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SIMULATION RESEARCH ON INTERACTION BETWEEN WIND AND SOLAR PHOTOVOLTAICS SYSTEMS

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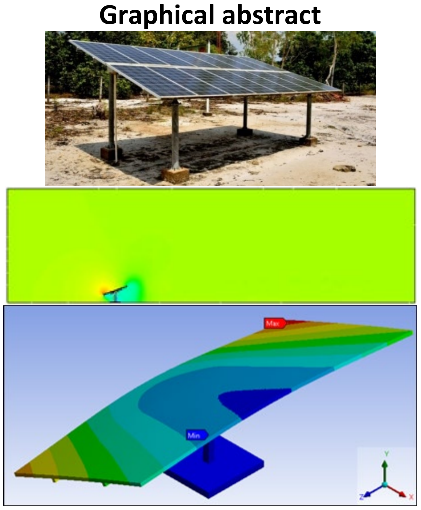
Graphical abstract



Abstract

There are many options for reducing greenhouse gas emissions from energy systems while still meeting the global energy needs. One of the options could be renewable energy. Renewable energy has a huge potential to mitigate climate change, that can also provide people with utilities when using them. Renewable energy, if properly implemented, would contribute to socio-economic development, access to energy as a safe source of energy, and reduction of negative impacts on the environment and health. In the most demanding conditions, increasing the share of renewable energy in the energy mix will require policies to stimulate changes in the energy system. This research was focused on the solar photovoltaics (PV) system, especially on the interaction between wind and the PV system. The wind had a cooling effect to the PV system. The wind speed could greatly affect the operating performance of a PV system, especially in windy locations. In this paper, different velocity (from 3 to 15m/s) and incident angle of wind (from 0 to 180 degree) were used to carry out first the strength of PV system and then the influence of wind to the PV system by using ANSYS software. The PV system was found durable under these conditions. Velocity and direction of wind had strong effect to aerodynamic characteristics of solar panels.

Keywords: Solar Photovoltaics, Solar Panels, Wind Load, CSD, ANSYS.

1.0 INTRODUCTION

Wind loads were the most important loads on PV system. It caused the maximum load force that changed in all directions and could cause mechanical damage as well as destabilizing of the PV system, which reduced the performance of receiving solar energy. Typically, the PV system was damaged at strong winds, such as typhoon in Taiwan [1]. Following Naeiji et al. [2], during extreme wind events, the distributed pressures on residential scale rooftop PV panels' surface could 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. Therefore, determination of wind load was an important issue in design of the PV system. Structure of the PV system must support all wind loads, regardless of their installed position such as on the roof, on the lamppost, or on the ground.

For the PV panels on the ground, evaluation of wind load was an easier task than the PV panels installed at other locations. However, it also had its own difficulties. The PV panels mounts on the ground, where the wind flow was unpredictable due to the intense chaos of turbulence flow. Wind flow around solar panels caused a distribution of pressure on both two surfaces of the panels. The surface of solar panels must be supported a drag force, following wind direction, and a lift force, perpendicular wind direction. These forces create torque. In strong wind, these forces and torque can damage solar panel structure. Solar panels can be considered as an inclined flat. According to EN1991-1-4 [3], wind force acting on a structure was determined by total force coefficient, or local pressure coefficient. These coefficients were determined by summing up the difference of pressure on upper and lower surfaces for all wind directions. Wind load was determined by any of three methods proposed by American Association of Construction Engineers in ASCE 7-05 [1]. These three methods were called simplification method, analytical method, and wind tunnel method. The simplified method was not suitable for estimating the load on solar panels because they were not closed structures. The solar panels did not meet the requirements for both simplification and analysis. The main reason was the ability of easily created vortex and shake of solar panels [4]. Therefore, the research of wind effect on solar panels was conducted by the wind tunnel method or computational fluid dynamics (CFD) [5-17]. However, the accuracy of the CFD model must be corroborated with experimental data.

