wind tunnel and usage of 2D numerical analysis, and more importantly on the dependency CFD models to reflect the conditions of wind tunnel testing. Since the general trends and results are very similar to each other, it can be concluded that both experimental and numerical results provides confidence on the CFD analysis employed in this paper.

4. PARAMETRIC STUDY ON CONSECUTIVE PANELS

The wind loads and effects are known for the single solar panel thanks to the previous literature studies; however the changes and trends are not very clear for consecutive solar panels compared to the single placed solar panels. A parametric study is undertaken in this section in order to find the effects of different parameters on the wind loads acting on consecutively placed solar panels. For this purpose 6 different parameters are used, namely, normal and reverse wind flow, panel length (L), the distance between 2 consecutive solar panels (D), the clear distance from the ground (H), tilt angle-inclination (θ).

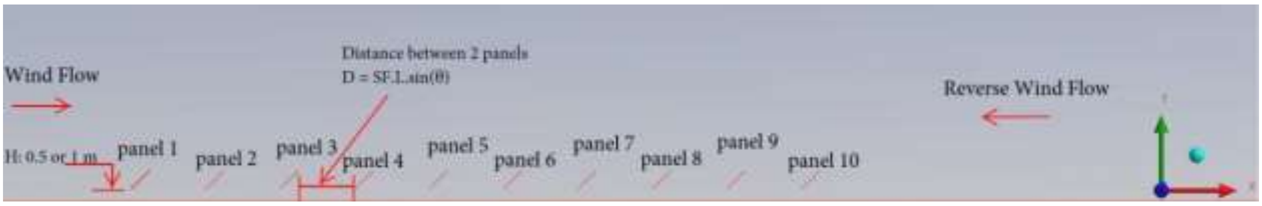

Fig. 4 CFD Panel Set up in ANSYS FLUENT

Horizontal distance D between the panels is taken as the shortest distance from the end projection of a panel to the nearest edge of the next panel. This distance is related to the panel length L, inclination angle θ and a spacing factor SF as given in the next equation.

$$D = SF \cdot L \cdot \sin(\theta) \tag{8}$$

where spacing factor (SF) is calculated in practice by companies through an optimization process so that shadowing of panels within a time range of target during daytime is eliminated in order to increase energy production; horizontal distance (D) is the distance between front most panel's end and posterior panel's start; L is the length of the panel; θ is the inclination angle of the panel is determined in order to maximize energy production. CFD panel set up is presented in Figure 4.

In this study, 2 different clear front heights from the ground, 3 different panel lengths, 5 different spacing factors between the panels, 6 different inclination of panels (IoP) and lastly normal and reverse wind flows are considered resulting in 360 CFD analysis cases in total, where the results are all documented in the thesis of (Uslu, 2014). These parameters are selected as shown in Table 3.

Table 3. Considered Parametric Study Values

	Parametric Values
H, Clear Front Height (m)	0.5 - 1.0
L, Panel Length (mm)	1000 - 2500 - 5000
SF, Spacing Factor	1 - 2 - 3 - 4 - 5
θ Inclination of Panel – IoP (˚)	7.5 - 15 - 22.5 - 30 - 37.5 - 45
Wind Flow Direction	Forward - Reverse

The wind speed of 40 m/s is chosen, since this value practically provides the target design wind speed for most regions in USA as specified by ASCE 07/10. The reason for the choice of 2D analysis is due to the nature of computation power needed to carry out 3D analysis for consecutively placed panels for 360 different cases of CFD analysis, and furthermore the reliability of results for angle of wind attacks in normal and reverse wind flow directions for a solar farm.

In these simulations, inclination of panels has been observed to have the largest effect on the wind loads acting on solar panels, where panel inclination is actually chosen according to the latitude of solar farm to be constructed. Small changes in panel inclination are observed to result in significant changes in wind loads. Using lower inclination angle usually decreases the drag, lift and moment coefficients. However, designer should be careful when using an inclination angle less than 15˚ for which sheltering effect is observed to be reducing. Spacing factor has also a major impact on wind loads, but this parameter is also mostly a fixed value chosen as a result of the latitude of the solar farm, in order to avoid shadowing of the panels.

