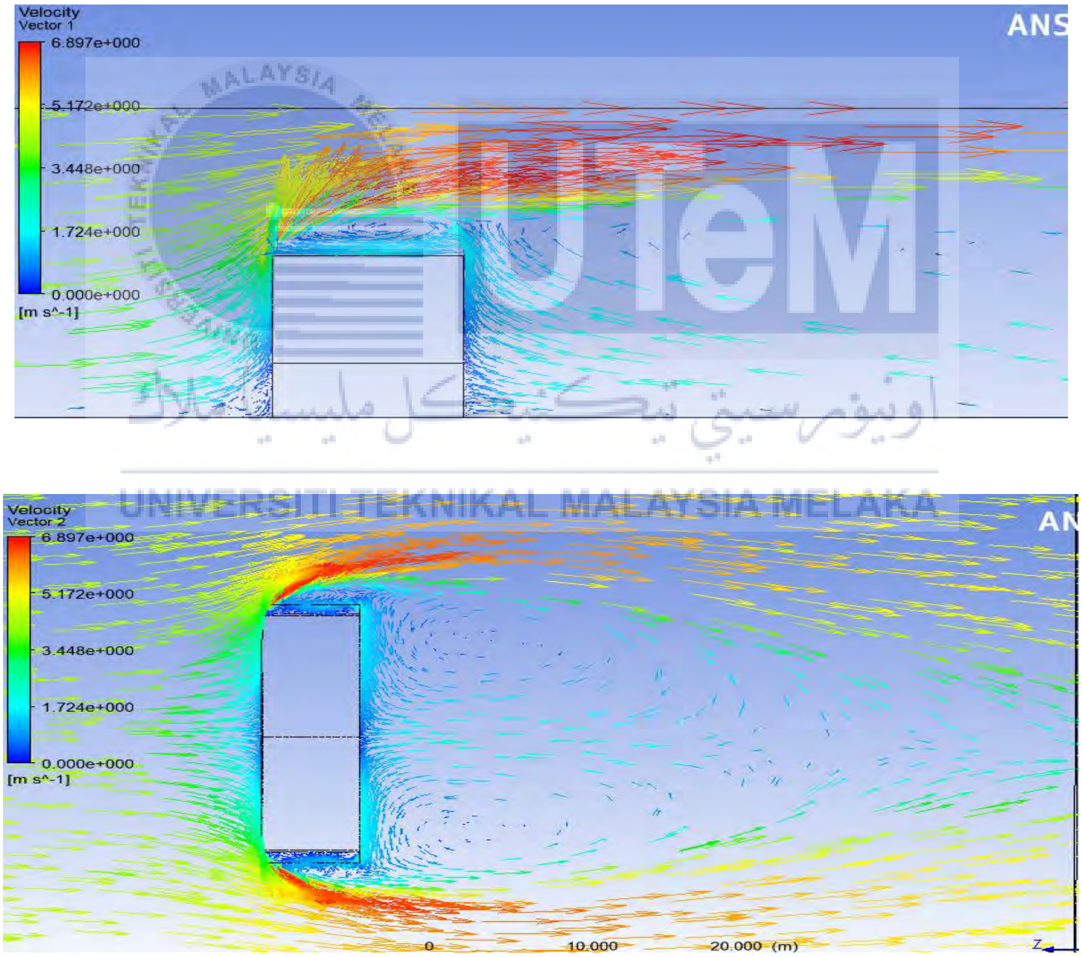
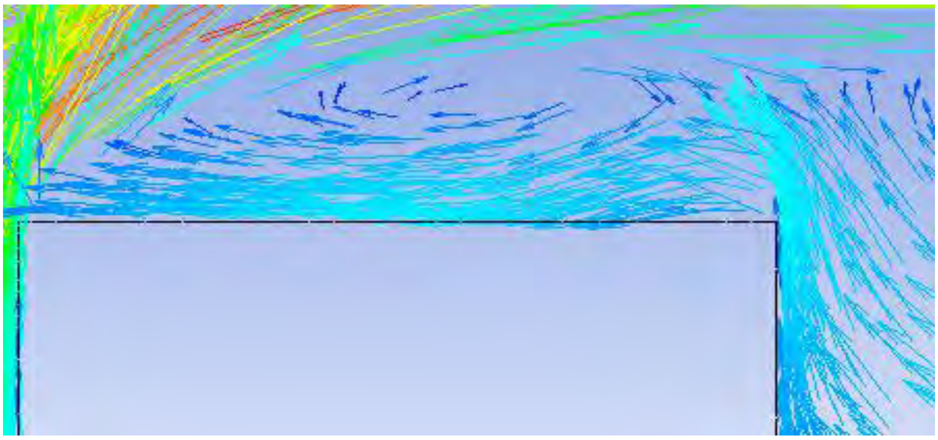


Figure 4.15: The wind flow field for house without solar panel under 90 ° wind direction from front and top plane view

a)



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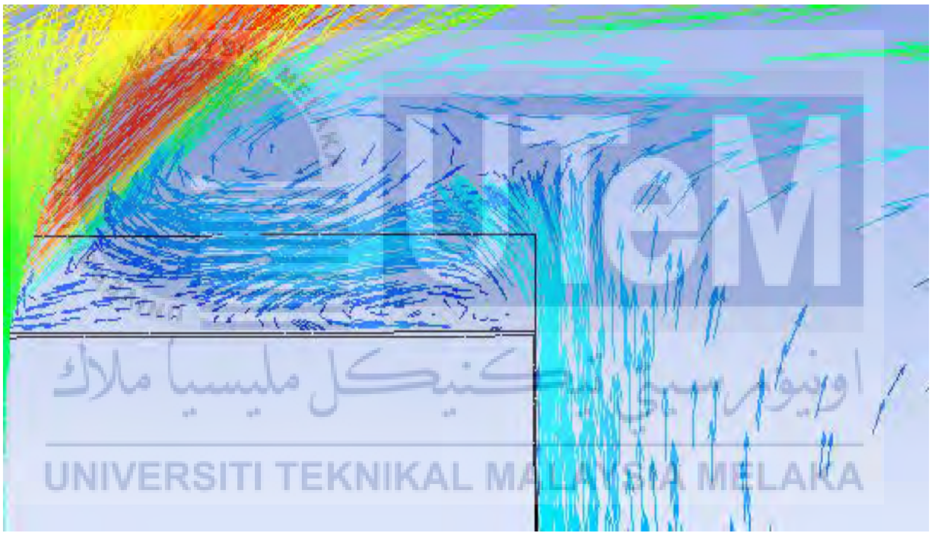
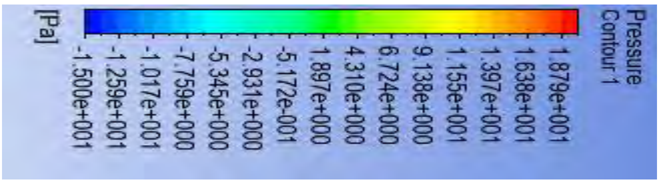
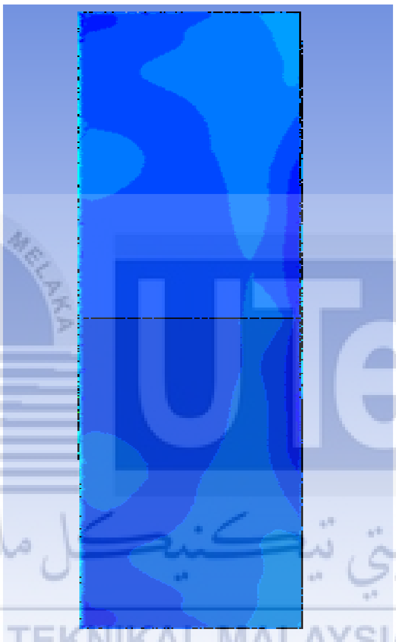


Figure 4.16: Recirculation between a) stream and roof and b) sides of the wall

Figure 4.17 presents the pressure contour of the roof under wind from the side direction. The pressure contour was almost symmetry between front roof and back roof. The whole structure of the rooftop was under negative pressure (lifting up force) because the entire roof is sheltered from the direct wind. The pressure at the lower corner edge and front edge was lower than the other part of the roof suggested high suction at the area. The pressure variation differences between middle, edge corner can create a torsion force. As stated by Akillu.T. Gorges [26] this may become critical as the roof failure depended on the roof structure support system.



a)