With the aim of simulation, the interaction between the wind and the solar panels, CFD model in ANSYS software was first carried out to determine pressure load on solar panels and then applied this pressure distribution as input load for computational structure dynamics (CSD) problem. The main parameters affecting the impact of wind on solar panels are wind velocity, wind direction, inclined angle of solar panels … For Vietnam's topography, according to World Bank report, average wind velocity at altitude of 50 m varied from 5 to 10 m/s and over 60% of Vietnam's area had wind velocity above 6 m/s. Therefore, in this study, the value of wind velocity was investigated from 3 to 15 m/s. Following Ayodeji's research [18], the case of reverse wind effected on the back of solar panels had a greater effect on the wind load acting on solar panels. In these cases, lift force was much greater than that of wind directly acting on the light side of solar panels. In addition, the case of oblique wind also made asymmetric distribution of pressure on solar panels and torque moment more affecting to PV system. Wind direction was considered, in this study, as front wind (0 degree), reverse wind (180 degree), crosswind (90 degree) and two cases of oblique wind (45 and 135 degrees). According to Ulsu [19], the inclined angle of solar panels had a great influence on wind load applied to solar panels. This research was performed with inclined angle from 7.5 to 45 degree. Accordingly, smaller inclined angle, lower lift, drag and torque coefficients. Therefore, this inclined angle was chosen of 20 degree. Mateus [20] researched experimentally effect of wind actions on PV panels for Angola, Western region of southern Africa. Strength analysis of solar panels was estimated at wind velocity 9 m/s, zero wind direction and 30-degree inclined angle for solar panels. This research used PV system of Mateus [20] with Vietnam climate by using simulation method.

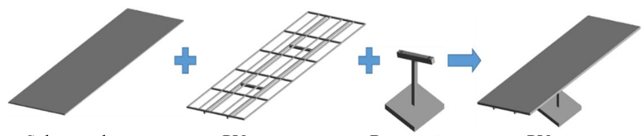
2.0 METHODOLOGY

Interaction between wind and the PV systems was carried out using ANSYS software. First, flow on and around the PV system, called the CFD problem, was carried out to identify pressure load on the PV system. Then, strength analysis was estimated by solving the CSD problem.

PV System Model

The solar panel array consisted of 25 solar panels with dimension of each panel was 1.96 m in length, 0.99 m in width and 0.046 m [20] (Figure 1a). Panels were placed with 5 rows and 5 columns, where these solar panels were designed to be placed within a 0.002 m gap between them. Thus, the solar panels had 9.808 m in length, 4.958 m in width and 0.046 m in depth. The solar panels were mounted at 2.5 m height from ground level to its center of gravity. The solar cells assemblies were typically covered with glass and mounted in an aluminum alloy frame. In the CSD calculation, Young's Modulus was $7*10^4$ Pa and $7.1*10^{10}$ Pa for glass and aluminum alloy respectively. Solar panels were inclined an angle, β = 20 degree, with horizontal wind direction. Figure 1b presented geometry of solar panels model.

a. Actual PV system [19]



b. PV system model

Figure 1 PV system

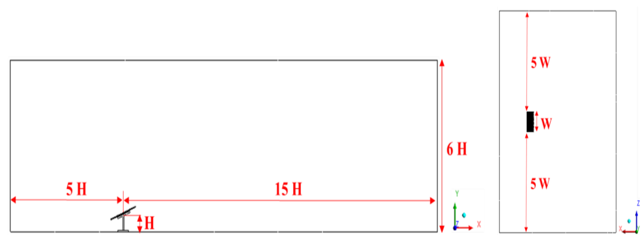
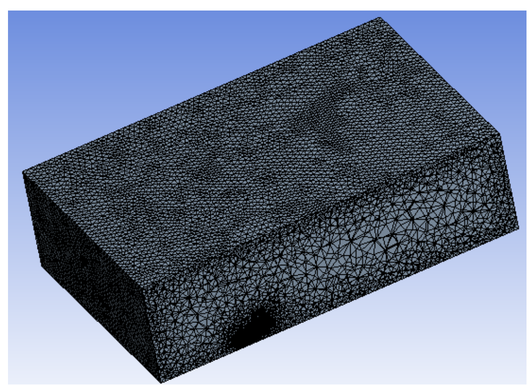


Figure 2 Computational domain



a. CFD

b. CSD

Figure 3 Meshing grid

Computational Domain

Computational domain was identified in Figure 2 for the CFD problem, where H was height of the PV system from its center of gravity to ground (H = 2.5 m) and W was width of the PV system (W = 9.8 m). For the CSD problem, computational domain was structure of the PV system as shown in Figure 1.

Meshing Grid

The computational domain was meshed with $1.1*10^6$ unstructured elements for the CFD problem (Figure 3a) and $0.09*10^6$ unstructured elements for the CSD problem (Figure 3b).