In this paper, the panel length that appears to be the only independent parameter with regards to the latitude location of the solar farm will be discussed in detail, while the rest of the influence of other parameters is available in (Uslu, 2014). By the way, clear distance from the ground is also an independent parameter, but it has minor effect on the wind loads compared to the level of influence of the rest of the parameters considered in this study.

Discussion on the influence of panel length will be presented for the following case: clear height from ground H is taken as 0.5 m, spacing factor SF is set to 3.0, and inclination of panel IoP is considered as 22.5˚. For the normal flow direction, the normal force coefficient on the first panels under varying panel lengths is very close to each other (Figure 5). Furthermore, it is also observed that increasing the panel length from 1.0 m to 2.5 m or 1.0 m to 5.0 m results almost the same level of slight increase on normal force. A similar observation also holds for the normal force experienced by the succeeding panels. The normal force coefficients at 9th panel are observed to be very close to each other under varying panel lengths, except than a slight increase for 1.0 m panel length. Physical reason behind these changes is due to the sheltering effect provided by longer panels onto the succeeding panels.

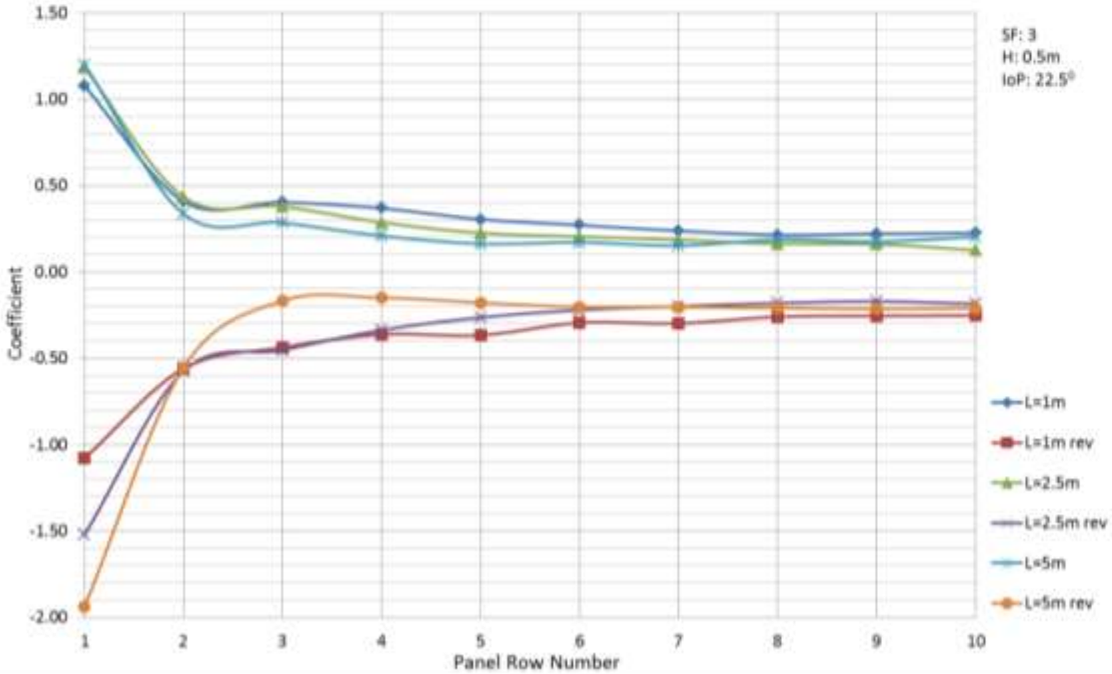

Fig. 5 Normal Force Coefficients on Panels for Panel Lengths 1 m, 2.5 m, 5 m

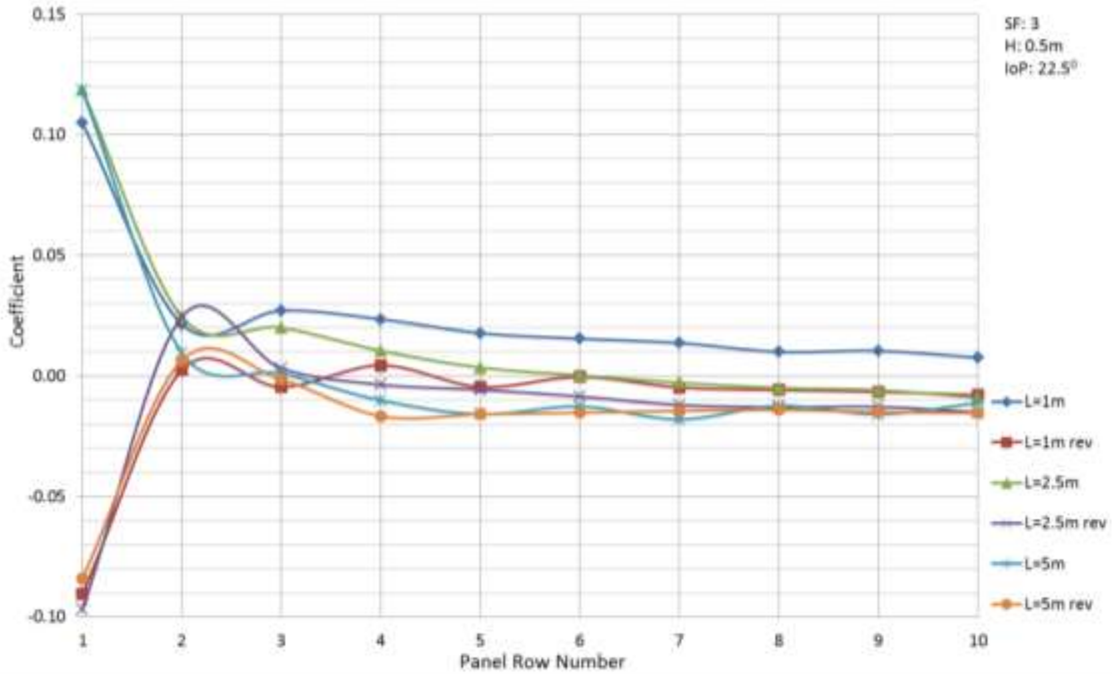

Fig. 6 Moment Coefficients on Panels for Panel Lengths 1 m, 2.5 m, 5 m

For the case of reverse wind flow, a totally different picture arises for the first panels in **오류! 참조 원본을 찾을 수 없습니다.**6. It is observed that as the panel length increases from 1.0 m to 2.5 m, normal force increases close to 50%, and as panel length increases from 1.0 m to 5.0 m, drag coefficient almost doubles. As the panel length increases, the reverse wind flow finds a much larger obstruction surface, thus a larger volume of wind has to pass underneath the panel through a fixed clear front height of 0.5 m. As the panel length reduces, the amount volume in this regards finds it easier to pass underneath the panel through 0.5 m gap. This physical action completely reverses trend right after the second panel. It is also important to see that the normal force on the second panel is the same for all panel lengths. The normal force on the 9^{th} panel for all panel lengths also get very close to each other. The sheltering effect for 5 m panel length is the largest and for 1 m panel length is the lowest. With regards to the discussion on moment coefficients, for both cases of wind flow directions, it is observed that only the very first panel facing the wind experiences the largest moment actions, and the succeeding panels experience diminishing moment actions that may very well be ignored.

3. CONCLUSIONS

Inclination of panels and then the spacing factor between the panels are the most influential parameters in designing a solar farm, where both of these parameters are solely determined from the latitude location of the solar farm, and thus they are in most cases not free parameters to choose. In this paper, only the influence of panel length is presented due to this restriction.

It is observed that panel length has major impact on the wind loads acting on solar panels. Although the drag, lift and moment coefficients are nearly the same for the normal wind flow direction for 1 m and 5 m panel lengths, in the reverse wind flow direction, the drag and lift coefficients almost double for the first row panels, when panel length increases from 1 m to 5 m; thus, special attention is needed with regards to the design of especially first row panels when panel length increases.

Although not presented in this paper, with regards to the influence of panel inclination and spacing factor, the changes in these parameters have also significant influence on the sheltering provided through the solar farm as documented by (Uslu, 2014). For spacing factor parameter, influence on first row is small, but the rest of the couple of panel rows experience significant variations. For panel inclination parameter, not just the first panel row, but the first couple of panel rows should be carefully designed for both forward and reverse wind flow directions.

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