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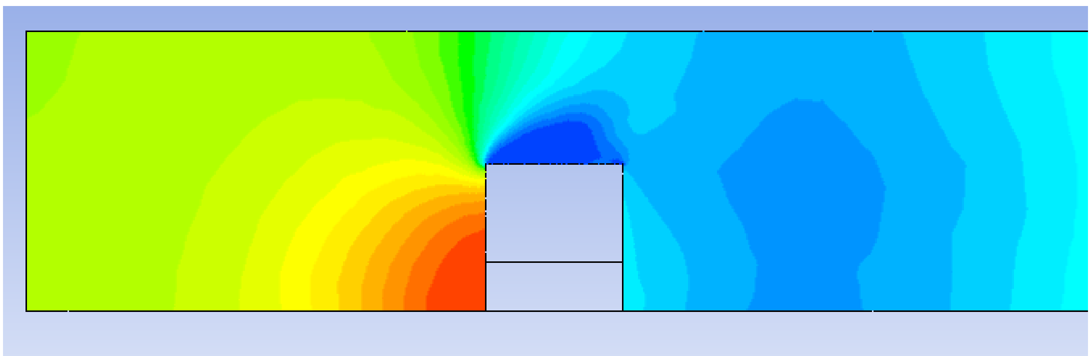
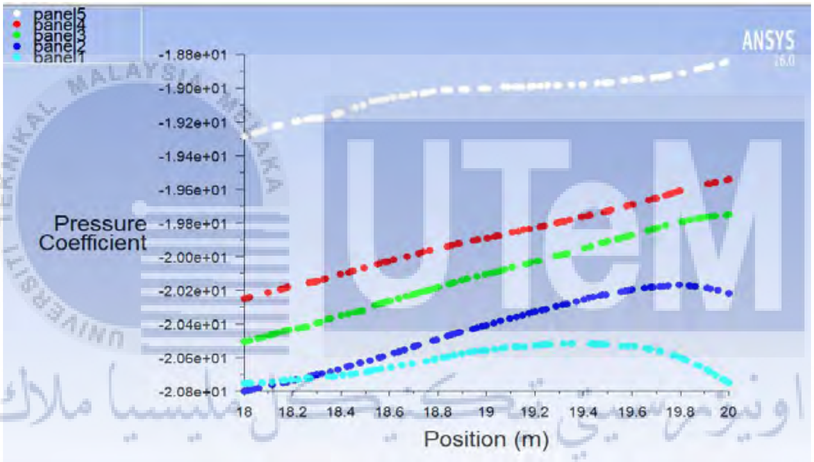


Figure 4.17: Pressure contour house without panel under 90 ° wind direction a) at rooftop b) from front plane view

Based on wind flow field and pressure contour, it was found out that the whole structure of the roof was in negative pressure. There was variance in pressure coefficient Cp as shown in Figure 4.18. The first panel location to experience wind had the highest negative pressure. The second highest negative pressure occurred at panel 2 location followed by panel 3 till panel 5. The values were affected by the wind direction 90° as the wind was now facing the sides of the panel. As the wind travel, the pressure gradually changes to positive pressure. Panel 1 location was the closest from air inlet while panel 5 location was the farthest from air inlet. Hence the difference in Cp value.

a)



b)

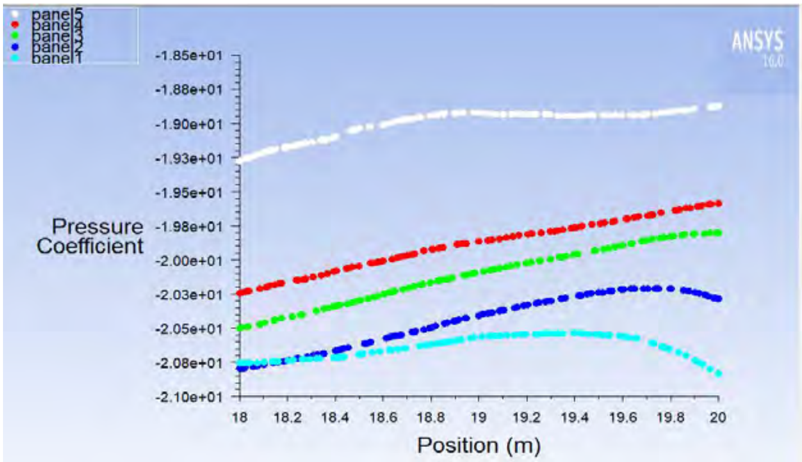


Figure 4.18: Pressure coefficient for roof without solar panel under 90 ° wind direction a) top location of solar panel b) bottom location of solar panel

4.5.2 Wind loading on residential house with panel

For the house with panel, there are two simulated model, which are the house with panel angle parallel to the roof pitch (20 °) and house with panel angle + 10 ° (30 °). Both models are tested with same constant wind speed 4.5 m/s at 0 ° wind direction (-X direction) and 90 ° wind direction (-Z direction). 5 panel with specified dimensions are placed, making it into an array of solar panel. The boundary condition was the same as model without panel. The results of the simulation are discussed.

4.5.2.1 Panel tilt angle parallel to roof

i) 0° Wind direction

The introduction of solar panel to the house structure has changed the wind flow field. The presence of solar panel slightly changed the flow field compared with the smooth wind flow of the house without panel. The gap between panel and roof influenced the flow surrounding the rooftop area. Wind was forced through the gap interacting with the surface area of the panel and generating upward flows beneath it. Figure 4.19 and 4.20 show that the wind flow collided with the edge of the solar panel first before it was separated over and under the solar panel before merging

The perturbation of the solar panel further impacted the flow above the ridge of the roof as seen in Figure 4.21. When the wind directly impinged on the sloped roof, it has significant inertia. The perturbation from the solar panel generated local turbulence. When the wind reached and separated at the ridge, the turbulence from solar panel cascaded with the flow, thus affecting the enveloping stream. Hence the reason recirculation region at the leeward side was occurred higher near the ridge compared with previous result from house without panel

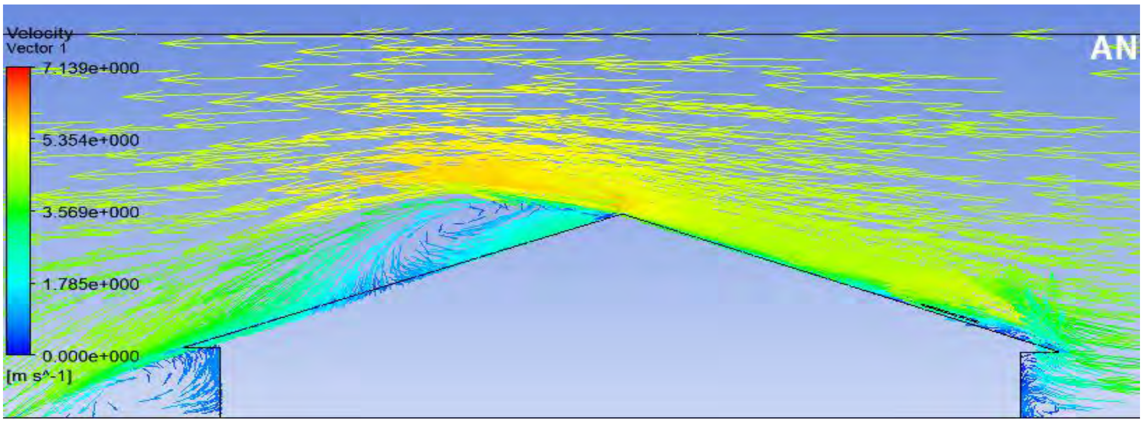


Figure 4.19: The wind flow field for house with solar panel tilt angle parallel at 0 ° wind direction from side plane view

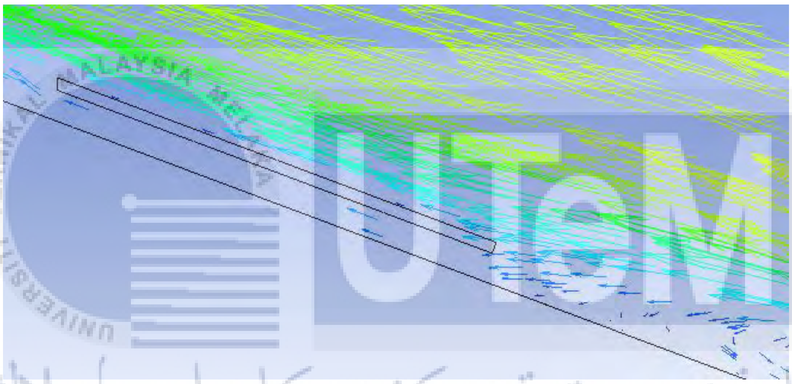


Figure 4.20: Wind flow beneath the solar panel gap

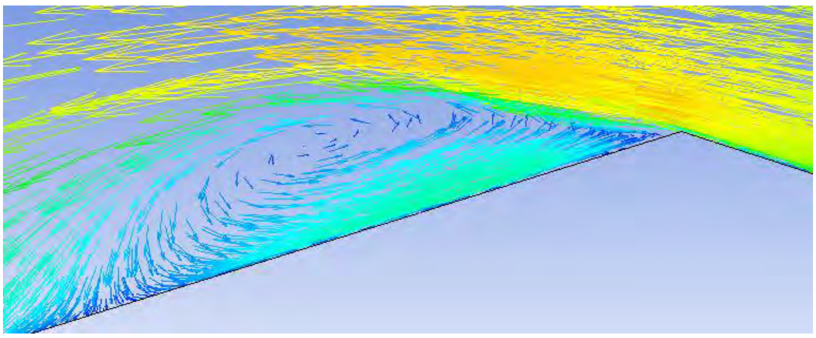
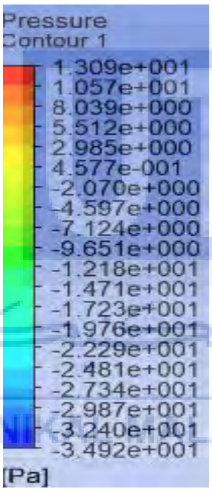


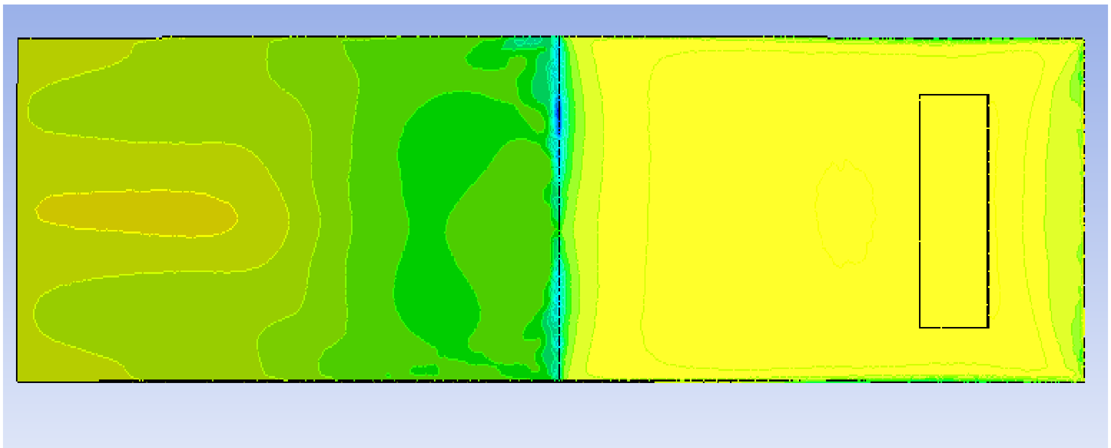
Figure 4.21: Recirculation occurred higher at the back of the roof.

