EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2021, 22(6), 61–68
https://doi.org/10.12912/27197050/141526
ISSN 2719–7050, License CC-BY 4.0

Received: 2021.08.08
Accepted: 2021.09.03
Published: 2021.09.17

Comparative Analysis of Effect of Wind Loads with Variation in Altitude and Angle of Inclination of Wind Direction on Solar Panels

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ABSTRACT

Solar panels are used in wide range of applications like power generation, automobiles, electronic devices etc. They are trending devices which develop power from abundantly available solar energy. In spite of this advantage, they are affected by wind loads, which result in wind induced loading. Determining this is very essential because, the drag and lift forces applied on the solar panels due to the wind loads play a crucial role in the accomplishment of performance in the solar panels. In this work, an attempt was made to carry out a comparative analysis of the effect caused by the wind forces on different array sizes, altitudes, orientation of the solar panels at different wind speeds (5 m/s, 25 m/s) and at different inclination angles the wind (0°, 45°, 135° and 180°. The ultimate objective of this work was to analyze the effect caused by wind forces based on these combinations of the parameters. Different shapes of solar panels like rectangular and hexagonal shaped were analyzed for normal and optimized conditions. Moreover, wind load analysis was carried out for different altitudes like on the ground and on the roof top. The outcomes depict that the wind forces on front region of the conventional solar panels is higher when compared to the optimized solar panel.

Keywords: wind loads, lift force, drag force, altitude, orientation angles, rectangular panel, hexagonal panel

INTRODUCTION

The most familiar devices of collecting the solar power are the photo voltaic (PV) solar panels, which are usually installed on flat or inclined building roofs, or at terrestrial level. When the PV panels are exposed to high altitudes, they are subjected to high wind speeds. The damage of solar panels and solar water heating systems installed on flat-roofs was reported by Chung et al. [1] in Taiwan region, where approximately 3.5 typhoons are recorded each year on average. Due to such wind-induced hazards, thorough verifications were carried out by numerous researchers.

Aly and Girma [2] studied the outcomes related to model scale for the ground mounted photo voltaic solar panels. Experiments were conducted on structures using CFD simulations and concluded that under certain conditions, the results provided by CFD simulations furnished more accurate outcomes than the results obtained by the wind tunnel experimental test. CFD numerical simulations were also performed for small groups of photo voltaic solar panels by Pratt and Kopp [3] and recommendations were formulated regarding the angle of attack and the critical spacing between the arrays of the PV panels. Bitsuamlak et al. [4] "collated the outcomes of numerical analysis with wind that of the tunnel tests for the panels that are mounted on ground". They found that there are very minute variations in the pressure coefficient at the middle, as well as over the side panel of each row. Radu et al. [5] performed experiments on the structures of flat roofed solar panels. Their experiments focussed on the boundary layer in the wind tunnel model for simple as well as for consecutive rows.

Chung, et al. [6] conducted an experimental study in a low-speed wind tunnel, to investigate the mean surface pressure distributions and uplift force at different wind speeds past the solar collectors mounted on flat roofed buildings situated in typhoon susceptible regions. They have also carried out structure tests for unit PV panels. Schellenberg et al. [7] carried out an analysis on parallel mounted arrays of PV panels. Shademan et al. [8] reported various parameters causing the sheltering effect on the prime row of panels. They reported that, it is difficult to carry out field assessments in PV solar panels. In case of top surface of the panels, it will be too difficult, because in the course of operations, equipment causing obstructions cannot be mounted on the top region possessing the silicon cells. If any such devices are mounted, it causes hindrance to the collection of solar energy. Hence a lot of the sector measurements are performed for the rear surface of the PV panels, or on the supporting frame. With the help of the formulations recommended by the designing codes, the wind force over the upper surface of the console is determined. Based on such measurements, the committee of "Structural Engineers Association of California's (SEAOC) Solar Photovoltaic System" prepared a report which focused on the features of wind course on roof mounted photovoltaic panel arrays. Mehrdad and Horia [9] determined the wind loading on solar panels at different azimuthal and inclination angles. They concluded that the wind-structure interaction is actually much more complex, and the strain measurements on the PV solar panel will not capture the actual cause of the deformation of the PV panel, this being directly associated with the wind flow patterns formed round the PV panel and its frame network. In order to verify the flow pattern of the wind, the pressure distribution across various points over the surface of the PV panel, Computational Fluid dynamics (CFD) simulations were performed by the aid of the Ansys Fluent Software for two wind speeds of 10 m/s and 26 m/s, with different angles of striking.