Boundary Conditions

For the CFD problem, the boundary conditions included (Figure 4):

- Velocity inlet: In reality, wind velocity was a function of altitude. However, in this study, the wind velocity was considered as a uniform value. According with the wind velocity in Vietnam at altitude 50 m, five values of wind velocity are considered in CFD simulation such as 3; 6; 9; 12; 15 m/s with wind direction varied from 0 to 180 degree. Here there, five exposed values of wind direction were 0; 45; 90; 135 and 180 degrees.

- Pressure outlet: the pressure was equal ambient pressure. The ambient temperature was 25 degrees Celsius, and the atmospheric pressure was 1 atm.

- Wall: The solar panels, support and ground were solid objects. Thus, the “wall” condition was applied to these surfaces.

For CSD problem, distribution of pressure on PV system was set as input boundary condition.

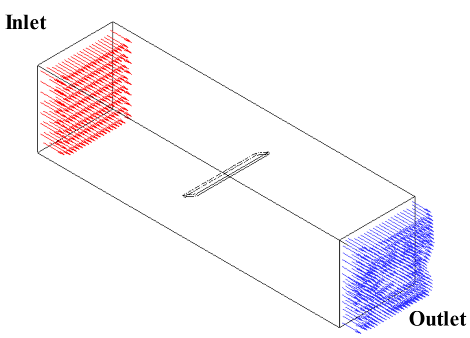


Figure 4 Boundary conditions

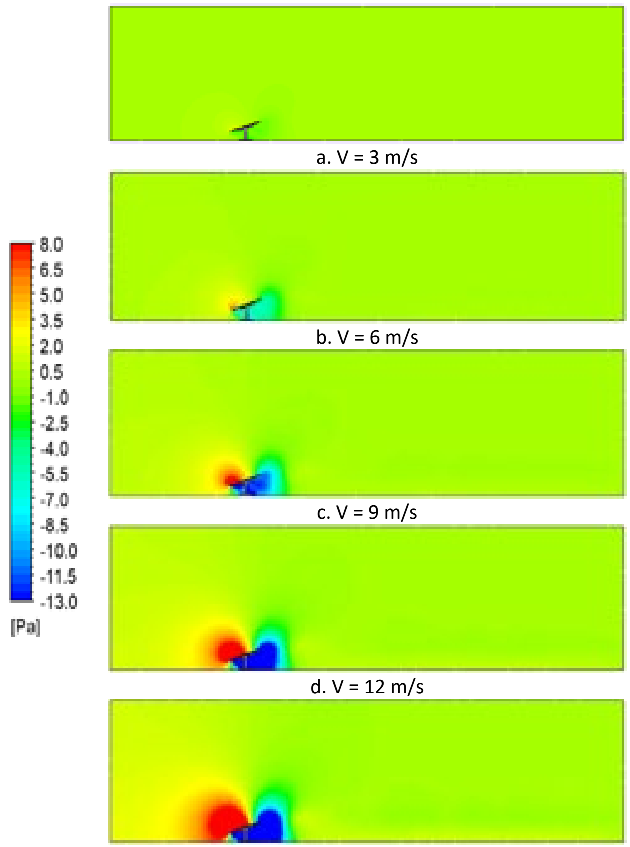
Turbulence Model

The SST k-ω turbulence model was chosen due to its good behavior in adverse pressure gradients and separating flow. The shear stress transport (SST) formulation combines the best of two worlds. The SST formulation also switches to a k-ε behavior in the free-stream and thereby avoids the common k-ω problem that the model is too sensitive to the inlet free-stream turbulence properties.

3.0 RESULTS AND DISCUSSION

Influence Of Wind Velocity

Influence of wind velocity was carried out within wind direction of zero-degree, inclined angle of solar panels of 20 degree and with a range of velocity from 3 to15 m/s.