Figure 4.22 shows the roof pressure contour of roof with solar panel. The pressure contour was almost identical to the roof without solar panel. The turbulence caused by the solar panel that affecting the stream slightly changed the contour especially at the back of the roof (leeward side).

The front roof at windward side experienced positive pressure (down lift) while the roof at the back displayed variable pressure magnitude and range. The back roof experienced negative pressure (down-lift) because of the sheltering effect from the windward side and also due to the flow separation at the ridge. Recirculation further affecting the negative pressure value due to the suction force.



a)



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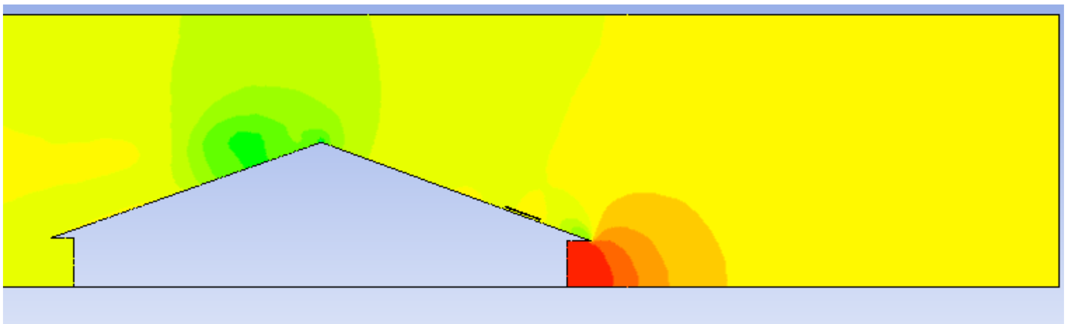


Figure 4.22: Pressure contour of house with panel tilt angle parallel under 0° wind direction. a) at rooftop b) at side view

It can be observed the presence of the solar panel affecting the pressure contour as shown in Figure 4.23. The wind collides with the bottom of the solar panel first, causing the flow to separate over and below the panel. The area collided experiences higher pressure than the top area of the panel. The edge effect significant caused negative pressure along the edge of the solar as observed in Figure 4.24. Due to the gap between panel and roof is parallel, the wind flows smoothly underneath the solar panel. The pressure at bottom surface of the panel was almost symmetry with the pressure at top surface of the panel. When there was a gap between the panels and roof, this greatly reduced the difference in pressure between top and bottom surfaces and this results in much lower aerodynamics load. While the flow at top was different with the flow at bottom but the difference is minimal. [26]

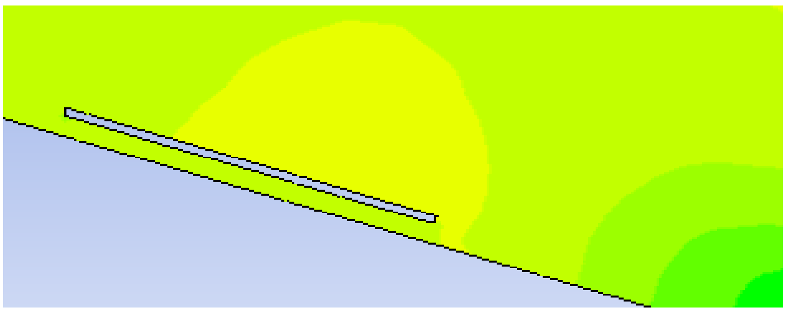
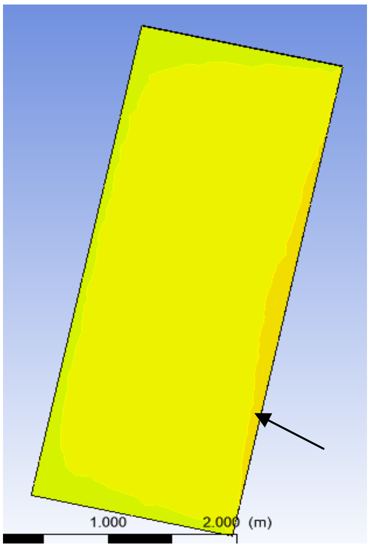


Figure 4.23: Pressure contour near the solar panel at side view



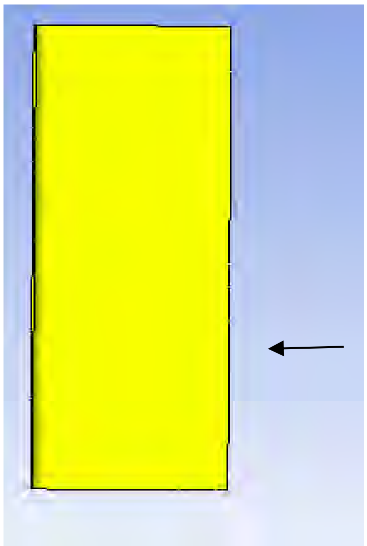


Figure 4.24: Pressure contour at top and bottom surface the solar panel (Arrow is wind direction)

From the pressure coefficient Cp graph below (Figure 4.25), it can be seen the changed in value when comparing it with the graph of Cp obtained without panel. The effect of solar panel on roof top was more noticeable. Cp value started in positive and gradually decreased to negative. The same pattern happened at the bottom of the solar panel. This is because the flow collided with the feet of the solar panel with high pressure. It was symmetry because of the wind direction.

As the wind travel on the panel surfaces, the velocity and pressure decreased. The flow at top and bottom panel merged at the head of the solar panel and beyond non panel area where it can be seen Cp gradually increased.

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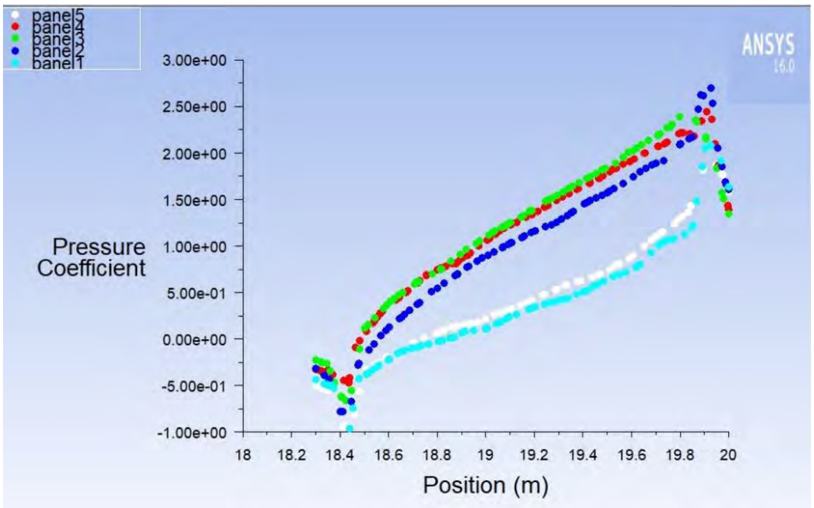
a)



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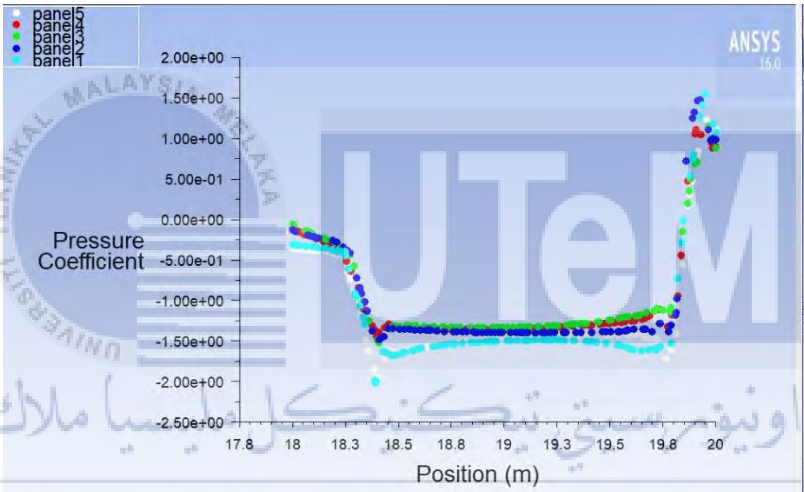


Figure 4.25: Pressure coefficient for roof with solar panel under 0 ° wind direction a) top surfaces of solar panel b) bottom surface the solar panel

ii) 90° Wind direction

The incoming wind flow collided with the wall of the house causing it to separate, forcing it to separate around the house and over the roof. Due to absence of a wall and flows high inertia, the flow separated at the edge of the roof, creating recirculation zone above the roof (Figure 4.26). The presence of solar panel further affected the flow separation and recirculation, changing the flow field. This is because the increment in surface area interacting with the flow.

