April 2013

Experimental investigation of wind effect on solar panels

Ayodeji Abiola-Ogedengbe
The University of Western Ontario

Supervisor
Kamran Siddiqui
The University of Western Ontario

Graduate Program in Mechanical and Materials Engineering

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

© Ayodeji Abiola-Ogedengbe 2013

Follow this and additional works at: http://ir.lib.uwo.ca/etd

Part of the Aerodynamics and Fluid Mechanics Commons, Civil Engineering Commons, Energy Systems Commons, and the Other Mechanical Engineering Commons

Recommended Citation
http://ir.lib.uwo.ca/etd/1177

This Dissertation/Thesis is brought to you for free and open access by Scholarship@Western. It has been accepted for inclusion in Electronic Thesis and Dissertation Repository by an authorized administrator of Scholarship@Western. For more information, please contact tadam@uwo.ca.
EXPERIMENTAL INVESTIGATION OF WIND EFFECT ON SOLAR PANELS

(Thesis format: Integrated Article)

by

Ayodeji Abiola-Ogedengbe

Graduate Program in Engineering Science
Department of Mechanical and Materials Engineering

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master in Engineering Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

©Ayodeji Abiola-Ogedengbe 2013
Abstract

Photovoltaic Solar Panels for electricity generation are outdoor low-rise structures that are vulnerable to damage by the wind. The existing building codes do not contain information about the impact of the wind on these structures and hence do not provide comprehensive guidelines to mitigate such impact. The present study is a contribution to the ongoing efforts to codify the wind loading on solar panels. In this study, experimental investigations were conducted on the scaled model of a ground-mounted solar panel structure whose surface is geometrically similar to an inclined flat plate and mounted on three-legged support. The panel comprises of gaps, which divide it into an array of 24 smaller units. The objective of this study is to determine the wind pressure distribution on the panel and characterize the flow dynamics around it. The pressure measurements were conducted through taps connected to pressure transducers for both head-on (0°, 180°) and oblique (30°, 150°) wind directions with the panel inclined at 25° and 40°. The results indicate that larger inclination angles increased the wind forcing on the panel. At a panel inclination of 25°, velocity fields of the wind approaching head-on at 0° were captured to examine the flow field using particle image velocimetry (PIV) technique. The mean and turbulent velocities around the panel are computed and presented. The results indicate that the gaps between each unit of the panel influenced the wind loading pattern on the solar panel.

Keywords

Wind Engineering, Wind Tunnel Testing, Solar Panels, Pressure Test, Particle Image Velocimetry (PIV), Photovoltaic
Co-Authorship Statement

This is an integrated-article thesis which contains two articles included as chapters. The author of this thesis is the primary author of both articles. The article in Chapter 2 is co-authored by Dr. Horia Hangan and Dr. Kamran Siddiqui who were supervisors on the research conducted and advised on the writing. Chapter 3 is an article co-authored by Dr. Kamran Siddiqui and Dr. Horia Hangan who were supervisors for the research and advised on the writing.
Acknowledgments

I give thanks to God, who enabled me to complete this thesis.

I am grateful for the financial support of my supervisors; Dr. Kamran Siddiqui and Dr. Horia Hangan. Dr. Siddiqui dedicated countless hours to edit my drafts and provided valuable feedbacks. During the course of my research work, I am fortunate to have met Dr. Girma Bitsuamlak and Dr. Aly Sayed whose timely contributions ensured that I did not give up on this work when I could. I am grateful to Ahmed Elatar; a friend whose support I have always counted on since the beginning of my studies and through my experiments.

I am grateful to my mom, grandma and siblings, thousands of miles away for their enduring love and supports. To those I call friends here in London; your supports have been immeasurable – my housemates, friends in church and school. Thank you. Special thanks to Jennifer Ehiwario for the support and encouragements through the challenges and the success of this work.

Also, I will acknowledge friends at the Teaching Support Center – Nanda Dimitrov and Nadine Le Gros for their trainings and personal advice which helped me to navigate the challenges of graduate life in Western.

To everyone who contributed to my work and life in Western University, I am grateful.
# Table of Contents

Abstract ............................................................................................................................... ii
Keywords ............................................................................................................................ ii
Co-Authorship Statement................................................................................................... iii
Acknowledgments .............................................................................................................. iv
Table of Contents ................................................................................................................ v
List of Tables ................................................................................................................... viii
List of Figures .................................................................................................................... ix
List of Appendices ............................................................................................................ xii
Nomenclature ................................................................................................................... xiii

Chapter 1 ............................................................................................................................. 1
  1 General Introduction ...................................................................................................... 1
    1.1 Background ............................................................................................................. 1
    1.2 Motivation ............................................................................................................... 5
    1.3 Objectives ............................................................................................................... 6
    1.4 Thesis Layout ......................................................................................................... 7
    1.5 References ............................................................................................................. 7

Chapter 2 ........................................................................................................................... 10
  2 Experimental investigations of wind effect on a standalone photovoltaic structure.... 10
    2.1 Introduction ........................................................................................................... 10
      2.1.1 Background ............................................................................................... 10
      2.1.2 Literature review ....................................................................................... 11
    2.2 Experimental Details ............................................................................................. 15
      2.2.1 Model and instrumentations ........................................................................ 15
List of Tables

Table 1-1: Percentage Blockage of the BLWT 1 and BLWT 2 by the solar panel model ............... 7
List of Figures

Figure 1-1: Vertical profile of wind approaching a solar panel........................................................... 3

Figure 1-2: Solar panel damaged by strong wind in Taiwan [5] ............................................................ 3

Figure 2-1: Image of the 1/10 scaled model of the PV structure built with aluminum (a) front view (b) back view................................................................................................................................. 15

Figure 2-2: Tap Layout on the model of the PV structure. There are 64 taps on each surface of the model shown by the open circles........................................................................................................ 16

Figure 2-3: Experimental setup of the pressure test in the wind tunnel............................................ 17

Figure 2-4: Mean wind velocity profile measured in the wind tunnel compared with the NBCC open terrain velocity profile........................................................................................................ 18

Figure 2-5: Illustrations show (a) the inclined solar panel and the approaching wind, (b) the various angles and directions of the wind relative to the model during the test................................. 20

Figure 2-6: Illustration of normal, lift and drag force coefficients....................................................... 20

Figure 2-7: Validation of pressure test by results by comparing the \( C_p \) on the model at 30\(^\circ\) inclination with the results of Fage and Johanssen [1] on a 29.85\(^\circ\) inclined flat plate............. 21

Figure 2-8: Contour map of \( C_p \) across the PV structure shows centre similarity at 0\(^\circ\) wind direction ....................................................................................................................................................... 22

Figure 2-9: Plots compare the effects of the gaps on the \( C_p \) across the panel for both the 25\(^\circ\) (left) and 40\(^\circ\) (right) inclined panel at 0\(^\circ\) wind direction................................................................. 23

Figure 2-10: Plots shows that the smooth wind exposure (Exp 2) increases the \( C_p \) across the panel for both the 25\(^\circ\) (left) and 40\(^\circ\) (right) inclined panel at 0\(^\circ\) wind direction. ................................................................. 23

Figure 2-11: Contour plot of \( \Delta C_p \) at reverse head-on wind direction affirms that the largest net positive pressure occurs at the leading edge (LE) ................................................................. 24
Figure 2-12: Comparison of Cp across the solar panel with and without the inter-panel gaps for 25° (left) and 40° (right) panel inclination. The wind approaches the model head on, at 180°........... 25

Figure 2-13: A comparison of the Cp on the model inclined at 25° (left) and 40° (right) for two different exposures. Wind approaches the model head on, at 180°............................................................ 25

Figure 2-14: Plots show the effect of inclination angle when the wind approaches head on at 0° (left) and 180° (right). The Cp was generally higher on the panel at 40° than 25° at both head on wind angles. .................................................................................................................................... 26

Figure 2-15: Contour plot of pressure distribution (Cp+) over the panel inclined at 25 degree when the wind approaches at 30°. ............................................................................................................... 27

Figure 2-16: Cp plots across the left and right halves of the model with the wind flowing from 30° angular directions and the model inclined at 25°. The pressure distributions are not similar on both sides at this wind direction................................................................. 27

Figure 2-17: Cp plots across the left and right halves of the model with the wind flowing from 30° angular directions and the model inclined at 40°. The pressure distributions are not symmetrical for both sides at this wind direction........................................................................................................... 28

Figure 2-18: Cp plots across the left and right halves of the model with the wind flowing from 150° angular directions and the model inclined at 25°. The pressure distributions are not similar on both sides at this wind direction...................................................................................................... 29

Figure 2-19: Cp plots across the left and right halves of the model with the wind flowing from 150° angular directions and the model inclined at 40°. The pressure distributions are not similar on both sides at this wind direction...................................................................................................... 29

Figure 2-20: The drag coefficients C_D and lift coefficients C_L on the panel due to wind impacting the panel head on at angles 0° (left) and 180° (right)........................................................................................................ 30

Figure 3-1: A 3D Model of the Photovoltaic Table tested in the Wind Tunnel ...................... 39

Figure 3-2: Setup of the Particle Image Velocimetry Flow Measurement in the Wind Tunnel..... 39
Figure 3-3: The vertical profile of the mean wind velocity ............................................................ 41

Figure 3-4: Illustration of the four Measurement Planes showing the shadowed region and the vertical profile of the approach wind. ........................................................................................................ 43

Figure 3-5: Vector Plot of the Mean Velocities at each grid point for the four measurement planes labeled (a) Section I (b) Section II (c) mean vertical velocity Section II (d) mean streamwise velocity at section II, (e) section III (f) mean vertical velocity Section III (g) mean streamwise velocity at section III, and (h) Section IV at \( \text{Re}_L = 4 \times 10^6 \). ............................................................................................... 48

Figure 3-6: Profile of the mean velocity at various spatial locations in all measurement sections across the photovoltaic panel for \( \text{Re}_L = 4 \times 10^6 \) (o) and \( \text{Re}_L = 1 \times 10^7 \) (*). ........................................................................... 51

Figure 3-7: Vector Plot of the Turbulent velocities at each grid point for the four measurement planes labeled (a) Section I (b) Section II (c) Section III and (d) Section IV at \( \text{Re}_L = 4 \times 10^6 \). .......................... 54

Figure 3-8: Profiles of the stream-wise RMS turbulence intensity at various spatial locations in all measurement sections across the photovoltaic panel for \( \text{Re}_L = 4 \times 10^6 \) (o) and \( \text{Re}_L = 1 \times 10^7 \) (*). 56

Figure 3-9: Profile of the cross-stream RMS turbulence intensity at the four spatial locations in all measurement sections across the photovoltaic panel for \( \text{Re}_L = 4 \times 10^6 \) (o) and \( \text{Re}_L = 1 \times 10^7 \) (*). 58

Figure 3-10: Schematic of pressure tap locations relative to gap between panels. ▲, tap upstream of the gap; Δ, tap downstream of the gap........................................................................................................ 61

Figure 3-11: Cp values along the panel at \( y/W = \pm 0.99 \) (left) and \( y/W = \pm 0.67 \) (right). ●, without the gap, ▲, with the gap. “1” represents the pressure tap located upstream of the gap, and “2” represents the pressure tap located downstream of the gap. ........................................................................... 61

Figure 3-12: Cp values along the panel, near its mid-plane at \( y/W = -0.01 \) which coincides with the plane of the velocity measurement. “1” represents the pressure tap located upstream of the gap, and “2” represents the pressure tap located downstream of the gap. ........................................................................... 62
List of Appendices

Appendix 1: License agreement to re-use Figure 1-2 ................................................................. 71