a. V = 3 m/s

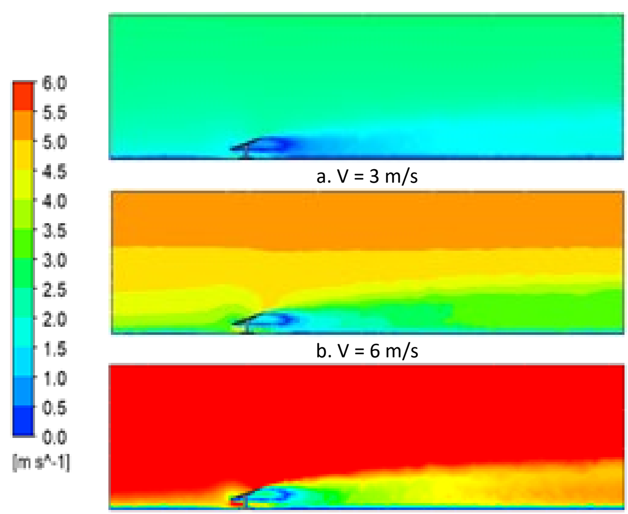
b. V = 6 m/s

c. V = 9 m/s

d. V = 12 m/s

e. V = 15 m/s

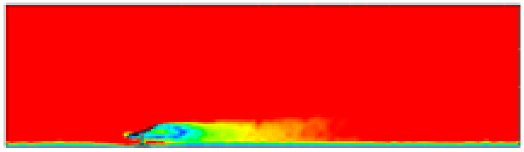
Figure 5 Distribution of pressure



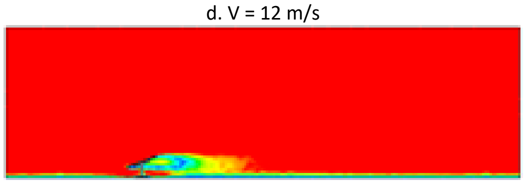
a. V = 3 m/s

b. V = 6 m/s

c. V = 9 m/s

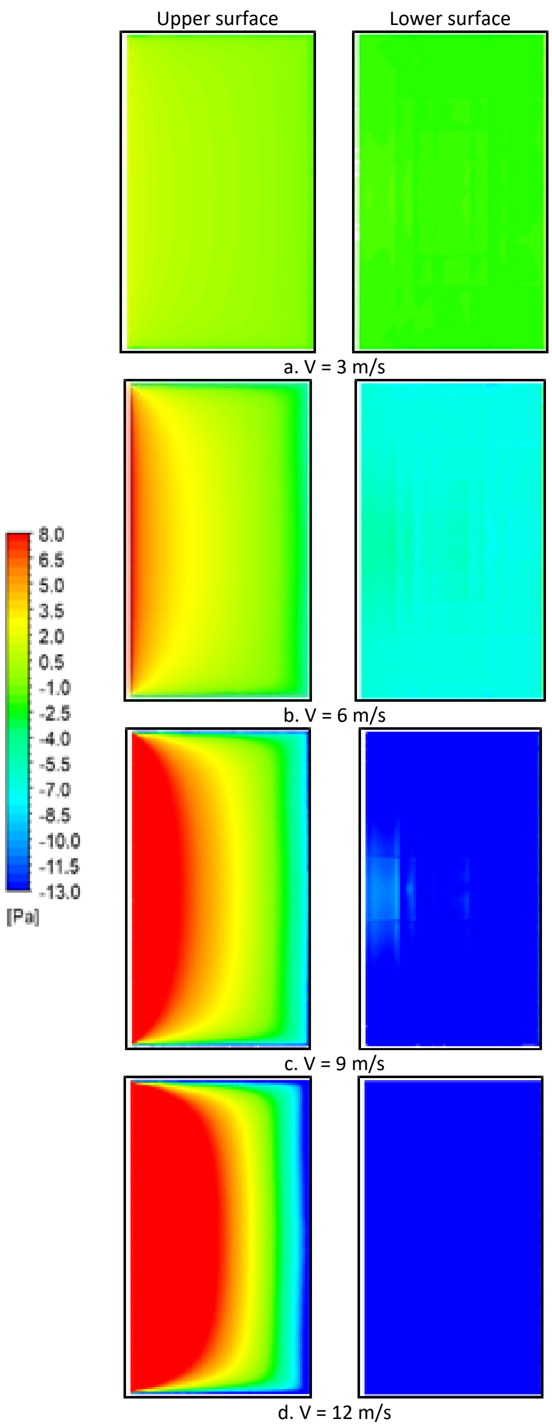


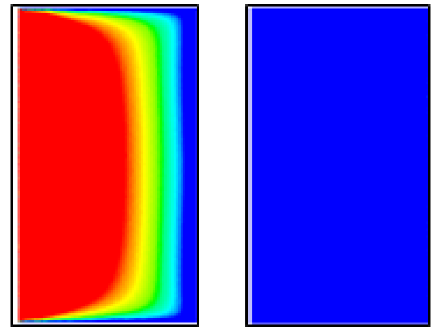
d. V = 12 m/s



e. V = 15 m/s

Figure 6 Distribution of velocity





e. V = 15 m/s

Figure 7 Distribution of pressure on PV - wind velocity

Distributions of pressure were presented in Figure 5. Pressure was maximum at leading edge position where the wind was first contact to solar panel. This position was also called stagnation point. The stagnation point at upper surface had maximum pressure and lowest velocity. The distribution of pressure on the upper surface had opposite tendency as on the lower surface. Upstream flow had higher pressure than downstream flow.