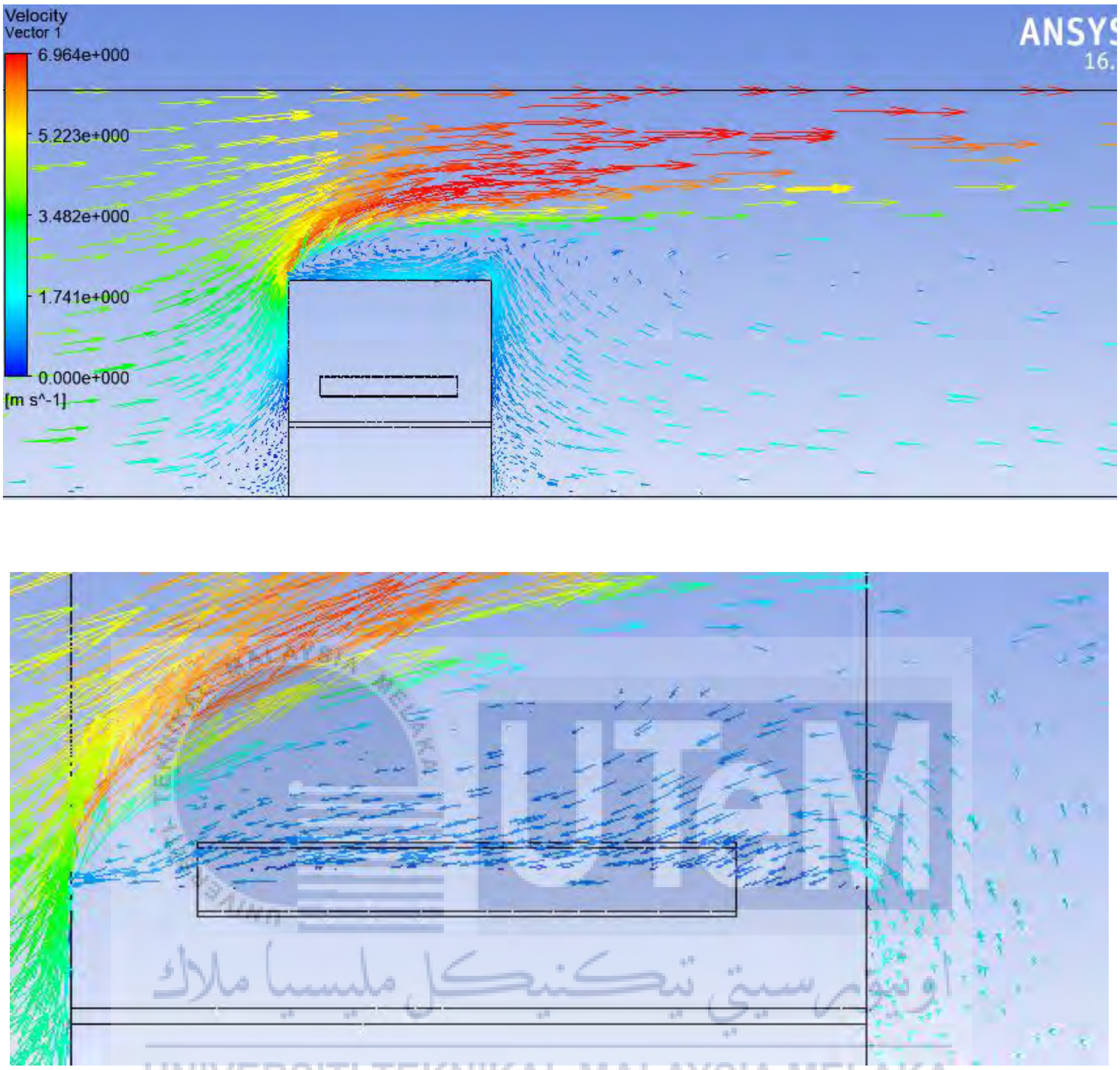
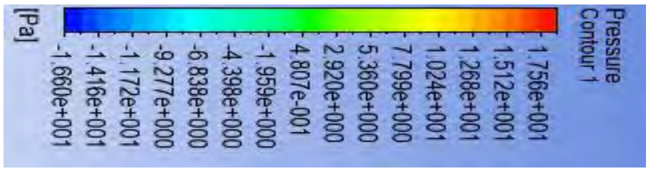
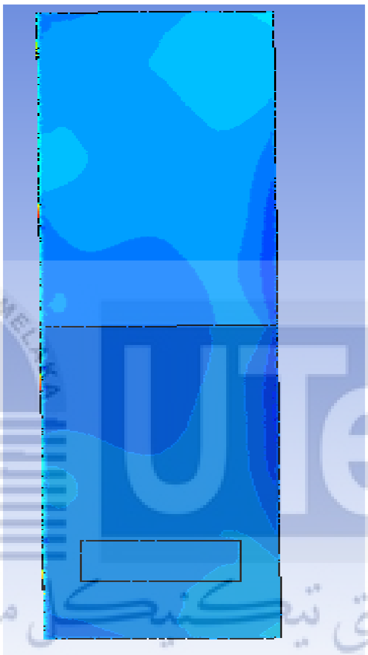


Figure 4.26: The wind flow field house with panel at wind direction 90° a) at ridge b) at the panel

Figure 4.27 shows the pressure contour of the rooftop with solar panel in 90° direction. The contour is almost symmetry with only slight changes compared to the rooftop without panel. The corner edge of the experienced higher negative pressure. The panel closest to the inlet experience highest negative force than the panel farthest from the inlet because the separated flow at the edge above the panel had highest velocity and inertia. This created higher suction acting to lift the roof and panel off the house. The pressure at bottom of the panel was symmetry with the pressure of the roof on that particular area due to pressure equalization as seen in Figure 4.27 and 4.28.



a)



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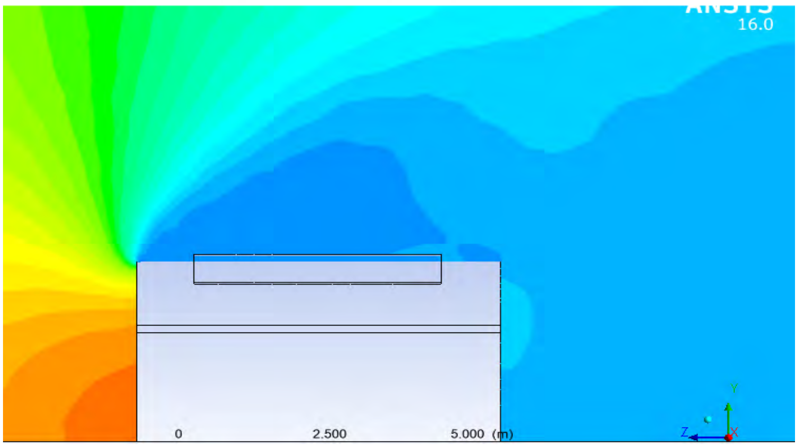


Figure 4.27: Pressure contour of house with panel tilt angle parallel under 90 ° wind direction a) rooftop b) front plane

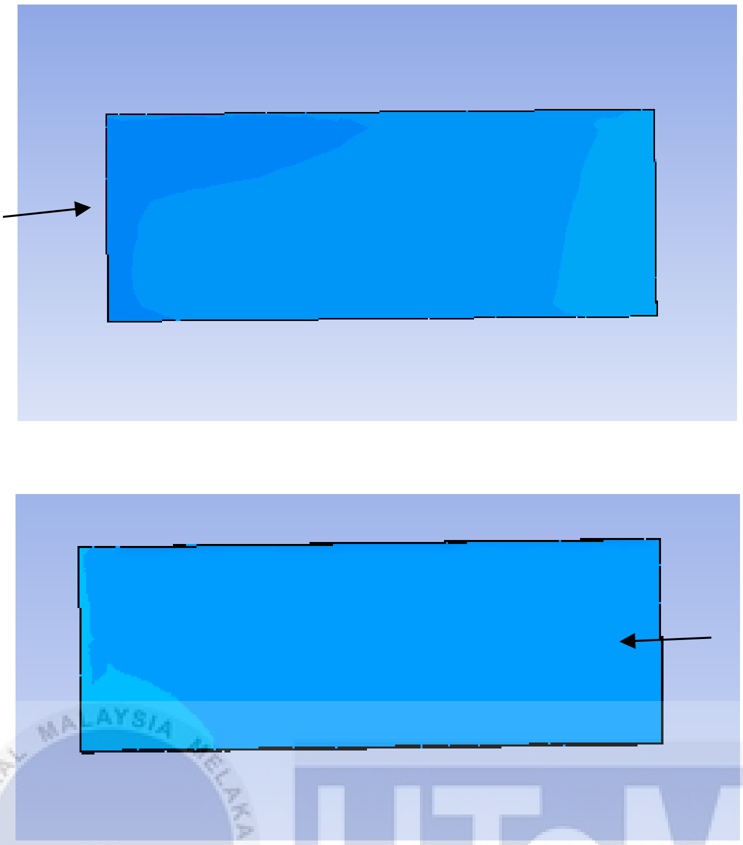
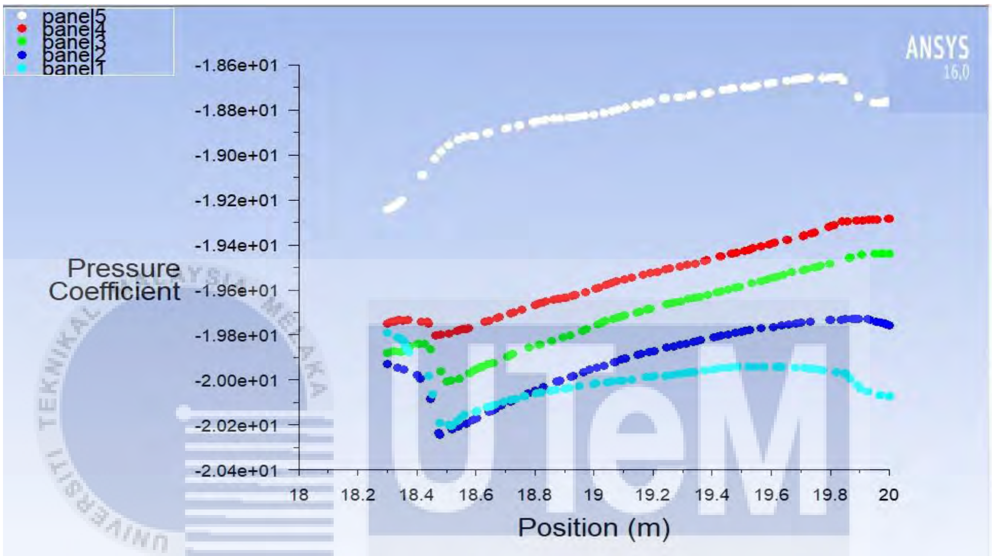