Appendix 2: Uncertainty calculation for PIV measurements .................................................... 72
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area (m²)</td>
</tr>
<tr>
<td>B</td>
<td>Panel breadth (m)</td>
</tr>
<tr>
<td>C</td>
<td>width of upstream structure (m)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Coefficient of drag</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Coefficient of lift</td>
</tr>
<tr>
<td>$C_N$</td>
<td>Normal force coefficient</td>
</tr>
<tr>
<td>$C_{pi}$</td>
<td>Coefficient of pressure at tap, i</td>
</tr>
<tr>
<td>$C_{p+}$</td>
<td>Pressure coefficient at upper surface of panel</td>
</tr>
<tr>
<td>$C_{p-}$</td>
<td>Pressure coefficient at lower surface of panel</td>
</tr>
<tr>
<td>$\Delta C_p$</td>
<td>Differential pressure coefficient of taps on opposite surfaces</td>
</tr>
<tr>
<td>$\Delta C_{pi}$</td>
<td>Differential pressure coefficient at tap, i</td>
</tr>
<tr>
<td>D</td>
<td>Drag (N)</td>
</tr>
<tr>
<td>H</td>
<td>Height (m)</td>
</tr>
<tr>
<td>$h^+$</td>
<td>hole</td>
</tr>
<tr>
<td>L</td>
<td>Length (m)</td>
</tr>
<tr>
<td>$L_F$</td>
<td>Lift (N)</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Pressure at tap, i</td>
</tr>
<tr>
<td>$P_{ref}$</td>
<td>Reference pressure</td>
</tr>
<tr>
<td>q</td>
<td>Dynamic pressure (Pa)</td>
</tr>
</tbody>
</table>
Re_L \quad \text{Reynolds number (length based)}

S \quad \text{Distance between structures (m)}

u \quad \text{velocity (m/s)}

u_g \quad \text{gradient wind velocity or speed (m/s)}

u_{\text{ref}} \quad \text{reference velocity (m/s)}

W \quad \text{Width (m)}

x/L \quad \text{normalized position on panel length}

y/W \quad \text{normalized position on panel width}

z \quad \text{height from the ground (m)}

z_g \quad \text{gradient height (m)}

z_\alpha \quad \text{Ground surface roughness (m)}

z_{\text{ref}} \quad \text{reference height (m)}

\textbf{Greek Symbols}

1/\alpha \quad \text{Terrain exponent}

\alpha \quad \text{Inclination angle (°)}

\beta \quad \text{Latitude of site (°)}

\rho \quad \text{Density (kg/m}^3\text{)}

\textbf{Abbreviations}

ABL \quad \text{Atmospheric Boundary Layer}

ASCE \quad \text{American Society of Civil Engineers}
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLWTL</td>
<td>Boundary Layer Wind Tunnel Laboratory</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Telluride</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal-oxide-semiconductor</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>FiT</td>
<td>Feed-in-tariff</td>
</tr>
<tr>
<td>LE</td>
<td>Leading edge</td>
</tr>
<tr>
<td>NaN</td>
<td>Not-a-number</td>
</tr>
<tr>
<td>NBCC</td>
<td>National Building Code of Canada</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>TE</td>
<td>Trailing edge</td>
</tr>
</tbody>
</table>
Chapter 1

1 General Introduction

1.1 Background

The global electricity generation is projected to be almost double from 18.8 trillion kWh in 2007 to 35.2 trillion kWh in 2035 [1] to meet the electricity demand caused by two major factors; population growth and the improved lifestyle particularly in the developing countries. Fossil fuels, in particular coal and natural gas have been projected as the dominant energy source contributing almost 70% of the energy supply for the power generation to meet this growing demand [1]. This heavy reliance on fossil fuel in particular on coal to meet the growing energy demand, will have severe consequences on the global climate which could jeopardize the living environment of the future generations. Due to the harmful effects of fossil fuels on the environment, there is a growing concern on limiting their use and switching to clean alternative energies such as solar, wind and biomass, to meet the energy needs and reduce the consumption of fossil fuels and their carbon footprint.

One of the widely commercialized solar energy technologies is the photovoltaic (PV) solar cells that convert the sunlight directly into electricity. The solar cells are made of semiconductors materials such as Silicon or Cadmium Telluride (CdTe). Sunlight contains energy particles called photons. When light from the sun incidents on a solar cell, the photons are absorbed by the semiconductor material. The absorbed photons knock electrons ($e^-$) out of their atoms in the semiconductor creating a hole ($h^+$). The design of the semiconductor diode ensures that the released electrons move in a single direction and produces electricity [2]. Sets of solar cells are combined to make a solar panel. They are installed by fastening them to a framework or support structure as standalone units or as an array of PV units. A standalone solar PV structure may also comprise of several individual panels arrayed as a single structure.

In Canada, the Government of Ontario is promoting the use of solar panels for electricity generation through the Feed-in-Tariff (FiT) program. The FiT program provides incentives
to homeowners, farmers and businesses to generate electricity from solar panels and sell it
to the electricity grid at a much higher rate than the rate at which they buy electricity from
the hydro utility. For example, for less than 10 kW setups, the government pays 54.9cents
and 44.5cents per kilowatt-hour for rooftop solar panels and ground-mounted solar panels
respectively [3]. Last year, the private sector in Ontario reportedly spent over C$9 billion in
renewable energy projects [4]. This is an indication of the economic importance of solar
panel investments. One of the main obstacles in the wide spread commercialization of PV
solar panels is its cost, which resulted in a long payback period. The risk factor associated
with its partial or complete damage by wind further elevates the financial risk of the
customer and hence, its marketing and commercialization. Currently, the impact of wind
loading on the PV panels (stand alone or array format) is not well understood and hence, the
associated damage risk is not well quantified. Furthermore, this lack of information also
hinders the aerodynamic design improvement of the solar panels to mitigate this risk.

Solar panels are commonly installed with an inclination angle equal to the latitude of the
site. Studies have shown that as wind impinges on an inclined solar panel, it flows around it
and induces unequal pressure on its two surfaces. The surfaces of the solar panels thereby
experience the drag force in the direction of the wind flow and lift force in the direction
perpendicular to the flow. These forces produce the torque. The drag force is expressed
as, \( D = \frac{1}{2} \rho u^2 AC_D \), while the lift force is given as, \( L_F = \frac{1}{2} \rho u^2 AC_L \),
where, \( \rho, u, A, C_D \) and \( C_L \) refers to air density, wind velocity, projected area, coefficients of
lift and drag, respectively. Torque is expressed as the product of force and the displacement
vector from the point where the force is applied. These forces are depicted schematically in
Figure 1-1. In case of strong winds these forces and the resulting torque could damage the
solar panel structure. An example of such damage is shown in Figure 1-2 where a severe
typhoon damaged the solar collectors in Taiwan [5]. Although there are practical limits to
the protection of solar panels in extreme wind situations, nonetheless proper understanding
of the wind phenomenon at the site can help prevent solar panel damages by more frequent
wind gusts.

Wind engineering researches developed from the need to protect high-rise, typically slender
structures from wind damage. The investigations conducted on the World Trade Center are
one of the early projects that defined wind engineering studies [6, 7]. Wind codes have been developed as receptacles for the knowledge obtained from wind engineering. Investigations of wind effect on low-rise structures are now common [8-10] and they have provided valuable data into various wind codes. However, existing wind codes do not yet have a guide for solar panels. The *National Building Code of Canada* states that structures should be designed so that they can withstand pressures and suction from the strongest wind generated in that area based on wind statistics.

![Figure 1-1: Vertical profile of wind approaching a solar panel.](image)

![Figure 1-2: Solar panel damaged by strong wind in Taiwan [5]](image)

Engineers can determine the wind loading using any of the three methods proposed by the *American Society of Civil Engineers* in the ASCE 7-05 manual [11]. The three methods are known as the simplified method, analytical method and wind tunnel method. The simplified ASCE Method is not suitable to estimate the loads on solar panels because they are not
enclosed structures. Eligible structures for the analytical method should not be on a site for which wake buffeting will be considered [12]. Solar Panels do not meet the requirements for both the simplified and analytical methods. This is because solar panels are known to be susceptible to vortex shedding and wake buffeting [13, 14]. Therefore, studies of wind effect on solar panels are conducted using wind tunnel method or Computational Fluid Dynamics (CFD). However, the accuracy of CFD modeling relies on its validation with the experimental data. The common techniques used in wind tunnel studies of structures are flow visualizations, hot-wire anemometry, local pressure taps and high frequency force balance [15].

Full scale test of the solar panel in the wind tunnel is not practical due to the blockage restrictions. Wind tunnel testing guidelines set by ASCE [11] requires that the projected area of the model should be less than 8% of the wind tunnel cross sectional area to avoid blockage effects. Similitude between model and full-scale prototype must also be satisfied.

Some notable wind tunnel studies on solar panels are available in the open literature. The report of Miller and Zimmerman [17] on their study commissioned by the United States Department of Energy indicates that fences and barriers can be used to reduce the wind load on solar arrays and end plates are suitable to reduce large loads on individual panels. The researchers arrived at this conclusion after observing that structures upstream of the flow shelter those located downstream. The sheltering effect on downstream panels was also observed by Radu et al. [18] from the wind tunnel studies of solar panel models installed on the roof of a scaled model of a five-storey building. Using CFD studies, Shademan [13] estimated that for a solar panel inclined at 30°, beyond a critical spacing of $S/C = 1$ (where $S$ is the distance between both structures and $C$ is the width of the upstream structure), the sheltering effect of an upstream structure on the wind load of the downstream panel becomes negligible.

Kopp et al. [14] tested an array of six slender solar modules in the wind tunnel to determine the location of the highest system torque and the critical loading angle of the wind approaching the panel. A full scale wind load test on solar panels installed on a pitched roof was conducted by Geurts et al. [19] to measure the maximum lift force on the solar panel
based on the pressure coefficient, $\Delta C_p$. They recommended $\Delta C_p$ value of -0.3 for the upward acting force and 0.2 for the downward acting force on a single solar panel on the rooftop. The uplift force on the model of a solar panel fitted with water heaters in Taiwan was measured in the wind tunnel by Chung et al. [5]. They recommended fitting a guide plate on the solar panel to reduce the wind uplift.

Past studies also examined the impact of specific geometrical features on the wind loading of solar panels. Radu and Axinte [20] studied the wind load on the structural supports of solar panels and the load transmitted to building attics on which the solar panels were installed. Wu et al [21] tested the model of a heliostat, which has similar geometry as a solar panel. They examined the effect of the gap of various sizes on the facet of the heliostat. They determined that while the gaps do increase the wind loading on the structure, they need not be considered for structural designs of the system, as they constitute very small fraction of the total area.

Various wind studies measured the wind load on specific geometrical shape of solar modules. Each test and its conclusions were therefore unique to the configuration of the solar structure tested [13-20]. Few studies investigated the dynamics of the wind flow around the solar panels [13, 14 and 18].

1.2 Motivation

Presently, the existing building codes do not provide guidelines for the estimation of wind load on solar structure of any geometry. This gap is due to the fact that research work on wind load on solar structures remains on-going and largely inconclusive in a generic sense for solar structures. In some practice, the code’s provisions for building roof are adapted to estimate the load for solar panels. Aside from a few panel-installed parallel to the pitched rooftops, many solar panels exist as complete structures with their own support system. As solar energy structures are becoming more popular, there is a need to expedite research to understand the impact of the wind on them. A relative quick way to undertake this research is through CFD. However, undertaking comprehensive investigation through CFD is computationally very expensive and wind tunnel tests remain an acceptable method. There
are past studies, which estimated the wind loads on these structures, but the results of those studies cannot be applied in a generic sense since they are based on specific geometries. Also, the mechanisms by which the wind interacts with the solar structures remain an under-explored research area. The present work is a contribution to the on-going efforts in establishing a standard knowledge base of the wind loading and their effect on typical solar panels.

1.3 Objectives

The objectives of this research are:

1. To study and measure the load exerted by the wind on a solar panel structure with regards to its geometrical configurations and the wind environment into which it is situated.
2. To investigate and understand the mechanisms by which the wind impacts and affects a panel structure.

This research provides a framework to investigate wind effect on PV panels and also provide benchmark data that could be used by the industry, for building code improvement as well as for the CFD modeling.

The design of the PV solar panel used in this study was based on the panels produced by First Solar (the industrial partner on this project). The standalone model has been geometrically scaled down to 1/10\textsuperscript{th} of its full-scale dimensions. At this scale, blockage ratio of the model and various tests sections of the wind tunnel are shown in Table 1-1. As the table shows, the blockage recorded at the smallest cross section in the wind tunnel is 3.4%, which is less than the ASCE requirement. For dynamic similarity, it is required that the Reynolds numbers at full scale and model scale must be equal. For Reynolds number to be equal at this scale, a velocity 10 times the field velocity is required in the wind tunnel, which is difficult to produce in the available wind tunnel. However, it has been shown that at sufficiently high Reynolds Number (> 2 \times 10^4), pressure coefficient at any location on a bluff body is independent of the Reynolds number [16]. Thus, the Reynolds number
similarity is no longer necessary. This satisfies another requirement for the minimization of Reynolds number effect on pressure and forces for the wind tunnel tests [10].