Behind solar panel, a vortex was observed (Figure 6). This vortex induced low pressure region behind solar panel. This vortex became stronger with increasing of wind velocity.

Pressure on upper surface of solar panels was higher than that on lower surface (Figure 7). This remark induced a negative lift force to solar panel. This difference also became more quantitative when wind velocity increased from 3 to 15 m/s. At upper surface, pressure was found maximum at leading edge, then reduced to trailing edge of solar panels. At lower surface, there was no remarkable phenomenon for tendency of pressure.

Pressure on upper surface of solar panels was higher than that on lower surface (Figure 7). This remark induced a negative lift force to solar panel. This difference also became more quantitative when wind velocity increased from 3 to 15 m/s. At upper surface, pressure was found maximum at leading edge, then reduced to trailing edge of solar panels. At lower surface, there was no remarkable phenomenon for tendency of pressure.

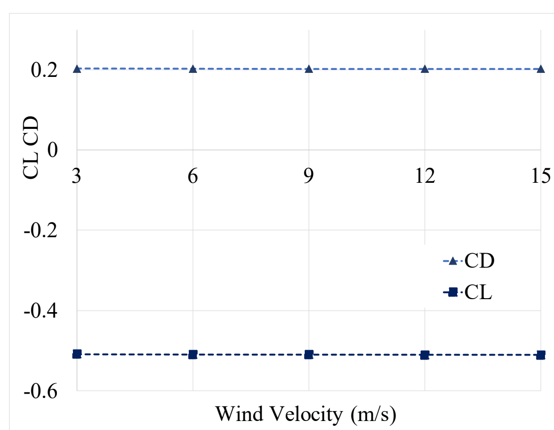
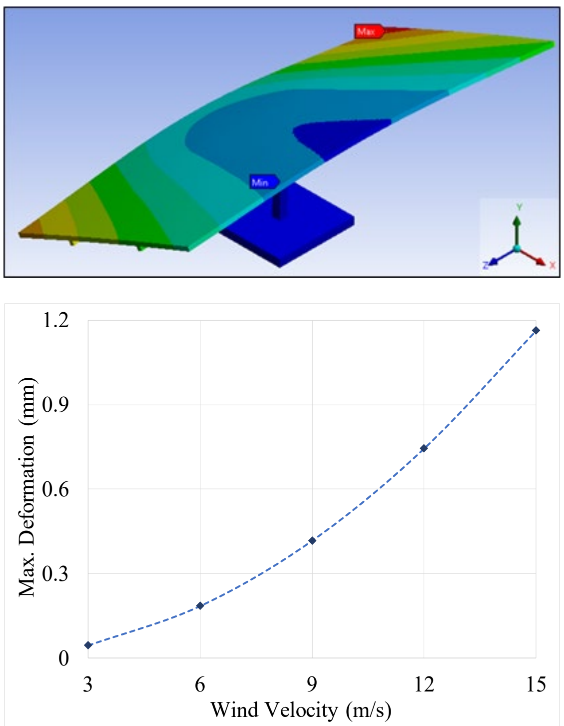


Figure 8 Aerodynamic characteristics – wind velocity

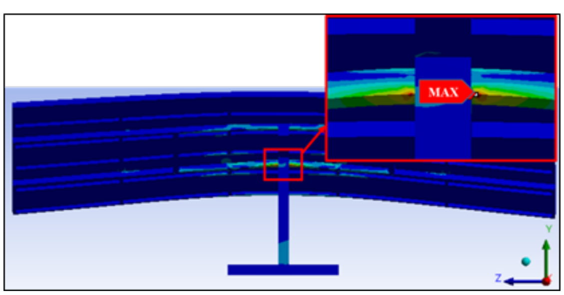
According to the calculated results as shown in Figure 8, the wind affected a negative lift force to solar panels. It explained that the solar panels adhered with ground. When the velocity of wind increased from 3 to 15 m/s, lift force increased and drag forces decreased but with a very small difference. The aerodynamic quality of solar panels was quite uniform about -2.5 with wind velocity varying from 3 to 15 m/s. The variable of aerodynamic characteristics of solar panel was quite small. So, the 6 m/s of wind velocity was chosen to estimate the simulation about direction of wind.