Figure 4.28: Pressure contour at top and bottom surface of the solar panel under 90° wind direction (Arrow is wind direction)

Introduction of solar panel when wind direction is 90° slightly changed the Cp value when comparing it house without panel as shown in Figure 4.29. Since panel 1 is exposed to the flow first and edge effect, its Cp value is the highest negative value. It can be observed the Cp from 20 m to 18.4 m is gradually decreased. The head of the solar panel (located at 18.4 m) received higher negative pressure than feet of the solar panel at 20 m. The sudden increment of Cp value at 18.2 m (non-solar panel area) shows the effect of solar panel presence to the surface above roof top.

Cp value at the bottom of solar panel was less than the top of solar panel. The negative value also lower than bottom Cp without solar panel. The reason was because of the flow sheltering by the top of the panel. This shows that panel top panel surfaces experiences most of the high suction force that lifting the panel away from the roof.

a)



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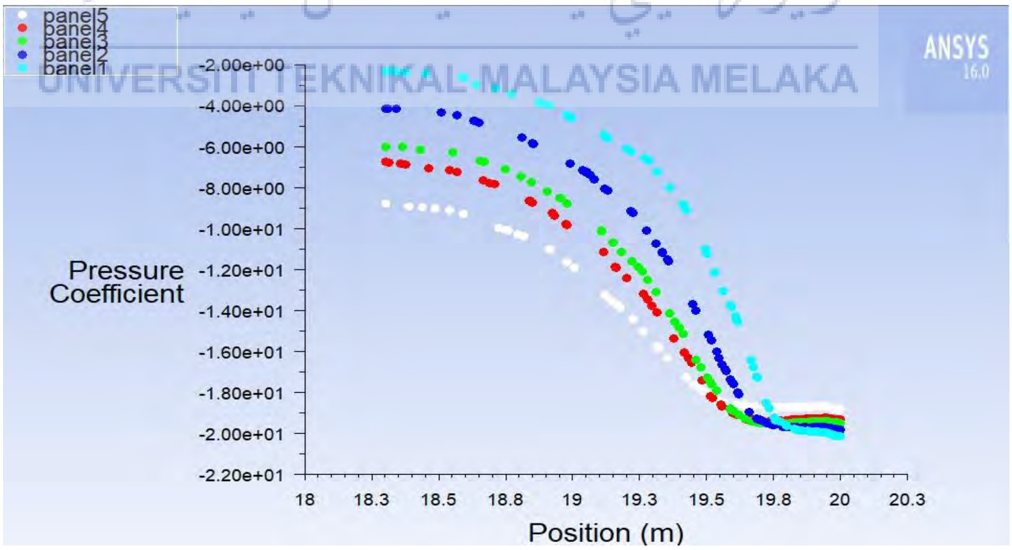


Figure 4.29: Pressure coefficient for roof with solar panel under 90° wind direction a) top surfaces of solar panel b) bottom surface the solar panel

4.5.2.2 Panel tilt angle +10 ° to roof

i) 0° Wind direction

The wind flow field is almost similar to the rooftop with panel tilt angle parallel to the roof. Recirculation still occurred at the top of the overhang and the back-rooftop area near the ridge. However, the introduction of changes in tilt angle of the solar panel caused drastic change in enveloping stream. When the tilt angle of the solar panel has increased, it acted as a slope other than the slope of the roof as shown in Figure 4.31. The wind flow collided with the edge of the solar panel first before it was separated over and under the solar panel. Wind was forced through the gap, interacting with the surface area of the panel and generating flows beneath it.

Over the solar panel top surfaces, the wind flows at the solar panel slope with significant velocity and inertia. The flow then separated at the end edge of the solar panel causing recirculation underneath the area of the panel. The flow then feeds on the recirculation after it separated until it reached the ridge of the rooftop where the flow separated again as seen in Figure 4.30.

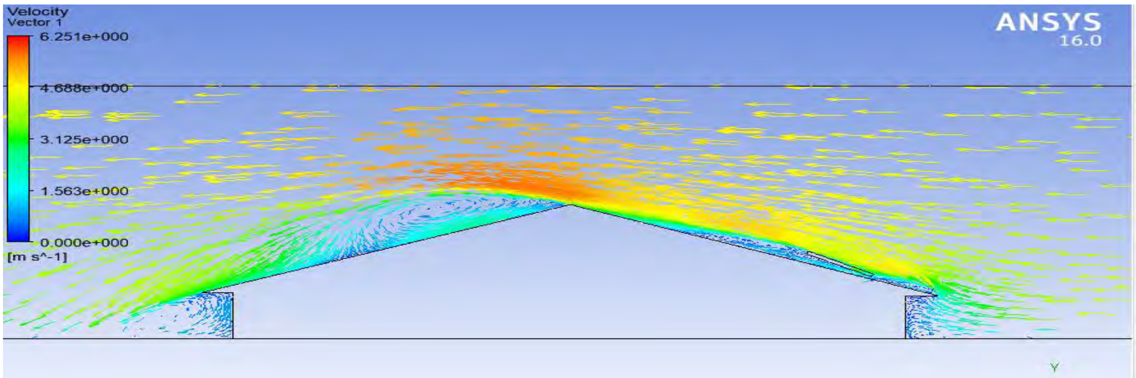


Figure 4.30: The wind flow field for house with solar panel tilt angle +10 ° under 0° wind direction