The scope of this scientific research was to carry out a systematic study of wind-persuaded pressure focused on the surface of solar panels, arranged on the land or over the top of the structures. Research works were carried by numerous researchers, they are unique and cause confusion. Some of the works carried out in this area are mentioned below. Ted Stathopoulos et al. [10]. reported the setbacks of existing norms in the design considerations for solar collectors and photo voltaic systems in wind loading and codes of practice. They concluded that a replacement comprehensive study would be necessary so as to place together a group of provisions for various configurations which include both point and area-averaged loads.

Surendar et al. [11] carried out CFD simulations on an array of solar panels mounted at the ground plane and exposed to wind speeds for 5 m/s and 25 m/s to calculate the influence of pressure on each panel in the array, where the panel is placed at 18º to ground plane and 72º to the latitude. The arrangement and simulation were done using CFD. They presented simulations and optimization of the required parts and areas that are affected by the wind, which helps in predicting the dislocations of the photo voltaic panels mounted on the ground. Georgeta et al. [12] investigated and analysed the influence of load on 300 arrayed panels for the different angles of attack. They have reported on the distribution of pressure and pressure coefficients. Mehrdad and Horia [13] reported on simulations studies using CFD to estimate the wind forces. They carried an analysis of the critical case scenario with several azimuthal angles between 0° to 180° using RANS Turbulence Model. Ayodeji et al. [14] reported on the pressure field and distribution of pressure of stand-alone PV panels over the top and bottom surfaces. The solar array was analysed using experiments by structure tests for different directions.

Aly and Girma [15] focused their studies on the effect of sensitivity on Solar panels of test model scale mounted on the ground using B.L.T.W, i.e., physical behaviour of the structure by using the experimental investigations. Workman et al. [16] carried out simulation and experimental studies of the solar arrays mounted on the ground using RANS & LS to analyse the distribution of pressure on the panels and the magnitude of the wind speed. Chowdhury et al. [17] studied the ground mounted solar panels using 3D RANS simulations using an unsteady solver with the panel inclination of 25º using (K-ω) SST turbulence model to determine the mean pressures and coefficient of drag. Gregory and David Banks [18] carried out a study on the solar panels mounted on roof tops to analyse wind forces by selecting the PU panels considering ASCF 7–0.5 structure test to assess the requirements of solar panels. Shademan et al. [19] reviewed various investigations on wind flow over the solar panels array mounted on ground at various flow directions. They administered for gap management and optimized spacing to scale back destructive effects on 2*2 sub panels. Surendar et al. [20] studied pressure and other related coefficients of solar panels by examining experimentally using the model equipped with measuring devices. From the studies presented above, it is observed that the various experimental and numerical works show case the influence of wind loads on the various types of solar panels. However, the data on aerodynamic effects like the drag and lift forces is limited in the literature. Hence this work focused on the determining the drag and lift force under various conditions like at different angles of orientation and at various faces on the solar panels.