Table 1-1: Percentage Blockage of the BLWT 1 and BLWT 2 by the solar panel model

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Smallest Cross Section (m²)</th>
<th>Blockage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLWT 1</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>High Speed Test Section BLWT 2</td>
<td>8.5</td>
<td>1.44</td>
</tr>
<tr>
<td>Low Speed Test Section BLWT 2</td>
<td>20</td>
<td>0.61</td>
</tr>
</tbody>
</table>

1.4 Thesis Layout

The first chapter is an introduction to the research work, which provides a description of the problem that this work aims to address, and the justification for it. A brief historical narrative of wind engineering and the methodologies it employs are given followed by a short review of past literatures on the subject of the research. The motivation and the objectives of this work are then presented. Chapter two is a report of the pressure measurement conducted on the scaled model of a solar panel. The chapter presents the quantitative results of the pressure force exerted on the solar panel by the wind. The third chapter presents the experimental investigation into wind flow across the solar panel. Both qualitative and quantitative descriptions of the flow are presented with the aim of understanding the dynamics of the flow that contributes to the wind loads measured in chapter two. The fourth chapter presents a general conclusion based on the measurements reported in chapters two and three in a bid to understand how the wind flow impacts and affects the given solar panel.

1.5 References


Chapter 2

2 Experimental investigations of wind effect on a standalone photovoltaic structure

2.1 Introduction

2.1.1 Background

Photovoltaic (PV) or solar modules are becoming increasingly popular for domestic as well as industrial electricity generation. Advancements in solar energy technology continue to improve their overall efficiency and long-term reliability. These improvements are motivated by the continual depletion of other sources of energy especially fossil fuels, which are also source of increasing environmental concerns. Among various alternative sources of energy, PV modules are the fastest growing and most popular globally with worldwide annual investments exceeding US$100 billion [1]. PV modules are vulnerable to wind damage; nevertheless there are no provisions of wind load in building standards and codes to design these structures. This is a major motivation for this study.

The most common PV modules are rectangularity shaped flat plates usually referred as PV panels or PV structures. They may be inclined at an angle or installed parallel to the horizontal. Ground mounted PV modules are commonly inclined for optimal energy extraction while flat rooftop mounts are usually horizontal driven by constraints other than energy generation. When inclined, the latitude of the location where they are installed usually determines the inclination angle, $\alpha$ of the module’s plate. This is to allow the PV panel to capture maximum amount of the sun’s light. The common rule of thumb is $\alpha = \beta \pm 15^0$ (where $\beta$ is the location’s latitude and $+15^0$ is for the winter season while $-15^0$ is for the summer season) for adjustable PV modules. The prototype of this study, located in south-western Ontario ($\beta = 40^0$) is fixed at an angle, $\alpha = 25^0$ to the horizon. However, at these inclinations, the wind forces of lift and drag can be tremendously higher.
Wind load on structures is usually estimated experimentally in the wind tunnel or using computational fluid dynamics (CFD). When carefully and well carried out, the results from experiments can be used to validate the results obtained using CFD (for example, see Meroney [2]). To conduct a successful wind tunnel test, the structure is subjected to the same wind conditions that exist on the physical site. This involves matching the mean wind velocity profile, the turbulence intensity profiles and the ratio of the test structure’s height to ground surface roughness (Jensen number, $H/z_o$) on the site with that in the wind tunnel. The common instrumentation for load measurements in wind tunnel experimentation includes load cells and pressure transducers. While load cells measures the overall load on a structure, the pressure transducer instrumentation, also adopted in the present study, can be used to measure the pressure load at several points simultaneously on upper and lower surfaces of the PV panel. In this study, the net pressure coefficients across the solar panel are measured and the effects of variable parameters such as wind terrain exposure, inclination angle and the gaps between individual panels are presented to produce the forces acting on the PV panel.

2.1.2 Literature review

The nature of the load induced on a structure by the wind depends, largely on the characteristics of the wind such as its direction, speed, exposure conditions and the shape of the structure. Ground mounted PV modules, which are the subject of this study, are typically low-rise structures. They are therefore immersed within the lowest region of the atmospheric boundary layer (ABL) where the flow of the wind is highly unpredictable due to the intense turbulence actions [3]. The mean velocity profile of the wind in this region is largely influenced by the ground roughness. Although in nature, for any particular terrain, roughness cannot be accurately determined owing to variations in the size, shape, distribution and density of the roughness elements (trees, grasses, buildings, etc.) [4]. In wind experiments, a power law is commonly used to characterize the mean wind velocity profile and turbulence characteristics [5]. The exponent of the power law is dependent on the terrain (roughness) and provided in various codes such as the National Building Code of Canada (NBCC) [6] and its American counterpart from the ASCE [7].
The wind loads on various types of solar modules had been measured in the wind tunnels and reported in the literature. Early examples include the wind load experimental tests on arrays of flat plate PV panels, commissioned for testing by the US Department of Energy [8]. The results of the test show that upstream flow sheltering elements such as barriers and fences can be used to reduce the wind loads on PV arrays while end plates were found most suitable in reducing the large load measured on the panels at the corners of the array. Radu et al. [9] tested an array of solar panel models, mounted on the roof of a scaled five storey-building model in a boundary layer wind tunnel. Their tests were performed on three different building models with flat roof. Each building had different kind of attics. The results showed that the front row panels had higher pressure and force coefficients. These front row panels shelter the panels behind them from the wind action. In subsequent studies, the lift forces on the support structures of these panels were also investigated [10]. They concluded that using appropriate building attics could reduce wind loads on PV modules installed on building rooftops. Wood et al. [11] also tested PV modules mounted on the flat rooftops of a scaled building model in a wind tunnel. The pressure on the scaled building roof was simultaneously measured which agreed well with the full-scale results of the Texas Tech experimental building. In the test, they varied both the clearance height between the rooftop and the panel and the lateral spacing between the panels. Except at the leading edge where slight variation was recorded, their results showed no significant changes in the overall pressure on the modules from the variation of the clearance height and panel spacing.

An array of six parallel slender solar modules were tested by Kopp et al. [12] in the wind tunnel at a Reynolds number of $7.6 \times 10^4$ and wind speed of 15m/s. They determined the location of the highest system torque on the modules as well as the critical loading angle of the approach wind. A linearized model to predict the peak system torque of these modules was subsequently presented. Full-scale outdoor experiments were carried out on rooftop-mounted PV modules by Geurts et al. [13] to investigate lift forces on the panels. The PV modules were mounted parallel to a pitched roof. The wind speed and wind direction were measured using a cup anemometer and directional vane position at a height of 10m above the ground. The pressure difference at the top and underside of the panel were measured to determine the wind load. The maximum lift force on the solar panel, which is dependent on
wind direction, corresponded with a pressure coefficient, $C_p$ value of -0.55. A differential pressure coefficient, $\Delta C_p$ value of -0.3 for the upward and 0.2 for the downward acting force was recommended for a single solar panel on such rooftops.

A 1/3 scaled model of a sun-tracking PV modules [14] were tested by Velicu et al. [15] in an open circuit wind tunnel. The drag and lift forces on the PV modules were measured using force transducers. The results showed that the force coefficients on the PV panel increased as the panel tilt angle increased from 0° to 90°. The force coefficients also increased as the wind velocity increased. Chung et al. [16] conducted wind tunnel tests to investigate the uplift on flat-plate PV collectors used for water heating. The PV modules were inclined at an angle of 25°. The pressure measurements were taken along the centerline of the panel surfaces. A guide plate was attached to the test model of the PV collector to reduce the wind uplift. The effectiveness of this guide plate was investigated by varying its angular orientation at wind velocities ranging from 20m/s to 50m/s. The results showed that the differential pressures coefficients $\Delta C_{pi}$ were highest at the front, lower edge of the panels, similar to observations by Shademan [17]. The $\Delta C_{pi}$ reduced downstream of the panel and steadily rise towards the rear edge. The heights of the panel from the ground were varied during the tests. The result showed that the differential pressure coefficient, $\Delta C_{pi}$ close to the rear edge increased with the height, thereby reducing the wind uplift. The least wind uplift was measured when the guide plate was installed at an angle of 90° to the wind direction at the rear of the PV collector.

Wind load tests have also been conducted on other photovoltaic geometries. Hosoya et al. [18] tested four different parabolic dish models in a boundary layer wind tunnel. One model used a high-frequency force balance to measure lift and drag dynamic wind loads. A second model used strain gages to measure the pitching moment. The third plastic model used pressure taps to measure the pressure distribution over the dish surface. Arrays of the PV dish collectors were tested using the fourth model. This fourth model had several dummy mock-ups surrounding the instrumented model. A turbulent boundary layer wind flow representing an open country was simulated for the tests. The tests were conducted at Reynolds number less than 50,000 and there was minimal effect of turbulence intensity on the mean horizontal force. The flow was visualized using titanium dioxide smoke, which
showed that the flow stagnated at the windward face of the concentrator while separation was observed at the leeward face.

Shademan [17] carried out wind load investigations on standalone and array PV modules using CFD. Six configurations of the standalone solar panel were tested. Their results were validated with the experimental results of a flat plate [19]. The results showed that as the inclination angle of the standalone panel increased, the drag force induced by wind load also increased. The tests were conducted at three wind angles of 30°, 60° and 90°. In all of the cases, maximum drag was produced at wind angle of 90° and on the panels at the bottom row of a standalone system. Panels at the front row of arrays shelter other panels from the wind, therefore reducing the drag force experienced by the sheltered panels. However, Shademan [17] identified the critical spacing between the panels, beyond which the drag force reduction on the downstream panels was not significant.

Meroney [2] used different turbulence models to simulate the flow around PV modules. The study estimated the drag, lift and overturning moments on the solar panel support systems. Static pressure results on the panels at 0° and 180° wind angles showed higher pressures at the front rows of panels, consistent with the experimental observations of Radu et al. [9] and Shademan [17].

Wu et al. [20] investigated the effect of the gaps between panels on the surface of a heliostat was investigated through CFD and experimental tests. Heliostats have similar geometrical configurations as PV panels. A 1/10 scaled model of the heliostat was used for the wind tunnel experiments, similar to the length scale of this current study. The computational model of the CFD test was greatly simplified due to the huge cost of modeling the flow near the gap. Both the experimental and numerical results showed that the overall wind load slightly increased with an increase in the gap size. The CFD results showed that this increase was due to the flow acceleration through the gap, which caused a decrease in the static pressure at the gap’s outlet. Therefore the overall drag force increased due to the resultant decrease in the leeward pressure coefficient.

This present study was experimentally conducted in a boundary layer wind tunnel. The aim is measure the wind load on the PV module, and to determine the effect of varying parameters such as wind exposure and inclination. A comparison between the load on the
model and its flat plate equivalent (without the gaps between individual panels) will also be presented.

2.2 Experimental Details

2.2.1 Model and instrumentations

The model of the PV structure for this study was built at the University Machine Shop of the University of Western Ontario using aluminum. It is a one-tenth scaled replica of its prototype and it is fitted with a weighted disc at its support to give it the required balance. The full scale prototype of this model consists of 24 individual panels in a 4 x 6 array which are held together with hinges thereby leaving gaps between each panel. The top plates of the PV structure model were machined from two flat aluminum plates and grooves were machined to create the gaps between each of the 24 panels. Its overall dimensions are 0.72m x 0.24m x 0.17m and the support legs are spaced 0.3m apart. The model is adjustable for different inclination angles during the tests. To connect the instrumentation, a total of 128 holes or “taps” were drilled on the two aluminum plates that made up the upper and lower flat surfaces of the model. Vinyl pressure tubes of length 50.8cm and diameter 0.24cm were sandwiched between the aluminum plates, with one end connected to the taps and the other end extending out from both sides of the model. This ensures that the upper and lower surfaces of the model were not obstructed with the pressure tubes. The model is shown in Figure 2-1 and the layout of the taps on the surfaces of the model is shown in Figure 2-2.

Figure 2-1: Image of the 1/10 scaled model of the PV structure built with aluminum (a) front view (b) back view.
Figure 2-2: Tap Layout on the model of the PV structure. There are 64 taps on each surface of the model shown by the open circles.