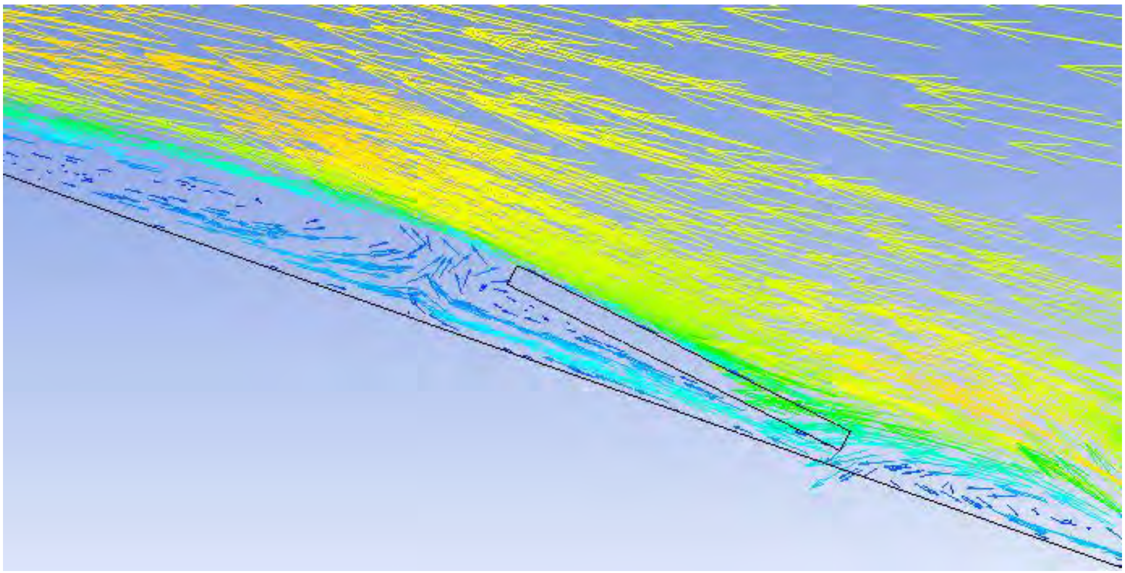


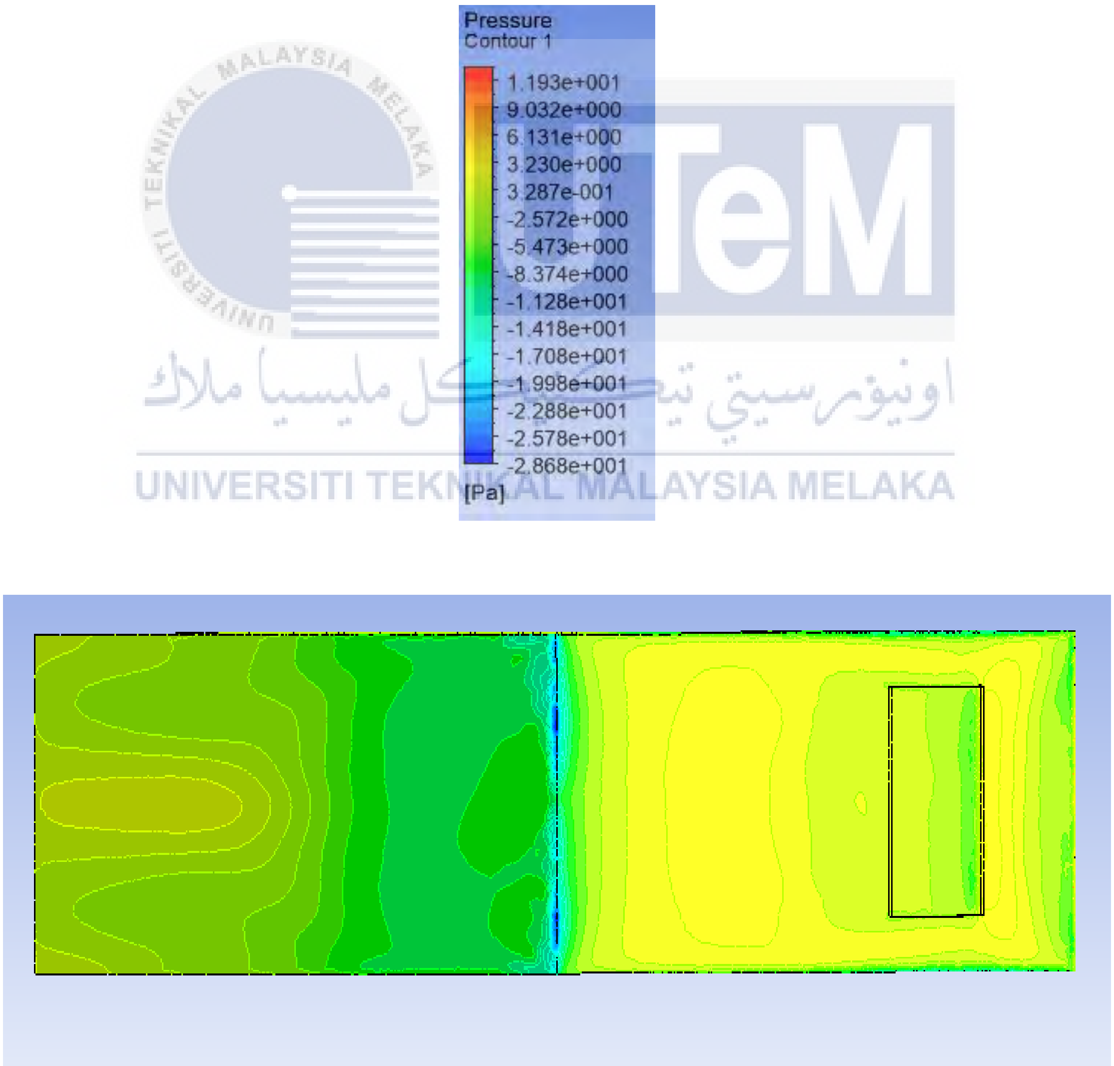
Figure 4.31: Wind flow field at solar panel tilt angle+10 °

Figure 4.32 shows the pressure contour of the rooftop with the tilt angle of the solar panel is +10° to the roof angle. The edge of the roof experienced negative pressure due to the flow separation at the overhang that created recirculation and edge effect. The pressure at the ridge region is lower than the front and back because of the flow separation the leeward side of the roof experiences up lift due to large swirling region as shown in Figure 4.34. The recirculation created suction force to the rooftop causing the area to experience up lift. This is almost similar to pressure contour of roof with parallel tilt angle solar panel.

The changed in tilt angle of solar panel changed the flow field at the area around the panel as shown in Figure 4.33. Middle area of the front roof is no longer in positive pressure value. The contour at the middle windward was not symmetry due to the presence of the solar panel. The lower edge of the solar panel experiences positive pressure due to the collision of the separated wind from the overhang that has high velocity and inertia.

The increase in tilt angle make the panel steeper for the wind flow and resulted in variation of pressure magnitude and range at the top of the panel (Figure 4.35). Also, the bottom of the panel experiences negative pressure (down lift). Recirculation occurs at this area create suction pressure hence the negative value This means that the panel is experiencing lifting, pulling them away from the house structure.

In this case, the gap between panel and roof has increases. The drastic differences brought on by gap beneath the panel can be attributed to pressure equalization. Panel with gap experiences greater forces than no gap. Panel being slightly elevated from the roof and being exposed to higher aerodynamics forces from faster, more energetic, flow away from the roof. Pressure equalization cannot overcome the increased speed of the flow on top of the panel



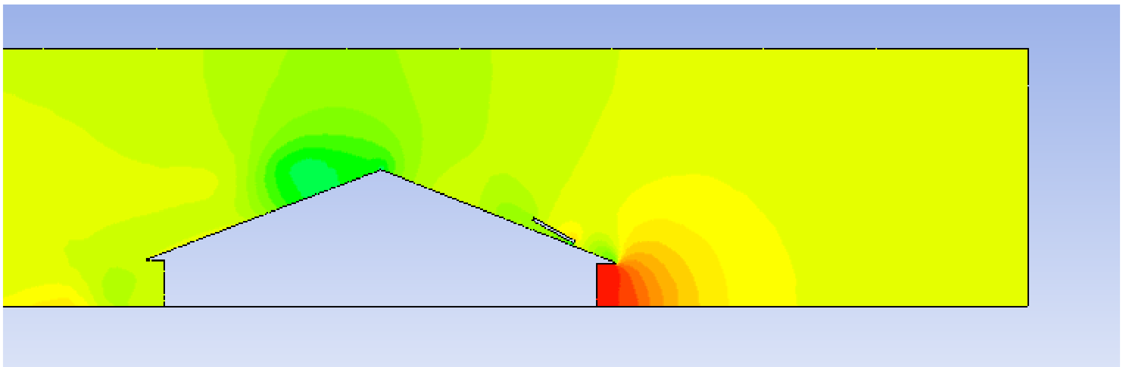


Figure 4.32: Pressure contour of house with panel tilt angle +10 ° under 0 ° wind direction a) rooftop b) side plane view

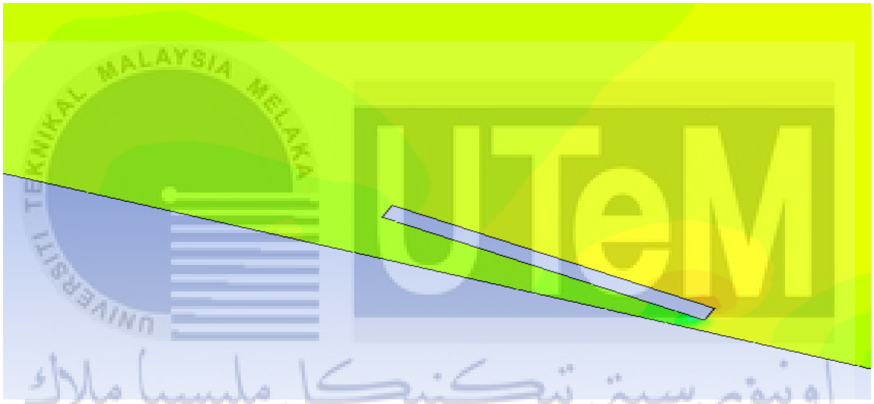


Figure 4.33: Pressure contour at solar panel

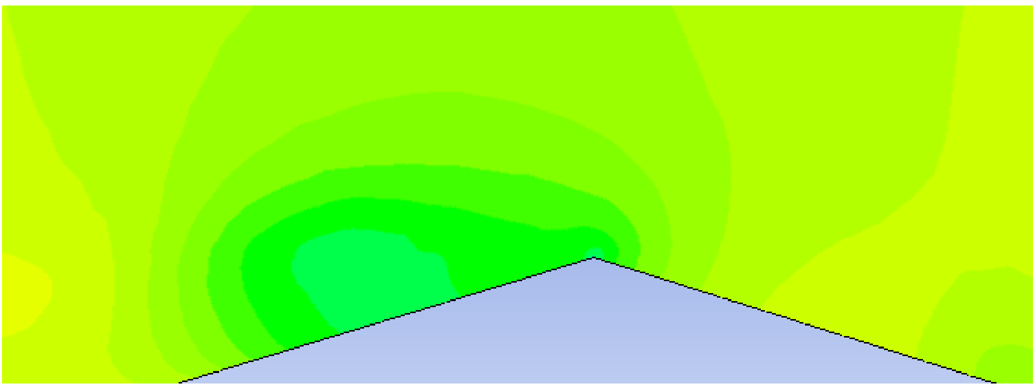


Figure 4.34: Pressure contour at the ridge affected by the increased of solar tilt angle