Physical Models

Numerical models of rectangular and hexagonal shaped solar panels of the same area were developed using Solid works. Fig.1 shows the numerical models of traditional rectangular ground mounted solar panel. Optimized Ground mounted solar panels of hexagonal shape are as depicted in Fig.2. For the ground mounted arrayed solar panels, full scale model was used, the volume of the domain was 60m X 35m X 7m. Size volume was subjected with approximately 28 arrayed ground mounted solar panels for both initial and optimized models. The arrayed solar panels to which the flow is perpendicular were placed in a controlled computational domain. A gap of 1.3m was provided between each traditional rectangular solar panel, whereas, for optimized hexagonal case, it was 1.2m. Numerical models were meshed using the automatic meshing method. Unstructured mesh was used for meshing both the models.Fig.3 shows the meshed numerical model of the traditional rectangular array of panels. Tetrahedrons were selected with patch conforming method. Face size meshing is also added in order to increase the accuracy to the mesh generator. There are 6 faces of solar panel used for the face sizing, where two of these form the top and bottom faces of the panels and the rest of the faces are results of thickness of the panel at the edges. Fig.4 shows the meshed model of the optimized hexagonal solar panel array [21].

Numerical Method

Reynolds Averaged Naiver Strokes (RANS) equations were implied as governing equation in boundary layer. For simulating the wind velocity profile, power law coefficient is considered as 0.15, turbulence intensity of 10% was assigned boundary condition at the inlet. No-Slip condition at the walls was applied for top and side faces of computational domain. Pressure outlet was specified as the outlet condition. Relative pressure was specified as 0 Pascal. Standard boundary condition at the wall was used at the base of Computational Domain and on the surface of the PV panel. The Y+ values were kept in the order of 30–120. Reynolds number incorporated in simulation was in the range of 2.4×10^5 to 3.6×10^5. The 3D meshed model contained around 2.6 million nodes and nearly 5 million cells

Governing Equations

K-ε turbulence model was employed to determine wind pressure using least square cell based method to solve the equations. Continuity, momentum equations (RANS equation) were modified by the solver by including variables, turbulence kinetic energy (k) and rate of dissipation (ε). SIMPLE algorithm was used for solving pressure velocity coupling and semi-implicit method

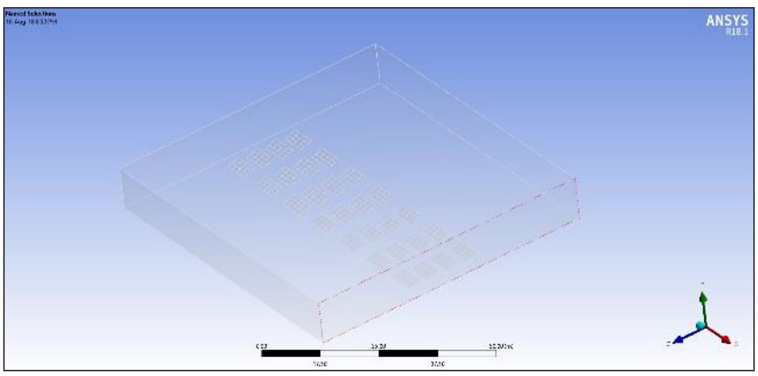

Figure 1. Numerical model of traditional rectangular shape panel mounted on the ground

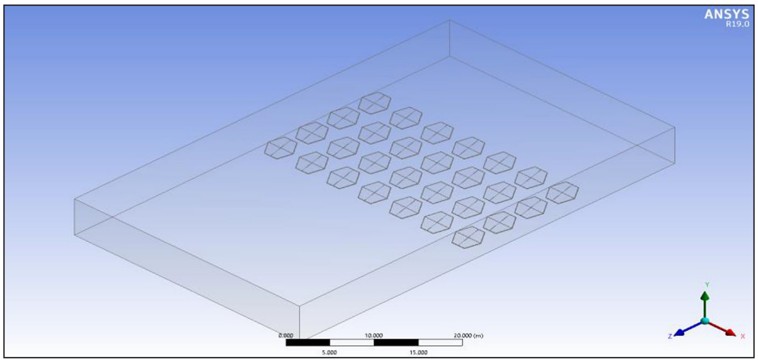

Figure 2. Numerical model of Optimized hexagonal shaped panels mounted on the ground

was used for pressure linked equations. upwind discretization scheme of equation of second order was adapted for solving convection and viscous terms. Time step of size of 0.25s with 98 time steps was iterated with 1000 iterations with each time step to obtain time vs. force curve for unsteady analysis. The following equations Eq. (1) and Eq. (2) were used in solving the numerical problem.