The free end of each pressure tube then connects to another tube of the same length and diameter via short brass restrictors. These restrictors add the needed damping to the pressure instrumentation system. The free ends of these other tubes then connect to 8 scanners devices manufactured by Scanivalve Corporation. Each scanner connects to 16 pressure tubes from the model.

The scanner devices are transducers, which convert the pressure, read at each tap to an electrical signal and transmit it to the wind tunnel’s computerized data acquisition (DAQ) system. Each of the eight scanners is connected to eight separate channels on the wind tunnel DAQ system. A ninth channel on the wind tunnel DAQ connects to pitot-tube devices placed near the model to measure the approach velocity and the free stream velocity at an undisturbed height above the model. The pressure data, in volts collected during the tests were analyzed and transformed to coefficient of pressure, $C_p$ values. The setup of the model in the wind tunnel is as shown in Figure 2-3.
2.2.2 Flow development

The study was conducted for an open terrain wind exposure scaled for testing models up to 1:20. The pressure tests were conducted at the Boundary Layer Wind Tunnel Laboratory (BLWTL 1) at the University of Western Ontario. This is an open return wind tunnel, which has a length of 33m and a width of 2.4m. Its height varies from 1.5m at the entrance to 2.15m at the test area. This wind tunnel is able to simulate wind profiles at the typical scale of ~1:400. Since the PV structure is a low-height structure, it is physically immersed within the lowest 10m of the atmospheric boundary layer (ABL). Therefore only the flow at this region was modeled in the wind tunnel. The wind profile representative of the open terrain exposure for this test was obtained after various trials. The flow conditioning elements used to model the flow include three isosceles triangular spires, rectangular roughness blocks, a fence and a bar trips. These elements were positioned upstream of the model. The ensuing wind velocity profile closely matches the mean wind velocity profile in an open terrain exposure obtained from the NBCC using the power law given as:

\[ u(z) = u_g \left( \frac{z}{z_g} \right)^{1/\alpha} \]  \hspace{1cm} 2.1
Where $u_g$ is the gradient wind speed, and $1/\alpha$, the terrain dependent exponent is given as 0.16 in the NBCC [22]. The values of $u_{ref}$ and $z_{ref}$ for the terrain were determined following the reverse method used by Shademan [18]. The comparison of the NBCC profile and the measured profile from the experiment are shown in Figure 2-4. The wind tunnel tests were repeated with the ground roughness elements removed to create a different smooth exposure. Therefore the effects of the ground roughness on the wind load across the photovoltaic panel were investigated.

![Mean wind velocity profile measured in the wind tunnel compared with the NBCC open terrain velocity profile.](image)

Figure 2-4: Mean wind velocity profile measured in the wind tunnel compared with the NBCC open terrain velocity profile.

2.2.3 The pressure tests

During the test, the instrumented model was placed on the test section area, downstream of the tunnel (see Figure 2-3). The model stood on a pneumatic controlled turntable and connected to the wind tunnel pressure DAQ system as earlier described. The wind tunnel was operated at the full speed ($15 m/s$) of the tunnel with a velocity scale of nearly 1:1. This gives a time scale of 1:10. Each test was conducted for 6 minutes, which represents one hour at full scale, and also statistically-long enough to obtain accurate mean of the pressure readings. The tests were carried out for 36 wind angles at 10-degree intervals from 0° to 350°. However, the results from many of the oblique wind angles were discarded during analysis owing to the perceived influence of the vinyl tube instrumentations, which extends
from both sides of the model. The results presented here include those for two head on
angles, 0° and 180° and two oblique angles, 30° and 150° (Figure 2-5).

2.3 Results and Discussions

As previously described, a total of 128 measurement taps are situated on both surfaces of the
PV model. The non-dimensional pressure coefficient values at various taps, on both surfaces
of the model, \( C_{p(i)} \) were obtained by converting the pressure measured at each tap \( (P) \) to the
dimensionless form, using the dynamic pressure, \( q \) at the reference height according to
equation 2.2.

\[
C_{p(i)} = \frac{P_{i} - P_{ref}}{q}
\]  

Where \( q = \frac{1}{2} \rho V_{ref}^2 \), and the reference height is taken at the lowest point of the inclined
model’s surface. The pressure coefficient values on the model’s surface, which faces the
approaching wind are considered as positive, \( (C_{p+}) \) while the pressure coefficients measured
on the opposite surface are negative \( (C_{p-}) \). Therefore, the net pressure \( (\Delta C_{p}) \) is the aggregate
of the pressure coefficient values on adjacent taps on the model. Such that

\[
\Delta C_{p} = C_{p+} + C_{p-}
\]  

The net pressures exert normal forces on the panel. The normal force coefficients \( C_{n} \) on the
surface, \( s \) of the panel can be obtained by integrating \( \Delta C_{p} \) over the breadth, \( B \).

\[
C_{N} = \frac{1}{B} \int_{0}^{B} \Delta C_{p}(s)ds
\]  

The lift coefficient is the vertical component of the normal force coefficient, while the drag
coefficient is the horizontal component such that \( C_{L} = C_{N} \sin \alpha \) and \( C_{D} = C_{N} \cos \alpha \) as
depicted in Figure 2-6.
Figure 2-5: Illustrations show (a) the inclined solar panel and the approaching wind, (b) the various angles and directions of the wind relative to the model during the test.

Figure 2-6: Illustration of normal, lift and drag force coefficients.
2.3.1 Validation of pressure results

The experimental results of Fage and Johanssen [19] have been a suitable benchmark for studying the pressure load due to flows over inclined flat plates. To validate the results from this study, the coefficient of pressure on the PV model without the gaps and inclined at 30° was compared with the coefficient of pressure results on the flat plate experiment of Fage and Johanssen [19] at almost similar inclination angle of 29.85°. The wind flows head on, at angle 0° to the test models in both experiments. The leading edge (LE) is the lower end of the plate, while the trailing edge (TE) is the higher end. The plot of the result in Figure 2-7 shows that the $C_p^+$ at the upper surfaces of the PV model closely matches the flat plate result. At the back of the panel however, the $C_p^-$ on the PV model was slightly lower than the flat plate’s. This can be attributed to the influence of the three-legged support structures, which are absent in the experimental flat plate model of Fage and Johanssen [19].

Figure 2-7: Validation of pressure test by results by comparing the $C_p$ on the model at 30° inclination with the results of Fage and Johanssen [1] on a 29.85° inclined flat plate

2.3.2 Head on, forward wind direction (0°)

The CFD tests by Shademan [17] on a solar panel of similar geometry had shown that the panel is critically loaded when the wind impacts it head-on at 0°. The pressure distributions on the upper surface of the model at this wind direction show symmetry about its mid plane. The contour plot of $C_p^+$ for a 0° wind direction on a panel inclined at 25° is shown in Figure 2-8.
Figure 2-8: Contour map of $C_p$ across the PV structure shows centre similarity at $0^\circ$ wind direction.

The pressure distributions on either half of the panel are similar at this wind angle as can be seen from the contours. The contour plot also reveals that the magnitude of the pressure coefficients is largest at the leading edge where the flow first impinges on the model. Shademan [17] had previously identified these locations as critical loading areas on PV panels of similar geometry at $0^\circ$ wind direction. The pressure induced by the wind on the surface reduces towards the trailing edge of the model.

Effects of the gaps: The effect of the gaps on the pressure distribution on both surfaces of the model was studied by plotting the $C_p$ values across plane A with and without the gaps. The plot for both panels inclined at $25^\circ$ and $40^\circ$ is shown in Figure 2-9. The figure shows that there is a near uniform pressure distribution on the lower surfaces of the model exposed to the wake. On the upper surface however, the $C_p$ values are highest at the leading edge and reduces towards the trailing edge. Due to the influence of the gaps, the $C_p$ values on the upper surface are reduced on all taps, with the exception of a location near the trailing edge. This tap is situated downstream of the nearby gap unlike other taps which are situated downstream of the gap. The presence of the gaps therefore makes each panel on the structure behave as separate flat plates; with the highest pressure at their leading edges and lowest at the trailing edges.
Figure 2-9: Plots compare the effects of the gaps on the Cp across the panel for both the 25° (left) and 40° (right) inclined panel at 0° wind direction.

Effects of terrain exposure: The test results for the open terrain exposure were compared with a smooth exposure to investigate the effect of exposure change on the pressure values. The plots in Figure 2-10 show the comparison. The pressure measured at the leading edge of the panel in open terrain exposure was used as the reference pressure to normalize pressure measurements at both exposures.

Figure 2-10: Plots shows that the smooth wind exposure (Exp 2) increases the Cp across the panel for both the 25° (left) and 40° (right) inclined panel at 0° wind direction.

The plots show that the pressure coefficients of the smooth exposure are generally higher than that for the open terrain exposure, which is likely due to the higher wind velocities
within the surface boundary layer under smooth exposure. This effect is more pronounced on the model at 40° inclination.

2.3.3 Head on, reverse wind direction (180°)

When the flow approaches the solar panel head-on in the reverse direction, i.e., 180° degree, the lower surface now faces the approaching wind while the upper surface lies in the wake of the wind flow. The pressure distribution on the lower surface, which now faces the oncoming wind, is also similar across the mid plane. The largest net positive pressures due to the wind are exerted on the leading edge of the model as seen in Figure 2-11. This edge had been the trailing edge in the 0° wind direction. This result is similar to previous observations and suggests that when the wind approaches the PV structure head on, the largest net pressure across the panel occurs at the leading edge of the panel.

Figure 2-11: Contour plot of ΔCp at reverse head-on wind direction affirms that the largest net positive pressure occurs at the leading edge (LE).

Effects of the gaps: The comparison of the $C_p$ plot across the PV panel, for the 180° wind angle with and without the gaps can be seen in Figure 2-12. There is a uniform distribution of the $C_p$ across the upper surface in the wake region, most especially at 40° inclination without the gaps. At this configuration, the upper surface is better sheltered from the wind flow. The $C_p^+$ on the lower surface of the panel is highest at the leading edge of the model.
Effects of the terrain exposure: Similar to the results obtained for the $0^\circ$ wind direction; there is a significant effect of exposure on the wind loading. The smoother terrain causes an increase in the net pressure across the model. Consistent with previous observations, at $40^\circ$ inclination; model was more sensitive to the change in the exposure as seen on the right in Figure 2-13.

Figure 2-13: A comparison of the Cp on the model inclined at $25^\circ$ (left) and $40^\circ$ (right) for two different exposures. Wind approaches the model head on, at $180^\circ$. 
2.3.4 Effect of the inclination angles at head on wind direction

In many cases, the various plots of the pressure coefficients show that when the wind flowed head on, the pressure across the panel was greater at 40° inclination. The plots of Figure 2-14 specifically illustrate the effect of inclination angle.

![Figure 2-14: Plots show the effect of inclination angle when the wind approaches head on at 0° (left) and 180° (right). The Cp was generally higher on the panel at 40° than 25° at both head on wind angles.](image)

2.3.5 Oblique wind directions (30° and 150°)

When the wind approaches the model at angles other than 0° and 180°, there is no similarity on the pressure distribution over the panel. This can be seen from the contour plot of $C_p^+$ over the model (Figure 2-15). Plots of $C_p^+$ and $C_p^-$ values on the upper and lower surfaces respectively, taken from either half of the model are shown in Figure 2-16. These plots also show that the pressure distribution is not symmetrical at the panel’s mid plane.
Figure 2-15: Contour plot of pressure distribution ($C_p$) over the panel inclined at 25 degree when the wind approaches at 30°.

Figure 2-16: $C_p$ plots across the left and right halves of the model with the wind flowing from 30° angular directions and the model inclined at 25°. The pressure distributions are not similar on both sides at this wind direction.

Effects of gaps at 30° wind angle: The plots of Figures 2-16 and 2-17 on both halves of the model show that the influence of the gaps on the pressure distribution is different on either side due to the asymmetry. On the right half, the gaps increase the $C_p^+$ on the upper surface, but reduces it on the lower planes of the left half, similar to when the wind approached the model head on.
Figure 2-17: Cp plots across the left and right halves of the model with the wind flowing from 30° angular directions and the model inclined at 40°. The pressure distributions are not symmetrical for both sides at this wind direction.

Similar $C_p$ distribution pattern was obtained for 330° wind angle, but in an inverted sense to the pattern of Figure 2-17. This is the effect of the reversed orientation of the model to the wind. The inversion of the $C_p$ distribution pattern was obtained for all cases with and without the gaps and was consistent with the results for all oblique angles from 10° through 80°.