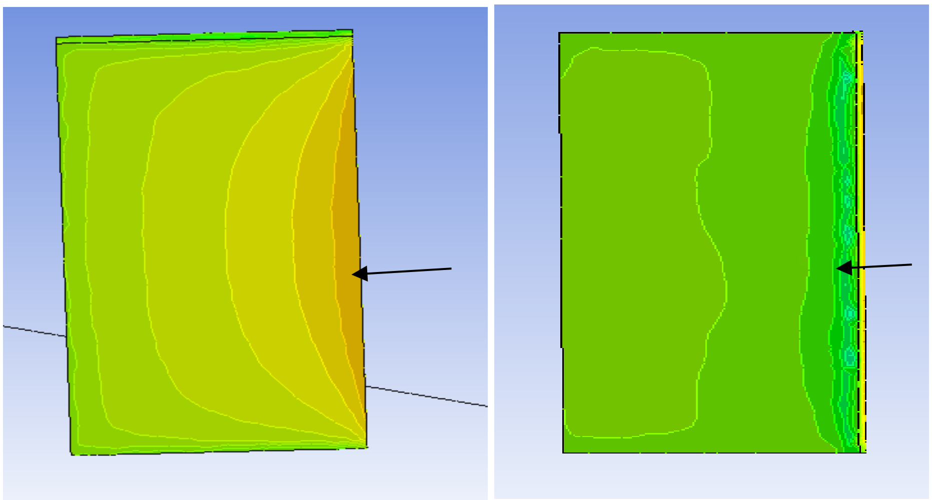


Figure 4.35: Pressure contour at top and bottom surface the solar panel house with panel tilt angle+10 (0 ° wind direction)

To further analyze the effect of tilt angle on roof mounted solar panel, pressure coefficients were compared with roof mounted solar panel parallel tilt angle. Panel tilt angle difference was only 10° in this simulation. From top Cp value, it can be seen the value was much higher. The highest positive value was at the feet of solar panel. The Cp value distribution along the line was more symmetry and the values were not much far apart from each panel. The graph descended as the flow approached the head of the solar panel until it reached negative Cp value at non panel area. These values also were higher than parallel tilt angle. This is contributed by the flow separation and recirculation forming at the head of the solar panel. (Figure 4.33)

As for bottom Cp value as seen in Figure 4.36, when tilt angle is parallel it was negatively equal and symmetry along the line with a slight increment after the flow passed the non-solar area. However due to an increase of tilt angle, the value is no longer equal. The change in tilt angle had increased the area underneath the solar panels.

Thus, expanded the area the flow can interact with. The feet of the solar panel experienced higher negative Cp value as shown in Figure 4.37. It was then gradually increased. However, by the time the flow reached the non-panel area, the bottom Cp value was still in negative value. This shows that changing tilt angle increased the negative pressure acting on the bottom surfaces of solar panels which mean higher suction force pulling the panels away from the roof

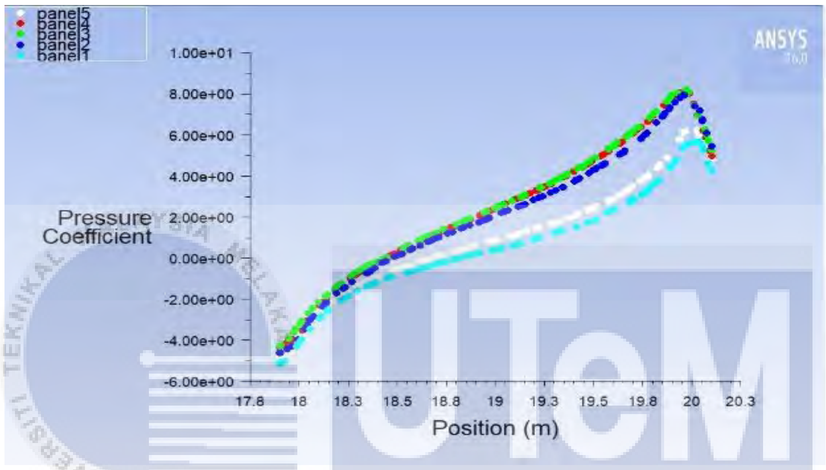


Figure 4.36: Pressure coefficient Cp at top of solar panel tilt angle + 10 ° under 0° wind direction

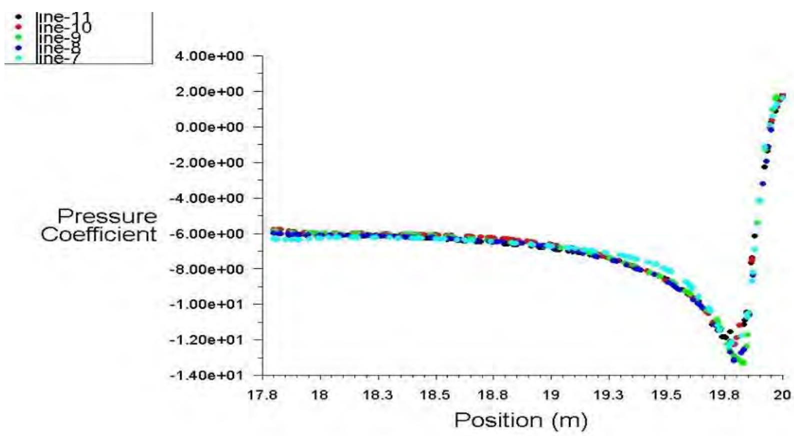
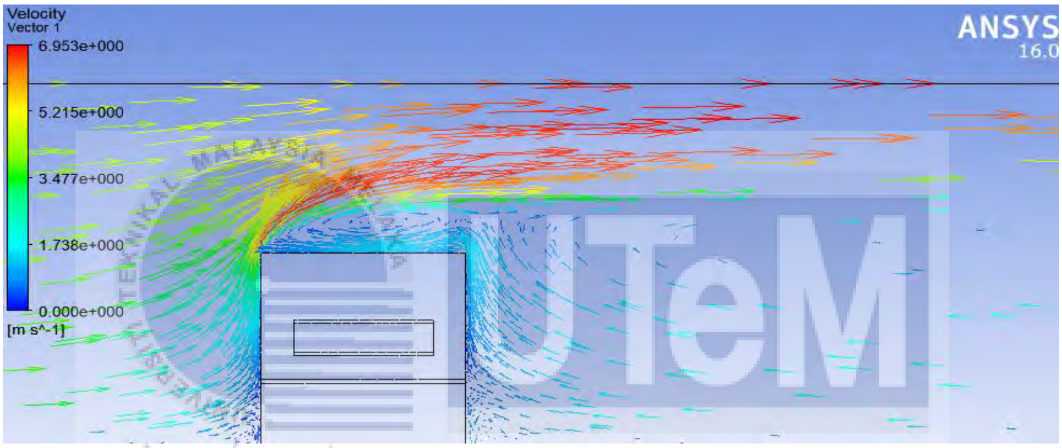


Figure 4.37: Pressure coefficient Cp at bottom of solar panel tilt angle + 10 ° under 0° wind direction

ii) 90° Wind direction

Due to absence of a wall and flows high inertia, the flow separated at the edge of the roof, creating recirculation zone above the roof. The flow feeds the circulation after it separated. The presence of solar panel further affecting the flow separation and recirculation, changing the flow field. This is because the increment in surface area interacting with the flow. The increased in tilt angle has increased the surface area interacting with the flow as seen in the Figure 4.38 and 4.39

a)



b)

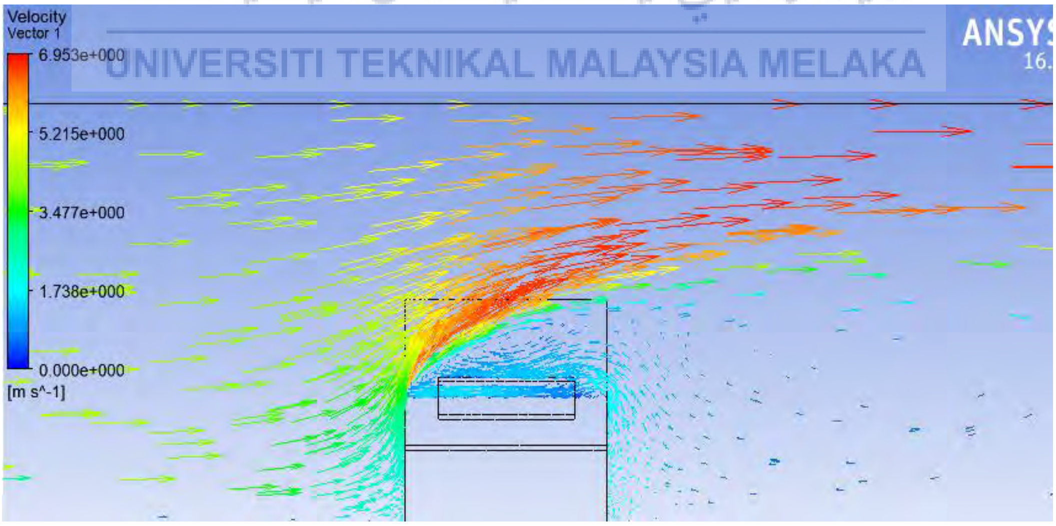


Figure 4.38: The wind flow field for house with solar panel tilt angle +10° under 90° wind direction a) at ridge b) at the edge of the solar panel

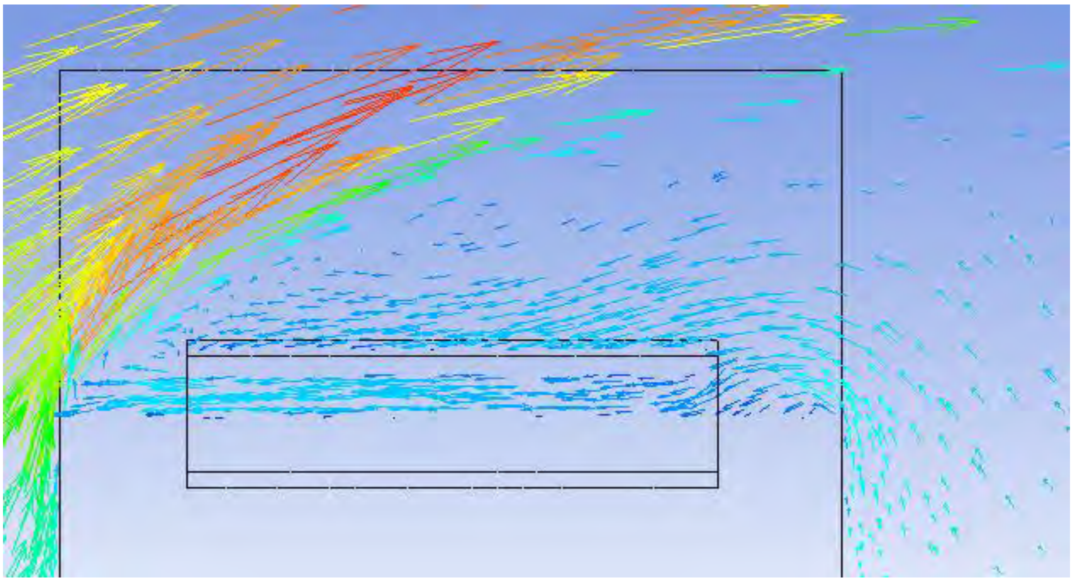


Figure 4.39: Recirculation at the edge of solar panel

The pressure contour for the rooftop (Figure 4.40) was not in symmetry because of the effect of the tilt angle. Due to sheltering effect, whole rooftop was under negative pressure. The corner edge experienced higher negative pressure. The panel near the inlet experienced highest force than the panel farthest from the inlet because the separated flow at the edge above the panel had highest velocity and inertia. This created higher suction acting to lift the roof and panel off the house.

In this case, the increased of tilt angle further influenced the negative pressure on top and bottom of the solar panel. It can be seen the top of the panel experienced higher negative pressure compared to bottom of the panel. From Figure 4.41, it could be seen the negative pressure under the panel was more obvious due to increase in area above the roof where the area was block by parallel panel before. The lifting force exerted on the area top surface of the panel was more than bottom surface of the panel.

Figure 4.40: Pressure contour of house with panel tilt angle +10 ° under 90 ° wind direction a) rooftop b) front plane view

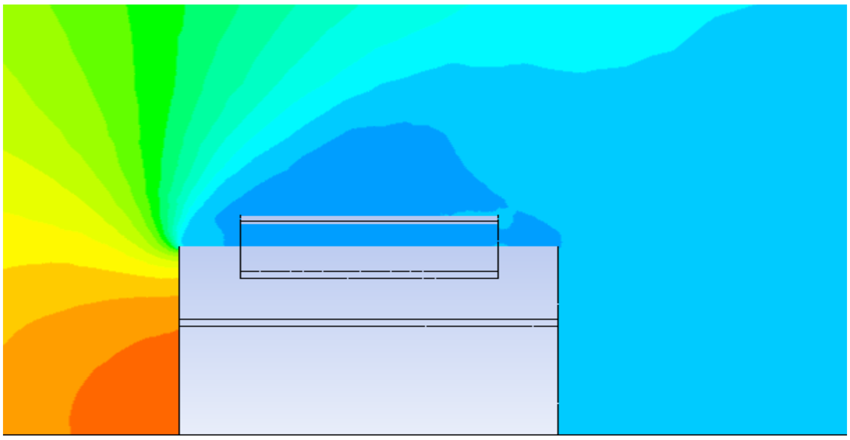


Figure 4.41: Obvious negative pressure under the panel due to increase in area

Figure 4.42: Pressure contour at top and bottom surface the solar panel for house with panel tilt angle+10 (90 ° wind direction)

Increasing tilt angle has increased the negative Cp values as shown in Figure 4.43. Top pressure coefficient Cp distribution pattern was almost the same with parallel tilt angle solar panel. All of panel shows a decrement in Cp value with panel 1 had the highest negative value and panel 5 had the lowest negative value. This was due to the wind direction that affected the pressure on rooftop.

For bottom Cp, all panel was no longer had the same value at the feet of the solar panel area. Because the area under the panel had rose, bottom of the panels was no longer being sheltered by top of the solar panel. Hence the reason why the bottom Cp had high negative Cp value. This shows that increasing tilt angle had increased the suction force acting on top and bottom of the solar panel.

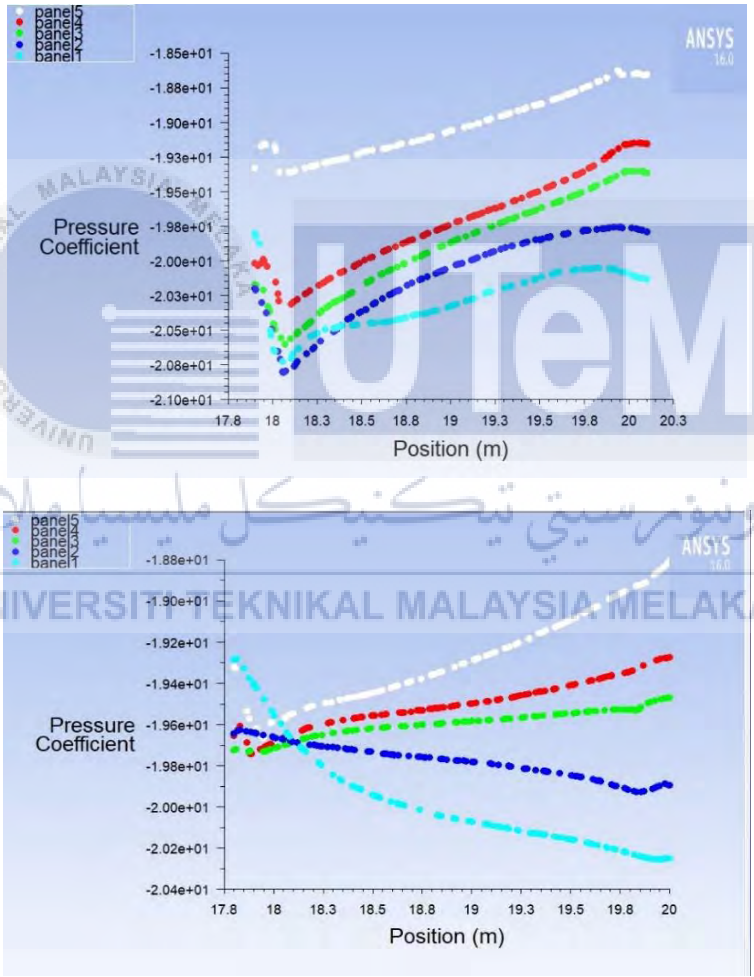


Figure 4.43: Pressure coefficient Cp at top and bottom of solar panel tilt angle + 10 ° under 90 ° wind direction

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Wind loading analysis on roof mounted photovoltaics panel is studied in this report. Solar PV is briefly introduced and the factors needed to consider when installing the solar panel. One of the important factors was the wind loading which can caused damage to the panel, ground or roof depending on where it is mounted. The phenomena behind the subject was studied. The critical parameters, tilt angle and wind direction were identified and selected. The method of analyzing was chosen. The aim was to simulate the wind load that occurred around the solar panel with the existing critical parameters.

It was observed that changes in wind angle resulted in complex flow patterns Wind direction has influence in sheltering effect, recirculation, edge effect, flow symmetry and separation acting on the roof. This can be seen from the vector flow field differences from 0° to 90° wind direction. The presence of panel changed the wind flow field surrounding the rooftop. Depending on the tilt angle of the panel, swirling region could occur and had effect on the flow field in the panel area.

A lot can be analysed from the pressure contour and pressure coefficient obtained in the simulation. The pressure on the rooftop was varied and depended on wind direction. Changing wind direction completely affecting the pressure acting on the rooftop where 90° wind direction causing the whole structure in negative pressure. Introduction of solar panel to the roof structure affected the pressure of the structure. When the tilt angle of the panel was 20°, the array and roof structure were under minimum lifting force due to pressure equalization. But when the tilt angle increased to 30°, the area of the array and roof structure experienced higher lifting force. This shows that increasing panel tilt angle had drastically changing the pressure acting on the roof and the solar panel. This means that keeping the tilt angle parallel to the roof can minimized the suction force acting on the panels and roof structures. The results of the wind flow field, pressure contour and pressure coefficient that varied greatly shows the difference of wind loading acting on the rooftop with or without solar panel.

5.2 RECOMMENDATIONS

There are lots of improvement that can be made in the simulation. The improvement can be made by adding multiple tilt angle for the solar panel. Wind direction can be study at 45 ° which the wind comes into contact with the corner edge of the house first. Hence the edge effect significance can be study. Number of panels can also be increased. Instead of an array of solar panel consist of 5 panel, multiple more can be placed on the rooftop making it rows of solar arrays the setting enables to investigate the sheltering effect of solar panel at the front row to the solar panel at the back row. This way the effect of tilt angle and wind direction on solar PV can further be study and understand. For future investigation, the simulation can be done with different geometric settings such as more complex type of roof, flat roof with parapet and others to observe the geometrical influences to the wind loading on solar panel.

For better validation, the result should be compared with experimental results. However experimental results that satisfy research scope and objective could not be found during the whole course of this simulation work. The limitation of hardware hindering the capability to run the simulation where each of the model took about 5 hours to simulate. This put limitation to number of models could be simulated due to long hour of calculating time. For smoother calculating time, high end computer is needed. Mesh study also cannot be done due to the lack of time. In future work, it has to be done so that the meshing value will not affecting the result and save computing time.

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