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_j}(\rho K U_j) = = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial K}{\partial x_j}\right] + G_K + G_b - \rho\epsilon - Y_m + S_K \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)\frac{\partial}{\partial x_j}(\rho\varepsilon U_j) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial\epsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2\frac{\varepsilon^2}{K + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{K}C_{3\varepsilon}G_b + S_\varepsilon \tag{2}$$

where: $C_1 = max\left[0.43, \frac{n}{n+5}\right]$,

$$n = S\frac{K}{\varepsilon}, S = \sqrt{2 \times S_{ij} \times S_{ij}}$$

G_k is creation of turbulence in kinetic energy due to mean velocity gradient
G_b is creation of turbulence in kinetic energy by virtue of buoyancy
Ym means the addition of oscillating amplification in compressive turbulence to overall rate of dissipation

The constants specified are: $C_{1\epsilon}$=1.44, C3ϵ=1.9, σ_k=1, σ_ϵ=1.2

S_k and S_ϵ are user defined source terms

Boundary Conditions

The top boundary and side boundaries of the air domain were specified as symmetry to enlarge the flow space near these boundaries, where this boundary specification also eliminates the necessity of mesh refinement near these boundaries. The bottom portion of the air domain was described as rough wall boundary condition that needs the specification of roughness height and constant. It is also necessary to mention the boundary condition between the air and the panel and the supporting structural components of the panel (if exists), where this boundary is selected as smooth wall. The front region of the air domain was defined

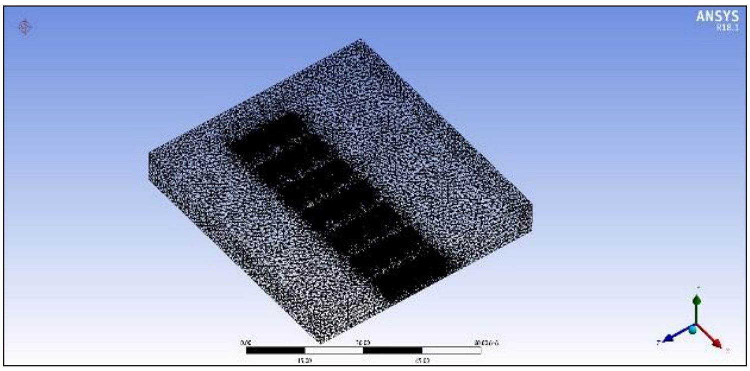

Figure 3. Meshed model of the traditional ground mounted solar panel array

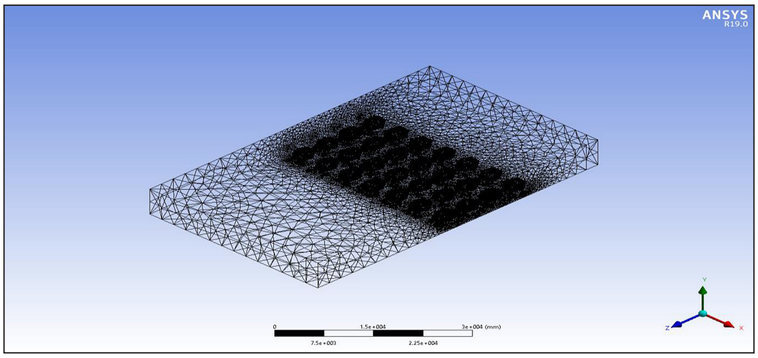

Figure 4. Meshed model of optimized hexagonal solar panel array

as velocity inlet and the back face was assigned as pressure outlet. The difference in the pressure was not specified inside the air domain. Since the panel volume is much cramped compared to the amount of/ air domain, the element sizes through the thickness across the panel were significantly refined. It was necessary to accurately capture the turbulent flow of air near the wall zone as well. It necessitated significant mesh refinement near the bottom wall region and around the panels.