Effects of gaps at 150° wind angle: At 150° degree, the wind approaches the panel from the reverse directions to the 30°, whereas the upper surface lies in the wake of the flow and has $C_p^-$. The plots of the $C_p^+$ and $C_p^-$ on the lower and upper surfaces respectively on both half of the model are shown in Figures 2-18 and 2-19. The effects of the inter-panel gaps are evident on all plots for both inclinations.
Figure 2-18: Cp plots across the left and right halves of the model with the wind flowing from 150° angular directions and the model inclined at 25°. The pressure distributions are not similar on both sides at this wind direction.

Figure 2-19: Cp plots across the left and right halves of the model with the wind flowing from 150° angular directions and the model inclined at 40°. The pressure distributions are not similar on both sides at this wind direction.

2.3.6 Drag and lift forces

The coefficients of drag and lift forces at the mid-plane of the model are presented in 2-20 for the critical case, when the wind impacts the PV model head on in open terrain exposure.
The drag coefficients $C_D$ and lift coefficients $C_L$ on the panel due to wind impacting the panel head on at angles 0° (left) and 180° (right).

The net drag forces on the panel were negative for the 0° wind direction and positive for the reverse 180° direction. The gaps between individual panels increased the negative lift coefficients on the model. The exception occurred at the 40° inclination, when the wind approaches at 180°, the gaps increased the positive lift. At a wind angle of 0°, there is a negative lift (or counter-lift) on the model compared to an overall positive lift when the wind flows in the reverse (180°) direction. The counter-lifts were reduced by the influence of the gaps. However, at a wind angle of 180°, the lift on the panel with gaps inclined at 40° was higher than the lift in all other cases. The lift and drag forces were higher in the 40° inclined panel than the 25° panel when the wind is at 180° direction.

## 2.4 Conclusions

The flow of wind over the model of a photovoltaic structure exposed to wind flowing over an open terrain has been investigated. The results show that the net pressures across the panel, induced by the wind are greater in smoother exposures. It was also found that the inter-panel gaps on the PV structure affect the overall load on the panel. The investigations conducted by Wu et al. [20] on similar geometry for a heliostat had indicated that the influence of the gaps can safely be ignored for structural design of the structure since their gaps were small compared to the overall size of the heliostat. The size of this particular PV panel however, is significantly smaller than the heliostat of Wu et al. [20]. Hence, the gaps should be considered for structural designs of the structure. However, an optimal size for the
gaps was not investigated in this study. The lift and drag forces due to the wind were higher when the panel inclination angle was increased from $25^\circ$ to $40^\circ$. Hence, we can recommend that all energy-related factors being equal, these PV panels should be installed at $25^\circ$ rather than $40^\circ$.

2.5 Acknowledgement

The authors will like to acknowledge financial contributions from Ontario Centre for Excellence, First Solar Inc. and the University of Western Ontario. Special thanks go to Dr. Girma Bitsuamlak for his valuable comments.

2.6 References


Chapter 3

3 Experimental investigations of wind effect on a standalone photovoltaic table: particle image velocimetry measurements.

3.1 Introduction

Photovoltaic (PV) modules (also known as solar panels) are systems that convert solar radiation into electricity. These systems are gaining popularity as a clean substitute to fossil fuels for power generation. It is the fastest growing technology among the current renewable systems. For instance, in 2011, the PV installations around the world increased by 75% from the previous year compared to wind (20%), biodiesel (15.6%) and hydro (2.7%) [1]. In Canada, the government of Ontario provides incentives to homeowners, farmers and businesses to generate electricity from PV solar panels. These small power producers can sell surplus electricity to the power grid at a much higher rate than the rate at which they buy electricity from the hydro utility [2].

A typical PV panel is comprised of PV cells and is attached to a support frame and hence appears as a relatively thin flat surface, inclined at an angle approximately equal to the latitude of the site. They are either mounted on rooftops or on the ground and are exposed to the wind which exerts forces on them. These forces in the form of drag or lift or a combination of both could have detrimental effects on the panel in the presence of strong winds. Drag and lift forces on a flat panel could result from the shear stress at the panel’s surface or the difference in pressure induced by the wind on both sides of the panel or a combination of both phenomenon. It is important to have a better knowledge of the wind flow field around PV panels, which would help in getting an improved understanding of the interaction of the wind field with the panel structure and its potential effects. This will lead to the development of techniques to mitigate the damage risk.

Several numerical and experimental studies have been conducted to investigate the wind
forcing on PV panels. Radu et al. [3] investigated the wind forcing on both an isolated and an array of model PV panels on the roof of a model building at the length scale ratio of 1:50 in a boundary layer wind tunnel. The flow behavior was visualized using smoke, which revealed increased turbulence on the roof, where the solar panel was installed. They found that the lift force was dominant regardless of the wind direction. The force magnitude was found to be large on the standalone panel compared to the array of panels due to the wake effects produced by the upstream rows of panels on the downstream rows in the array.

Wood et al. [4] conducted wind tunnel experiments to measure the wind load on a 1:100 scaled model of a solar panel array mounted on a model building. The influence of solar panel’s presence on the building roof pressure was investigated and it was found that the solar panel increased the net pressure on the building roof only at the leading edge and reduced the net pressure at other locations on the building roof. Chung et al. [5] compared two different methods for reducing the lift force on the solar panel used for water heating whose geometry is similar to that of the PV panels. The first method used a guide plate attached to the front edge of the panel and the second method involved changing the vertical height of the panel. Their results indicated that the guide plate, when attached to the panel at a normal orientation to the direction of the oncoming wind was more effective in reducing the wind-induced lift on the panel.

Shademan and Hangan [6] investigated the wind load on solar panels at different inclination angles and wind directions by simulating the flow around solar panels using computational fluid dynamics (CFD). The panel inclination angles of 30° and 35° and the wind directions of 30°, 60° and 90° were considered, where 90° wind angle represented the case when the wind approaches the panel head on. They found that at 90° the panel experienced the maximum drag, as expected. Results also showed the development of corner vortices at 30° and 60°. The optimal distance for drag force between sets of panels in tandem arrangements was also investigated. It was found that the drag force on the panel increased when the distance between the front and downstream panels was greater than the panel width.
The flow of fluid around a flat plate at zero and non-zero angles is a suitable reference for the study of the flow field around PV panels. At zero angular inclinations, the drag force on a flat plate is primarily due to the shear stress on the surface of the plate induced by the flowing fluid. At sufficiently large inclination angles, the contribution of surface shear stress to the drag force becomes negligible as the force due to the pressure differential across the surface becomes significant. Several past studies on the flat plate had been concerned with the investigation of the flow separation and vortex shedding from the plate’s leading and trailing edges. The Strouhal number is a non-dimensional measure of the frequency at which vortices are shed from a body immersed in a flowing fluid. Fage and Johansen [7] studied the airflow over an inclined flat plate at 18 different inclination angles, which ranged from 0.15° to 90°. It was observed that at inclination angles greater from 5.85°, the force exerted on the plate was primarily due to the pressure differential across the surfaces. The velocity of the flow was measured through hot wire anemometry. At inclination angles greater than 14.85°, they observed that the underside of the plate had a uniform pressure distribution. At inclination angles between 30° and 90°, the Strouhal number of vortex shedding was approximately constant at 0.148. They used smoke to visualize the flow patterns over the plate and found that the longitudinal spacing of the vortices shed from the plate increased with an increase in the inclination of the plate.

Kiya and Arie [8, 9] numerically investigated the flow across flat plates inclined at 60° subjected to a uniform flow [8] and a shear flow [9]; the latter depicting a practical form of wind flow of an atmospheric boundary layer. The shear flow was modeled by including a shear parameter, to the flow equation (the shear parameter equals to zero for uniform flows). The study was conducted using the discrete vortex approximation method. The results showed that the periodic vortex shedding occurred at both the leading and trailing edges of the plate. In uniform flow, the shed vortices were in the same direction as the time-averaged lift force on the plate. In the shear flow however, the patterns of the shed vortices were similar to that of ordinary Karman Vortex Street formed behind a symmetric bluff body in a uniform flow. The Strouhal Number of the shed vortices in uniform flow was 0.14 and in the shear flow, it increased linearly with the shear parameter. As the shear parameter was increased, the time averaged drag coefficient on the plate also increased.
Analytical models have also been used to predict the pressure distribution on the surface of inclined flat plates. The experimental pressure results of Fage and Johanssen [7] are usually considered as a benchmark to validate results from various analytical model predictions. The analytical model developed by Wu [10] and Abernathy [11] produced satisfactory comparison with the experimental data when the plate was inclined at $30^\circ \leq \alpha \leq 90^\circ$. At lower inclination angles, the pressure results predicted from these models failed to agree well with the experimental results. Yeung and Parkinson [12] however, modified the models by introducing a circulation parameter to generate new boundary conditions from previously documented experimental data by Abernathy [11]. The results from their model agreed well with the experimental data for angles as low as $5.85^\circ$ up to $90^\circ$ [12].

The Particle Image Velocimetry (PIV) technique was utilized by Lam & Leung [13] to study the flow over an inclined flat plate at angles of $20^\circ$, $25^\circ$ and $30^\circ$. They observed continuous vortex shedding from the leading and trailing edges of the plate. The vortices shed from the trailing edge of the plate possessed higher strength than those shed from the leading edge when measured at the same location, downstream of the plate. Also the patterns of the vortices were asymmetrical about the horizontal mid of the plate, parallel to the ground and their convection speed, downstream of the plate was estimated to be 80% of the free-stream flow velocity.

While the flat plate flow problem is a classical one, there are nonetheless several unreported aspects of the physical nature of the flow, especially at non-zero inclination angles in non-uniform flows. Also, unlike the flat plate, the PV panel includes other auxiliary supports and features, which does affect the flow field. Therefore, the results from an inclined plate would not completely describe the physics of the flow field around a PV structure.

The above literature review shows previous research that had been conducted on the flow over flat plates and various solar modules. The effect of the shear in the wind is found to be significant to the induced load. However, the primary focus of most available literature on solar panels was the estimation of the wind load, while little information is available on
the quantitative description of the flow field or the turbulent properties of the flow around them. It has also been found from the literature search that the wind affects various PV structures differently based on their location, geometrical features and orientation. The present investigation will examine the evolution of the wind flow towards and across the model of a photovoltaic structure in an open terrain environment. The mean and turbulent velocity vectors from this study will be used to provide both quantitative and qualitative description of the flow field. These will help to understand how the wind interacts and exerts its forces on ground mounted photovoltaic structures of this geometry.

3.2 Experimental Details

3.2.1 Experimental setup and facilities

The experiments were conducted in the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario. The tunnel is of the open-circuit type with an overall length of 33m, width of 2.4m and height which varies from 1.5m at the flow inlet to 2.15m at the test section. This wind tunnel has a maximum wind speed of 9.2 m/s and it is regularly used to study wind flow and pressure on buildings and other structures at geometric scales in the range of 1:400 to 1:600 [14]. The model of the PV structure used in this study was a 1/10\textsuperscript{th} scaled version comprised of 24 individual panels mounted in the form of a $4 \times 6$ array with small gaps (1.3 mm) between the panels. The model was built from a 3.175mm thick aluminum plate and has the overall dimensions of 730 mm $\times$ 249 mm. Grooves of width 1.3mm were machined on the aluminum plates to mimic the 24 individual panels (see Figure 3-1). The model was mounted on a three-leg support, which allowed changing the inclination angle of the model from 25\degree to 40\degree. The experiments were conducted at 25\degree inclination angle of the PV panel. The model was placed on the wind tunnel’s turntable, which was situated 26 m from the inlet section of the wind tunnel. The model was painted with black color to prevent light reflections from its surface during the measurements. Light reflections are inimical to the experimental technique as they can bias the results during the processing of the experimental data. Likewise, the floor in the
immediate vicinity of the model and the walls of the tunnel within the field of view of the camera were painted in black.

Figure 3-1: A 3D Model of the Photovoltaic Table tested in the Wind Tunnel

Particle Image velocimetry (PIV) technique was used for measuring two-dimensional velocity fields. The schematic of the PIV setup for this study is shown in Figure 3-2. The PIV system used in the experiments comprised of a water-cooled dual head Class 4 Nd:YAG Laser with a wavelength of 532nm and a maximum output of 50mJ. Its laser head emits a 4mm diameter light beam. The light beam emitted by the laser head entered the wind tunnel through a 4.5mm hole drilled on the tunnel’s Plexiglas wall.