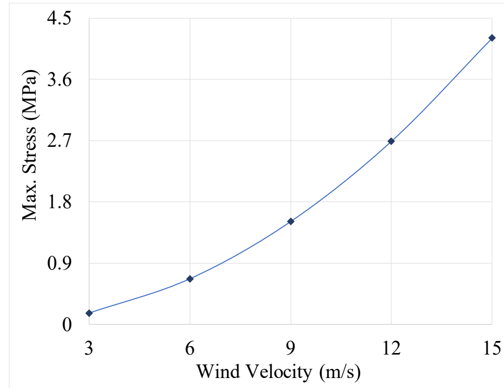
Total deformation of solar panel was presented in Figure 9a. The solar panels were deformed at four corners. In it, the lower left corner in the direction of the wind was the largest distortion of about 0.046 mm at wind velocity 3 m/s. This maximum of total deformation increased quite quick with increasing of wind velocity.

In regard Figure 9b, equivalent stress was found maximum at vertical bar of support of solar panel. The maximum value was about $0.168*10^6$ Pa at wind velocity 3 m/s. This value increased until $4.208*10^6$ Pa at wind velocity of 15 m/s. This maximum value was lower than the limit stress of aluminum alloy ($7.1*10^9$ Pa). Thus, this solar panels were durable with wind velocity from 3 to 15 m/s.



a. Deformation





b. Stress

Figure 9 Structure characteristics – wind velocity

Effect Of Wind Direction

This section reviewed the effect of wind direction (or attack angle AOA = 0; 45; 90; 135 and 180 degrees, as shown in Figure 10) within velocity of wind 6 m/s and inclined angle of 20 degree.

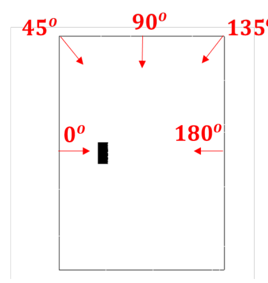


Figure 10 Wind direction

Distributions of pressure were shown in Figure 11. Pressure at upper surface of solar panels was higher than that at lower surface and maximum at leading edge where the wind was first contact to solar panels, for example value of pressure 8.0 Pa and -4.0 Pa respectively for zero inclined solar panel in Figure 11.a. Through this remark, it could be concluded that whenever direction of wind, there was a vortex behind solar panels. Only at vertical wind, the wind resistance surface was quite small, so the difference of pressure upper and lower surface was small. It could explain a small force was induced at this case.

Distribution of pressure at zero attack angle (Figure 11a) had opposite tendency with that at attack angle of 180 degree (Figure 11e). The position of maximum pressure was at upper leading-edge side of solar panel for zero-degree attack angle, but at lower leading-edge side of solar panel for attack angle of 180 degree. Upper pressure for zero attack angle was high, while upper pressure for attack angle of 180 degree was low. This observation created an opposite direction of lift force for these two attack angles.

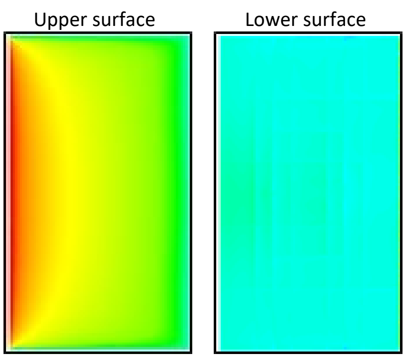
The same tendency was found out for attack angle of 45 and 135 degree. However, the position of stagnation point was different with those two attack angles. The stagnation point was observed at bottom corner of upper tip side and at bottom corner of lower tip side of solar panels for attack angle of 45 degree (Figure 11b) and 135 degree (Figure 11d) respectively

[17]. For this pair of attack angle, the lift force had also opposite direction.

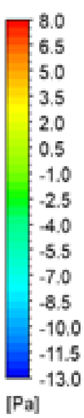
At attack angle of 90 degree, the difference of pressure between upper and lower surfaces was small due to small resistance surface (Figure 11c). The vortex behind solar panels was also weak.