RESULTS AND DISCUSSION

Effect of drag force on roof mounted solar panels at different orientation of angles

CFD simulations were carried out on different orientations of panels arranged in a line. A comparative study was carried out to analyze the influence of drag force on the roof mounted panels at different angles of wind velocities. The angles of inclinations of wind velocities considered are 0°, 45°, 135° and 180°. The influence of the drag forces on different panels with the change in wind velocities of 5m/s and 25 m/s for different models like conventional model and optimized models and at 0°, 45°, 135°, 180° angle of orientation is as shown in the Figures 5–8.

In Figure 5, at the normal orientation, drag forces are maximum for the panel 2. The maximum drag force acting on the panel 2 is around 1250 N at a wind speed of 25 m/s for the conventional model. In Figure 6, at the inclination of 45° to the wind speed, the drag forces on the panels are almost same. In Figure 7, with the inclination of wind speed of 135°, the drag force on the second panel is greater when compared to other panels in the row at a wind speed of 5m/s for the conventional model. In Figure 8, i.e., with the inclination angle of wind of 180°, the drag force on the third panel in a row has maximum drag force at a wind speed of 5 m/s for the conventional model.

Effect of drag forces on various faces of the models in a solar farm

Two models of ground mounted rectangular and hexagonal shaped panels, were considered for analysis. The influence of drag forces and lift forces were analyzed for different rows of the panels in a solar farm. A comparative analysis was carried out for two different angles of

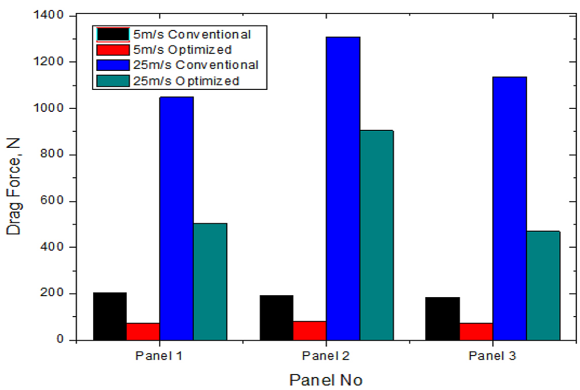

Figure 5. Effect of drag force on different panels and models of the panels at 0° angle of orientation

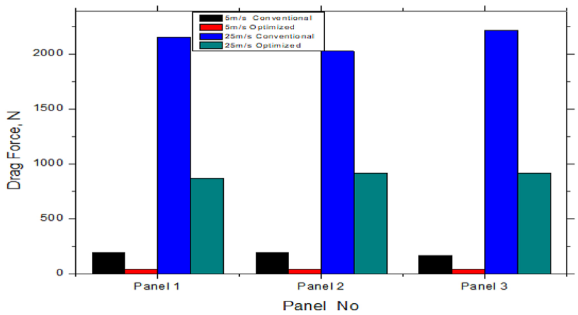

Figure 6. Effect of drag force on different panels and models of the panels at 45° angle of orientation

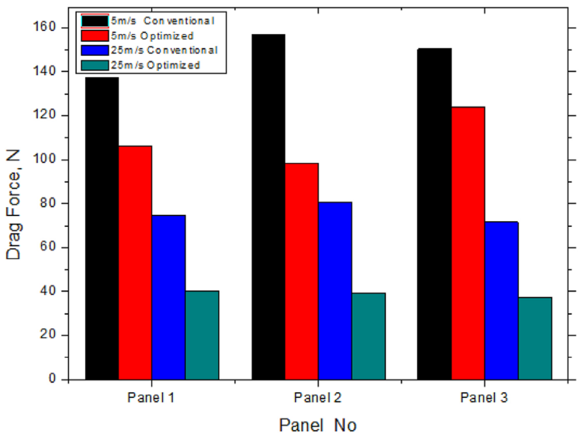

Figure 7. Effect of drag force on different panels and models of the panels at 135° angle of orientation

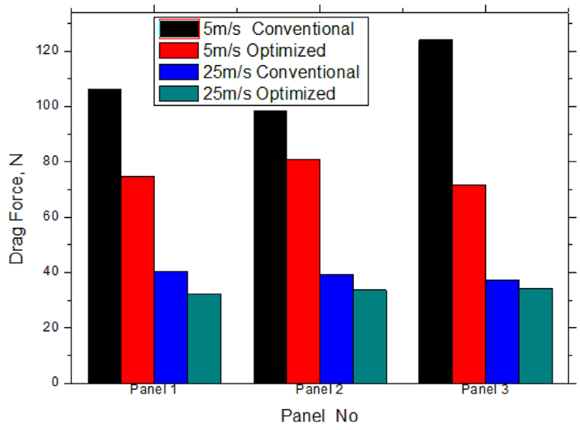

Figure 8. Effect of drag force on different panels and models of the panels at 180° angle of orientation

inclination of the wind velocity. The angles of orientation considered are 0° and 180° respectively. Analysis is carried out on front and back portions of the panels for different rows in solar farm. Figures 9–10 show the comparative analysis of the effect of drag forces on the front and back portions of the rectangular shaped panels at different wind speeds of 5 m/s, 25 m/s respectively. The maximum drag force was on the panel 3 in the row on the front face with a drag force of around 2250 N at a wind speed of 25 m/s. Panel 2 in the row had the maximum drag force of around 1300N on the rear face at a wind speed of 5 m/s.

Figures 11–12 show the influence of drag force on front and back faces of the hexagonal shaped panels of row 1 in the farm at two different wind speeds of 5 m/s and 25 m/s. The maximum drag force on the front face was on panel 5 at wind speed of 25 m/s and was around 1500 N. The maximum drag force on the back face was on panel 5 at 5 m/s and is 60 N. Figures 13–16 show the influence of lift force on the front and back faces of the rectangular and hexagonal panels. It was found that the maximum lift force on the front face of the rectangular solar panels is on the panel 4 at a wind speed of 25 m/s. The maximum lift force was 6500 N. The maximum lift force for rectangular panels on the back face of panel is on second panel at a wind speed of 25 m/s and is around 3750 N. The maximum lift force on the front face of the hexagonal solar panels was in the panel 5 and was 4500 N at 25 m/s. The maximum lift force on the back face of the hexagonal shaped solar panels was in panels 3, 4 and 5 and is around 4100 N.

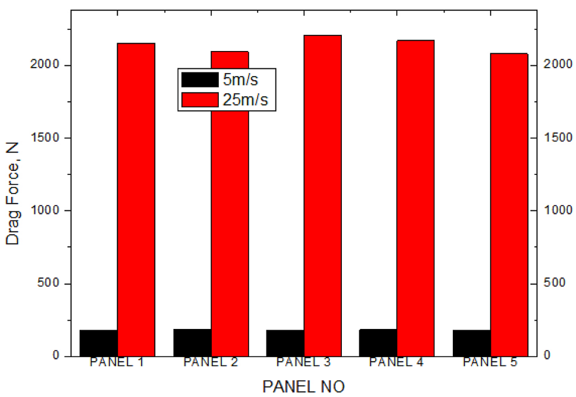

Figure 9. Comparison of drag forces on row1 of the rectangular panel of farm with the variation in the wind velocity on the front face

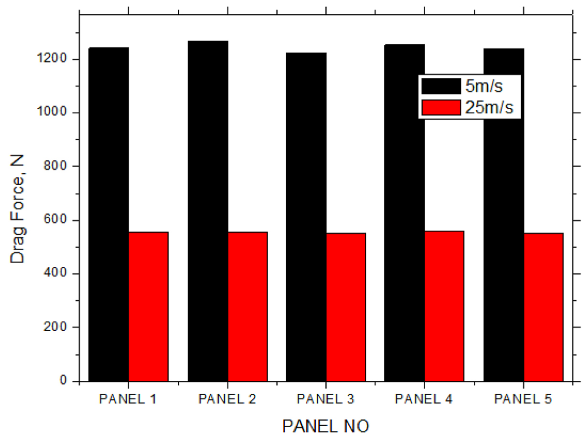

Figure 10. Comparison of drag forces on row1 of the rectangular panel of farm with the variation in the wind velocity on the back face

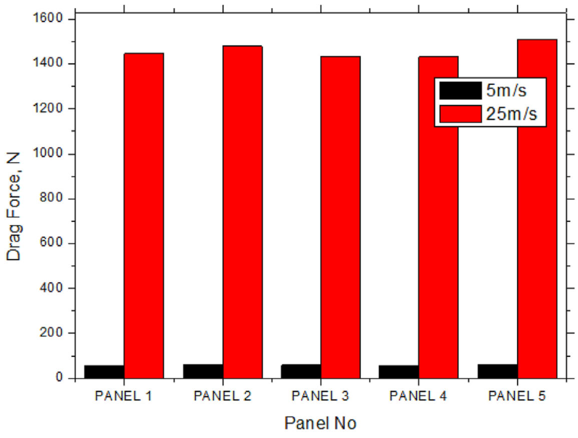

Figure 11. Comparison of drag forces on row1 of the hexagonal panel of farm with the variation in the wind velocity on the front face

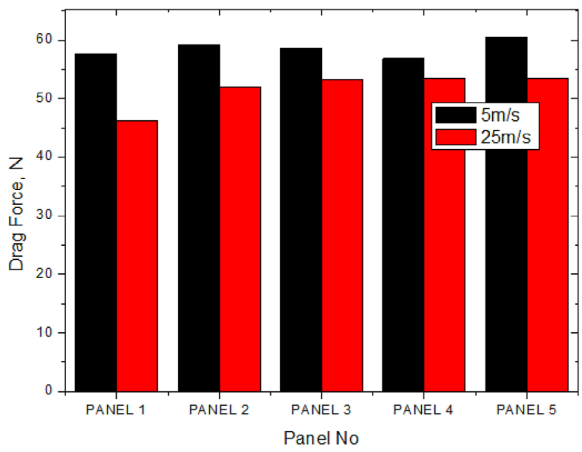

Figure 12. Comparison of drag forces on row 1 of the hexagonal panel of solar farm with the variation in the wind velocity on rear face

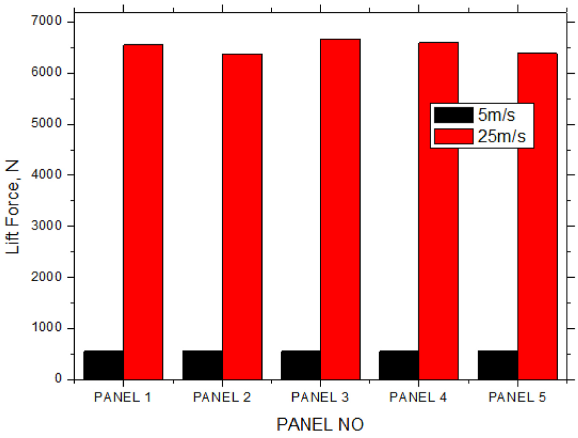

Figure 13. Comparison of lift forces on row1 of the rectangular panel of farm with the variation in the wind velocity on the front face

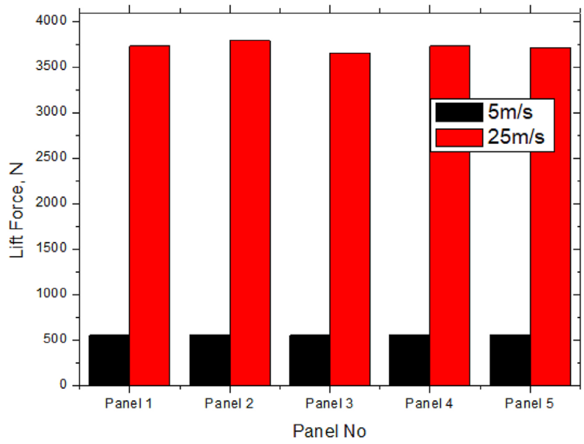

Figure 14. Comparison of lift forces on row1 of the rectangular panel of farm with the variation in the wind velocity on the back face

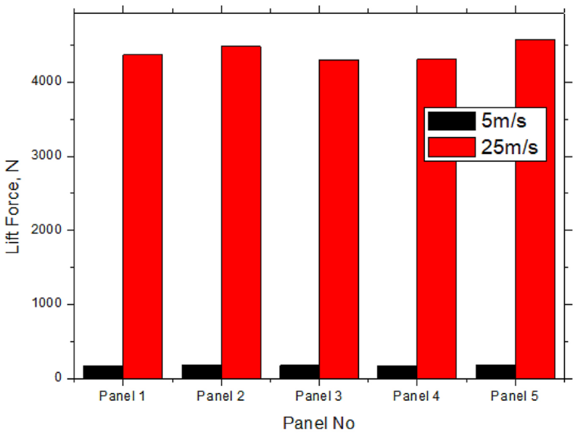

Figure 15. Comparison of lift forces on row1 of the hexagonal panel of farm with the variation in the wind velocity on the front face

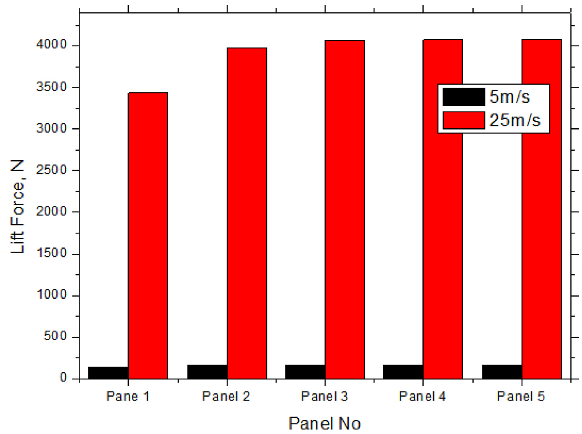

Figure 16. Comparison of lift forces on row1 of the hexagonal panel of farm with the variation in the wind velocity on the back face

CONCLUSIONS

An aerodynamic analysis was carried out on panels in a farm at different wind speeds of 5m/s and 25m/s. The angle of inclination of the wind velocity was varied as 0°,45°, 135°, 180°. The analysis was carried out on front and back faces of two different models of rectangular and hexagonal shapes. The drag and lift forces were analyzed for different cases.

For roof mounted solar panels, with the augmentation in the angle of inclination in the wind speed, there is a reduction in the drag forces in rectangular as well as hexagonal shaped panels. The maximum drag force was at 45° of angle of inclination in the wind speed and is 2500 N. At this angle of inclination in the wind speed, the drag force was greater than the hexagonal shaped panel. The drag force on the hexagonal shaped panel was 1000 N.

For ground mounted solar panels, the maximum drag force was on rectangular shaped solar panel and was around 2000 N. For the hexagonal shaped solar panel, it was found to be only 1500 N. The drag force was maximum at the front face. The lift force for rectangular shaped panel was 6500 N at the front face. For the hexagonal shaped solar panel, the lift force was 4500 N. From the outcomes, the panels of hexagonal shape are prone to less drag and lift forces when compared to the conventional rectangular shape panels.

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