Figure 3-2: Setup of the Particle Image Velocimetry Flow Measurement in the Wind Tunnel.
A set of optics placed inside the tunnel was used to change the light beam direction and to form the light sheet. A 4 megapixel high speed CMOS Camera (Flare, IO Industries) with the resolution of 2052 × 2048 pixels was used to capture images of the flow. The camera was connected to an image acquisition system (Core DVR Express, IO industries). Image acquisition software installed on a computer was used to synchronize the camera and the pulse generator that controlled the timing of laser pulses as well as to control the recording of the images.

### 3.2.2 Description of the wind profile

To investigate the wind flow around low-rise structures in the wind tunnel, Tieleman [15] recommended that both mean wind velocity and turbulent intensity profiles must be carefully simulated especially at the leading edge of the structure. An empirical power law usually used to obtain the mean wind velocity \(U(z)\) profile is given as,

\[
U(z) = u_g (z/z_g)^{1/a}
\]

(3.1)

Where \(z_g\) is the gradient height— this is the height above the ground at which the influence of the ground roughness on the wind velocity can be neglected, \(u_g\) is the wind velocity at the gradient height, \(z\) is the height from the ground, and \(1/a\) is a terrain-dependent power law exponent, which is defined in various wind codes. The physical site for the actual solar modules is an open terrain exposure ‘C’ type in southwestern Ontario, Canada. The values of the power law parameters for this wind exposure were taken from the National Building Code of Canada (NBCC). Using the NBCC parameters, the power law exponent, \(1/a\) is given as 0.16 and the gradient height, \(z_g\) is 274 m, which gives a gradient wind speed of 42.5 m/s. Therefore the wind velocity profile for the location was obtained at full scale as,

\[
U(z) = 42.5(z/274)^{0.16}.
\]

(3.2)

Figure 3-3 compares the mean wind velocity profiles measured in the given wind tunnel with that obtained from equation (3.2). The results show that overall, both profiles matched reasonably well. Similarly, there is a power law relationship for turbulent intensity profile, which is given as,
\[ I(z) = c(z/10)^{-d}. \]  

3.3

Where, \( I \) is the turbulence intensity \([16]\) and the open terrain parameters \( c \) and \( d \) are obtained from the NBCC as 0.2 and 0.14 respectively.

![Figure 3-3: The vertical profile of the mean wind velocity](image)

The discrepancy is attributed to scale mismatch due to the fact that the wind tunnel is primarily designed for modeling the atmospheric boundary layer (ABL) typically at a scale of 1:400. Cochran \([17]\) and Marshall \([18]\) had identified scale mismatch as the cause of the observed turbulence discrepancies in wind tunnel studies of low-rise structures. Scaled models for low rise structures tend to be fairly large due to resolution and instrumentation limits. Therefore to accommodate the model size, only the lowest region of the ABL, i.e. the surface layer should be modeled. The modeled surface layer must be sufficiently thickened to obtain the correct wind exposures (turbulence intensities and turbulence scales) on the model. Scale mismatch has implications on experimental results and should be accounted for when it occurs. For example, Hua \([19]\) found discrepancies in the gust loading factors measured on aeroelastic models when compared with the full-scale results.
due to mismatch of the integral length scale of the turbulence. Also, mismatch of the turbulence intensity is the known cause of the underestimation of the surface peak pressure coefficients [17, 20, and 21] in wind tunnel model studies of low-rise structures. For low-rise structures, Tieleman [22] showed that the small-scale turbulence of the incident wind is a more important variable to match than the large scale ones as it poses relatively more effect on the drag and pressure forces on the structures. At a scale of 1:50 or less, obtaining a close match for the turbulence intensity profile in the wind tunnel is an issue of ongoing investigation in the wind engineering community [23]. Despite the scale mismatch, some studies have shown that the scaling effects are not too stringent on a 1/10\textsuperscript{th} model of a solar panel. Aly and Bitsuamlak [21] using similar wind profile as in the present study, showed that the mean wind load on solar panels are independent of the geometric scale in the range 1:10 to 1:50. Furthermore, the pressure coefficients obtained from the present 1/10\textsuperscript{th} scaled model agreed well with that obtained from the CFD simulations on a full scale PV panel [24]. These close agreements are due to the fact that the size of PV solar panels relative to the atmospheric boundary layer is small and hence the differences in the wind velocity at its leading and trailing edges are very small, even at the full scale.

The mean wind characteristics (mean velocities and turbulence) were physically modeled and conditioned to thicken the surface layer appropriately by using combinations of a turbulence grid, three vertical spires, vortex generators and a 304.8 mm fence at the inlet section of the wind tunnel. Various rectangular floor elements of heights 50.8 mm and 101.6 mm were used to simulate the appropriate surface roughness for the open terrain wind exposure.

3.2.3 Experimental procedure

To implement the PIV technique for velocity measurements, the flow in the wind tunnel was seeded with olive oil droplets of approximately 1 \( \mu \text{m} \) in diameter. As the wind tunnel was an open circuit type, seeding the wind tunnel was rather difficult. To ensure sufficient seeding in the measurement region, the oil droplets were introduced into the wind tunnel at two different locations; one locally, close to the test section and another upstream of the
model. The latter seed location was 4m upstream of the model where the seed was delivered through a 50mm diameter hose. The local seeds were introduced 1m upstream of the model with a 25 mm diameter, 200mm long PVC pipe which has eight 4mm diameter holes distributed on its surface to locally spread out the oil droplets over the model.

In order to capture the flow behavior around the model at high resolution, PIV measurements were performed in the mid-vertical plane at four locations around the model, hereinafter referred to as sections I, II, III and IV (see Figure 3-4). The PIV measurement plane over the model was slightly offset from the model’s mid-plane to coincide with the locations of 4 pressure taps through which pressure measurements had previously been carried out.

![Figure 3-4: Illustration of the four Measurement Planes showing the shadowed region and the vertical profile of the approach wind.](image)

Due to the orientation of the light sheet, shadow was formed in the wake region of the panel where images of the seed particles cannot be obtained due to very low signal-to-noise ratio (SNR). Similarly, the width of the panel also created its projection in the camera image plane hence affecting the SNR of seed particles’ images in the projection region. Therefore, velocity vectors could not be computed in these regions and hence they were excluded from subsequent analysis. These regions are marked as the shaded sections in Figure. As the figure shows, in the wake region, only the velocity field above the trailing edge of the panel was captured. The measurements were made at the free stream velocities of 8.8 m/s and 3.2 m/s. The corresponding Reynolds numbers based on the panel length (L = 249 mm) and the velocity of incident flow at panel eave’s height are $1 \times 10^7$ and
4×10^6, respectively. In each section, images were acquired at a rate of 53 Hz for three minutes, capturing 9600 PIV images to obtain 4800 velocity fields.

The acquired images were visually inspected for adequate seeding before processing. To obtain instantaneous velocity field, the cross correlation technique was carried out on pairs of successive PIV images by correlating 48 × 48 pixels interrogation windows in the first image with the corresponding 96 × 96 pixels search windows on the second image of the image pair. The vector resolution was increased to 24 × 24 pixels by using a 50% overlap of the interrogation windows. As Figure 3-4 shows, most of the measurement sections (II, III and IV) contained shadowed and/or projection regions and due to the low SNR, cross-correlation technique generates false vectors in those regions that must be excluded. To exclude bad vectors in these regions, binary masks were created where zeros (0’s) correspond to the bad regions and ones (1’s) correspond to the good regions. These masks were applied to every velocity field in that measurement section and all velocity vectors in the bad regions were assigned as NaN (Not-a-number). In the next step, a scheme was used to detect any spurious vectors in the good regions and replace them with the median of the eight neighboring vectors [25]. Note that in the good regions that border the excluded sections, only the vectors in the good region were considered in the local median test. After replacing spurious vectors, all vectors were mapped to the grid point using Adaptive Gaussian Window interpolation.

The error (uncertainty) in the PIV velocity field was estimated to be about ±5.9 cm/s which is ±2.5% of the free stream velocity. The details of the error computation are provided in Appendix 1.

### 3.3 Results

#### 3.3.1 Mean velocities

The mean velocities were obtained by time-averaging the instantaneous velocities at a given grid point. The two-dimensional mean velocity fields in sections I, II, III and IV are presented in Figure 3-5 to get an overview of the mean flow behavior around the panel.
Figure 3-5: Vector Plot of the Mean Velocities at each grid point for the four measurement planes labeled
(a) Section I (b) Section II (c) mean vertical velocity Section II (d) mean streamwise velocity at section II,
(e) section III (f) mean vertical velocity Section III (g) mean streamwise velocity at section III, and (h)
Section IV at Reₗ = 4 x 10⁶.
In section I (Figure 3-5a), the flow is relatively uniform and in the streamwise direction indicating that the mean flow approaching the panel is undisturbed. In section II, the flow impinges on the panel at its leading edge and flows past the panel while attached to its top surface; its mean directions begin to change according to the inclination of the panel. At the underside of the panel, the flow is directed towards the ground; an indication of likely flow separation at the underside of the panel. The projection of the panel in the camera image does not allow full measure of the velocity fields in the immediate vicinity of the underside of the leading edge. The plot also shows that the flow near the ground accelerates, which is likely due to the area reduction, as expected. In section III, shown in figure 3-5e, the flow above the panel in general, remains attached to the top surface of the panel and aligns with the panel as it continues to flow over the panel surface. As mentioned in the experimental setup section, the panel structure has slots that represent the gap between individual panels (see Figure 3-1). These slots serve as the through pass for the flow resulting in local flow divergence in the vicinity of these slots. In figure 3-5e, the mean streamwise velocity of the flow over the panel appears to reduce. This is due to the reason that upstream of the panel, the resultant velocity comprised almost entirely of the streamwise component. When the flow approaches the panel, its inclination induces a vertical velocity component, and hence the fraction of the streamwise velocity in the resultant velocity vector is reduced. Figure 3-5c shows that the vertical components of the mean velocities were negligible until the flow reached the vicinity of the panel. In figure 3-5f, very close to the surface, the magnitude of the vertical component of the mean velocity is very small and above this region, the vertical mean velocity magnitude increases and then reduces as the height increases. The vector field of the horizontal component of the mean velocity vectors at section III is shown in figure 3-5g. Figure 3-5h shows the mean velocity field in the wake region. Due to the shadow effects, velocity fields in wake region only above the trailing edge of the panel were captured. The flow recovers its mean streamwise direction shortly after leaving the trailing edge of the model.

The velocity fields in figure 3-5 provide a good qualitative perception of the two-dimensional mean velocity field over the panel. To obtain a better quantitative assessment of the mean flow behavior and its variation on and around the panel, the mean velocity profiles normalized by the free stream velocity at different axial locations are plotted in
figure 3-6 for both Reynolds numbers. Their locations based on x/L’ are: section I, -1.2 and -0.75; section II, -0.4, -0.2, 0.05 and 0.25; section III, 0.38, 0.51, 0.63, 0.77, 0.85 and 0.98; section IV, 1.2, 1.4 and 1.65. The plots show that further upstream of the panel, the mean streamwise velocity has a typical boundary layer profile. However, when approaching the panel, the flow near the ground accelerates. A plausible explanation for this trend is that as the flow impinges on the leading edge of the plate, it bifurcates, as the air under the panel has to flow through the narrow region bounded by the ground and the underside of the plate. This narrowing of the flow area accelerates the flow, which is evident in the velocity profile at the leading edge of the panel and underneath the panel at x/L’=0.05.

Furthermore, the flow approaching the panel faces relatively higher flow resistance due to the vertical projection of the panel, and hence it tends to find the path of least resistance which for the flow near the leading edge of the panel is the passage near the ground as mentioned above. Thus, the upstream flow as it approaches the panel tends to accelerate near the ground. These results indicate that the panel influences the upstream flow approximately from x/L’ =-1.3. The influence of the leading edge of the panel can be seen in the upstream profile plot up to x/L’ = -0.75; as the flow velocity can be seen to reduce in the plane of the panel’s leading edge. This trend is similar for both Reynolds numbers.