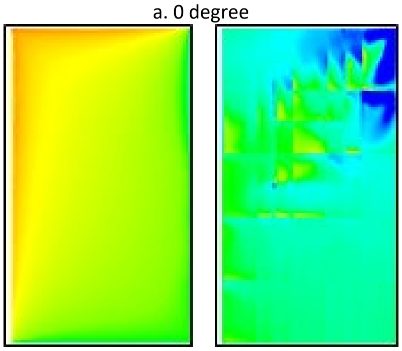
In regard Figure 12, wind direction had strong affect to aerodynamic characteristics of solar panels. With increasing of wind direction, drag coefficient increased for attack angle from 0 to 90 degree, then reduced for attack angle from 90 to 180 degree. The drag coefficient was minimum at vertical wind (attack angle of 90 degree).

The lift coefficient was negative with zero and 45-degree attack angle, while it was positive at attack angle from 90 to 180 degree. The negative value of lift force showed that solar panels was kept at its fixed position. However, the positive value of lift force caused solar panels to be pulled out of its fixed position. It seemed that the solar panels could not keep its fixed position for direction of wind from 90 to 180 degree. The lift coefficient and drag coefficient were smallest for attack angle of 90 degree due to smallest resistance surface and weakest vortex behind solar panels.

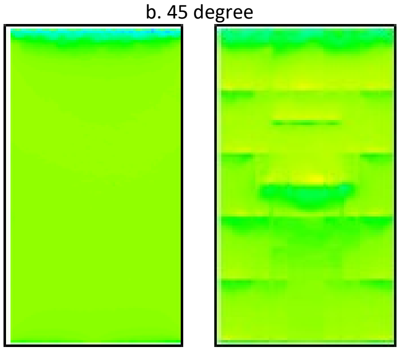


a. 0 degree

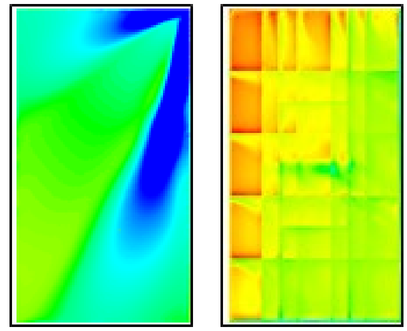




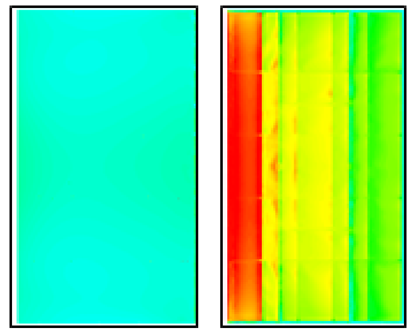
b. 45 degree



c. 90 degree



d. 135 degree



e. 180 degree

Figure 11 Distribution of pressure on PV - wind direction

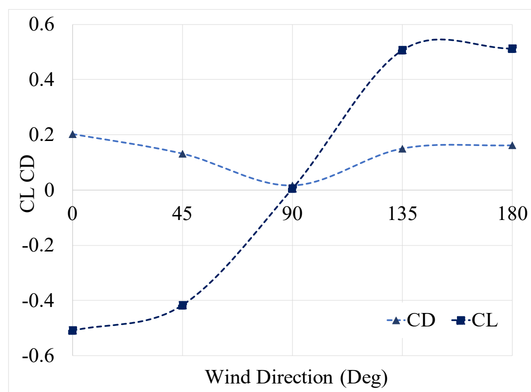
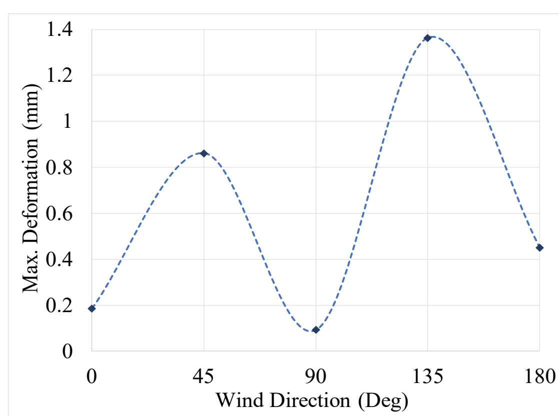
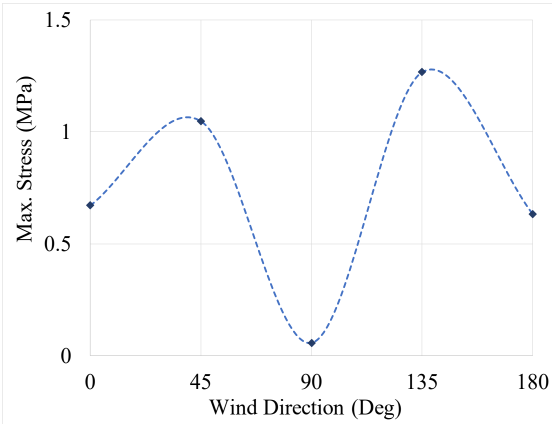


Figure 12 Aerodynamic characteristics – wind direction



a. Deformation

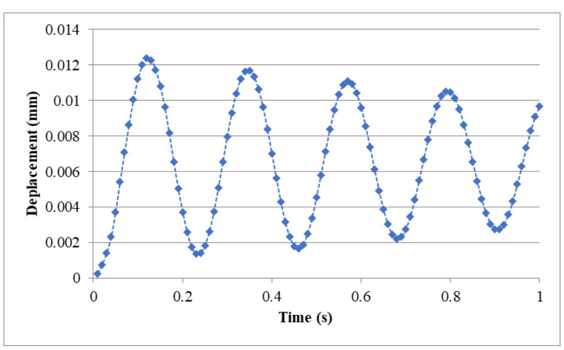


b. Stress

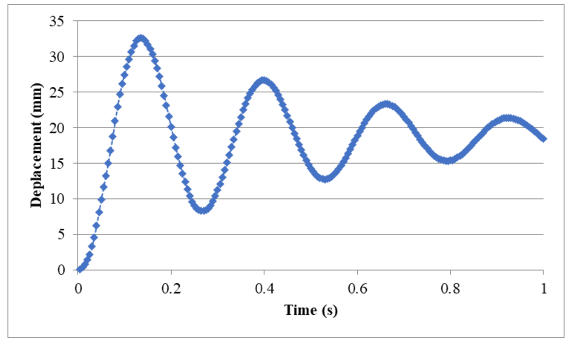
Figure 13 Structure characteristics – wind velocity

Maximum total deformation and maximum equivalent stress of different wind direction were presented in Figure 13. These values had the same tendency. The smallest value was at attack angle of 90 degree. The highest value was at attack angle of 45 and 135 degrees. The position of maximum total deformation was at position of maximum pressure, while the position of maximum equivalent stress was at contact of solar panels and support. From 0 to 180 degree of attack angle, maximum value of equivalent stress was lower than the limit stress of aluminum alloy ($7.1*10^9$ Pa). Thus, this solar panels were durable with wind direction from 0 to 180 degree. However, these solar panels were not kept its fixed position for attack angle from 90 to 180 degree due to positive induced lift force. But, for attack angle from 0 to 45 degree, solar panels were durable and kept its fixed position.

For more detail, oscillation of flat plate was represented by oscillation of the wing tip point (leading-edge tip) (Figure 14). The oscillation of this point under the reciprocal effect of the structure and the flow would create a stable, convergent, or divergent response when oscillating at the leading-edge of the tip was off. In these studied cases, the oscillation of the leading-edge tip tended to convergent. It meaned that the flat plate was stable in studied conditions.



a. Velocity 20m/s & Attack angle 0°



b. Velocity 15m/s & Attack angle 5°

Figure 14 Displacement of leading-edge tip of flat plate

4.0 CONCLUSION

In this research, the interaction between wind and solar photovoltaics systems was successfully solved by using ANSYS software. The PV system was durable under wind velocity from 3 to 15 m/s and wind direction from 0 to 180 degree. There was a vortex behind solar panels that increased the difference of pressure between upper and lower surface. Wind velocity from 3 to 15 m/s had an evidence effect to aerodynamic characteristics and created a negative lift force to solar panels. This negative lift force explained the PV system kept its fixed position on the ground.

Wind direction had a strong effect to aerodynamic characteristics of solar panels. For 0 to 45 degree of wind direction, solar panels were durable and kept its fixed position due to negative lift force. While, for 90 to 180 degree of wind direction, solar panels were durable but could not keep its fixed position on the ground due to positive lift force.

The pressures were maximum at leading edge position where the wind was first contact to solar panel, that could lead to considerable structural damage. Therefore, the shape of boundary of PV system could be changed to eliminate this local damage.

However, it is necessary to validate these numerical results with experimental results or other numerical results in the future.

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