The profiles show the presence of a boundary layer generated on the top surface of the panel. There are two distinct regions in the profile shown. The mean velocity profiles show that with an increase in height, away from the surface, the mean velocity magnitude decreases (in the inner region) and then increases until it becomes equal to the free-stream velocity. In the inner region adjacent to the panel surface, the fluid layer has a strong streamwise velocity gradient. Above this layer in the outer region, the flow shows a gradual increase in the mean streamwise velocity with height. The inner region of strong velocity gradient is observable at x/L = 0.25 and 0.51. This is due to the acceleration of the flow through the slots on the panel. This accelerated inflow of air causes changes in the static pressure near the gap. A discussion of the gap effect is provided in section 3.5.2.
Figure 3-6: Profile of the mean velocity at various spatial locations in all measurement sections across the photovoltaic panel for $\text{Re}_L = 4 \times 10^6$ (o) and $\text{Re}_L = 1 \times 10^7$ (*).
Recently, Wu et al. [26] studied the effect of gaps between flat mirrors mounted on a heliostat used in central tower type concentrated solar thermal plant. They also observed the local acceleration of the flow at the gap and concluded that the effect of the gap is local and does not influence the overall load on the heliostat. Note that for their study, the ratio of gap to the mirror size was much larger than the typical ratio of the gap and the PV panel.

A sharp decrease in the mean streamwise velocity magnitude is observed in the wake region due to the flow separation. The vertical location in the mean velocity profile where the sharp decrease in the velocity magnitude starts could be considered as the upper edge of the flow separation region. The velocity profiles at different locations downstream of the panel indicate some wake expansion in the separation region downstream of the panel as expected however, the extent of the expansion is relatively limited. The results also show that the mean flow structure remains almost the same at both Reynolds numbers and hence independent of the Reynolds number in this range.

3.3.2 Turbulent velocities

The turbulent velocity at each grid point was obtained by subtracting the time-average mean velocity from the instantaneous velocity. The snapshots of the turbulent velocity fields in different sections are shown in Figure 3-7 to illustrate the behavior of the turbulent flow over the panel. The velocity map of the flow upstream of the panel (figure 3-7a) shows the typical structure of the turbulent flow, which contains eddies of various sizes. As the flow reaches the panel, (figure 3-7b) it shows relatively stronger velocity magnitudes. On the top surface of the panel, the roll up of eddies is evident and they are clearly shown over the length of the surface in figure 3-7c. The size of eddies rolling over the panel surface appears to be z/h≈0.5. Some indication of the flow separation is evident in figure 3-7d. The overshoot of the rolling eddy from the panel surface is also visible.
Legend

- 1.6 m/s

Legend

- 2 m/s
Figure 3-7: Vector Plot of the Turbulent velocities at each grid point for the four measurement planes labeled (a) Section I (b) Section II (c) Section III and (d) Section IV at \( \text{Re}_L = 4 \times 10^6 \).
The turbulent velocity fields over the panel also indicate the presence of large-scale turbulent structures above the rollup eddies whose size exceeds the physical span of the camera field of view and thus, cannot be resolved in the PIV velocity fields.

The profiles of streamwise turbulent intensities at different streamwise locations on and around the panel are shown in Figure 3-8. The plot shows that upstream of the panel in Section I, the streamwise turbulent intensity gradually increases from ground towards the free-stream region. This behavior is different from the classical turbulent intensity profile in wall-bounded flows where the turbulent intensity shows a decreasing trend away from the wall. A plausible explanation for this trend could be that the panel influenced the upstream flow. As discussed earlier, the panel influenced the upstream mean velocity field (see Figure 3-6). Although the mean velocity profiles did not show significant deviation from the typical boundary layer trend in Section I, the panel in this section could have influenced the turbulent velocity field. The turbulent velocity field in this section (Figure 3-7a) also shows strong vortices in the region away from the surface, indicating higher turbulence level in the free-stream region. The turbulent intensity magnitudes in the free-stream region are close to 0.2. The NBCC model for the open terrain predicted the streamwise turbulent intensity values in the range 0.2-0.25 in the region which is consistent with the present estimates.

The results in figure 3-8 also show that the streamwise turbulent intensity profiles remains almost the same as the flow approached the panel. This trend continued on the panel surface i.e. the streamwise turbulent intensity magnitude is relatively low at the surface and gradually increased towards the free-stream region. However, at the trailing edge of the panel, the turbulent intensity trend and magnitude changed. It is observed that the streamwise turbulent intensity significantly enhanced at the trailing edge with a peak magnitude of almost 0.4. This enhanced turbulent intensity was confined to a thin layer and its magnitude decreased sharply above this layer. This turbulence enhancement continued downstream of the trailing edge i.e. in the wake region. The enhancement of streamwise turbulent intensity is due to the flow separation.
Figure 3-8: Profiles of the stream-wise RMS turbulence intensity at various spatial locations in all measurement sections across the photovoltaic panel for $Re_L = 4 \times 10^6$ (o) and $Re_L = 1 \times 10^7$ (*).
Previous studies investigating the flow separation in other geometric configurations reported that the peak magnitude of turbulence is located at almost the same height as the separation point (e.g. see Hudson et al. [27]; Shaikh and Siddiqui [28]). The present results showed the enhanced turbulent intensity magnitudes at almost the same height as the trailing edge, which is consistent with these studies.

The profiles of the vertical turbulent intensity are plotted in Figure 3-9. The plot shows similar trends as that of the streamwise turbulent intensity. The plots of figure 3-8 and figure 3-9 showed that the magnitudes of streamwise and vertical turbulent intensities are quite comparable. Inside the inner region, at $x/L' = 0.25$ and $0.51$, the streamwise turbulence intensity first drops, then rises as expected in a boundary layer (see Figure 3-8). The initial drop in turbulence intensity is due to the presence of the gaps at the locations. At other locations away from the gaps, the effect is not seen. The vertical turbulence intensities of Figure 3-9 show the same trend at the locations of the gap.

### 3.4 Discussions

#### 3.4.1 Mean and turbulent velocities

The results presented above indicate that a panel influences the flow field around. Results in Figure 3-5 and Figure 3-6 show that the upstream mean velocity field within the distance equal to the panel height is influenced by the panel approximately up to a distance of $x/L' \sim 1.3$. The mean flow near the ground accelerates as it approaches the lower end of the leading edge and becomes approximately equal to the free stream velocity (see figure 3-6). Over the panel top surface, the mean flow, which is in the streamwise direction upstream of the panel, changes its direction to align with the panel surface inclination. The mean profile indicates that the gap between the individual panels (simulated through slots in the model panel structure) influences the mean flow behavior in the vicinity of the panel surface. The flow accelerates through the gap between the panels. As the distance from the panel surface increases, the streamwise velocity continues to increase and gradually become equal to the free stream velocity.
Figure 3-9: Profile of the cross-stream RMS turbulence intensity at the four spatial locations in all measurement sections across the photovoltaic panel for $\text{Re}_L = 4 \times 10^6$ (o) and $\text{Re}_L = 1 \times 10^7$ (*).
At the panel’s trailing edge, the mean flow transforms back into predominantly the streamwise direction and separates off the trailing edge. The wake region continues to grow downstream of the trailing edge of the panel as expected. The panel also influences the turbulent velocity field upstream of the panel. The turbulent intensities upstream of the panel near the ground are relatively lower in magnitude than that in the free stream region. Immediately above the panel’s top surface, the magnitude of turbulent intensities is low over most of the panel length but increases substantially at the trailing edge of the panel and into the wake region. Some weak rolling vortices are also observed over the panel surface (see Figure 3-7c). From the turbulence perspective, these results show that above and upstream of the panel the turbulence is relatively weak and the main contribution of the panel to the turbulence is in the wake region. The influence of the gaps on the turbulent velocity field is local to the location of the gaps near the surface of the panel.

The velocity fields in this study are presented for the panel inclination angle of 25°, where the inclination angle is not very large. The panel inclination angle is almost equal to the latitude angle of the site, thus for practical purposes, it is not expected that the solar PV panel inclination would increase beyond 45°. Hence, the present results could be cautiously used to speculate the flow behavior at higher inclination angles. Based on the present results, it is expected that with an increase in the panel inclination, the flow acceleration beneath the panel leading edge would increase and over the panel surface, the alignment of the mean flow with the panel surface caused a further decrease in the magnitude of the mean streamwise velocity and an increase in the mean vertical velocity as shown in the plots of Figure 3-5c, Figure 3-5d, Figure 3-5f and Figure 3-5g. Furthermore, the wake region is also expected to be large.

In Figure 3-8 and Figure 3-9, the streamwise and vertical turbulence intensities of the flow approaching the model and at the leading edge of the model were about 0.2 and they are relatively constant across the vertical height of the measurement plane. Near the vicinity of the model’s top surface, there is a relatively large turbulent gradient and at the locations of the gaps, the trend of the turbulence intensities indicates that at the gaps, the turbulence is larger than it would have been without the gaps. Across the height of the measurement region in Section II, the streamwise intensities show more variations than the vertical
component. In the wake region there is also a large gradient as the intensities are relatively higher within the free shear. The streamwise intensities within the free shear reach up to 0.4 near in the wake separation region and reaches 0.5 for the cross-stream component. Outside the free shear in the wake (section IV), the cross-stream component varies less across the vertical height than the streamwise component as also observed in section III, over the model area.

3.4.2 Surface pressure near the gaps and mean velocities

The pressure fields on both surfaces of the PV panel were obtained by instrumenting the model with pressure taps and associated transducers as shown in figures 2-1, 2-2 and 2-3. The pressure taps on the model were located either upstream or downstream relative to the inter-panel gaps on the model. Figure 3-10 shows these tap locations relative to the inter-panel gaps on left half of the panel. Figure 3-11 shows the $C_p$ values along the panel at two positions; $y/W = \pm 0.99$ and $y/W = \pm 0.67$. These positions were selected because they contained pressure taps, both upstream and downstream of a given gap. Plots clearly show the impact of gap on the pressure distribution on the panel surface i.e. the pressure immediately upstream of the gap is lower than that immediately downstream of the gap. This trend can be explained through the velocity data shown earlier, which was obtained in the vicinity of the inter-panel gaps near the mid-panel location.

As discussed earlier, figures 3-6 and 3-8 show that the mean and turbulent velocity magnitudes near the surface are influenced by the gap. The results indicated that immediately upstream of the gap, the mean velocity accelerated and the turbulent velocity showed an increase in magnitude. This flow acceleration upstream of the gap reduces the static pressure as measured. This effect is further confirmed by plotting the $C_p$ values obtained from the pressure taps located in the vicinity of the measured velocity plane as shown in figure 3-12. The four pressure taps on this plane were located at the normalized locations $x/L = 0.21, 0.45, 0.78$ and 0.95 on the upper surface of the solar panel; with the tap at $x/L = 0.78$ being downstream of a nearby gap where the pressure is increased. The presence of the gaps thereby makes each of the 24 panel members on the solar structure to act as separate flat plates in array.
Figure 3-10: Schematic of pressure tap locations relative to gap between panels. ▲, tap upstream of the gap; ∆, tap downstream of the gap.

Figure 3-11: Cp values along the panel at y/W = ±0.99 (left) and y/W = ±0.67 (right). ●, without the gap, ▲, with the gap. “1” represents the pressure tap located upstream of the gap, and “2” represents the pressure tap located downstream of the gap.
Figure 3-12: Cp values along the panel, near its mid-plane at y/W = -0.01 which coincides with the plane of the velocity measurement. “1” represents the pressure tap located upstream of the gap, and “2” represents the pressure tap located downstream of the gap.

3.5 Conclusions

The results from the experimental measurements of the flow field in the vertical plane across the scaled model of a standalone photovoltaic module have been presented. The two dimensional spatial flow velocity fields are presented at two Reynolds numbers. The results showed no Reynolds number effect. The velocity fields indicate the presence of large-scale turbulent structures, which dominates the dynamics of the turbulent activities around the panel. The oncoming flow bifurcates at the leading edge of the panel and remains attached on the panel’s surface as it creates a boundary layer over it. The wind flow pattern through the inter-panel gaps were observed and found to have altered the pressure distribution on the surface of the panel as it flows through the gaps and changes the mean velocities and turbulence intensities measured near the region.

Since the load on the solar panel at this orientation is primarily due to the pressure differential across the panel, future test should include a PIV study at the underside of the model to measure the flow velocities behind the panel. Also, other wind directions, especially oblique angles such as 45°, 135° and 90° should be tested, since the unsymmetrical orientation of the model to the flow direction at those angles would
potentially produce more interesting results such as the visualization of flow features which were not seen at these head-on wind directions.

Finally, in the wind tunnel testing on low-rise structures, it is a requirement that we simulate the highly viscous layer nearest to the ground where the structure lies. As had been pointed out in the literature review, the simulation of this region remains difficult in conventional boundary layer wind tunnels since they are designed to test structures at larger scales up to hundreds of meters of the ABL. Artificially simulating the lowest 10 m of the ABL to make its shear parameter remains the biggest challenge in wind tunnels which are known to produce straight flows. From private communications with researchers and industry experts, we believe that a wind facility, with the capacity to produce flows simultaneously from various directions to simulate the required shearing properties of the near-ground ABL region could potentially produce laboratory flows with sufficient turbulence intensities and length scale for future studies on PV panels.

3.6 Acknowledgements

The authors acknowledge the financial contributions from the First Solar Inc., Ontario Center of Excellence and the University of Western Ontario.

3.7 References


Tunnel Modeling Criteria and Techniques in Civil Engineering Applications, edited by Reinhold, TA (pp. 137-185).


Chapter 4

4 General conclusions

A $1/10^{th}$-scaled model of a solar panel of rectangular geometry was tested in a wind tunnel to investigate the pressure load due to the wind and the nature of the wind flow around it. Two sets of experiments were conducted. The first set of experiments employed pressure taps instrumentation to simultaneously measure the pressure on the upper and bottom surfaces of the panel. The measured pressures were non-dimensionalised in the form of pressure coefficient, $C_p$. The second set of experiments was conducted to measure the flow around the panel at mid-panel location by using state-of-the-art particle image velocimetry (PIV) technique at two Reynolds numbers. The PIV images were processed to obtain the instantaneous velocity fields in two-dimensional planes. These velocity fields were used to compute the mean and turbulence velocities, in the streamwise and vertical directions of the flow.

4.1 Summary and Discussion of Results

The pressure study examined the wind load on the solar panel at two inclination angles of 25° and 40°, as well as four wind angles. The first inclination angle is the default angle of the solar panel’s prototype, while the second inclination angle is the same as the latitude of the solar panel site in southwestern Ontario. The four wind angles were 0°, 180°, 30° and 150°. The first two wind angles correspond to the cases when the wind approached the solar panel head-on and at the last two angles, the wind direction was oblique to the solar panel. These four wind angles correspond to the critical directions for wind loading on panels of such geometries that was identified in Shademan’s [1] CFD research. The wind loads at these wind angles were therefore measured and compared. Due to the fact that the geometrical configuration of the solar panel included gaps between individual members of the 24 panels that make up the solar panels, the effect of those gaps on the wind load was also investigated. Results from this study are presented in Chapter 2, which show that the reverse wind angles, for the head-on (180°) and oblique (150°) cases are more critical to
the wind lift as the leading edge of the panel bears the greatest lift at these directions. The effect of the inter-panel gaps on the $C_p$ was particularly noticeable on the taps closest to them in all cases. At $0^\circ$ wind angle, the gaps reduced the $C_p$ on these taps, while at $180^\circ$ wind angle, the $C_p$ typically increased. The $C_p$ distribution on the panel surfaces is symmetrical about the mid plane of the panel when the wind approached head on. This distribution was asymmetrical for the oblique wind angles, as expected. The effect of the gap was also asymmetrical on both sides of the panel at oblique wind angles. For instance, at $30^\circ$ wind angle, the gaps reduced the $\Delta C_p$, and hence the wind-load on the left side, while it increased $\Delta C_p$ on the right side. The panel experienced greater load in the smooth wind exposure with higher wind velocity in the atmospheric surface layer compared to the typical open country exposure. The results showed that the wind load is greater on the panel at $40^\circ$ than $25^\circ$.

The subsequent flow studies sought to measure and evaluate the wind flow across the solar panel at its default inclination angle so as to understand the mechanisms by which the wind affects the solar panel. The results from this study are reported in Chapter 3 for the wind flowing head-on at $0^\circ$ towards the solar panel, inclined at $25^\circ$. Two dimensional flow fields of the mean and turbulent velocities were presented at four sections across the solar panel. Across these flow fields, vertical profiles were plotted to show the trend of the mean velocities and turbulence intensities. It was observed that the leading edge of the panel influences the flow field upstream of the panel up to $x/L' = 1.3$. As the flow bifurcates at the leading edge of the panel, the flow within the underside of the panel and the ground accelerates. Separation is expected to occur at the underside of the panel, although this region was mainly invisible to the measurement due to orientation of the experimental setup. On the surface of the panel, mean direction of the flow changes according to the orientation of the panel as it flows towards its trailing edge. It is seen that on the surface of the panel, the flow flows through the gap to the panel’s underside. Accelerated flow and increased turbulence were observed near the gaps. The presence of the gap therefore significantly altered the pressure distribution on the surface of the panel as confirmed from the pressure measurements. Beyond the trailing edge of the panel, downstream of the flow, a separation zone is observed where the largest turbulence in the flow is found. Results
also showed that both the mean and turbulent flow structure around the panel is almost independent of the Reynolds number within the range $4 \times 10^6$ to $1 \times 10^7$.

4.2 Contributions to knowledge

Present study has demonstrated the impact of wind direction on the distribution of the wind load on solar panels. If the dominant wind directions at the site where solar panels are installed are known, wind shelters can be placed upstream of the panel in the dominant wind directions to reduce the wind load. This study has provided detailed information about the pressure fields on both upper and lower surfaces of the solar panel at the critical wind directions and two inclination angles. The effect of gaps between individual panels and the inclination angle of the panel on the wind load exerted on the structure has been quantified. In the absence of the gaps, the loads on the surface of the solar panel would be similar to that obtained on a flat plate inclined at the same angle. Finally, this study has quantified the mean flow field across the solar panel and its associated turbulence characteristics. The dynamics of the wind flow at the gaps on the solar panel was investigated and its effect on the surface pressure distribution was determined.

4.3 Future Recommendations

A general limitation of the pressure test of the current study is the intrusion of the wind flow by the instrumentation tubes, which protrude from both sides of the model. This prevented larger oblique wind angles such as $45^\circ$, $90^\circ$, $135^\circ$, etc. from being tested, as the tubes will severely influence the flow. Future pressure test on solar panels should therefore avoid such pitfall by rerouting the instrumentations tubes differently to allow more wind angles to be tested. Furthermore, the geometric scale of the model can be increased within appropriate limits of resolution to be close enough to the typical scales suitable for various wind tunnels. This will help improve the match of the turbulence characteristic of the wind flow generated in the wind tunnel to allow peak and rms load measurements. The mean load however, in unaffected by the turbulence mismatch as studies have shown that at scales of 1:10 to 1:50, the mean load do not vary [2].
The re-circulating flow in the wake region is known to heavily influence the wind load measured in Chapter 1. However, the present study was not able to measure the flow velocities in this region due to experimental limitations. Hence, further PIV measurements conducted to visualizing the underside of the panel will be useful to quantify the flow field therein. Finally, as the inter-panel gaps are now known to influence wind loading for solar panels of this configuration, the optimal size for these gaps should be investigated in future studies similar to the study conducted by Wu et al [2] on such gaps for a heliostat.

4.4 References


Appendices

Appendix 1: License agreement to re-use Figure 1-2

This is a License Agreement between Ayodeji Abiale-Ogedengbe (“You”) and Elsevier (“Elsevier”) provided by Copyright Clearance Center (“CCC”). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.

Supplier: Elsevier Limited
The Boulevard, Langford Lane
Kidlington, Oxford OX5 1GB, UK

Registered Company Number: 1582984

Customer name: Ayodeji Abiale-Ogedengbe
Customer address: Boundary Layer Wind Tunnel
London, ON N9A 5B9

License number: 3072481391565
License date: Jan 19, 2013

Licensed content publisher: Elsevier
Licensed content publication: Journal of Wind Engineering and Industrial Aerodynamics
Licensed content title: Reduction of wind uplift of a solar collector model
Licensed content author: K. Chang, H. Cheng, Y. Liu
Licensed content date: August-September 2008
Licensed content volume: 96

Licensed content issue:
Number of pages: 13
Start Page: 1294
End Page: 1306
Type of Use: reuse in a thesis/dissertation
Portion: figures/tables/illustrations
Number of figures/tables/illustrations: 1

Are you the author of this Elsevier article? Yes
Will you be translating? No

https://dx.doi.org/10.1016/j.jweia.2012.10.001
Appendix 2: Uncertainty calculation for PIV measurements

The errors in the PIV velocity field are calculated following the method described by Cowen and Monismith [1] as the total error due to the velocity gradient, particle diameter, out of plane motion, interpolation and dynamic range. The calculation of these errors relies on Figures 5(a-f) in Cowen and Monismith [1], herein referred to as CM. This method was recently used in Greig [2] to estimate the error in their PIV measurement. The figures in CM provide a mean and rms value for each error parameter which would be summed to obtain the total error value for the parameters. To obtain the error due to the velocity gradient, the largest average velocity gradient in the measurement was first obtained from section IV in the wake region and found to be $1.34 \times 10^{-6}\text{ pixels/pixel}$. The velocity gradient error is then calculated as the sum of the error differences between CM’s $0.03\text{ pixels/pixel}$ gradient and the error due to the largest average velocity gradient of this study obtained from figure 5e in CM. According to the figure, the error due to CM’s gradient has a mean value of $-0.03\text{ pixels}$ and rms value of $0.08\text{ pixels}$, and from this study, the mean and rms values of the gradient error both give $0.00\text{ pixels}$. The total error due to the velocity gradient is therefore the sum of the mean and rms errors, which is obtained as $0.05\text{ pixels}$.

The particle diameter is an average of $1\mu\text{m}$, which is smaller than $1\text{ pixel}$ ($97\mu\text{m}$); and since the smallest resolution captured by the image is $1\text{ pixel}$, the particle diameter is set to $1\text{ pixel}$. The error due to the $1\text{ pixel}$ particle diameter from CM’s figure 5a has a mean value of $-0.03\text{ pixels}$ and an rms value of $0.095\text{ pixels}$ for a total of $0.065\text{ pixels}$. Greig [2] suggested a $30\%$ adjustment to the particle diameter error to account for peak locking. The total error due to particle diameter is therefore calculated as $1.3 \times 0.065 = 0.0845\text{ pixels}$.

The motion of particles in the third axial direction gives the out-of-plane motion error. This error is estimated by the sum of the mean and standard deviation of the particle displacements in the third axis and it is obtained as $0.3918\text{ pixels}$, which is equal to $0.0383\text{ mm}$. Since this displacement is less than the $2\text{ mm}$ thickness of the laser sheet, the error due to the out-of-plane motion may be conveniently ignored. The interpolation error is estimated from CM’s figure 5f. The estimate of the interpolation error for 4800 velocity field from this graph is $0.08\text{ pixels}$. 
The total error, which is the sum of the total errors for each of the parameters, can therefore be estimated thus:

\[ 0.05 + 0.0845 + 0.08 = 0.2145 \text{ pixels} \]

Given that the error is produced in both the streamwise and cross-stream directions of the measurements and assuming equal values for both directions, the total error can be taken as the square root of the sum of the squares of the error for both directions:

\[ \sqrt{0.2145^2 + 0.2145^2} \text{ pixels} = 0.3034 \text{ pixels} \]

This is converted to cm/s, by dividing by both the time interval, \( \delta t \) (in seconds) between successive images and the spatial resolution of each image (in pixel/cm). The total average error in the PIV measurements is therefore estimated as 5.925 cm/s which equal 2.52% of the average velocity.

References


Curriculum Vitae

Name: Ayodeji Abiola-Ogedengbe

Post-secondary Education and Degrees:

Federal University of Technology Akure
Akure, Ondo State, Nigeria

University College London
London, England
2008-2009 M.Sc.

The University of Western Ontario
London, Ontario, Canada
2010-2013 MESc.

Honours and Awards:

Shell Nigeria Undergraduate University Scholarship
2001-2006

Petroleum Technology Development Fund
Postgraduate scholarship
2008-2009

Western Graduate Research Scholarship
2010-2012

Related Work Experience:

Teaching Assistant
The University of Western Ontario
2011-2012

Publications: