EXPERIMENTAL AND NUMERICAL INVESTIGATION OF SNOW REMOVAL FROM PHOTOVOLTAIC SOLAR PANELS

by

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Abstract

A key challenge to the wide-scale implementation of photovoltaic solar panels (PV) in cold and remote areas, is dealing with the effects of snow and ice buildup on the panel surfaces. However there currently is no practical mechanism to remove snow-cover from PV surfaces and long shut-down periods occur for plant operators. The objective of this study is to evaluate different types of heating snow removal systems for PV modules and to present methodologies and tools to improve PV systems modelling and output prediction.

A numerical model is presented to predict thermal snow removal from a PV panel. The model can predict snow melting or snow sliding from horizontal and inclined panels. A set of experiments was conducted using a small-scale PV panel in a freezer to provide a correlation for snow sliding from the panel. The correlation was implemented in the model to predict snow sliding situations.

To validate the model and study thermal snow removal from a full scale PV panel, outdoor tests were conducted under natural conditions including different snowfall conditions. Two heating methods were investigated: embedding an electrical resistance heater to the back of the panel and imposing a reverse current through the solar cells. The results showed that ice dam and icicles formation at the bottom of the panel prevented the snow cover from sliding off the panel. In addition, the effect of heating the entire panel surface or partially heating the panel was investigated.

An insulation equipped with a venting channel were proposed to use for the PV panels. This insulation improves the performance of snow removal from the panels, while having a minimum effect on the panel performance during a regular sunny day. To enhance the snow removal from the panel, the vents would be closed while opening the vents enhance the heat transfer from the panel during a sunny day. Radiation heat transfer between the panel and the insulation was also improved by coating the insulation. Outdoor tests were conducted under natural condition to study the performance of the proposed insulation during hot summer days. In terms of panel temperature and power output, the results showed promising
improvement compared to using a single insulation without any modifications and especially without vents.

Finally, it was proposed to remove snow from photovoltaic-thermal panels (PV/T) by circulating hot fluid through the back of a panel. Conducting outdoor tests revealed that this method can clean the panel from snow in a short period of time. The experimental results were compared with the results given by the numerical model presented in this study. To compare the required energy for snow removal with the amount of energy generated by the panel after snow removal during a day, a non-dimensional number was proposed. Using this number and conducting a case study showed that this snow removal method can be beneficial for the PV and PV/T systems.
Co-Authorship

This dissertation is in manuscript format, each manuscript chapter is based on the following published or soon to be published articles.

Chapter 3

Chapter 4

Chapter 5
Ali Rahmatmand, Stephen J. Harrison, Patrick H. Oosthuizen, The effect of a snow removal system insulation on the photovoltaic solar panels during the summer, to be submitted to the journal of Solar energy.

Chapter 6
Ali Rahmatmand, Stephen J. Harrison, Patrick H. Oosthuizen, Investigation of snow removal from photovoltaic-thermal (PV/T) panels, to be submitted to the journal of Photovoltaics.

I acknowledge the strong support provided by my co-authors on all papers. However, all the work contained within these publications is my own, and my co-authors provided advisory and direction in the development of the final product. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.
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# Table of Contents

Abstract ................................................................................................................................. ii
Co-Authorship ........................................................................................................................ iv
Acknowledgements ............................................................................................................. v
Table of Contents ................................................................................................................ vi
List of Figures ...................................................................................................................... x
List of Tables ....................................................................................................................... xvi
List of Abbreviations ......................................................................................................... xvii
Chapter 1 Introduction ....................................................................................................... 1
  1.1 Background and Motivation ......................................................................................... 1
  1.2 Objective, Approach, and Scope ................................................................................. 6
    1.2.1 Contribution of Research ...................................................................................... 8
    1.2.2 Thesis Outline ....................................................................................................... 9
Chapter 2 Literature Review ............................................................................................. 13
  2.1 Snow properties ......................................................................................................... 13
    2.1.1 Density ................................................................................................................ 14
    2.1.2 Effective thermal conductivity ............................................................................ 16
    2.1.3 Latent heat of fusion .......................................................................................... 18
    2.1.4 Permeability ........................................................................................................ 18
    2.1.5 Reflectivity of a snow surface ............................................................................ 19
  2.2 PV module dynamics .................................................................................................. 20
  2.3 Snow Effects on PV Systems ...................................................................................... 24
  2.4 Physics of snow sliding .............................................................................................. 30
  2.5 Numerical research on snow effects .......................................................................... 34
  2.6 Snow shedding methods ............................................................................................ 36
  2.7 Snow removal from other applications ...................................................................... 39
Chapter 3 Numerical and experimental study of an improved method for prediction of snow melting and snow sliding on photovoltaic panels ......................................................................................... 41
Abstract ............................................................................................................................... 41
  3.1 Introduction ................................................................................................................ 42
  3.2 Methodology .............................................................................................................. 45
    3.2.1 Numerical model development ......................................................................... 45
Chapter 4 An experimental investigation of a thermal method for snow removal from Photovoltaic solar panels ................................................................. 75

Abstract .............................................................................................................. 75

4.1 Introduction .................................................................................................... 76

4.1.1 The effect of snow accumulation on PV output ........................................ 76
4.1.2 Snow removal methods for PV panels ....................................................... 78
4.1.3 Deicing techniques for other applications ............................................... 79

4.2 Methodology .................................................................................................. 81

4.2.1 Heating methods ....................................................................................... 82
4.2.2 Measurement facilities and instrumentation .............................................. 84
4.2.3 Uncertainty analysis ................................................................................. 87

4.3 Results and Discussions ................................................................................ 88

4.3.1 Observations of snow removal from the panels ......................................... 88
4.3.2 The effect of PV panel frame detail ........................................................... 98
4.3.3 Heating area effects ................................................................................. 101
4.3.4 Heating by reversing current through the panel ......................................... 101
4.3.5 Required energy for snow removal ............................................................ 102
4.3.6 Case Study ................................................................................................ 109

4.4 Conclusion ...................................................................................................... 113

Acknowledgements .............................................................................................. 116

Chapter 5 The effect of a snow removal system insulation on the photovoltaic solar panels during the summer ............................................................. 117
Abstract ......................................................................................................................... 117

5.1 Introduction ............................................................................................................... 118

5.2 Methodology ........................................................................................................... 121
  5.2.1 Uncertainty analysis ......................................................................................... 126

5.3 Mathematical Modeling ........................................................................................ 127
  5.3.1 Governing equations ....................................................................................... 128
  5.3.2 Grid study and computational domain study .................................................... 128
  5.3.3 Boundary conditions ....................................................................................... 129

5.4 Results and Discussions ....................................................................................... 130
  5.4.1 Experimental results ....................................................................................... 130
    5.4.1.1 The effect of the size and configuration of the vents ..................................... 130
    5.4.1.2 The effect of the solar radiation ................................................................. 134

5.5 Numerical results .................................................................................................. 137
  5.5.1 Parametric analysis ......................................................................................... 139
    5.5.1.1 Panel installation tilt angle ......................................................................... 139
    5.5.1.2 Surface emissivity of the insulation .......................................................... 140
    5.5.1.3 Wind speed .............................................................................................. 140
    5.5.2 Comparing snow loss for PV panels during the winter with the effect of insulation on the panel output during the summer .......................................................... 142

5.6 Conclusion ............................................................................................................. 143

Acknowledgements ..................................................................................................... 144

Chapter 6 Investigation of snow removal from photovoltaic-thermal (PV/T) panels .......... 145

Abstract ......................................................................................................................... 145

6.1 Introduction ............................................................................................................. 146

6.2 Methodology .......................................................................................................... 149
  6.2.1 Measurement facilities and instrumentation ...................................................... 150
  6.2.2 Experiment procedure ...................................................................................... 152

6.3 Results and discussion .......................................................................................... 153
  6.3.1 Heat sources .................................................................................................... 156
  6.3.2 Snow removal time .......................................................................................... 159
  6.3.3 Numerical modelling ......................................................................................... 161
    6.3.3.1 Inputs for the numerical model ................................................................. 161
    6.3.3.2 Comparing the numerical data with the experimental results ..................... 162
    6.3.4 Non-dimensional number for PV panel snow removal ................................... 164
6.3.4.1 Case study ........................................................................................................ 166
6.4 Conclusion .................................................................................................................. 170
Acknowledgements ........................................................................................................ 171
Chapter 7 Conclusions and Further work ..................................................................... 172
  7.1 Important findings of this study .............................................................................. 172
  7.2 Future work ............................................................................................................. 176
    7.2.1 Standard tests for imposing current through a panel .................................... 176
    7.2.2 Panel frame design ......................................................................................... 177
    7.2.3 Snow removal research network .................................................................... 177
References ....................................................................................................................... 179
Appendix A ....................................................................................................................... 187
  Calibration of Sensors and Uncertainty Analysis ....................................................... 187
    A.1 Calibration of Flowmeter .................................................................................. 188
    A.2 Calibration of thermocouples .......................................................................... 190
    A.3 Propagation of Measurement Uncertainty ...................................................... 194
      A.3.1 Uncertainty in the Heat Transfer Rate ....................................................... 194
Appendix B ....................................................................................................................... 196
  Sample numerical code ............................................................................................. 196
List of Figures

Figure 1.2.1 Latest NREL's (US National Renewable Energy Laboratory) report for best Research-Cell efficiencies for different types of PV solar systems including monocrystalline, polycrystalline and thin film up to 2015 (Crabtree and Lewis, 2007) ................................................................. 3

Figure 1.2.2 Flowchart outlining the project approach .................................................................................. 10

Figure 2.1 Snow crystal classifications according to Magono and Lee (Morrison, 1983) ........................................ 14

Figure 2.2 Effective thermal conductivity vs. snow density. The $k_z$ and $k_{xy}$ are the directional components of the computed effective thermal conductivity, $k_{eff}$ provided by Calonne et al., (2011) ................................................ 17

Figure 2.3 Comparison of experimental data for permeability of snow (in red) with Eq. (0.5) and some other numerical results ........................................................................................................... 19

Figure 2.4 I-V curve from Kyocera KC200GT PV module: (a) under constant temperature and (b) under constant irradiance (Coelho and Martins, 2012) ....................................................................................... 21

Figure 2.5 A typical PV Cell's I-V and Power Curves (Solmetric, 2011) ............................................................. 22

Figure 2.6 Module schematic showing bypass diode arrangement. In this case a single cell is shaded, leading to the bypass diode engaging and reducing output of the module by 33% (Andrews, 2015) ......................... 23

Figure 2.7 Module schematic showing bypass diode arrangement. In this case a portion of at least one cell per diode is shaded, causing the engagement of all three bypass diodes and reducing module output by 100% (Andrews, 2015) .................................................................................................................. 23

Figure 2.8 The blue bars show the number of days at which the reference PV system was covered with snow. The purple curve gives a percentage estimation of yearly lost yield by snow covered modules (Becker et al., 2008). ............................................................................................................... 26

Figure 2.9 Probability of snow accumulation on PV panels normalized by the median of its intensity (Time-lapse digital camera was used) (Andrews et al., 2013b). ................................................................. 28

Figure 2.10 Coefficient of friction, $\mu$, as a function of the measured flow velocity for dry, wet snow and slush avalanches (Platzer et al., 2007) ........................................................................................................ 31

Figure 2.11 Influence of temperature on the static friction on various real skis (Bowden, 1953) .................... 33

Figure 2.12 The total time a module was covered with snow, normalized by the total covered time of the control module based on the contact angle (Andrews et al., 2013b). Note that coating ho1 at 20° (marked by an asterisk) only contains data from one winter, and the remainder of points contains data from both winters. ......................................................... 38

Figure 3.1 The snow cover temperature on a panel was modeled using three nodes on the present model. The first node was located at the snow cover surface, the second node was at the center of the dry snow layer, and the third one was located at the center of the slush layer. ........................................................................................................ 47

Figure 3.2 A linear increase for the slush layer height is considered in the model if the panel is tilted, $h_{slop}$. An equivalent constant slush layer thickness, $h_{sat}$, is also considered provided that the constant height slush
layer has the same volume as the slush layer with gradient height. The equivalent slush layer height was
used to find the gradient height.

Figure 3.3 The snow pack placement for each test and thermocouples configurations

Figure 3.4 Comparison between the snow height decrease and water run-off rate for snow melting on a
horizontal surface predicted by the present model and the experimental data provided by Hockersmith
(1999) for several heat fluxes.

Figure 3.5 Comparison between measured and predicted panel temperatures using the present model at the snow
pack location (T1). The heater had a response time of 50 sec. to heat up itself and then heat the panel.

Figure 3.6 The difference between the time required for the snow pack to slide off the panel and the time
required for the panel to reach 0°C where the panel is in touch with the snow pack for some of the test
cases.

Figure 3.7 A correlation between the measured energy required for snow sliding from the panel, E, the panel tilt
angle, $\theta$, snow cover mass per unit area, m, and ambient temperature, $T_{amb}$. A linear regression was fitted
to the experimental data.

Figure 3.8 The ratio of the net energy production of a PV system (located in Toronto CA) from sunrise to sunset
during several sunny days (from TMY data) after snowfall to the maximum energy production of the
system on that day. At each hour of the day, it is assumed that the panel was covered by snow before that
time. The energy required for removing snow from the panel was calculated by the presented model
assuming 570 W/m² heating power, the ambient temperature of -5°C and snow density of 175
kg/m³.

Figure 4.1 Panels mounted at 30, 45 and 55 degrees tilt angles with the horizontal along with the weather station.
The picture was taken using the monitoring camera.

Figure 4.2 The configuration of heater, thermocouples and two layers of insulation on the back of the panels.

Figure 4.3 Photos of snow melting sequence, shown as a duration of time through the heating process. The PV
panel shown on the right was heated by the thin film heater bounded to the rear of the panel. The adjacent
panels were unheated reference panels. The conditions for this test (No. 5) were: test date=09/01/2017,
panel tilt angle= 30 degree, ambient temperature= -5.47°C, relative humidity= 91%, solar radiation= 120
to 160 W/m², snow density= 48 kg/m³, Initial snow cover thickness= 3 cm and wind speed=0.93m/s.

Figure 4.4 Photos showing a comparison between PV panel heating by carbon resistance film heater and self-
heating of PV cells by imposed reverse electrical current. For the panel with applied reverse current, the
lower edge of the panel frame was removed to facilitate snow sliding. Snow sliding was observed on this
panel assisting the snow shedding process. The conditions for this test (No. 5) were: test
date=09/01/2017, panel tilt angle= 45 degree, ambient temperature= -5.47°C, relative humidity= 91%,
solar radiation= 120 to 160 W/m², snow density= 48 kg/m³, Initial snow cover thickness= 2 cm and wind
speed=0.93m/s.

Figure 4.5 Photos of snow melting sequence, shown as a duration of time through the heating process. The PV
panel shown on the left was heated by the thin film heater bounded to the rear of the panel. The adjacent
panels were unheated reference panels. The conditions for this test (No. 5) were: test date=09/01/2017,
panel tilt angle= 55 degree, ambient temperature= -5.47°C, relative humidity= 91%, solar radiation= 120
to 160 W/m², snow density= 48 kg/m³, Initial snow cover thickness= 1 cm and wind speed=0.93m/s.
Figure 4.6 The temperature variation of the panels at tilt angles of 30, 45 and 55 degrees are shown during the heating process for test number 9 on 16/02/2017. The conditions for this test (No. 9) were: test date=16/02/2017, panel tilt angle= 30, 45 and 55 degrees, ambient temperature= -7.42°C, relative humidity= 68%, solar radiation= 450 to 490 W/m², snow density= 50 kg/m³, and wind speed=1.47 m/s. The panel temperature remained approximately around the melting point until the snow layer melted or slid off the panel, then the panel temperature started to increase rapidly. The upper half of the panel was cleaned faster than the lower half since the snow cover slid down from the upper half to the lower half.

Figure 4.7 Temperature of the panels at all angles (30, 45 and 55 degrees) showing that the upper half of the panel increased in temperature faster than the lower half because of snow sliding from the upper half to the bottom of the panels.

Figure 4.8 Ice bridges formed between the panels and the snow cover. The panel temperature at the section which is not in contact with the snow cover (under the ice bridge) increased rapidly. If the ice bridge collapsed on the surface, the panel temperature would drop again.

Figure 4.9 Photo of icicles formed at the bottom of a PV panel with frame compared to the panel without frame for the 45° tilt angle. The ice dam and icicles impeding the snow cover from shedding.

Figure 4.10 Partial snow cover at the bottom of a panel due to the frame effect. The shape of snow cover reveals that the snow on the upper half of the panel slid down and was impeded from sliding off at the bottom edge due to the frame effect.

Figure 4.11 Comparing the snow-cover mass per unit area with the equivalent snow-cover mass per unit area calculated based on the heater heat flux (180 W/m²), ambient temperature and the melting time (eq. 4.4) for the experiments presented in Table 4.3 except test case No. 6 as it was a freezing rain and snow. The required energy for snow removal is proportional to snow-cover mass.

Figure 4.12 The required energy for melting snow vs the snow-cover mass per unit area. Each symbol represents a test case. The required energy for melting snow for each test case is shown in the left axis and the measured melt time for heater heat flux of 180 W/m² in the right axis. The solid line shows the theoretical required energy (TRE) for melting snow without considering any solar radiation. Dash lines show the required energy for melting snow after considering a certain value of solar radiation available to assist the snow removal process (albedo effect of 0.2 was considered for all cases (Andrews and Pearce, 2013; Warren, 1982)).

Figure 4.13 The correlation for the provided energy for melting snow on each test based on the available solar radiation and the heater power (180 W/m²) for the actual snow-cover mass per unit area and the equivalent snow-cover mass calculated based on the ambient temperature, the solar radiation and the heater power for each test (Eq. 4.7).

Figure 4.14 Comparison of melting time between panels with frame (heated by heater) and without frame (heated through reversing current) at 45° tilt. The snow type categories were adopted from Ross (1995). The first three columns on the left are for the situations where the snow cover on the panel was either thin and light or was frozen to the panel, and the snow sliding did not occur. The two columns on the right show the situation in which the snow cover was thick and heavy enough to slide off the panel without frame, while the frame at the bottom edge of the other panel prevented snow sliding.

Figure 5.1 Comparison of the I-V (current vs. voltage) and P-V (power vs. voltage) curves of two panels before mounting the insulation on the back of one of the panels at two different solar radiation intensities. The panels’ performance are identical within 1%.
Figure 5.2 Front and back views of the panels with and without insulation. One of the panels was insulated using the Polyisocyanurate foam insulation with thickness of 10 mm and R value of 0.54 (m2C/W). The air outlet and inlet channels located at the top and bottom of the panel increases convective heat transfer from the back of the insulated panel.

Figure 5.3 Schematic figure of insulated panel and thermocouples location as well as inlet and outlet vents located at the bottom and top of the panel. Another thermocouple was located on the inside surface of the insulation at the same location as the highlighted thermocouple in the picture.

Figure 5.4 Domain size and mesh density around the panel. Three different domain sizes and mesh densities were examined for the numerical simulations to ensure the independency of the numerical results from the domain size and mesh density.

Figure 5.5 Comparing I-V and P-V curves of panels with and without insulation for different vent sizes at top, bottom, and center of the insulation. The solar radiation at the time of this experiment was approximately I=985 ± 20 W/m². The panel performance is the lowest when there is no vent, and the performance is highest for the configuration of “Top vent= 3 cm, bottom vent= 6 cm”. Adding another vent at the center of the insulation did not show a significant improvement for the panel performance.

Figure 5.6 Comparing temperature distribution on panels with and without insulation for different vent sizes at top, bottom, and center of the insulation. The solar radiation at the time of these experiments was approximately I=985 ± 20 W/m². The panel temperature is the highest when there is no vent.

Figure 5.7 Comparing temperature distribution and I-V curves between panels with and without insulation with 6 fins. Fins are 1.5 m long and 2 cm high at the back of the insulation. The vents configuration is “Top vent= 3 cm, bottom vent= 6 cm”. The averaged wind speed was U≈3 m/s. The solar radiation at the time of this experiment was approximately I=968 ± 20 W/m².

Figure 5.8 Comparing temperature distribution between panels with and without insulation at different solar radiations. The vents configuration is “Top vent= 3 cm, bottom vent= 6 cm”. The averaged wind speed for all cases was U=3-3.5 m/s. The higher solar radiation leaded to higher temperature difference between the insulated and uninsulated panels.

Figure 5.9 Comparing the experimental temperature distributions on the back of the panels with and without insulation with the results given by the numerical simulations. The vent sizes were as top vent = 3 cm and bottom vent = 6 cm, and the insulation surface emissivity and wind speed were ε=0.9 and U=1 m/s for this simulation.

Figure 5.10 Streamlines and velocity distribution around the panel and inside the frame (ε=0.9 and U=1 m/s). The flow field around the inlet is magnified on the picture on the right. It shows that there is a circulation zone at the very bottom of the panel.

Figure 5.11 The effect of changing the tilt angle on the panel temperature. The vent configuration was as top vent = 3 cm and bottom vent = 6 cm (ε=0.9 and U=1 m/s). Increasing the panel tilt angle decreases the overall panel temperature.

Figure 5.12 The effect of changing the insulation emissivity, and the wind velocity (U) on the panel temperature. The vent configuration was as top vent = 3 cm and bottom vent = 6 cm. Increasing the insulation inside surface emissivity and wind speed decrease the overall panel temperature.
Figure 6.1 The panel with hot fluid circulation on the back was insulated using Polyisocyanurate foam insulation board with thickness of 20 mm and RSI value of 0.99 (m²°C/W), and the reference panel was uninsulated. Three thermocouples type T located on the front surface and one thermocouple attached on the back of each panel.

Figure 6.2 Schematic of experiments setup and apparatus used in this study. The panel on the right was not connected to the loop to serve as a reference panel.

Figure 6.3 Boiler and reserving tank were used to heat the working fluid through the heat exchanger, and the working fluid was then pumped to the back of the panel after each snowfall event.

Figure 6.4 Photos of snow melting sequence, shown as a duration of time through the heating process. The PV panel shown on the right was heated by circulating hot fluid through the back of the panel. The adjacent panels were unheated reference panel. The conditions for this test (No. 3) were: test date=07/02/2018, panel tilt angle=45 degree, ambient temperature=-5°C, relative humidity=88%, averaged solar radiation=119 W/m², snow density=157 kg/m³, Initial snow cover thickness=1.8 cm and wind speed=2.77 m/s.

Figure 6.5 The area covered by the piping system on the back of the panel affecting the snow melting on the front surface of the panel. The covered area by the piping system is shown inside the rectangular shape.

Figure 6.6 The inlet and outlet temperature of the fluid entering and exiting the panel for the test No. 2: test date=30/01/2018, panel tilt angle=45 degree, ambient temperature=-8°C, relative humidity=66%, averaged solar radiation=229 W/m², snow density=103 kg/m³, Initial snow cover thickness=2 cm and wind speed=2.5 m/s.

Figure 6.7 The solar radiation distribution during the test No. 2: test date=30/01/2018, panel tilt angle=45 degree, ambient temperature=-8°C, relative humidity=66%, averaged solar radiation=229 W/m², snow density=103 kg/m³, Initial snow cover thickness=2 cm and wind speed=2.5 m/s.

Figure 6.8 Comparing the surface temperature of the heated panel and reference panel at different locations...

Figure 6.9 The variation of \( R_t \) defined in equation (6.2) versus the required time for snow removal from a panel. \( R_t \) represents the effect of snow cover density and height, ambient temperature and the heat sources on the required time for snow removal (RTS) from a panel assuming that the entire snow cover is melted. The solid line shows the best linear fitting to all data.

Figure 6.10 Variation of AR defined by equation 6.3 with the snow removal time. For each day, it was assumed that the panels were covered by snow from the snowfall during the previous days. At each hour, the AR value was calculated provided that the sun came out on that hour (the sky was fully covered by cloud before that hour), and the system can function during the rest of the day after removing the snow. The first data point for each day shows the AR value if the snow is removed before the sunrise. The test conditions assumed to be ambient temperature=-5°C, snow cover thickness=3 cm, snow cover density=175 kg/m³.

Figure 6.11 Comparing the AR value for different snow cover thickness for the January 1. The test conditions assumed to be ambient temperature=-5°C and snow cover density=175 kg/m³.

Figure A.1 Measured flow rates using the turbine flow meter against the gravimetric flow rates. The dash line is a linear regression analysis with the assumption of zero bios error (going through the 0).
Figure A.2 A residual plot of the errors (the dash lines are the 95% confidence interval) .......................................................... 190

Figure A.3 Thermocouple from the test apparatus was immersed into the calibration temperature bath through the Guildline............................................................................................................................................. 191

Figure A.4 Calibrating the input and output measurements of the fluid entering and exiting the PV/T panel. The magnitude of the error bars was determined based on the one standard deviation of the reading of the thermocouple for 5 minutes with 0.25Hz. A third order polynomial was fitted to the data by the method of least-squares to correct the data...................................................................................................................................................... 192

Figure A.5 Thermocouple readings error after correction. The dash lines are the 95% confidence interval for each thermocouple............................................................................................................................................. 193
List of Tables

Table 1.2.1 Yearly available green energy by solar fluxes, wind and biomass as well as human energy consumption for 2010 (Nrel, 2014) .......................................................... 2

Table 2.1 Densities of various snow types categorized by Ross, (1995) .................................................. 15

Table 2.2 Daily snow loss predictions for a PV system located in the Natural Bridges National Monument in Utah by Brench, (1979) .................................................................................. 25

Table 3.1 Comparing the snow Melting time on a horizontal surface predicted by the current model and experimental data provided by Hockersmith (1999) for several heat flux rate ........................................... 63

Table 3.2 Comparing the snow melting time rate on a horizontal asphalt pavement predicted by the current model with the experimental data provided by Chen et al. (2011) ................................................................. 64

Table 3.3 Comparing the predicted snow removal time by the presented model with the experimental results ... 69

Table 4.1 The PV panel characteristics at STC (1000 W/m2, Cell Temperature 25°C) .................................... 82

Table 4.2 The measurement facilities used in this study .................................................................................. 85

Table 4.3 Listing of the snow removal experiments conducted during this study and a summary of the tests conditions and results ........................................................................................................ 1

Table 5.1 The panel characteristics at standard test condition (1000 W/m2, Cell Temperature 25°C) ....... 122

Table 5.2 The measurement facilities used in this study .................................................................................. 125

Table 5.3 The effect of vent size on the insulated panel performance compared to the uninsulated reference panel (negative percentage shows increment for the insulated panel compared to the reference panel) .............. 132

Table 5.4 The percentage (%) of reduction between the insulated panel and the reference panel at different solar radiations for the short circuit current (Isc), open circuit voltage (Voc), maximum power point voltage (Vmp), maximum power point current (Imp) and maximum power (Pmp) ................................................................. 136

Table 6.1 The PV panel characteristics at standard test condition (solar radiation 1000 W/m², Cell Temperature 25°C) ........................................................................................................................................ 149

Table 6.2 The measurement facilities used in this study .................................................................................. 151

Table 6.3 Listing of the snow removal experiments conducted during this study and a summary of the tests conditions and results (q is the fluid heat flux and RTS is the required time for snow removal) .... 154

Table 6.4 Comparing the predicted required time for snow removal (RTS) predicted by the model presented by Rahmatmand et al. (2018) with the measured time during the tests in this study ......................... 162

Table A.1 Uncertainty in heat transfer rate measurements for tests conducted on the PV/T panel ............... 195
**List of Abbreviations**

*Latin symbols*

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>panel area (m²)</td>
</tr>
<tr>
<td>Al</td>
<td>albedo of snow</td>
</tr>
<tr>
<td>(C_p)</td>
<td>specific heat of snow (kJ/kg K)</td>
</tr>
<tr>
<td>(G_r)</td>
<td>solar radiation (W/m²)</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number</td>
</tr>
<tr>
<td>h</td>
<td>convective heat transfer coefficient (W/m²K)</td>
</tr>
<tr>
<td>(h_{fg})</td>
<td>latent heat of fusion for snow (334 kJ/kg)</td>
</tr>
<tr>
<td>(h_s)</td>
<td>snow cover thickness (m)</td>
</tr>
<tr>
<td>I</td>
<td>panel current (A)</td>
</tr>
<tr>
<td>K</td>
<td>conductive heat transfer coefficient (W/mK)</td>
</tr>
<tr>
<td>k</td>
<td>Snow permeability (m²)</td>
</tr>
<tr>
<td>L</td>
<td>length of the panel (m)</td>
</tr>
<tr>
<td>m</td>
<td>mass of the snow cover per unit area (kg/m²)</td>
</tr>
<tr>
<td>(\dot{m})</td>
<td>mass flow rate per unit area (kg/(m²s))</td>
</tr>
<tr>
<td>q</td>
<td>heat flux (W)</td>
</tr>
<tr>
<td>(q_f)</td>
<td>fluid heat flux per unit area (W/m²)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynold number</td>
</tr>
<tr>
<td>Res</td>
<td>the resolution of the DAQ (K)</td>
</tr>
<tr>
<td>RSI</td>
<td>insulation thermal resistance (m²°C/W)</td>
</tr>
<tr>
<td>P</td>
<td>pressure drop (Pa)</td>
</tr>
<tr>
<td>(P_m)</td>
<td>maximum power(W)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>t</td>
<td>melting time (s)</td>
</tr>
</tbody>
</table>
U  wind velocity (m/s)

u  uncertainty (K)

v  fluid flux through the snow cover (m/s)

V  PV panel voltage (V)

x  vertical distance from the top of a panel (m)

y⁺  normalized distance from the wall

**Greek symbols**

α  absorption coefficient

ε  emissivity

ρ  Snow density (kg/m³)

μ  fluid viscosity (Pa·s)

σ  Stephan-Boltzman constant (5.672×10⁻⁸ W/m²K⁴)

σₘ  standard deviation of the mean

σₛ  scattering coefficient

Ω  solid angle

ηₗ  PV panel efficiency

**Sub- and superscripts**

a  DAQ accuracy

amb  ambient

cal  calibration

Conv.  convective heat transfer from the snow surface

Cond.module  conduction heat transfer through the module

Cond.snow  conduction heat transfer through the snow cover

m  maximum
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mp</td>
<td>maximum Power</td>
</tr>
<tr>
<td>n</td>
<td>estimated uncertainty for the 60Hz noise signal</td>
</tr>
<tr>
<td>oc</td>
<td>open Circuit</td>
</tr>
<tr>
<td>solar</td>
<td>Incident solar radiation</td>
</tr>
<tr>
<td>sc</td>
<td>short Circuit</td>
</tr>
<tr>
<td>total</td>
<td>Total snow cover height</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background and Motivation

The world currently relies heavily on coal, oil, and natural gas to meet its heating and other energy needs. However, the reserves of fossil fuel are limited and will be depleted in the near future at its current consumption rate (Cheng, 2017). Combustion of fossil fuels is one of the primary means by which electricity is produced, leading to heavy concentrations of pollutants in the air, contributing 3/4 of all carbon, methane and other greenhouse gas emissions, making them the primary source of greenhouse gas (Satterthwaite, 2008).

The finite resources of fossil fuels and their adverse environmental impacts have encouraged researchers to search for green sources of energy. There are several natural sources that have the potential to generate green energy such as sunlight, wind, rain, tides, waves and geothermal heat. Green and renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off-grid) energy services.

Among green energy sources, solar energy is potentially of great importance. The amount of solar energy reaching the surface of the planet is large. The energy received in one year is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and even mined uranium (Gcep, 2013). The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans, and land masses (Smil, 1991). The total solar energy absorbed by Earth's atmosphere, oceans, and land masses is approximately
3,850,000 exajoules (EJ) per year. This is more energy in one hour than the world used in 2002 (Gcep, 2013).

Table 1.2.1 compares the available energy from different renewable sources of energy and human energy consumption for the year 2010. This comparison reveals the high potential of solar energy resources; however it should be determined how much of this energy can be collected for human consumption. There are several ways to utilize sunlight to provide heat or electricity. One of the most efficient methods is photovoltaic (PV) cells which directly converts sunlight into electricity.

Table 1.2.1 Yearly available green energy by solar fluxes, wind and biomass as well as human energy consumption for 2010 (NREL, 2014)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Available Energy (EJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy</td>
<td>3,850,000</td>
</tr>
<tr>
<td>Wind</td>
<td>2,250</td>
</tr>
<tr>
<td>Biomass</td>
<td>200</td>
</tr>
<tr>
<td>Primary energy use (2010)</td>
<td>539</td>
</tr>
<tr>
<td>Electricity (2010)</td>
<td>67</td>
</tr>
</tbody>
</table>

1 Exajoule (EJ) is 10^{18} Joules or 278 billion kilowatt-hours (kWh).

Figure 1.2.1 shows the growth rate of PV cell efficiency from 1975. The commercial solar cells (single-crystal silicon) with the highest efficiency are about 24% efficient (Crabtree and Lewis, 2007). There are different types of solar cells (monocrystalline, polycrystalline and thin film). Monocrystalline solar panels have the highest efficiency rates since they are made out of the highest-grade silicon, but they are the most expensive. Thin film solar cells such as amorphous silicon (a-Si) are the least efficient ones (between 4–10%); however they are the cheapest solar cells. In terms of expense and effectiveness, Polycrystalline Silicon solar cells are
classified between mono and thin film solar cells (Andresen, 2002; Andresen et al., 2011; Ebong et al., 2010; Jelle et al., 2012; Wawer et al., 2011).

Despite the environmental issues associated with the use of fossil fuels and great potential of PV systems as a more sustainable and green form of energy, PV is not yet a significant contribution of the annual power supply needs of the world (Eia, 2010; Gsr, 2010). The tipping point for solar PV adoption is considered to be when the technology achieves grid parity (Denholm et al., 2009; Song et al., 2009). Grid parity refers to the lifetime generation cost of the electricity from PV being comparable with the electricity prices for conventional sources on the grid (Branker et al., 2011; Pernick and Wilder, 2008). Energy storage can also be another limitation for the PV industry, as PV panels do not generate energy during the night.

Figure 1.2.1 Latest NREL's (US National Renewable Energy Laboratory) report for best Research-Cell efficiencies for different types of PV solar systems including monocrystalline, polycrystalline and thin film up to 2015 (Crabtree and Lewis, 2007)
It has been shown that depending on the location, the cost of solar PV has become comparable to that of conventional sources (Breyer et al., 2009; Gsr, 2010; Swanson, 2009). However, in order to keep the PV industry competitive with the conventional energy sources, it is necessary to address some meteorological and technical limitations against improving PV cells performance. The loss factors for PV system efficiency can be classified into two main categories (Ueda et al., 2006):

- Those which reduce the input energy, e.g., cloud cover, environmental issues, etc.
- Those which lower the conversion efficiency.

The first category refers to parameters which affect the received solar irradiation by PV array including shading or snow-cover, regular loss (such as Dirt, Degradation) and incident angle or reflection. PV panel output depends on ensuring that solar panel surfaces are not shaded by obstructions such as snow and ice. The problem is severe as even partial snow cover on PV modules may significantly reduce the output of a complete string of PV panels.

Loss factors which lower the conversion efficiency include module temperature, DC resistance (voltage drop and energy loss due to the resistance of the cable and voltage drop at the blocking diode), DC to AC PV-inverter efficiency and others. Although these loss factors are still relevant, the current technology for PV-inverters with efficiencies of higher than 90% have reduced the importance of this loss category as compared to the loss factors which reduce the input energy to the PV cells (Kjaer et al., 2005, 2003; Lohner et al., 1996; Meinhardt et al., 1999; Papanikolaou et al., 2003).

By improving the PV systems to overcome some of the difficulties discussed above, the cost of solar photovoltaic systems is decreasing. As a result, PV systems have received more attention in a widening group of areas including those in sub-optimal latitudes and climates (Branker et al., 2011). As such, in 2009 nearly three-quarters of PV resources were installed in countries that
experience some amount of snowfall, namely; Germany, Czech Republic, Japan, and most recently Canada (Prices, 2010). These installations have been driven mostly by government subsidies; however, the industry has a combined focus to modify and improve the PV system performance for being used in such areas.

Previous studies have indicated that annual energy losses for a PV system due to snow can be as high as 15% for a low profile system in Truckee California, to 0.3-2.7% for a highly exposed 28-degree tilt roof mount system in Germany. The energy loss for PV system due to snow (snow loss) depends on the orientation and tilt angle of the PV modules and meteorological factors (Becker et al., 2008; Brench, 1979; Marion et al., 2013, n.d.; Ross, 1995; Townsend and Powers, 2011.; Yoshioka et al., 2003)

Thus, for keeping PV systems competitive with conventional resources, especially in countries with significant amounts of snowfall, more attention needs to be given to the effect of snow on the performance of PV systems, and possible solutions need to be investigated. It has been shown that the snow cover can reduce PV systems efficiency more than 90% during the winter months (Marion et al., 2013; Townsend and Powers, 2011). Although few researchers have studied the effect of snowfall on solar photovoltaic performance, there currently is no practical mechanism to remove snow-cover from PV surfaces, and long shut-down periods can occur while plant operators wait for mild weather.

Due to the noticeable energy loss caused by snow for PV systems installed in regions with snowy climate, snow removal from PV systems can be a new challenge for using this technology in areas with higher annual snowfall. Some methods that have been proposed in the literature for snow removal from PV panels include the surface coating of the panels (Andrews et al., 2013a) and some passive and active heating methods (Van Straten, 2017; Weiss and Weiss, 2016). However, the results of these methods were either not satisfactory or not enough information was provided to show that these methods are applicable for actual PV systems. As a result, several
open questions remain to be answered regarding snow removal methods from PV systems. These questions are:

- What are the possible methods for snow removal from PV panels?
- How effective are these methods in terms of energy consumption and ease of construction?
- Can these methods improve the levelized cost of electricity generation to compensate for their initial construction cost?
- Can these methods pass the standard tests defined for PV panels or new standard test needs to be considered?

The present work tries to answer some of these questions. In particular, this thesis focuses on thermal deicing of PV systems. The snow melting and snow sliding mechanisms are investigated experimentally and numerically to measure how much energy the proposed thermal methods in this study required to remove snow from a PV panel.

1.2 Objective, Approach, and Scope

A review of the literature reveals that for many years the primary concern of researchers was to reach a point that the lifetime generation cost of the electricity from photovoltaic technology is comparable with the electricity prices for conventional sources on the grid (grid parity). In other words, concern was with whether the PV system can pay for itself over its lifetime and provide unsubsidized profits for its installers. However, after reaching this tipping point for solar PV adoption, the next step considered has been overcoming some external limitations (based on the location where PV system is installed) which reduce or restrict the efficiency of PV cells.

As mentioned, the recent growth of the photovoltaic industry has created a significant investment and a large installation of PV systems across the world including regions in sub-optimal latitudes and climates. Particularly in cold regions that experience annual snowfall, snow
coverage can lead to relatively high losses in the generated energy, while there is a high demand of electricity during winter months, especially for the building heating purposes. Therefore, the next step in making PV technology a profitable industry is to study and build effective deicing systems for PV panels.

Although most of the proposed methods for snow removal from PV panels have proved to be unsuccessful, the thermal method has high potential if all aspects of using this method are considered. In this method, the panel is heated in some ways to melt or slide snow off the panel. Besides an investigation by Weiss and Weiss, (2016), there is no study in the literature investigates the performance of such a system and presents the pros and cons of using the thermal method for snow removal from PV panels.

Thus, the main goal of this study is to evaluate different types of heating deicing systems for PV modules and to present methodologies and tools to improve PV system modelling and output prediction. Specifically, this thesis will focus on the prediction of the required time and energy for snow removal from PV panels. It is critical to predicting how much energy is required to remove snow from a panel as compared to the amount of energy that the panel can generate after removing snow from it. In order to find the most efficient system, three different heating mechanisms are presented and investigated in this study. These methods are using a heater bonded to the back of a PV panel to heat the panel, imposing reverse current through the PV panel, and heating photovoltaic-thermal (PV/T) panels by circulating hot water through the back of the panel. As the PV/T panels already have a piping system on the back of the panel (which can be used to heat the panel), there is no need to change the design of the panel or add extra appliances to it.

In addition, for proper heating of a panel, using an appropriate insulation can also be beneficial if it does not interfere with the panel’s function during the seasons without any snow. The positive effect of using insulation for snow removal from PV panels can be significant
compared to its negative effect on the panel performance during the summer. As a result, further investigation is required to provide more insight in this area. There are some studies in the literature regarding the insulation effect on the performance of photovoltaic-thermal (PV/T) panels, but there are no studies of the effect of insulation on PV panel performance.

1.2.1 Contribution of Research

The present work has:

1. increased the technical and economic feasibility of using photovoltaic solar panels across the world, particularly in cold climate regions.
2. furthered the widespread use of renewable, solar energy that will reduce fossil fuel consumption and reduce harmful greenhouse gas emissions;
3. developed and verified a general prediction model for snow removal from photovoltaic solar panels either installed horizontally or at an angle to the horizontal.
4. determined the key design and operational factors that affect the performance of a PV system installed in a snowy climate.
5. produced a preliminary assessment of the feasibility of using a thermal snow removal system attached to a PV system;
6. introduced an insulation system for PV systems which can enhance the snow removal process from the panels during the winter, but does not reduce the system performance significantly during a regular sunny day.
7. compared the performance of several thermal snow removal systems for the photovoltaic and photovoltaic-thermal system; and
8. illustrated the effects of incident solar radiation and climatic conditions on the performance of the snow removal system and consequently the PV system.
1.2.2 Thesis Outline

In the present thesis, a general numerical prediction model is presented to predict the energy and time required for snow removal from PV panels by using a heating method. The results have been validated using the experimental data. In the next step, to study the possible heating methods for snow removal from PV panels, three different heating strategies were examined. Two methods were investigated for heating a PV panel, and one method for heating PV/T panels. The two heating methods examined for PV panels are 1) electrical heating by a resistance thin film heater installed on the back of the PV panel, and 2) electrical heating due to the application of reverse current through the PV cells. Besides, an experimental study was conducted to remove snow from a PV/T panel by circulating hot water to the back of the panel. The experiments were conducted outdoors under natural weather conditions. Specially prepared and instrumented PV modules were mounted at various tilt angles. The study included unheated PV panels as baselines samples. The heated panels were insulated from the back to improve the heating performance. As using permanent insulation can affect the performance of the PV system during the warm seasons, the effect of insulating the panel during the summer is also investigated. The work was completed according to the plan laid out in Figure 1.2.2.
Figure 1.2.2 Flowchart outlining the project approach
The results of this study should provide valuable information to predict and decide whether a thermal snow removal method can be beneficial to the PV systems owner/operators based on net energy delivery.

According to the thesis outline shown in Figure 1.2.2, this thesis consists of the following chapters:

- In Chapter 2, a comprehensive literature review is presented. The numerical and experimental studies regarding snow removal from PV panels are reviewed as well as the proposed snow removal methods for PV panels. The general properties of snow are also reviewed to provide a deeper insight into the nature of the snow cover on PV panels.

- In Chapter 3, the development of an improved numerical model to predict snow sliding or snow melting on horizontal and tilted PV panels is described. The model relies on the use of improved definitions of the boundary conditions and improved models of the heat and mass transfer in the snow layer. The snow covering a panel was modelled as a porous media, and the governing equation for the porous environment was used to predict the rate of meltwater drainage from the snow cover on a tilted panel. In addition, a set of experiments on a small scale PV panel that was performed in a controlled situation to study the physics of snow sliding from a PV panel is described. Based on the experimental results, an empirical correlation is proposed to predict the required energy for snow sliding from inclined panels.

- In Chapter 4, after investigating the thermal method for snow removal from PV panels using the small-scale panel, outdoor tests under natural conditions performed for full-scale PV panels are described. Two heating methods for PV panels have been examined experimentally. Specially prepared and instrumented PV modules were heated by 1) using an electrical resistance thin film heater mounted on the back of the panel, and 2) forcing reverse current through the PV cells. Outdoor tests were conducted under
different natural snowfall conditions. Solar radiation, ambient temperature, relative humidity and wind speed were also measured during each test. The issues associated with using these methods are discussed, and recommendations are provided for PV system owner/operator.

- In Chapter 5, an experimental and numerical investigation of the insulation effect on a PV panel performance during the summer are presented. The panels were insulated to improve the heating methods proposed in Chapter 3. Although using the insulation can increase the performance of a heating snow removal system for PV panels, it can also reduce the efficiency of the panels during the summer. Using the insulation on the back of a PV panel can increase the panel temperature resulting in lower PV performance. To reduce this effect, a modified insulation system has been proposed to reduce the adverse effect of having insulation during the summer. The proposed insulation had two vents at the very top and bottom of the panel and was painted black on the side facing the panel. In the summer, natural convection through the vents and radiation heat transfer between the panel and the insulation help to control the panel temperature. The performance of the insulated system was examined under different natural conditions.

- In Chapter 6, experimental results for heating a photovoltaic-thermal (PV/T) panel are presented by circulating hot water through the back of an insulated PV/T panel. Outdoor tests were conducted under natural conditions. The results for the heated panel are compared with the results for a reference panel. The reference panel was uninsulated and empty, with no fluid circulation. The comparison shows that this method can clean the panels in a short period of time. In addition, a suitable piping system configuration for the back of a PV/T panel is proposed to enhance the snow removal process.

- Finally, in Chapter 7, a summary of the results of this study is presented. Concluding remarks and recommendations for future work are also presented.
Chapter 2

Literature Review

In this section, previous studies on the physical properties of snow and snow effects on PV systems are reviewed to provide a better understanding of the importance of snow effect on the PV system performance. The proposed numerical methods for the prediction of the snow effect on PV systems have been compared as well as some deicing systems. The pros and cons of each method are presented. The results reveal the need for a proper deicing system for using PV panels in cold regions and the importance of the current study.

2.1 Snow properties

To provide a proper snow removal system for PV panels, an adequate understanding of snow properties is required. Initially, it may seem that snow and ice properties should be very similar however scientifically they are very different materials.

The formation of snow crystals, and subsequently, the formation of a snow-cover, are highly complex processes, and the variability of snow particles and snow-cover reflects this (Ross, 1995). Snow-cover is a complex porous medium made of air and up to three phases of water (ice, water vapor, and liquid water). During snowfall, snow crystals collide and form aggregates. Fallen snow on the ground evolves through metamorphism, sintering, riming and various other processes (Ross, 1995). Around 80 different natural snow crystals have been classified (Morrison, 1983) where particles such as ice pellets and hail are not included (Figure 2.1). Therefore, snow-cover can denote a whole range of phenomena having a wide range of properties rather than a single phenomenon.
In response to this complexity, different classification systems for snow-cover have been proposed which include a large number of primary features such as density, free water content, impurities level, grain shape and size, temperature of the snow, permeability, strength and hardness exhibited by the snow-cover (Morrison, 1983; Ross, 1995). In this study, only specific properties of snow-cover which are related to the problem being considered and the effect of these properties have been considered.

2.1.1 Density

Density is an important physical property of snow since most of the complex classification systems rely on density to define other properties such as permeability, thermal conductivity, etc. The densities of various types of snow are listed in Table 2.1. Table 2.1 shows that the wind speed can change the density of snow. In addition, even the density of fresh snow that is
deposited without strong wind speeds varies considerably; for instance, Goodison et al., (1981) found that fresh snow density in Canada varied from 70 to 165 kg/m$^3$. The variation of fresh and dry snow density, $\rho$, with air temperature can be estimated using the Eq. (0.1) developed by Hedstrom and Pomeroy, (1998) and Pomeroy and Brun, (2001).

$$\rho = 67.9 + 51.25 \times e^{2.59T_{\text{amb}}}$$  

(0.1)

where $T_{\text{amb}}$ is the ambient temperature in °C. The correlation suggests fresh snow densities of 143 kg/m$^3$ at air temperatures of 1°C declining to 68 kg/m$^3$ for temperatures below than -10°C.

Table 2.1 Densities of various snow types categorized by Ross, (1995)

<table>
<thead>
<tr>
<th>Snow type</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild snow</td>
<td>10 to 30</td>
</tr>
<tr>
<td>Ordinary new snow immediately after falling in the still air</td>
<td>50 to 65</td>
</tr>
<tr>
<td>Settling snow</td>
<td>70 to 95</td>
</tr>
<tr>
<td>Very slightly toughened by wind immediately after falling</td>
<td>63 to 80</td>
</tr>
<tr>
<td>Average wind-toughened snow</td>
<td>280</td>
</tr>
<tr>
<td>Hard wind slab</td>
<td>350</td>
</tr>
<tr>
<td>New firn snow(left over from last season and has been recrystallized)</td>
<td>400 to 550</td>
</tr>
<tr>
<td>Advanced firn snow</td>
<td>550 to 650</td>
</tr>
<tr>
<td>Thawing firn snow</td>
<td>600 to 700</td>
</tr>
</tbody>
</table>
2.1.2 Effective thermal conductivity

Heat transfer through snow (being a combination of a solid and a fluid or fluids) is more complicated than through either a solid or fluid alone. In dry snow, heat transfer involves (Mellor, 1978):

- Conduction in the network of ice grains and bonds,
- Conduction across air spaces or pores,
- Convection and radiation across pores (probably negligible), and
- Vapor diffusion through the voids.

To avoid the complexity of considering the details of heat transfer through snow, researchers usually define an effective thermal conductivity, $k_{eff}$, for the snow to treat all heat transfer mechanisms as an equivalent conduction (Domine et al., 2011; Sturm et al., 1997; Yen, 1981). The effective thermal conductivity accounts for all the above types of heat transfer through the snow. To estimate the effective thermal conductivity of snow, researchers usually relate that to the density of the snow since the density is more comfortable to measure (Domine et al., 2011; Sturm et al., 1997; Yen, 1981). Most recently, using 3D imaging techniques and needle-probes, Calonne et al., (2012) measured the effective thermal conductivity variation with snow density, and compared the results with previous correlations. The lowermost $k_{eff}$ values were obtained for fresh snow, exhibiting values as low as 0.06 W/mK ($k_z \sim k_{xy}$) at a density of 103 kg/m$^3$. Refrozen wet snow showed the largest values, with $k_{eff}$ values near 0.77 W/mK at a density of 544 kg/m$^3$. The data indicated that, overall, the measurements from needle-probes were significantly lower than those obtained with other methods, and neither the temperature dependency of air/ice thermal conductivity nor the snow anisotropy could explain the observed discrepancy, showing the complexity of measuring snow properties (Figure 2.2).
Figure 2.2 Effective thermal conductivity vs. snow density. The $k_z$ and $k_{xy}$ are the directional components of the computed effective thermal conductivity, $k_{eff}$, provided by Calonne et al., (2011). * refers to the method (needle-probes) used to measure the thermal conductivity.

To avoid non-desirable complexity in defining the effective thermal conductivity of snow, $k_{eff}$, the values of $k_{eff}$ were fitted to the snow density by Calonne et al., (2011) leading to the following equation:

$$k_{eff} = 2.5 \times 10^{-6} \rho^2 - 1.23 \times 10^{-4} \rho + 0.024$$  \hspace{1cm} (0.2)
2.1.3 Latent heat of fusion

In considering the latent heat of fusion of snow, the snow mass can be treated as ice by ignoring the mass of air in the snow. Therefore, the latent heat of fusion for snow is approximately 333 kJ/kg at standard atmospheric pressure and 0°C (Ross, 1995).

2.1.4 Permeability

The permeability of snow, $k$ (m$^2$), is the property of snow that controls the ease with which a fluid, typically air or water, can move through the snow (Domine et al., 2008). The permeability is defined based on Darcy's law (the governing equation of flow of fluid through a porous media):

$$
\nu = -\frac{k}{\mu} \frac{dp}{dx}
$$

(0.3)

Where $dp/dx$ is pressure gradient (Pa/m), $\mu$ is fluid viscosity (Pa.s), and $\nu$ is the fluid flux per unit area (m/s). The permeability is sensitive to the nature of the interconnected pore spaces. It also depends on the crystal structure and the snow layering, as well as on snow metamorphism. The permeability of snow is typically measured by drawing air through a snow sample and measuring the pressure drop and air flow rate through the sample and then calculating the permeability using Darcy’s law (eq. (0.3)) (Domine et al., 2008). Since the most common measurable snow variables are density ($\rho$ in kg/m$^3$) and grain radius ($r_{vis}$ in m), the proposed correlations in the literature relate permeability to these physical snow parameters as the following equation by Shimizu, (1970).

$$
k = 0.308 r_{vis}^2 e^{-0.0078\rho}
$$

(0.4)

where $r_{vis}$ is the equivalent sphere radius. The general validity of this correlation has been questioned by Jordan (1999) as the Eq. (0.4) was obtained using a limited number of snow types. More recent works (Calonne et al., 2012; Courville et al., 2010) proposed a new correlation which significantly differs from Eq. (0.4) for low snow densities based on calculations from tomographic images of snow samples.
\[ k = 3.0r_{\text{vis}}^2 e^{-0.013\rho} \]  \hspace{1cm} (0.5)

where the equivalent sphere radius, \( r_{\text{vis}} \) in m, was determined from the Specific Surface Area (SSA) by using the following equation:

\[ r = \frac{3}{(\rho_{\text{ice,SSA}})} \]  \hspace{1cm} (0.6)

The (SSA) of snow is a measure of the area of the air-snow interface. Its usual definition is the surface area of snow crystals accessible to gases per unit mass (Legagneux et al., 2002). According to these equations, increasing density reduces porosity and therefore pore size and permeability. Figure 2.3 compares these correlations with recent experimental data.

![Figure 2.3 Comparison of experimental data for permeability of snow (in red) with Calonne et al., 2012 equation (Eq. (0.5)) and some other numerical results](image)

2.1.5 Reflectivity of a snow surface

The reflectivity of the snow surface plays an essential role in the amount of energy available to cause snow melting. Large portions of the shortwave radiation (the incident solar radiation)
that reach the snow surface can be reflected. To estimate the amount of solar energy absorbed by
the pack, Albedo ($Al$) is defined as the percentage of the incident shortwave radiation that is
reflected from the snow surface, which varies from 80% for new-fallen snow to 40% for melting,
late-season, ripe snow (Andrews and Pearce, 2013; Warren, 1982). The amount of energy
available for snow melting from the absorption of shortwave radiation ($Q_s$) is given by:

$$Q_s = (1 - Al)I_i$$

(0.7)

where $Al$ is albedo (expressed as a decimal fraction), and $I_i$ is incident solar radiation (kJ/m$^2$)
(Usac, 1998).

2.2 PV module dynamics

A PV module converts sunlight directly to electricity using the photovoltaic effect. The
photovoltaic effect is the ability to emit electrons as a result of receiving light. Some materials
including semiconductors have this ability. Silicon is one of the well-known semi-conductors
being used for manufacturing solar cells. Semiconductors have a characteristic bandgap, which
indicates the amount of energy required to promote an electron from the valence band to the
conduction band of the semiconductor.

As sunlight (composed of photons) hits the silicon atoms of the solar cell, the photons transfer
their energy to release an electron from valence to the conduction band. Any photons below the
energy of the bandgap will not excite an electron to the conduction band, and any photons above
this energy level will impart additional energy to the electron, which is lost through
thermalization (Andrews, 2015). Free electrons need to be directed into an electric current. This
involves creating an electrical imbalance within the cell to conduct the electrons.

To create this imbalance, small quantities of other elements are squeezed into silicon bound
structures. This process can create two types of silicon: n-type which has spare electrons, and p-
type, which is missing electrons. Placing these two materials side by side inside a solar cell creates an electric field across the cell.

The response of a solar cell to light is determined by its current-voltage (or I-V) curve. As it can be seen in Figure 2.4, depending on the cell temperature and effective irradiance, solar cells can operate at a variety of current-voltage states.

![I-V curve from Kyocera KC200GT PV module: (a) under constant temperature and (b) under constant irradiance (Coelho and Martins, 2012).](image)

Figure 2.4 I-V curve from Kyocera KC200GT PV module: (a) under constant temperature and (b) under constant irradiance (Coelho and Martins, 2012).

There are three significant points of interest in the I-V and P-V (power vs. current) curves: short circuit current, $I_{sc}$, open circuit voltage, $V_{oc}$, and maximum power point current and voltage $I_{mp}$, $V_{mp}$. (Figure 2.5).
The effective irradiance strongly affects the short-circuit current $I_{sc}$. Increasing the irradiance increases $I_{sc}$, while $V_{oc}$ almost does not change. This makes $I_{sc}$ an ideal parameter to measure and model the effects of changing effective irradiance on PV module performance (Andrews, 2015).

$V_{oc}$ is sensitive to the panel temperature as shown in Figure 2.4. Higher panel temperature leads to lower $V_{oc}$, while it does not affect $I_{sc}$ as much. Thus, $V_{oc}$ is a useful parameter to measure the response of a PV system to temperature changes.

A PV module consists of PV cells wired in parallel and series to increase current and voltage respectively. The voltage of the Panel (Module) depends on the number of series cells, whereas the number of parallel cells determines the current. For cells which are connected in series, shading of individual cells can lead to the destruction of the shaded cell or of the lamination material, so the Panel (Module) may blister. To avoid such an operational condition, Bypass Diodes are connected to the solar cells as in Figure 2.6. The diode isolates the shaded or broken cell section by allowing current to bypass it. It ensures that the reminders of the modules still operate under normal condition.
Figure 2.6 Module schematic showing the bypass diode arrangement. In this case, a single cell is shaded, leading to the bypass diode engaging and reducing the output of the module by 33% (Andrews, 2015).

Figure 2.7 Module schematic showing the bypass diode arrangement. In this case, a portion of at least one cell per diode is shaded, causing the engagement of all three bypass diodes and reducing module output by 100% (Andrews, 2015).
As a result, bypass diodes decide whether a partly shaded or covered panel operates or not. If a portion of a diode string is shaded, diode bypasses that section of the module (Figure 2.6). If a portion of cells in all diode strings are shaded, the entire module may be bypassed, as shown in Figure 2.7

2.3 Snow Effects on PV Systems

After discussing the snow properties and the complexity of snow formation as well as introducing different types of snow crystals, the effect of snow on PV system performance will be discussed in this section. The previous studies on PV system's snow loss are reviewed to indicate the severity of the issue for using PV systems in cold regions with a significant amount of snowfall.

Since the most important parameter for a PV system is the amount of received solar radiation, researchers have always been concerned about the effect of snowfall on PV systems. A solar array usually includes modules which are connected in series, therefore if only some cells are covered by snow, module output will drop and affect the performance of the whole array significantly (Nakagawa et al., 2003).

The first attempt to estimate the impact of snow on PV performance was performed in 1979 at the Natural Bridges National Monument in Utah (Brench, 1979). Using a simple linear empirical correlation, the author tried to determine the expected PV output and the losses in output due to snowfall. Since the pyranometer had been obscured by snow occasionally and there were some reliability issues about data logger, more than 50% of the data were discarded. Although this study led to no yearly estimation of snowfall loss, daily energy losses were presented by Brench, (1979) (Table 2.2).
Table 2.2 Daily snow loss predictions for a PV system located in the Natural Bridges National Monument in Utah by Brench, (1979)

<table>
<thead>
<tr>
<th>Snow depth</th>
<th>Tilt angle of 30° for modules</th>
<th>Tilt angle of 40° for modules</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 1 in</td>
<td>&gt; 1 in</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 in</td>
<td>&lt; 1 in</td>
</tr>
<tr>
<td>Daily loss</td>
<td>45%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>11%</td>
<td>5%</td>
</tr>
</tbody>
</table>

A Study of snow effects on grid-connected PV systems in Germany was undertaken by Becker et al., (2008). They used 6 years of data from the New Munich Trade Fair Center from 1999 to 2006 resulting in annual snowfall losses in the range of 0.3-2.7% (Figure 2.8). Although they did not mention how they determined these losses, this value is significantly less than 15% measured for a PV system in Truckee California (Townsend and Powers, 2011). Such a significant difference resulted from the very different annual and monthly snowfall for Munich as compared to Truckee California. For instance, in 2011 the average monthly snowfall for Munich was less than 30 cm (Becker et al., 2008), while it was more than 5 m for Truckee, California.

The effect of snow on the performance of PV system located in Truckee, California with an average 5 m (200 in) of snow per year have been investigated by Townsend and Powers, (2011). Three pairs of photovoltaic modules at fixed south-facing tilt angles of 0°, 24°, and 39° were installed such that one module of each pair was manually cleaned and thermostatically heated and another one was bordered to minimize edge effect. The recorded monthly snow losses ranged up to 80%, 90% and 100% of expected yields for 39°, 24°, and 0° tilt angles respectively. In addition, on an annual basis, losses were found to be 13%, 17%, and 26% for a low profile system with angles of 39°, 24°, and 0° with the horizontal respectively.
As mentioned before, comparing these values with those obtained in a study in Germany (Becker et al., 2008) reveals that depending on the average snowfall for a region, the snow loss for a PV system can be significantly high (even more than 90% of its monthly expected yield). These studies emphasize the need for more research on deicing methods for PV modules.

In addition, without performing a specific experiment for snow sliding from PV panels, Becker et al., (2008) observed that snow sliding occurred from module temperatures of +30 to -10°, but there is no data to prove whether increasing the module temperature improves or deteriorates the sliding rate. This matter can be important for any possible heating snow removal methods. However, more investigations are required to verify that.

Andrews et al., (2013b) tried to overcome the limitation of previous studies by using a novel measurement technology and multiple co-located module technologies and orientations. They

Figure 2.8 Snow Days and Lost Yield for PV panels at the New Munich Trade Fair (1999-2006) (Becker et al., 2008).
monitored multi-angle and multi-technology PV systems over two winters 2010-2011. Using
time-lapse digital photography, the accumulation and shedding of snow on the modules were
studied and recorded. As expected, two major snow shedding mechanisms were observed, sheet
sliding and pure melting.

For module tilt angles from 15 to 40°, there was a snow accumulation gradient, with the snow
was more likely to remain at the base of the module (Figure 2.9), while for modules angles at 10°
and below, an even snow distribution over the whole face of the module was found. This
indicated that snow was not sliding from the face of the module but rather melting on the face.
However, some modules at the same angle showed different patterns indicating the complexity of
the snow shedding phenomenon. In addition, modules at angles of 50° and 60° had a bias for
snow accumulation towards the top of the module, which may be due to the layer being exposed
to the ambient winds. Because of the small magnitude of the total snow in the winter of
2010/2011 at the test site compared to historical averages, the annualized losses due to snowfall
were reported up to 3.5%. These studies reveal that snow shedding is a complex phenomenon and
many factors may contribute to it.
Figure 2.9 Probability of snow accumulation on PV panels normalized by the median of its intensity (Time-lapse digital camera was used) (Andrews et al., 2013b).
As a result, some researchers tried to predict the snow sliding situations using meteorological factors. Marion et al., (2013, 2005) measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations during the winters of 2010-2011 and 2011-2012. The experiments included two residential systems with stand-off roof mounts and two small commercial systems, one with stand-off mounts on a tilted roof and the other rack-mounted on a flat roof. They measured monthly energy losses as high as 90% and annual losses from 1% to 12%. They related snow sliding to some factors such as ambient temperature, solar radiations, panel angle and daily snow depth.

Heidari et al., (2015) studied the effect of ground interference on snow shedding from PV panels. They mounted seven portrait-oriented modules placed at four tilt angles (0°, 15°, 30°, 45°) in Calumet, MI, USA. Three of the modules were rack-mounted high enough to prevent ground interference. The other four were mounted at grade similar to many commercial rooftop panels. The average snowfall for that year was 5.3 m. They measured a 5% to 12% annual energy loss for the elevated unobstructed modules. The obstructed modules experienced 29% to 34% energy loss revealing the importance of ground interference. They suggested that landscape array-oriented layout and perhaps snow-clearing mechanisms may be advantageous in snowy climates.

To ease the study of snow loss on PV systems, satellite imaging was used to identify when a PV plant is covered by snow by Wirth et al., (2010). However, there were two primary error sources from this form of detection which reduced the reliability of this method. First, false alarm, where satellite imagery shows the plant to be uncovered, while it is in fact covered, and second under prediction, resulting from an overestimation of times of snow cover. These two error mechanisms had values of 26% and 23% respectively, indicating the probability of errors in snow loss predicting using this method. Moreover, low data availability limits this technique as a consistent monitoring technology.
In summary, reviewing the literature shows notable energy losses for a photovoltaic (PV) systems caused by snow during winter months (up to 100%). Reported annual snow losses were as high as 0.3 to 15% depending on the site location and meteorological conditions. It shows that before installing a PV system in areas with a significant annual snowfall, the snow effect on the output of the system should be considered and the possible solutions should be investigated.

Although, there are only limited research studies on snow sliding from PV panels in the literature, considering some other snow sliding situations for other applications (such as avalanche and skiing) may provide some useful information regarding the physics of snow sliding from a surface.

2.4 Physics of snow sliding

Snow sliding and snow shedding are not only important for PV systems. For instance, snow-shedding is an undesirable issue when it jeopardizes human lives, buildings and road safety due to snow avalanches. On the other hand, ease of sliding on snow and ice is desirable in skiing and sledding. While there is no data regarding the friction coefficient of snow on PV modules, information about friction coefficient of snow for avalanche and real ski situations may provide some insights.

Snow-sheds are the usual tools being used in different regions to protect transportation routes and houses from avalanches (Platzer et al., 2007). These massive structures must withstand both the static and dynamic loads arising from snow avalanches. Dynamic loads arise from the normal and shear stresses exerted by dense snow movements. Using the exerted normal and shear stresses, the mean coefficient of friction, \( \mu \), can be deduced by using the following equation (Platzer et al., 2007).

\[
\mu = \frac{S}{N}
\]  

(0.8)
where $S$ and $N$ are the measured shear and normal stresses, respectively. Platzer et al., (2007) performed their experiments at the snow chute of the Swiss Federal Institute of Snow and Avalanche Research, located at the Weissfluhjoch to measure both the normal and shear forces exerted by snow avalanches on force plates. Measurements of shear and normal stress forces gave rise to the calculation of the dynamic friction coefficient for snow sliding over rough surfaces as shown in Figure 2.10. Interestingly, they found that the coefficient of friction for wet snow avalanches is higher than that for the dry snow avalanches. This finding can be important for developing a thermal snow removal system for PV systems. If the PV panel is heated, melted snow is retained by capillary action due to the permeability of snow and slush (saturated wet snow with water) may form in the lower layer of the snow cover with a higher friction coefficient as compared to that for the dry snow (Liu et al., 2007).

![Figure 2.10 Coefficient of friction, $\mu$, as a function of the measured flow velocity for dry snow, wet snow and slush avalanches (Platzer et al., 2007).](image-url)
In another study, using a shear cell in which two surfaces of annular snow and/or ice samples were in contact and sheared by rotation, Casassa et al., (1991) measured snow and ice friction coefficients. They performed the experiments under different conditions including snow temperatures of 0 to -25°C, normal stresses from 205 to 1292 Pa, and rotation velocities of 0.9 to 25.3 m/s.

They divided their data into two categories: friction coefficients smaller than 0.1 and a friction coefficient larger than 0.1. Based on their experimental results, ice and snow friction with other materials belong to the first category, and snow-snow friction belongs to the second category. Similar results have been reported by other researchers (Platzer et al., 2007).

The other research area which may be helpful is the friction for skis on snow and ice. It has been shown that although the static friction is high on cold snow (Bowden, 1953), when the sliding speed is high enough that a localized surface melting occurs, the friction falls to a low value owing to the localized surface melting produced by frictional heating (Bäurle et al., 2007). These results show that snow removal from PV panels can be possible by melting snow and creating a thin layer of water between the snow and the panel.

Bowden (1953) also found that a ski may slide more slowly on wet snow or slush above 0° (Figure 2.11). It should be noted that in these experiments, the snow density and nominal pressure were more than 300 kg/m³ and 2400 Pa which are usually higher than that for snow covering on PV systems. Buhl et al., (2001) showed that the friction coefficient increases with the decrease of both load and temperature.
Jelle, (2013) performed a set of experiments to measure the friction coefficient between snow and various types of roofing for different slope angles. Most measured friction coefficients (except those for rough surfaces) are of the order of that measured by Casassa et al., (1991) for snow-ice or ice-ice sliding.

Using this available data for the friction coefficient of snow for skiing, some researchers tried to predict snow sliding from PV panels. For instance, using the static coefficient of friction of a waxed wood ski on wet snow, Marion et al., (2013) concluded that the minimum tilt angle of modules should be 8° for snow sliding. However, other studies (Andrews et al., 2013b; Weiss and Weiss, 2016) showed that snow sliding from PV panel is much more complex than can simply be
modeled using the snow friction for skies. As a result, more investigation is required for snow sliding from the PV panels.

In summary, due to the discrepancy between the reported friction coefficients of snow for different surfaces, it can be concluded that the snow friction coefficient highly depends on the snow and the surface characteristics. As a result, although the similar cases (avalanche or skiing) may provide some preliminary data about snow friction coefficients between snow-cover and a PV panel, direct experiments on PV modules are required to address the lack of knowledge in this area.

2.5 Numerical research on snow effects

Before installing PV systems in cold regions, having some analytical models to estimate the impact of snow on the energy production can be beneficial. Therefore, some researchers have recently tried to introduce some prediction models for the snow effect on PV system output.

Townsend and Powers, (2011) proposed a generalized monthly snow loss model calibrated using experimental measurements for three panel-orientations at a BEW test station in Truckee, CA. They considered some effective key parameters including:

- An indicator of snowfall quantity such as inches/month
- An indicator of the array geometry such as tilt angle
- An indicator of ground interference based on additional array geometry parameters such as row slant length and distance to the ground
- Indicators of climate such as temperature, radiation, relative humidity, wind speed/direction, and snow moisture content

After utilizing different forms of equations to relate monthly energy loss to monthly snowfall and other parameters, a final equation was developed which had a 2% RMS error on an annual
basis. As a consequence of the variable nature of snowfall timing, quantity and quality, and its complex dependence on temperature, wind, humidity, and ground interference, short-term errors were higher. Despite reasonable monthly loss predictions by this model, the model seems to be case dependent since it is an empirical equation derived from limited experimental data. Andrews et al., (2013a) applied this correlation equation to their collected data set, and the predicted yearly losses for different module tilt angles had up to a 100% error.

To identify the snow effect, Andrews et al., (2013a) proposed a method in which a time series of so-called “synthetic days” was assembled. The goal of these synthetic days was to model the output of the PV module without the addition of external, stochastic factors such as dust and snow accumulation. A methodology was developed to accurately predict the short-circuit current of a PV module as a baseline to be compared with its actual performance under the effects of snow. Although this method cannot predict snow effect, it can provide a methodology for experimentalists to determine the time required to clear a module after a snowfall (Andrews et al., 2013a).

Most recently, Marion et al., (2013) developed a model for the prediction of PV system performance losses from snowfall. They considered two cases for snow remaining on a PV module: frictional forces and freezing to the PV module. Using friction coefficients given by the ski industry, they concluded that minimum tilt angle for wet snow sliding is 8°. However, in the previous section, some reasons were mentioned which cast doubt on this minimum requirement due to the variety of friction coefficients of skies. In terms of freezing to the PV module, they assumed that the module-snow interface temperature should reach 0°C to melt the snow. This assumption is also in conflict with the previous finding (Becker et al., 2008) which showed that a warm module might not lead to snow sliding from the panel.

Using experimental data for snow sliding situations, an equation was derived by Marion et al., (2013) to identify when the snow slides based on air temperature and an hourly plane of array
irradiance. The assumption of a zero degree air temperature for snow sliding was used in the correlation. Comparing the results with experimental data showed 1.5% error for annual energy losses and a 10.5% for monthly losses. As with other models, the use of an empirical correlation based on limited data increases the probability of the results being highly case-sensitive.

In general, due to the limited available data for each method, the proposed numerical models are all case dependent and far from being general models. Consequently, more numerical and experimental investigations are required to develop more general simulation methods.

2.6 Snow shedding methods

Since the removal of snow from photovoltaic solar cells has remained a big challenge, some studies have tried to propose snow shedding methods for PV panels.

The first attempt to clean solar cells from snow was done by Ross, (1995). He developed a new passive melting system, based on the reflection of light onto the rear surface of the modules. The main goal was to use reflected solar rays from the surroundings of a photovoltaic system with the minimum structure requirement by providing a low-cost solar thermal collector. A transparent box was mounted on the rear of the module including a dark side and a light transmitting enclosure which produced a greenhouse effect which increased the temperature of the cells.

Although this method accelerated the melting process, it still needed a significant time to melt snow (in some cases one or two days). In addition, even if this method leads to snow shedding from PV panels during the winter, the box mounted on the back will increase the panel temperature during the summer resulting in a lower panel performance. The decrease in panel efficiency in summer by using this method may exceed the improvement produced during the winter.

Van Straten, (2017) also presented a new design for PV panels in which a box was mounted on the back of the panel. A heater is placed inside the box with several channels to guide and
circulate warm air through the box. When the snow detector indicates that the panel is covered by snow, the heater will be turned on to melt the snow. This method is very similar to the one proposed by Ross, (1995). The only difference is that this method uses active heating rather than a passive method. As explained before, this method will be problematic during summer.

Andrews et al., (2013a) studied four hydrodynamic surface coatings, as well as one module with a prismatic glass as a reference. The following surface treatments were utilized: hydrophobic, hydrophilic, prismatic glass, and one unaltered module. The surface coatings tested did not have an appreciable positive effect on snow clearance, and in some cases tended to impede the shedding of snow. Figure 2.12 shows the total time a module was covered with snow, normalized by the total covered time of the control module. It appears from these results that at higher angles (60° from the horizontal) most coatings improved the snow shedding effectiveness while for panels with a lower tilt angle no snow shedding improvement was observed for any surface coating. The reason for this may rest on the greater shear forces between snow and glass at higher angles, however, it has been shown that losses due to snowfall are already relatively low for panels at higher angles compared to those at lower angles (Andrews et al., 2013b). Therefore, the improved clearance at these angles is not as beneficial to PV energy yield.
Figure 2.12 The total time a module was covered with snow, normalized by the total covered time of the control module based on the contact angle (Andrews et al., 2013b). ho represents hydrophobic coatings, (hy) represents a hydrophyllic coating. Note that coating ho1 at 20° (marked by an asterisk) only contains data from one winter, while the remainder of points contains data from both winters.

Recently, Weiss and Weiss, (2016) proposed an active method for melting snow on PV panels by reversing current through the panel. They tried to initiate the snow sliding from the panel provided that the clamping effect on snow at the edge of the panel frame is overcome by additional heating. The electrical circuit detail for bypassing the diode was provided. To test the proposed method, they just put a layer of snow on top of the panel surface manually instead of leaving panel outside during a real snowfall event. In addition, the effects of meteorological factors such as solar radiation, ambient temperature, wind speed, etc. were not considered in the experiment. Although they claimed that this method could remove snow from the panel, the results and limitations in their tests show that more investigation and real outdoor tests are required to assess the effectiveness of this method.

The challenge of removing snow from photovoltaic solar cell roofs was investigated by Jelle, (2013). Without providing any experimental or numerical data, he proposed some methods for
deicing roofs in the hope that it would initiate further works by others. Andersson (2017) suggested some similar methods for deicing building integrated photovoltaics without providing data. The proposed solutions are:

- Adding electrical heating cable to the panels
- Using heat loss from building roofs for melting the snow
- The geometry and architectural solution
- Spraying warm water to the panel
- The low friction non-sticky surface immediate removal solution

In summary, most of the efforts for removing snow from solar cells have been unsuccessful. The proposed methods have either no effect on snow removal or reduce the performance of the PV system during seasons without snow. As a result, more investigation is required in this area.

In addition, for active methods, the ratio of the required energy for snow removal to the energy saving after removing the snow-cover should be considered to ensure that the proposed method does not consume more energy than it saves.

### 2.7 Snow removal from other applications

Despite the fact that there have been few research studies on snow removal from PV systems, a lot of deicing mechanisms have been considered in the literature for other applications such as airplanes, wind turbines, etc. It, therefore, may be worth mentioning some of these methods.

Regarding wind turbines, icing mitigation systems result from two main strategies: anti-icing and de-icing systems (Parent and Ilinca, 2011). Both strategies can also be divided into two methods: passive and active. Some of these methods include: special coating (Dalili et al., 2009), black paint (Laakso et al., 2003), chemicals system (Patreau et al., 1998), flexible blades (Dalili et al., 2009), thermal system (Mayer et al., 2007), microwave (Mansson, 2004), electro impulsive/expulsive system (Dalili et al., 2009), etc.
In terms of airplane deicing systems, there are different methods including electro-thermal heaters (Wright et al., 1988), microwave deicing (Martin, 1991), pneumatic deicing boots (Drury et al., 2016; Palacios et al., 2015), deicing fluids (Laforte and Tremblay, 2017; Morita et al., 2015). Most of these methods are not applicable to PV systems due to the high risk of damaging the panels or due to the high energy consumption.

Deicing priorities vary depending on the application. Airplane deicing systems prioritize safety as opposed to PV systems which prioritize low energy consumption. Pneumatic deicing boots/inflatable bladders on wing leading edges have a high safety factor but have high energy consumption. These systems while applicable to airplanes are not practical for PV systems. Other methods such as de-icing fluids may corrode the iced PV module materials and can be expensive and environmentally damaging (Laforte and Tremblay, 2017; Morita et al., 2015).
Chapter 3

Numerical and experimental study of an improved method for prediction of snow melting and snow sliding on photovoltaic panels

Abstract

The photovoltaic power generating systems are being increasingly used all around the world. This includes regions with a significant amount of snowfall. Unfortunately, during the winter, snow accumulation on the PV panels can significantly decrease the output power generated by PV systems. Previous studies have shown that one approach to this problem is to, in some ways, heat the panels to melt or slide the snow layer off the panels. Although several numerical models have been proposed to simulate snow melting on the horizontal surfaces, there is no model for snow sliding or snow melting on tilted surfaces. An improved numerical model has therefore been developed to predict snow sliding or snow melting on horizontal and tilted PV panels. The model relies on the use of improved definitions of the boundary conditions and improved models of heat and mass transfer in the snow and slush layers. By modeling the snow covering a panel as a porous media, the governing equation for a porous environment, Darcy's law, was used to predict the rate of meltwater drainage from the snow cover on a tilted panel. In addition, a set of experiments have been performed in a controlled situation to study the physics of snow sliding from a PV panel. Based on the experimental results, an empirical equation was proposed to predict the required time for snow sliding (RTS) from inclined panels. The model has been validated for various snow cover thicknesses on the panel. The model has also been compared with results given by an earlier numerical method for horizontal surfaces. The comparison showed that the current model predicted melt times and meltwater drainage rates from the snow...
cover more accurately than the previous models. The main improvement of this model is to predict the required energy and time for snow sliding from tilted panels.

Keywords: Numerical model, Snow melting, Snow sliding, Photovoltaic solar panel, Horizontal and tilted solar panels

3.1 Introduction

One of the most efficient methods of converting solar energy into electricity is photovoltaic (PV) cells. In recent years, the lifetime generation cost of the electricity from the PV panel systems has become comparable with the cost of electricity generated by conventional sources, i.e., grid parity has been achieved (Branker et al., 2011; Denholm et al., 2009; Pernick and Wilder, 2008; Song et al., 2009). In fact, it has been shown that depending on the location, the cost of solar PV generated electricity has already dropped below that of conventional sources (Breyer et al., 2009; Swanson, 2009). In response to the cost decline of PV systems, more countries have started paying attention to this technology including those in sub-optimal latitudes and climates (Branker et al., 2011). As such, in 2009 nearly three quarters of PV resources were installed in countries that experience significant snowfall, namely the United States, Germany, Czech Republic, Japan, and most recently Canada (Prices, 2010).

Some barriers against keeping PV cell systems from being fully competitive with conventional electrical power generation systems (such as fossil fuel systems) are factors which either reduce the input energy to the panel or lower the conversion efficiency of the panel (Ueda et al., 2006). In areas with significant annual snowfall, losses associated with the snow cover of PV panels are of great importance. The snow covering the panels can strongly affect the PV cells output during the winter when there is a higher demand for electrical power particularly for building heating
purposes. The problem is severe as even partial snow cover on PV modules may significantly reduce the output of a complete string of PV panels (Nakagawa et al., 2003).

Several numerical and experimental studies have been carried out to investigate the effect of snow covering on PV panel output. The first such study was undertaken by Brench (1979) in 1979; however owing to some reliability issues more than 50% of the data obtained by Brench was discarded. He showed 40% daily snow loss depending on the snow cover thickness. Using 6 years of data obtained from 1999 to 2006 at the Munich Trade Fair Center, Becker et al. (2008) showed approximately 3% annual snow losses for that site with an average 30 cm annual snow precipitation. However, the effect of snow on the PV system performance located in Truckee, California with an average of 5 m of snow per year was approximately 15% on an annual basis. In terms of monthly energy losses due to the snow cover, it ranged up to 80%, 90% and 100% of the expected yields for 39°, 24° and 0° panel tilt angles (Townsend and Powers, 2011).

Some researchers have tried to propose a numerical model to predict the effect of snow on PV panel output. By considering some effective key parameters for snow removal from PV systems, Townsend and Powers (2011) proposed a correlation to predict monthly energy loss by using their experimental measurements. More recently, Marion et al. (2013) developed a similar model for the prediction of PV system performance losses from snowfall. Although these models can predict the snow loss for PV systems, they do not provide any information regarding the energy required for snow removal from the panel.

The significant losses associated with snow cover on PV systems show the necessity of an economical snow removal system for PV panels. Ross (1995) and Andrews et al. (2013a) tried to use a passive melting system and surface coating for PV panels respectively. The passive system was based on the reflection of light onto the rear surface of the modules and was used for panels installed in remote areas. This method could expedite the snow melting process on the PV panel but also increased the panel temperature during summer resulting in lower panel efficiency. Using
a hydrodynamic surface coating on the panel also did not show appreciable improvement of snow removal from the panel (Andrews et al., 2013a).

Past studies, therefore, indicate that a more effective snow removal method needs to be developed. Mechanical removal of snow from PV arrays has been rejected by plant operators due to the fragile nature of the glass panels used to support PV cells. As a result, recently some active thermal methods have been considered for snow removal (Weiss and Weiss, 2016). In these methods, the panel was heated by different ways causing the snow to slide off the panel or to melt the snow cover. The key challenge for using an active thermal method is the energy required for the method to remove snow cover from the panel. To investigate the details of such a system, numerical simulations of the system are required to calculate the energy required for snow removal and to evaluate the system performance.

Although some snow melting models for asphalt pavements have been proposed by Liu et al. (2007) and Rees et al. (2002), none of these models is appropriate for snow melting on PV panels. Both proposed methods applied heat only to horizontal surfaces (such as an asphalt pavement), while most PV panels have a degree of inclination with the horizontal which affects the heat and mass transfer mechanisms involved in the melting process. As a result, this study proposes a new snow melting model for inclined surfaces.

In this paper, a numerical snow removal model for inclined surfaces is presented which enables the evaluation of any thermal deicing or snow removal system used for inclined or horizontal surfaces including PV panels. A new mass transfer model is proposed by using Darcy’s law as well as a modified heat transfer model. To define the criteria for snow sliding from the panel in the model, a set of experiments on a small scale instrumented PV panel has been conducted under the control conditions. Using the experimental data, an empirical correlation is proposed to correlate the required energy for snow sliding from a tilted panel (from the horizontal) to the panel tilt angle and other environmental conditions such as ambient
temperature, snow cover thickness, cloud cover, etc. As a result, using available heat sources and weather data, the proposed model can predict the energy and time required for snow sliding or snow melting on any horizontal or tilted surfaces. The results predicted by this model are compared with the experimental data to validate the model.

3.2 Methodology

Previous snow melting models considered the transient nature of weather conditions during a storm to predict snow melting on different types of pavement over long periods of time. Accordingly, these models were optimized for multi-year predictions based on hourly weather data (Liu et al., 2007; Rees et al., 2002). An economical snow melting system for PV panels should not operate more than a couple of hours, otherwise, it may use more energy for snow removal from the panel than it can save after the snow removal. Therefore, using available snow melting models is not applicable to PV panels as they were designed for annual prediction with the time resolution of one or two hours. In addition, previous models assumed that snow melting is only occurring on a horizontal surface while PV panels are usually set at an angle to the horizontal which affects the melting process.

In this paper, modified heat and mass transfer equations were used for the snow melting model as well as appropriate initial and boundary conditions for PV systems. The modifications enabled the model to evaluate the performance of a thermal snow melting system for PV panels when the panel is uniformly heated from its rear surface.

3.2.1 Numerical model development

In the present model development, it is assumed that snow is a porous material composed of ice crystals, air, and water vapor (Liu et al., 2007). During the melting process from the lower surface of the snow layer (PV panel), a portion of the meltwater is retained and partly saturates the snow (Liu et al., 2007). Thus, two distinct layers may exist on the PV panel these being the dry snow layer at the top and the slush layer (which is saturated with water) at the bottom (Figure
Depending on the boundary conditions, different combinations of these layers may cover the PV modules. Several surface conditions were considered in the proposed model. Following the classification described by Rees et al. (2002), the possible surface conditions for a PV system considered here are as follows.

- **Clean surface**: the panel surface is free of ice and liquid and its temperature may be above or below freezing point (0°C).

- **Dry snow**: here the panel surface temperature is below freezing point and it is covered by the dry snow and free of liquid. Under these circumstances, the snow is treated as a porous matrix of ice.

- **Slush only**: the panel surface temperature is at the freezing point; the snow layer is saturated with liquid water and water penetrates the porous matrix from the bottom to the upper surface due to the capillary action.

- **Dry snow and slush**: a combination of a dry snow layer at the top and a slush layer at the bottom of the snow cover (see Figure 3.1).

Rees et al. (2002) and Liu et al. (2007) also considered hoarfrost and solid ice as other possible surface conditions. In the present model, these surface conditions were treated under dry snow category with different snow densities to reduce the complexity of the model.
There are some different criteria for snow removal from PV panels compared to snow melting on pavements or roads (Chen et al., 2011; Hockersmith, 2002). Depending on the panel tilt angle with the horizontal and the snow cover thickness on the panel and other environmental conditions, the snow cover may also slide off a panel rather than being melted on the panel (which is the only option for pavement and roads). It is actually more desirable for inclined PV panels to slide snow cover off the panel instead of melting the entire snow layer to reduce the energy consumption; however, if the panels are installed horizontally, the entire snow layer needs to be melted similar to the previous snow melting systems for pavements.

Another challenging aspect of the snow melting system for PV panels compared to the pavements is the energy consumption of the system. For the pavement melting system, the cost is usually not the first priority as compared to the safety of the roads; while energy consumption and

Figure 3.1 The snow cover temperature on a panel was modeled using three nodes on the present model. The first node was located at the snow cover surface, the second node was at the center of the dry snow layer, and the third one was located at the center of the slush layer.
cost are the first priorities for the PV panel snow removal system as the system is being used to increase the efficiency of the PV panels.

Considering these issues for a PV snow removal system, to simulate such a system, several parameters play key roles. These are the panel surface temperature, the snow thickness and density covering the panel, the heating flux being used for snow removal and the weather conditions. As was done by Liu et al. (2007), the weather data used in the present model are those found in standard weather records: ambient temperatures, wind speed, cloud cover fraction and solar flux values.

For each simulation, the initial conditions of the panel and the snow cover were determined based on the weather conditions (which were usually in a sub-freezing condition named as 'dry snow'). By heating the panel from the back (Figure 3.1), the panel surface temperature increased up to 0°C at which snow melting started. During the melting process, as mentioned above, a portion of the meltwater was retained and partly saturated the snow. Consequently, a slush layer formed and grew at the interface between the panel and the snow cover. The rest of the meltwater drained out of the snow layer. This condition was termed as 'snow-slush'. Continuous heating thickened the slush layer so that only a relatively thin layer of fully saturated snow existed. This condition was termed as 'slush only'. For the 'snow-slush' layer, it has been observed (Hockersmith, 2002; Jordan, 1999) that during snow melting process, the thickness of this layer increases until a maximum thickness is reached which will be explained in the following sections. This maximum thickness is reached when the capillary and gravity forces are in balance. The runoff water rate was increased to the melt rate after this point.

The snow melting process usually starts from the 'dry snow' condition for the snow cover and followed by the 'snow-slush' and then the 'slush only' conditions and ends up with a 'clear surface' condition. Three nodes (with specific assumptions for each of them) were considered in the snow
layer to calculate the heat transfer rate through the slush and dry snow layers. Figure 3.1 shows a schematic of the model configuration.

The assumptions were made in the model are:

- The dry snow layer is homogeneous and porous. According to the specific shapes of snow crystals, it is believed that the dry snow can be treated as a porous media (Domine et al., 2008; Liu et al., 2007). In addition, by defining an effective thermal conductivity, it is possible to avoid consideration of the small effect of directional thermal conductivity (Calonne et al., 2011).

- The slush layer is isothermal at the melting point of water 0°C because it is a mixture of ice and water (Hockersmith, 2002; Liu et al., 2007; Rees et al., 2002).

- Melting of snow occurs only at the PV module surface. It is assumed that the incident solar radiation does not affect the heat transfer balance for the dry-snow surface, as the dry-snow layer is assumed as a highly porous layer that is not opaque (depending on the snow layer thickness) (Liu et al., 2007). In addition, the ambient temperature during the snow removal process is usually below or close to the freezing point and heat transfer rate from the panel is much higher than the convective heat transfer with the ambient air. Even if the incident solar radiation or high ambient temperature can cause snow melting on the top surface of the snow cover, the meltwater would drain down to the slush layer adjacent to the panel. As a result, the effect of incident solar radiation in the energy balance was considered on the panel surface rather than the snow surface (see Figure 3.1).

- The snow melting process is treated as a one-dimensional heat transfer along the y-axis across the snow layer (Figure 3.2). Considering that the snow layer is assumed to be heated uniformly along the panel, and the dry snow layer is relatively thin as compared to the panel length \( (L \gg h_{\text{total}}) \), and the thermal conductivity of snow is
relatively low (Calonne et al., 2011), heat conduction along the snow layer \( (q_x) \) is negligible as compared to the heat transfer across the snow layer \( (q_y) \) i.e. \( q_x \ll q_y \).

- The heat and mass transfer equations on the slush layer are not coupled. Since the slush layer is isothermal, mass transfer from one section to another in the slush layer does not have any effect on the heat transfer. As a result, the mass transfer in the slush layer is calculated separately using Darcy's law (Whitaker, 1986) in the present model to compute the amount of run-off water from the snow cover.

- Assuming there is a relatively thin layer of snow with a low thermal conductivity over the module and a constant ambient temperature during the simulation, the dry snow layer is considered to be isothermal (Calonne et al., 2011; Liu et al., 2007; Rees et al., 2002).

A critical point in the simulation is to distinguish whether the surface is covered with 'slush only' or 'snow and slush'. The existence of a dry snow layer at the top of the snow cover can be very effective in the heat transfer rate through the snow cover since the thermal conductivity of the dry snow is relatively low (0.4 W/mK) (Calonne et al., 2011). Liu et al. (2007) in their model assumed that the slush layer thickness had already reached the equilibrium thickness which is an adequate assumption for long-term annual simulation but not the short-term simulations of the PV panel snow removal. As a result, in the present model, the thickness of the dry snow layer and slush layer were calculated at each time step. Consequently, two coupled transient mass balance equations should be solved to calculate the mass of ice and retained water. These equations are coupled with the PV module heat balance equation. Furthermore, the phase change modeling should contribute to the heat balance equation increasing its complexity. The resultant coupled equations need to be solved iteratively at each time step in a manner similar to that used in the model developed by Rees et al. (2002).
The main difference between the present model and the model developed by Rees et al. (2002) is that they used a simple heuristic approach to estimate the amount of run-off water. In the Rees' model (Liu et al., 2007) the runoff water was limited to 10% of the melt rate until the saturated layer is 2 in. thick (Rees et al., 2002). After this point, the runoff rate was increased to the melt rate to prevent more water being retained. Although this assumption may be adequate for a horizontal surface, it may not be adequate for the tilted PV panels. Since snow is a porous media, if the panel was tilted, the meltwater would run through the snow pore spaces until it would drain out of the snow cover. In the present model, to address this issue, Darcy's equation (the basic law governing the flow of fluids through porous media) was used to calculate the amount of runoff water moving through the snow pore spaces (Whitaker, 1986). Using Darcy's law, the water flux flowing through the pore spaces was calculated. The details of the model are explained in the following section.

In the presented model, five primary equations have been considered including a mass balance for the solid ice, a mass balance for the liquid water, and a heat balance for each node shown in Figure 3.1. These mass balance equations are coupled to the energy balance equations through the melt rate as explained in the following section.

3.2.2 Heat balance equations

Three heat transfer equations were considered for three nodes shown in Figure 3.1. In addition to the heat flux rate from the PV panel, shortwave (incident solar radiation) and longwave radiative heat fluxes, as well as convective heat transfer from the snow surface to the ambient air, can affect the heat balance of the snow covering a panel. As mentioned, it was assumed that incident solar radiation, \( q_{\text{solar}} \), does not affect the heat transfer balance for the dry-snow surface, as the dry-snow layer was assumed as a highly porous layer that was not opaque (Liu et al., 2007). Consequently, solar irradiance partly penetrated through the dry-snow layer and was
absorbed by the slush layer. As a result, the energy balance equation for each node (see Figure 3.1) is as follows.

\[
m_{\text{snow}} C_p \frac{dT_{\text{snow}}}{dt} = q_{\text{cond.snow}} - q_{\text{cond.surface}} \quad (3.1)
\]

\[
\rho_{\text{snow}} C_p \frac{T_{\text{surface}}^{n+1} - T_{\text{surface}}^n}{dt} = q_{\text{cond.surface}} - q_{\text{conv.}} - q_{\text{rad.LW}} \quad (3.2)
\]

\[
\dot{m}_{\text{melt}} h_f = q_{\text{cond.module}} + q_{\text{solar}} - q_{\text{cond.snow}} \quad (3.3)
\]

Where \( n \) is the time iteration number and \( h_f \) is the latent heat of fusion (KJ/kg) for snow. The rate of heat flux received from the PV modules to the snow, \( q_{\text{cond.module}} \), and the convective heat transfer between the snow surface and the ambient air, \( q_{\text{conv.}} \), will be discussed in the boundary condition section. Conduction heat transfer through the dry snow and slush layers (\( q_{\text{cond.snow}} \) and \( q_{\text{cond.surface}} \)), as well as longwave radiative heat flux \( q_{\text{rad.LW}} \), are given by (see Figure 3.1):

\[
q_{\text{cond.snow}} = -\frac{k_{\text{snow}}}{0.5(h_{\text{snow}} + h_{\text{sat}})} (T_{\text{snow}} - T_{\text{slush}}) \quad (3.4)
\]

\[
q_{\text{cond.surface}} = -\frac{k_{\text{snow}}}{0.5h_{\text{snow}}} (T_{\text{surface}} - T_{\text{snow}}) \quad (3.5)
\]

\[
q_{\text{rad.LW}} = \varepsilon\sigma(T_{\text{surface}}^4 - T_{\text{sky}}^4) \quad (3.6)
\]

Where all heat fluxes are per unit area (W/m\(^2\)); \( k_{\text{snow}} \) is the thermal conductivity of snow (W/(m.K)); \( T_{\text{snow}} \) is the temperature of the dry-snow node (°C); \( T_{\text{slush}} \) is the slush layer temperature (0°C); \( T_{\text{surface}} \) is the surface temperature of the snow layer; \( \varepsilon \) is the emissivity of snow and is the Stefan-Boltzmann constant (5.670373×10\(^{-8}\) (W/m\(^2\)k\(^8\))). The sky temperature \( T_{\text{sky}} \) is computed...
using the method proposed by (Duffie and Beckman, 2013; Iziomon et al., 2003) based on ambient temperature, relative humidity and cloud cover of the sky.

As mentioned, previous research studies have shown that it is possible to avoid consideration of the small effect of the directional thermal conductivity of snow by defining an effective thermal conductivity (Domine et al., 2011; Sturm et al., 1997; Yen, 1981).

To estimate the thermal conductivity of snow $k_{\text{eff}}$, an empirical equation was used to relate the effective thermal conductivity of snow, $k_{\text{eff}}$ (W/m$^2$k), to the density of snow (Domine et al., 2011; Sturm et al., 1997; Yen, 1981).

$$k_{\text{eff}} = 0.138 - 1.01 \times (\rho / \rho_{\text{water}}) + 3.238 \times (\rho / \rho_{\text{water}})^2$$

Where $0.156 < \rho / \rho_{\text{water}} < 0.6$. In addition, Yen (1981) mentioned that $k_{\text{eff}}$ is not sensitive to the snow temperature for snow with a density around 100 kg/m$^3$ and temperatures between 250 to 280 Kelvin.

Given that the snow cover reflects part of the incoming solar radiation, researchers have defined Albedo, $Al$, as the proportion of the incident solar radiation that is reflected by the snow surface. As a result, the portion of the incident solar radiation which is available for melting snow is as follows.

$$q_{\text{solar}} = (1 - Al) \times I$$

Where $I$ is the incident solar radiation (W/m$^2$). A wide range of Albedo effect has been reported in the literature based on the snow type ranging from 0.8 for fresh snow to 0.4 for melting, late-season, ripe snow (Andrews and Pearce, 2013; Warren, 1982). In this study, as the snow removal process usually happens shortly after a snowfall, an Albedo value of 0.8 is used.

### 3.2.3 Mass balance equations

Two mass balance equations were solved for the ice crystals and the liquid water in the dry snow and slush layers. The mass balance for the snow is given by:
\[ \frac{dm_{\text{snow}}}{dt} = m_{\text{snowfall}} - m_{\text{melt}} \]  \hspace{1cm} (3.9)

Where \( m_{\text{snowfall}} \) is the snowfall rate per unit area (kg/(sm²)), \( m_{\text{melt}} \) is the melting rate per unit area (kg/(sm²)); and \( m_{\text{snow}} \) is the mass of snow per unit area (kg/(sm²)).

The mass balance for the melted liquid water is given by:

\[ \frac{dm_{\text{liq}}}{dt} = m_{\text{melt}} - m_{\text{runoff}} \]  \hspace{1cm} (3.10)

where \( m_{\text{liq}} \) is the mass of liquid water per unit area (kg/m²), and \( m_{\text{runoff}} \) is the rate of run-off water (kg/s.m²).

As mentioned, since the snow layer is a porous media, it was assumed that the melted snow could flow through the snow layer if the panel was tilted. As a result, the governing equation for the flow of fluid on a porous media (Darcy' law) was used. Darcy's law relates the fluid flux, \( V \) (m/s), through a porous environment to the permeability, \( K \), of the media and the available pressure gradient, \( \frac{dp}{dx} \) (Pa/m), for flowing the fluid through the pores (Whitaker, 1986) (If the panel is horizontal, Lee's method was used to calculate the runoff water i.e. constant 10% of the melt rate was used as the runoff water rate until the saturated layer is 3 cm. thick (Hockersmith, 2002)).

\[ V = -\frac{K dp}{\mu dx} \]  \hspace{1cm} (3.11)

Where \( \mu \) (Pa.s) is the kinematic viscosity of water. The permeability of snow, \( K \) (m²), is the property of snow that controls the ease with which a fluid, typically air or water, can move through the snow (Domine et al., 2008). By drawing air through a snow sample and measuring the pressure drop and the air flow rate through the sample, some researchers have tried to calculate the permeability of snow and have proposed the empirical equations for that based on the snow density (Domine et al., 2008).
As the meltwater percolates through the snow cover, a gradient can be assumed for the slush layer height parallel to the PV panel based on the observations during the experiments performed in this study (will be explained in the next section) as shown in Figure 3.2. Considering an arbitrary volume on the slush layer with the thickness of \( dx \), \( \frac{dp}{dx} \) for the fluid flow on the slush layer can be calculated as follows.

\[
\frac{dp}{dx} = \rho g \sin(\theta) \tag{3.12}
\]

The mass flow rate of meltwater per unit area, \( \dot{m}_{\text{runoff}} \), can then be computed by using the calculated volume fluid flux, \( V \).

\[
\dot{m}_{\text{runoff}} = \rho_{\text{water}} VA \tag{3.13}
\]

Where \( A \) is the cross-section area of the slush layer (m\(^2\)).

Figure 3.2 A linear inclined slush layer height is considered in the model for the tilted panel, \( h_{\text{slop}} \), as well as an equivalent constant slush layer thickness, \( h_{\text{sat}} \).

To find the slush layer height, an equivalent constant slush layer thickness, \( h_{\text{sat}} \), was assumed provided that the constant height slush layer has the same volume as the slush layer with gradient height, \( h_{\text{slop}} \). As a result, the equivalent height is given by:
\[ h_{sat} = 0.5h_{slip} \]  
\[ h_{sat} = \frac{m_{liq}}{\rho_{liq} n_{eff}} \]  

Where \( n_{eff} = 1 - (\rho_{snow}/\rho_{liq}) \) is relative density between snow density, \( \rho_{snow} \), and liquid water density, \( \rho_{liq} \). As mentioned before, \( h_{sat} \) will increase until the equilibrium condition for the slush layer is reached (the capillarity force is balanced with the water column weight) which is assumed to be 3 cm in this study (Hockersmith, 2002, Liu et al., 2007). Similarly, the total height of the snow-slush layer \( h_{total} \) can be calculated from the mass of snow using:

\[ h_{total} = \frac{m_{snow}}{\rho_{snow}} \]  

Where \( m_{snow} \) is the total snow-cover mass per unit area (kg/m²).

The height of the dry snow layer can be found by using, \( h_{snow} = h_{total} - h_{sat} \). By using \( h_{snow} \), the mass per unit area (kg/m²) of the dry snow layer can then be found using:

\[ m_{snow} = \rho_{snow} h_{snow} \]  

### 3.2.4 Boundary Conditions

As the snow cover thickness is usually small as compared to the panel length, the snow melting process is treated as a one-dimensional process. Because of the small heat transfer area on the sides of the snow layer compared to the top and bottom surfaces, the snow cover sides were treated as the adiabatic surfaces.

The boundary conditions include two interfaces: 'snow-ambient air' at the top of the snow cover surface, and 'snow-PV surface' adjacent to the panel.

For the interface between snow and air, the convective heat flux is considered giving:
\[ q_{\text{conv.}} = h_c \left( T_{\text{surface}} - T_{\text{amb}} \right) \]  

(3.18)

where \( h_c \) is the convective heat transfer coefficient (W/m\(^2\)k) which is calculated by the correlation given by Incropera and DeWitt (1990) based on the wind velocity. \( T_{\text{surface}} \) and \( T_{\text{amb}} \) are snow surface and air temperature respectively.

In order to calculate the heat balance (Eq.(3.3)) at the boundary between the snow layer and the PV panel ('snow-PV surface' boundary), the rate of heat flux through PV modules, \( q_{\text{cond.module}} \) is required. A finite-difference method was used to solve the two dimensional heat conduction equation (Eq. (3.19)) that describes the temperature distribution within the PV module.

\[
\frac{\partial T}{\partial t} = (\alpha) \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] 
\]

(3.19)

where \( x \) and \( y \) are parallel and normal to the module surface respectively (Figure 3.2), and \( \alpha \) refers to the thermal diffusivity (m\(^2\)/s) of the PV module. The Euler method has been utilized to discretize this equation in time resulting in an equation with first order accuracy in time and second-order accuracy in space.

The 2-D heat transfer equation is solved for the PV module, while the 1-D heat transfer equation is solved for the snow layer. The reason is that unlike the snow layer, the PV module may not be isothermal since the location of the heater bonded to the panel may be changed. In the present simulations, a constant heat flux is assumed over the entire module surface.

### 3.2.5 Model Implementation

The 'snow-PV surface' boundary condition and the energy balance equations for the snow layer are coupled in the current model. There are a number of ways to deal with this coupling but in the present model, several steps have been introduced to increase the accuracy of the solution as compared to that of other snow melting models (Liu et al., 2007; Rees et al., 2002). In the first step, based on the initial conditions, the heat transfer between the snow layer and PV module was calculated until the interface temperature between snow and the module reaches the freezing
point temperature 0°C. The PV surface temperature assumed to be fixed at the freezing point of water during the rest of the snow removal process. The heat flux through the module calculated from the last time step was used to determine the snow melting rate. Consequently, the slush layer grew until the entire snow layer became slush (no dry snow layer). The simulation will be stopped when the entire snow cover is melted or the criterion for snow sliding occurs (which will be explained in the experimental result section).

3.2.6 Experimental Setup

The experimental setup consisted of a 30.5cm × 30.5cm glass panel with a resistance film heater bonded to the back. The heater was insulated by using a Polyisocyanurate foam insulation with a thickness of 25 mm and RSI value of 0.99 (m²C/W), and the entire system was weatherproofed using an aluminum tape. The panel was mounted on an adjustable steel frame to change the inclination angle of the panel with the horizontal. The heater was wired to an AC power supply (through a VARIAC transformer) to control the provided energy precisely. The constant heat flux rate, 570 W/m², was used for all test cases. Higher values than 570 W/m² were not considered as it could damage the panel, while the lower values would result in a long time to remove the snow cover from the panel which would not be economical. All the instruments were placed in a cold room with adjustable temperature (Figure 3.3). After calibrating the thermocouples (by using a thermocouple calibration water-bath – see Appendix A), 8 Copper and Constantin (type T) thermocouples were placed on the panel surface (Figure 3.3). The thermocouples were attached to an eight channel Omega USB-TC thermocouple temperature reader and data recorder. The data could then be uploaded onto a computer for processing. The cold room temperature was also recorded by using an extra thermocouple.

3.2.7 Experimental procedure

Using an ice cracker, manmade floppy snow was produced with a constant density of 400±20 kg/m³. After setting the panel horizontally, using a plastic circular mold with a diameter of 11cm,
a circular snowpack with a specific height was placed at the upper part of the panel (Figure 3.3b). To simulate falling snow on the panel, a fine mesh strainer with 0.5 mm grain size was used. All of the apparatus was kept in the freezer to minimize the ice melting during the process of making the snowpack. The snowpack and the panel temperatures were monitored until the steady state condition was reached with the air temperature inside the cold room. Tests for five different tilt angles of 10°, 20°, 30°, 45°, and 55° were undertaken. For each tilt angle, three snowpack heights (1 cm, 2 cm, and 3 cm) were examined.

After reaching the steady state condition, the tilt angle of the panel was set, and the constant power, 570 W/m², was supplied to the heater. Power was continuously supplied until the snowpack slid off the surface. The required time for snow sliding (RTS) was recorded for each experiment. A camera was mounted inside the cold room to monitor the melting process and record RTS precisely.
Figure 3.3 The snowpack placement for each test and thermocouples configurations
3.3 Result and discussion

The results of snow removal simulations from horizontal and tilted surfaces are presented and compared with experimental data in this section.

3.3.1 Horizontal Surfaces

The first comparison was drawn between the presented model results and the experimental results reported by Hockersmith (2002). Hockersmith performed a set of snow melting experiments using artificial snow on horizontal surfaces. The inputs for the present model were set based on the experiment conditions, i.e., the initial snow cover height, ambient temperature, the snow density, and the heat flux. The convection heat transfer coefficient of 1.5 W/m²°C between the snow surface and the ambient air and thermal conductivity of 0.3 W/m°C for the snow cover were assumed in the simulations, as Hockersmith (2002) used the same values for his model.

The predicted snow height and water run-off for several heat fluxes are compared with the experimental data in Figure 3.4. The largest differences between the experimental and numerical snow heights occurred during the last hour of the melting process. It is mentioned in the report describing the experiments that the deceleration of snowmelt rate during the last hour of the test could be caused by inhomogeneous melting resulting from densification of the snow crystals. If the snow was reorganized into a more efficient packing manner, the effect of that would be a reduction in the overall snow height (Hockersmith, 2002). However, there is a better agreement between the present model results and experimental data compared to the Hockersmith model (Hockersmith, 2002) resulting from the more detailed modeling of the slush layer and the model proposed for predicting the rate of water drainage from the snow layer.
Figure 3.4 Comparison between the snow height decrease and water run-off rate for snow melting on a horizontal surface predicted by the present model and the experimental data provided by Hockersmith (1999) for several heat fluxes.
Table 3.1 compares the predicted melt time by the present model with experimental values with the maximum difference of 7%. Given the discussed experimental uncertainties, this amount of error is acceptable.

**Table 3.1 Comparing the snow Melting time on a horizontal surface predicted by the current model and experimental data provided by Hockersmith (1999) for several heat fluxes**

<table>
<thead>
<tr>
<th>Heat Flux (W/m²)</th>
<th>Exp. melt time (min)</th>
<th>Old model (min)</th>
<th>Current model (min)</th>
<th>Error of current model</th>
</tr>
</thead>
<tbody>
<tr>
<td>234</td>
<td>730</td>
<td>705</td>
<td>774</td>
<td>6%</td>
</tr>
<tr>
<td>311</td>
<td>575</td>
<td>520</td>
<td>560</td>
<td>3%</td>
</tr>
<tr>
<td>468</td>
<td>445</td>
<td>415</td>
<td>433</td>
<td>3%</td>
</tr>
<tr>
<td>633</td>
<td>305</td>
<td>275</td>
<td>284</td>
<td>7%</td>
</tr>
<tr>
<td>780</td>
<td>235</td>
<td>230</td>
<td>235.8</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Chen et al. (2011) also presented snow melt time over two different types of pavement. A comparison of the melt times predicted by the present model with the experimental results is presented in Table 3.2. It should be noted that Chen et al. (2011) did not mention a certain value for the snow density except by using the phrase of "fresh snow". Assuming a certain value for the density of fresh snow (110 kg/m³) resulted in maximum 20% difference between predicted and measured melting times.

These comparisons show that the improvements included in the current model have significantly increased the accuracy of the melt time predictions and of the water run-off prediction, especially for lower heat fluxes. Lower heat transfer rates can be particularly important for predicting the performance of a snow melting system for PV panels because it may not be economical and safe to use high heat fluxes for PV panels (more than PV panel equivalent electrical power) due to the risk of damaging the panel.
Table 3.2 Comparing the snow melting time rate on a horizontal asphalt pavement predicted by the current model with the experimental data provided by Chen et al. (2011)

<table>
<thead>
<tr>
<th>Pavement type</th>
<th>Melting time (min)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>Num.</td>
</tr>
<tr>
<td>Asphalt AC50</td>
<td>217</td>
<td>209</td>
</tr>
<tr>
<td>Asphalt CAC50</td>
<td>309</td>
<td>246</td>
</tr>
</tbody>
</table>

Regarding meltwater run-off, a time delay was noticed for the water to drain from the snow cover in the experiments (Figure 3.4). As mentioned, during this early period of melting, the meltwater was wicked up into the pores of the snow to form a slush layer and did not run off the plate. In the current model, the maximum height of this saturated layer was taken to be 3cm for horizontal surfaces, based on the experiments (Hockersmith, 2002). During the last minutes of melting experiment (where there is the most discrepancy between numerical and experimental results), the amount of measured water run-off was affected by surface roughness, surface tension of water and orientation (Hockersmith, 2002). The present model predicted water run-off more accurately than the previous model by Hockersmith (2002).

### 3.3.2 Tilted Surfaces

As discussed before, a set of experiments was conducted for snow sliding from tilted surfaces at five different tilt angles with three snow pack heights for each angle. The measured panel temperature and time required for snow sliding were compared with the predicted values by the present model.

Figure 3.5 compares the experimental and numerical panel temperatures at snow pack location T1. There is a good agreement between the predicted panel temperature by the present model and the measured values. The slight discrepancy between the experimental and numerical results at the last minutes of the snow removal process could be caused by the response time of the heater. While a uniform constant heat flux was considered for the numerical method, the heater could not
provide a constant heat flux immediately after activating the heater. The heater had a response time (around 50 s) to heat up itself and start heating the panel (Figure 3.5). The response time was considered in the comparison. However, it still can cause a slight discrepancy between the results.

As shown in Figure 3.5, there were two situations for snow shedding: a) the panel surface temperature underneath the snowpack increased until it reached the freezing point. After the freezing point, the surface temperature remained constant till the snow pack slid off the panel; b) in some cases (Figure 3.5.b), the snowpack slid off the panel when the surface temperature was reached approximately the melting point of the water (0±1°C).

Densification of the snowpack adjacent to the panel surface can cause formation of some small snow bridges at the interface between the snow cover and the panel. It can cause an inhomogeneous snow melting process resulting in a longer snow removal time (even after the panel surface has reached the melting point temperature, see Figure 3.5.a).

Figure 3.6 shows the difference between the sliding time, \( t_{\text{slide}} \), and the time required for the panel temperature underneath the snowpack, \( t_0 \), to reach 0°C for some of the experiments. For the panel tilt angles of 20° and more, the snowpack slid off the panel before or at the time in which the panel temperature reached 0°C regardless of the snowpack height. It can indicate that for the panels installed at 20° or more, snow sliding from the panel can occur by heating the panel to the melting point (0°C), however, it also depends on the snow type and density. The time difference, \( t_{\text{slide}} - t_0 \), is usually within 1 minute. It is worth noting that an uncertainty analysis showed that the accuracy of the thermocouples and other instruments can cause an uncertainty close to 1 minute for the measured time required for snow sliding.
a) Snow sliding after reaching the freezing point (0°C), tilt angle: 30°, snowpack height: 2 cm

b) Snow sliding before reaching the freezing point (0°C), tilt angle: 45°, snowpack height: 3 cm

Figure 3.5 Comparison between measured and predicted panel temperatures using the present model at the snowpack location (T1). The heater had a response time of 50 sec. to heat up itself and then heat the panel.
A correlation between the measured energy required for snow sliding from the panel, $E$, the panel tilt angle, $\theta$, snow cover mass per unit area, $m$, and ambient temperature, $T_{amb}$. A linear regression was fitted to the experimental data.

**Figure 3.6** The difference between the time required for the snowpack to slide off the panel and the time required for the panel to reach 0°C where the panel is in touch with the snowpack for some of the test cases.

**Figure 3.7** $y = -5.1276x + 5.455$
Figure 3. shows a correlation between the measured energy required for snow sliding from the panel, the panel tilt angle, snow cover mass and ambient temperature. The vertical axis represents the ratio of the required energy for snow sliding to the required energy to increase the panel temperature to the melting point of water (0°C). The horizontal axis represents the portion of the snow cover mass per unit area acting parallel to the panel. Equation (3.20) was fitted to the experimental data.

\[
E^* = (m_{\text{snow}} C_p (0 - T_{\text{amb}}))^c \times (-5.12(\tan(\theta + \tan^{-1}(h_{\text{total}} / L)))^b + (m_{\text{snow}} g L)^c + 5.45) \]  

(3.20)

Where \( E \) (KJ/m²) is the energy provided by the heater during the snow removal process; \( m_{\text{snow}} \) is the snow cover mass per unit area, \( T_{\text{amb}} \) is the averaged ambient temperature; \( h_{\text{total}} \) is the total snowpack height and \( L \) is the panel length; \( a, b \) and \( c \) are the fitting coefficients \((a=0.26, b=0.28, c=0.13)\). The term \( \tan(\theta + \tan^{-1}(h_{\text{total}} / L)) \) corrects the tilt angle using the snowpack height and the panel length.

Equation (3.20) was used in the numerical model to predict the required time and energy for snow sliding. Equation (3.20) was only utilized for the tilted panels, while the time required for melting snow for horizontal surfaces (instead of sliding snow) was calculated as explained in the Methodology section.

It was mentioned in the literature that if the panel has a frame at the bottom edge, it may prevent the snow layer from sliding off the panel due to the freezing of the meltwater on the frame (Weiss and Weiss, 2016). In this situation, the entire snow layer should be melted. The proposed correlation could be valid for the snow removal from PV panels if the frame issue was resolved. As a result, in the numerical model, the user can choose between snow sliding and snow melting options for the tilted panels.

Table 3.3 shows the difference between the predicted time required for snow sliding (RTS) obtained by the present model and the measured values of the RTS during the experiments. The
actual RTS values may be subject to some unpredictable environmental effects such as cleanness of the panel surface, frame effect (Weiss and Weiss, 2016), wind effect, inhomogeneous heating, etc. Given the external factors affecting the RTS, the maximum error of 1.5 minutes between the numerical and experimental results presented in Table 3.3 is reasonable. Therefore, the presented model can provide a good estimate of the required time and energy for snow removal from horizontal and tilted panels by using heating methods.

Table 3.3 Comparing the predicted snow removal time by the presented model with the experimental results

<table>
<thead>
<tr>
<th>Panel tilt Angle degree</th>
<th>Snow Thickness (cm)</th>
<th>Amb. Temp. °C</th>
<th>Snow Removal Time Error</th>
<th>Error (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>-17.7</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>-14.75</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>-12.78</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>-16</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>-14.17</td>
<td></td>
<td>0.85</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>-18.72</td>
<td></td>
<td>0.91</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>-14.2</td>
<td></td>
<td>0.67</td>
</tr>
<tr>
<td>45</td>
<td>2</td>
<td>-14.95</td>
<td></td>
<td>0.74</td>
</tr>
<tr>
<td>45</td>
<td>3</td>
<td>-15.89</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>55</td>
<td>1</td>
<td>-9.83</td>
<td></td>
<td>0.64</td>
</tr>
<tr>
<td>55</td>
<td>2</td>
<td>-19.73</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>55</td>
<td>3</td>
<td>-12.33</td>
<td></td>
<td>0.24</td>
</tr>
</tbody>
</table>

3.4 Case study

A hypothetical case study has been performed to compare the energy required for removing snow from a PV system with the energy production of the system after removing snow. This case study can show the impact of implementing a heating snow removal system on the PV system. Specifically, the net energy production of a 16.3 m² PV array (i.e., 10 panels each of 1.63 m²) was calculated based on the time of the day snow removal was implemented such that the panel was
completely clear of the snow-cover. The assumptions considered for this case study are as follows.

- A roof-top PV system with total the array area of 16.3 m² located in Toronto, Canada was considered.
- The panels characteristics were $P_m = 295$ (W), $V_{mp} = 32$ (V), $I_{mp} = 9.2$ (A), $V_{oc} = 39.6$ (V), $I_{sc} = 9.6$ (A).
- The calculation was performed for several typical sunny (winter) days after a snowfall from the typical meteorological year (TMY) weather data for Toronto.
- The ambient temperature was assumed to be -5°C, the snow cover thickness on the panel was 3 cm, the snow density was 175 kg/m³, and the heating power, $q$, was 570 W/m².
- The hourly system production was calculated based on the method explained by Gilman (2015) using the Simple Efficiency Module Model.
- It was assumed that there is no PV output before the panels were completely clear of snow.
- The energy required for snow removal ($E_{heater} = q \times RTS$) was calculated by using the presented model.

As mentioned, based on the time of the day snow melting was implemented, the net energy produced by the panel, $E_{net}$, represents the energy captured during the remaining portion of the day minus the energy expended in removing the snow cover, i.e.,

$$E_{net} = \int_{t_{clear}}^{t_{sunset}} E_P dt - E_{heater}$$  \hspace{1cm} (8)

where: $t_{clear}$ is the time of the day that snow melting is completed, $t_{sunset}$ is the time of day sunset occurs and $E_{heater}$ is the energy expended for removing the snow. Assuming the day in question is clear from sunrise to sunset, then the relative benefit of completing snow removal by a certain
time of day can be calculated as the fraction of the clear sky energy $E_{cs}$ that is available, accounting for the energy used for snow melting as

$$FE_{CS} = \frac{E_{net}}{E_{cs}} = \frac{\int_{t_{clear}}^{t_{net}} E_{PV}dt - E_{heater}}{\int_{T_{sunset}}^{T_{sunset}} E_{PV}dt}$$  \hspace{1cm} (9)$$

In this case, the non-dimensional number, $FE_{CS}$, should be greater than 0 to justify implementing the snow melting protocol. Figure 3.8 shows $FE_{CS}$ calculated versus time of day that snow clearing is completed for two solar array tilt angles, 30°, and 45°. The benefit of snow removal is reduced as it is implemented later in the day; however, if the snow removal occurred before the sunrise, approximately 95% of the daily production of the system could still be achieved for the system installed at 30° and 45° tilt angles. On the other hand, without using the thermal snow removal system, the panels would be potentially covered by snow the entire day (Andrews et al., 2013b; Ross, 1995) and there would be no energy production.

This case study shows the noticeable effect of using a thermal snow removal mechanism on the PV systems output installed in the regions with annual snowfall. It should also be noted that although using a snow removal system can be beneficial for such a PV system in terms of the energy production during the winter, other factors such as capital cost of implementing the snow removal system, the value of energy produced by the system during other seasons, and the cost of electrical energy from the electrical grid should also be considered.
Figure 3.8 The ratio of the net energy production of a PV system (located in Toronto CA) from sunrise to sunset during several sunny days (from TMY data) after a snowfall to the maximum energy production of the system on that day. At each hour of the day, it is assumed that the panel was covered by snow before that time. The energy required for removing snow from the panel was calculated by the presented model assuming 570 W/m² heating power, the ambient temperature of -5°C and snow density of 175 kg/m³.
3.5 Conclusions

As the cost of solar PV is becoming comparable with the cost of conventional sources of energy, one of the main issues arising in the use of this technology to compete with conventional electrical power sources is the losses associated with partial shade and snow cover. One of the proposed snow removal methods for PV panels is the heating method. As a result, in this study, a modified snow melting and sliding model for PV panels was proposed. The model relied on the use of improved definitions of the boundary conditions as well as the modified heat and mass transfer in the snow and slush layers. It was shown that:

1. Regarding modeling of the snow melting on horizontal surfaces, the modification in the present model has improved the results as compared to those given by the earlier models. The present model predicted the meltwater drainage rate and the rate of snow cover thickness change more accurately than other models presented in the literature.
2. In terms of tilted panels, the meltwater drainage rate from a tilted panel was predicted by treating the snow cover as a porous media and using the governing equation for the porous environment i.e. Darcy's law. In addition, an empirical correlation was proposed for calculating the required energy and time for snow sliding from tilted panels based on the conducted experiments.
3. The present model can provide a good estimate of the required time and energy for snow removal from horizontal and tilted surfaces including PV panels if heating the panel is used as the snow removal method.
4. Some external factors can significantly affect the required time for snow sliding (RTS) from tilted panels including cleanliness of the panel, freezing of the snow cover to the panel frame, non-uniform heating, etc.
5. The case study for a PV system located in Toronto Canada showed that using a thermal snow removal system can be beneficial for the PV system in terms of net
energy production of the PV panels during the winter; however, some other factors such as the capital cost of implementing the snow removal mechanism, the effect of this mechanism on the system output during the other seasons, etc., should also be considered.

Acknowledgments

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Chapter 4

An experimental investigation of snow removal from Photovoltaic solar panels by using electrical heating

Abstract

A key challenge to the wide-scale implementation of photovoltaic solar panels (PV) in cold and remote areas is dealing with the effects of snow and ice buildup on the panel surfaces. In this study, a thermal method for snow removal from PV solar panels was experimentally tested. Nine PV panels were mounted at tilt angles of 30, 45 and 55 degrees (three panels at each angle). One of the panels at each angle was insulated on the back with a heater embedded between the panel surface and a back layer of insulation. The other two panels remained unheated as reference cases. Outdoor tests were conducted under natural conditions including different snowfall conditions. Solar radiation, ambient temperature, relative humidity and wind speed were also measured during each test. Results showed that the frame at the bottom edge of the panels prevented the snow cover from sliding off the panels. In addition, it was observed that the entire panel surface requires heat to remove snow, as the panel thermal conduction was not sufficient to conduct heat to unheated areas. To investigate these issues, the lower edge of the frame for one of the reference panels at tilt angle of 45° was removed, and the panel was heated using reversing electrical current flow through it. For most of the experiments with this panel, the snow cover slid off the panel in less than 30 minutes.

Keywords: Photovoltaic solar panels, Snow removal method, Heater, Reverse current, Frame effect
4.1 Introduction

Increased concern related to climate change is driving the development and implementation of alternative energy sources as a means to reduce emissions related to the use of carbon-based fossil fuels. The use of photovoltaics (PV) to generate electricity from solar energy is being promoted as a promising technology for supplying significant “green” energy to the electrical grid. The continuous decline of the cost of solar systems has driven research into photovoltaic-thermal (PV/T) systems all around the world. This includes regions with cold climates that can lead to snow and ice accumulation on collector surfaces (Breyer et al., 2009; Burrett et al., 2009; Swanson, 2009).

A key challenge to the wide-scale implementation of solar photovoltaics in cold climates like Canada is dealing with the effects of snow and ice buildup on the panel surfaces. PV panel output depends on ensuring that solar panel surfaces are not shaded by obstructions such as snow and ice. The problem is severe as even partial snow cover on PV modules may significantly reduce the output of a complete string of PV panels. As well, there currently is no practical mechanism to remove snow-cover from PV surfaces and long shut-down periods occur while plant operators wait for mild weather. Mechanical removal of snow from PV arrays has also been rejected by plant operators due to the fragile nature of the glass panels used to support PV cells.

Consequently, a thermal snow removal method to melt snow or induce the snow sliding off from PV panels would be beneficial in regions with significant snowfall.

4.1.1 The effect of snow accumulation on PV output

Several experimental and numerical studies have been performed to study the effect of snow on annual and monthly PV systems performance. Experiments on PV systems undertaken by Nakagawa et al. (2003) revealed that in a solar array which is connected in series if only some cells are covered by snow, the module output will drop. Previous studies have indicated that annual snow losses on a PV system can be as high as 15% for a low profile system in Truckee
California (south-facing panel tilt angle of 24°) and as low as 0.3-2.7% for a highly exposed roof mount system located in the New Munich Trade Fair Centre in Germany (south-facing panel tilt angle of 28°) depending on the orientation, tilt angle of the PV modules and meteorological factors (Becker et al., 2008; Brench, 1979; Marion et al., 2013; Ross, 1995; Townsend and Powers, 2011; Yoshioka et al., 2003).

Townsend and Powers (2011) mounted three pairs of photovoltaic modules at fixed south-facing tilt angles of 0°, 24° and 39° over a winter period. The recorded monthly losses caused by the presence of snow ranged up to 80%, 90% and 100% of expected yields for tilt angles of 39°, 24° and 0° respectively. In addition, on an annual basis, losses were found to be 20% on average for all panels. Recently, Marion et al. (2013) measured and modeled photovoltaic system energy losses from snow for specific locations in Colorado and Wisconsin. Their experimental study included the use of two residential systems with stand-off roof mounts and two small commercial systems. Monthly energy losses as high as 90% and annual losses from 1% to 12% were reported. In general, it can be concluded that the power loss from snow can range from 1% to 20% on an annual basis while it can be more than 90% during winter when there typically is high demand of electricity for building heating purposes.

Some researchers have studied factors affecting snow shedding. Andrews et al. (2013a, 2013b) investigated the effect of panel tilt angle on the shedding of snow on PV modules. As expected, two primary snow shedding mechanisms were observed: sheet sliding and snow melting. For module tilt angles of 15 to 40°, there was a snow accumulation gradient, with the snow more likely to remain at the base of the module. Conversely, for module angles of 10° and below, there was an even snow distribution over the whole face of the module, and the snow was more likely to melt on the panel surface rather than sliding from the face. It was noted by the authors that modules at tilt angles of 50° and 60° had a bias for snow accumulation towards the top of the
modules likely due to local prevailing winds; The annual losses due to snowfall were measured up to 3.5% due to the small amount of snowfall on that specific year.

Heidari et al. (2015) studied the effect of ground interference on snow shedding from PV panels. They measured 5% to 12% energy loss for the elevated unobstructed modules. The obstructed modules experienced 29% to 34% energy loss revealing the importance of ground interference. They suggested that a snow-clearing mechanism may be advantageous in snowy climates.

4.1.2 Snow removal methods for PV panels

Various snow removal methods for PV systems have been proposed in the past. One of the first attempts to clean snow from solar cells was made by Ross (1995). He developed a new passive melting system, based on the reflection of light onto the rear surface of the modules. A box was designed and mounted on the rear of the module including a dark side and a light transmitting enclosure which produced a greenhouse effect increasing the temperature of the cells. Although this method accelerated the melting process, it still required long periods to melt snow (in some cases one or two days) rather than melting the snow cover on PV panels after the snowfall.

The other proposed method for snow removal from PV panels was using hydrodynamic surface coatings on the panels. Andrews and Pearce (2013) studied several hydrodynamic surface coatings to determine the snow clearing effectiveness of these surfaces compared to conventional plain glass. The following surface treatments were utilized: hydrophobic, hydrophilic, prismatic glass, and one unaltered module. The surface coatings tested did not have an appreciable positive effect on snow removal, and in some cases tended to impede the shedding of snow.

Recently, Weiss and Weiss (2016) proposed an active method for melting snow on PV panels by reversing current through the panel. They tried to initiate the snow sliding from the panel provided that the freezing of the meltwater on the edge of the panel frame is prevented by
additional heating. They proposed an electrical circuit detail for bypassing the diode; however, they did not perform any experiments during an actual snow event. They just put a layer of snow onto panels manually instead of leaving the panel outside during real snowfall events. In addition, the effects of meteorological factors such as solar radiation, ambient temperature, wind speed, etc. were not considered.

Van Straten (2017) introduced a patent for snow removal from PV panels. He proposed to install a box on the back of a panel with a small electrical heater inside. By using the natural convection, warm air was circulated inside the box to heat the panel. No results were provided to show how long it takes to clear a panel from the snow by using this method. In addition, without providing any experimental or numerical data, some researchers have proposed other methods for deicing PV panels mounted on the roofs. The proposals included architectural solutions, electrical heating cable and radiation strategies (Andersson, 2017; Jelle, 2013).

4.1.3 Deicing techniques for other applications

Although few research studies have been conducted on snow removal from PV systems, several deicing mechanisms have been introduced for other applications such as airplanes, wind turbines, etc. Regarding wind turbines, icing mitigation systems focus on two main strategies: anti-icing and de-icing systems (Parent and Ilinca, 2011) which are further categorized as passive and active methods. Some of these methods include: special coatings (Dalili et al., 2009; Laakso et al., 2003), chemicals system (Patreau et al., 1998), flexible blades (Dalili et al., 2009), thermal systems (Mayer et al., 2007), microwave, and electro impulsive/expulsive systems (Dalili et al., 2009). Most of these methods may not be applicable for PV systems due to the high risk of damaging the panels or high energy consumption.

Deicing priorities vary depending on the application. Airplane deicing systems prioritize safety as opposed to PV systems which prioritize low energy consumption. Pneumatic deicing boots/inflatable bladders on wing leading edges have a high safety factor but have high energy
consumption. These systems can be applicable for airplanes but are not practical for PV systems. Other methods such as de-icing fluids may corrode the iced materials and can be expensive and environmentally damaging (Ryerson et al., 1999).

As a result, considering that a PV panel snow removal system should be energy efficient (not consume more energy than the snow-free panel would collect after cleaning the panel) and minimize the risk of mechanical damage for the panel, it seems that among the mentioned de-icing methods for other applications, thermal methods and special coatings might be applicable snow removal methods for PV panels.

This paper presents the results of an experimental study focused on thermal deicing of PV systems. In particular, the snow melting and snow sliding mechanisms were investigated to measure how much energy the proposed thermal methods required to remove snow from a panel. The experiments were conducted outdoors under natural weather conditions. Specially prepared and instrumented PV modules were mounted at various tilt angles that included unheated PV panels as baselines samples. The results of this study may provide valuable information to decide whether a thermal snow removal method can be beneficial to the PV systems or the owner/operators based on net energy delivery. Two heating methods were investigated: 1) electrical heating by a resistance thin film heater installed on the back of the PV panel, and 2) electrical heating due to the application of reverse current through the PV cells. The required energy for snow removal from a PV panel is measured, and the challenges related to the use of this method are discussed. In addition, the effects of meteorological factors on snow removal, e.g. solar radiation, ambient temperature, wind speed, etc. are presented.
4.2 Methodology

The required energy for snow removal from PV panels through heating the panels was measured by mounting nine PV panels at tilt angles of 30, 45 and 55 degrees to the horizontal at a site in Queen’s University (Kingston, Ontario, Canada) during two winters of 2016 and 2017 (Figure 4.1). Three panels were installed at each angle, two of them without any heating as reference cases (except the panels at the tilt angle of 45° had only one reference panel as will be discussed) and one with a heater bonded on the back of the panel. Since several factors affect snow removal from PV panels depending on the weather conditions, two reference panels were considered for each angle to ensure the validity of the results. The panel characteristics used in this study are given in Table 4.1.

Figure 4.1 Panels mounted at 30, 45 and 55 degrees tilt angles with the horizontal along with the weather station. The picture was taken using the monitoring camera.
4.2.1 Heating methods

Two methods were used for heating the panels: using electrical thin film heater mounted on the back of the PV panels, and reversing electrical current through the panel. The methods are described as follows.

1- Electrical resistance carbon film heaters with thickness of 0.338mm were used to heat the back surface of the panels. The heater only covered the lower 80% of the panel surface below the junction box (Figure 2.a) since it was not possible to fit this type of heater around the junction box. To minimize heat loss from the back of panels with heaters, insulation was applied to the back surface in two layers. The first layer of insulation was closed cell foam insulation with a thickness of 12.5 mm and an RSI value of 0.37 (m²C/W), and the second layer was polyisocyanurate foam board insulation with a thickness of 10 mm and an RSI value of 0.54 (m²C/W) (Figure 2.c and d). The heaters were connected in parallel to an AC power supply (through a VARIAC transformer). The current and voltage for each heater were measured.

2- As mentioned in the literature, one method for heating a panel is reversing electrical current through the panel. Photovoltaic cells are large junction diodes with a specific threshold voltage. Consequently, an externally driven current through the module can generate heat which can be sufficient for melting snow on a panel or initiating the snow sliding from the panel Weiss and Weiss (2016). To examine this method, one of the
reference panels at the 45° tilt angle was connected to a Sorensen XFR 150V-8A DC power supply for reversing current through the panel to heat the panel. Using reverse current can also eliminate the necessity for extra heating equipment (heater) attached to the panel. As a result, for 45° tilt angle, there was only one reference panel. For these tests, all “bypass” diodes were removed from the panel circuit.

Choosing the heat flux rate may affect the snow removal rate, energy consumption, risk of damaging the panel, etc. Although higher heat flux rate leads to a faster melting process which is more desirable, the panel power output under standard test conditions (STC) was chosen as a maximum power for heating. Using higher voltage and current than the PV panel capacity could damage the panel especially for an externally driven current through the panel. As a result, a 180 W/m² heating power was chosen for the heaters and 26V, and 6A (235 W/m²) was selected for an externally driven current through the module. The heat flux rate was the same for all experiments.

In terms of choosing different heat flux rates for the cases studied, it should be noted that the panel with reverse current was not insulated at the back, resulting in more heat loss from the back as compared to the panels with the heater and insulation on the back. This panel was not insulated as the primary goal of this part of the study was to examine the effectiveness of using the reverse current method under natural outdoor conditions. To reduce the effect of insulation on the comparison between the results of these two methods, a higher heat flux rate was used for the panel with reverse current (i.e., 235 W/m²) as compared to that used for the insulated panel with embedded electric resistance heater (i.e., 180 W/m²). The heat loss from the back of the panel without insulation was estimated by using the standard convective heat transfer relation, \( q = hA(\Delta T) \). A convective heat transfer coefficients of 5-10 W/m²K was assumed for the rear surface of the panel (Duffie and Beckman, 2013). During the experiments, it was observed that the temperature difference between the panel surface and ambient air ranged between 5 and 8°C.
Consequently, the averaged heat loss was estimated to be approximately 55 W/m²; however it is acknowledged that this value depends on local wind speed and ambient temperature.

As mentioned, removing snow cover from a panel can be achieved by melting snow or sliding snow cover off the panel. To reduce the energy consumption for snow removal, attempts were made to investigate the possible solutions for snow sliding off a panel rather than melting snow which requires more energy. It is possible more energy may be consumed in melting snow than in production after the snowfall. Regardless of the heating method used for snow removal (using thin film heater or reverse current), one of the issues mentioned in the literature by Weiss and Weiss (2016) for snow sliding from PV panels was the clamping effect of the panel frame. To investigate this issue, the frame at the bottom edge of the panel with reverse current was removed to study the effect of frame details on snow sliding.

4.2.2 Measurement facilities and instrumentation

The instrumentation used for this study is listed in Table 4.2. To measure the panel temperatures, six thermocouples (type T) were attached to the back of the panels with the heaters and one thermocouple was mounted on the back of each reference panel. On the heated panels, one of the thermocouples (T1) was placed above the heater and another one on the frame as shown in Figure 4.2.b. The thermocouples were attached between the panel and heater using a 0.2 mm thin layer of high-temperature silicone adhesive to minimize thermal resistance (due to potential air gaps) and to isolate them electrically from the heater (Figure 4.2). The thermocouple wires were routed toward the side edges of the panel. A Kipp and Zonen CMP21 pyranometer was used to measure solar radiation (Table 4.2). A UMB Smart Weather Sensor was used to measure the wind speed, ambient temperature and pressure. A Campbell Scientific CR1000 Data Acquisition (D/A) unit, with built-in cold junction compensation, was utilized to record all the thermocouple temperatures (using an AM25T multiplexer for 25 thermocouples), solar radiation and weather data. Images of the snow cover on the PV arrays were recorded with three digital
cameras every 10 minutes (one camera for each angle). In addition, the operator took a picture every 10 min during each experiment using a separate camera.

### Table 4.2 The measurement facilities used in this study

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>OMEGA Co.</td>
<td>Type T</td>
<td>Copper/Constantan thermocouple type T was used with 0.5 mm thickness for each wire.</td>
</tr>
<tr>
<td>Weather station, (wind speed, ambient temperature, relative humidity and pressure)</td>
<td>UMB Smart Weather Sensor</td>
<td>WS600</td>
<td>This station has an integrated ultrasonic wind sensor for wind speed and direction measurement as well as instruments for relative humidity and pressure measurements.</td>
</tr>
<tr>
<td>Global solar radiation at 45° tilt</td>
<td>Kipp &amp; Zonen</td>
<td>CMP21</td>
<td>It is mounted on the plane of the panels at 45° tilt angle (located mid-height) to measure incoming global solar radiation with a 180° field of view.</td>
</tr>
<tr>
<td>Campbell Scientific data logger</td>
<td>Campbell Scientific</td>
<td>CR1000 and AM25T thermocouple multiplexer</td>
<td>It was used to record the measurements and read signals from the other instruments. This device had 25 channels for thermocouples. The DAQ recorded data at 2Hz and stored the mean value every 30 sec.</td>
</tr>
<tr>
<td>Camera System</td>
<td>Night Owl</td>
<td>CAN-AHD10-841</td>
<td>It was used to monitor the modules. Security cameras capture 720p Hi-Definition video recorded by a 1 Terabyte Network Video Recorder (NVR) with HDMI output.</td>
</tr>
</tbody>
</table>
a) Electrical resistance carbon film heaters with thickness of 0.338 mm covered 80% of the panel area.

b) Thermocouples locations on the back of the panels with heater. Reference panels had only one thermocouple at T3 spot (all dimensions are centimeters)

c) Closed cell foam insulation with thickness of 12.5 mm and RSI value of 0.37 (m²°C/W) was used as the first layer of insulation

d) Polyisocyanurate foam insulation with thickness of 10 mm and RSI value of 0.54 (m²°C/W) was used as the second layer of insulation

e) Cross section view of the test panel assembly (not to scale)

Figure 4.2 The configuration of heater, thermocouples and two layers of insulation on the back of the panels
4.2.3 Uncertainty analysis

The uncertainty associated with the temperature measurements was estimated by propagating the estimated components uncertainties using RMS method. The estimated components uncertainties were the calibration uncertainty $u_{\text{cal}}$, the DAQ accuracy $u_a$, the 60Hz noise signal $u_n$ and the resolution of the DAQ (Res) (9806-1, 1994; Figliola and Beasley, 2015). The thermocouples were calibrated using a thermostatic bath in the range of -15 to 40° C. The calibration uncertainty assumed to be ±1°C. The DAQ accuracy and resolution were 0.5°C and 0.001°C respectively. In addition, during data logging, a 60Hz electrical noise was identified and caused a ripple in temperature readings. One of the film heaters attached to the panels caused this noise. As a result, the estimated uncertainty associated with the noise was assumed to be ±1.9°C. Although only the thermocouples of one of the panels had this issue, the uncertainty associated with the electrical noise was included in the error estimate for all temperature measurements.

As a result, the temperature measurement uncertainty was (Figliola and Beasley, 2015):

$$u_{\text{total}} = \pm \sqrt{u_{\text{cal}}^2 + u_a^2 + u_n^2 + \text{Res}^2} = \pm 2.1°C$$

(4.1)

where $u_{\text{cal}}$ is the calibration uncertainty, $u_a$ is the accuracy, $u_n$ is the uncertainty estimate associated to the noise signal, and Res is the resolution of the DAQ.
4.3 Results and Discussion

To melt snow or slide snow off a PV panel, the panel surface should reach 0°C (melting point of snow) or higher. In the present study, the thermal heating of a PV panel was investigated by 1) the addition of an electrical resistance heater on the back of the panel and, 2) reversing current through the panel (to do this, all bypass diodes were removed). The affecting parameters on snow shedding were studied.

4.3.1 Observations of snow removal from the panels

Figures 4.3, 4.4 and 4.5 show snow melting on panels at tilt angles of 30, 45 and 55 degrees for the test number 5 on 09/01/2017, respectively. The weather conditions and the other details of the test is shown in Table 3. As expected, the snow melting time increased with decreasing panel tilt, since the panels installed at the lower angle had more snow accumulation on them (Table 4.3). In addition, the snow cover on the panels at higher tilt angles was observed to slide off the panel. These observations are in a good agreement with the results presented by Andrews et al. (2013a), however, in the current study, the bias of snow accumulation towards the top of the panels for a 55° tilt angle (reported by them) was not observed. It should be noted that Andrews et al. (2013a) speculated that the wind effects were the reason for these observations. In this study, the test panels were not exposed to the wind as compared to the study by Andrews et al. (2013a) which may explain the discrepancy.
Figure 4.3 Photos of snow melting sequence, shown as a duration of time through the heating process. The PV panel shown on the right was heated by the thin film heater bounded to the rear of the panel. The adjacent panels were unheated reference panels. The conditions for this test (No. 5) were: test date=09/01/2017, panel tilt angle= 30 degree, ambient temperature= -5.47°C, relative humidity= 91%, solar radiation= 120 to 160 W/m², snow density= 48 kg/m³, Initial snow cover thickness= 3 cm and wind speed=0.93m/s.
a) Panels conditions before starting to heat the panels (t=0 min.)

b) Panels conditions after 10 min. heating

c) Panels conditions after 25 min. heating

d) Panels conditions after 35 min. heating

Figure 4.4 Photos showing a comparison between PV panel heating by carbon resistance film heater and self-heating of PV cells by imposed reverse electrical current. For the panel with applied reverse current, the lower edge of the panel frame was removed to facilitate snow sliding. Snow sliding was observed on this panel assisting the snow shedding process. The conditions for this test (No. 5) were: test date=09/01/2017, panel tilt angle= 45°, ambient temperature= -5.47°C, relative humidity= 91%, solar radiation= 120 to 160 W/m², snow density= 48 kg/m³, Initial snow cover thickness= 2 cm and wind speed=0.93 m/s.
Table 4.3 Listing of the snow removal experiments conducted during this study and a summary of the tests conditions and results

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date (mm/dd/yyyy)</th>
<th>Initial snow thickness (cm)</th>
<th>Snow density (kg/m²)</th>
<th>Solar radiation (W/m²)</th>
<th>Ambient temperature (C)</th>
<th>Average wind speed (m/s)</th>
<th>Melting: M, Snow Sliding: S</th>
<th>Time to clean the panel (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heater (160 W/m²) reverse current (45°-235 W/m²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30° 45° 55° 30° 45° 55° 30° 45° 55°</td>
</tr>
<tr>
<td>1</td>
<td>04/06/2016</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>173</td>
<td>N/A</td>
<td>-1.03</td>
<td>89 0.98 24 (M) 19 (M) 15 (M) ---</td>
</tr>
<tr>
<td>2</td>
<td>12/16/2016</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>24</td>
<td>160-240</td>
<td>-8.90</td>
<td>81 0.46 120+ (M) 18 (M) 18 (M) ---</td>
</tr>
<tr>
<td>3</td>
<td>12/19/2016</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>50</td>
<td>300-340</td>
<td>-8.60</td>
<td>79 1.08 no heater-just sun ---</td>
</tr>
<tr>
<td>4</td>
<td>12/22/2016</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>360</td>
<td>10-50</td>
<td>0.93</td>
<td>93 0.60 120 (M) 120 (M) 50 (M) ---</td>
</tr>
<tr>
<td>5</td>
<td>09/01/2017</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>48</td>
<td>120-160</td>
<td>-5.47</td>
<td>72 0.93 25 (M) 25 (M) 15 (M) 30 (S)</td>
</tr>
<tr>
<td>6</td>
<td>24/01/2017</td>
<td>2.5</td>
<td>2</td>
<td>2</td>
<td>Freezing rain + snow</td>
<td>45-130</td>
<td>-2.78</td>
<td>91 0.36 120+ (M) 120 (M) 120 (M) 110 (S)</td>
</tr>
<tr>
<td>7</td>
<td>01/02/2017</td>
<td>4.6</td>
<td>4</td>
<td>3</td>
<td>74</td>
<td>200-530</td>
<td>-3.73</td>
<td>79 0.79 100 (M) 60 (M) 50 (M) 0* (S)</td>
</tr>
<tr>
<td>8</td>
<td>13/02/2017</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>193</td>
<td>330-370</td>
<td>-3.95</td>
<td>68 0.85 3 (S) 70+ (M) 0* (S) 1 (S)</td>
</tr>
<tr>
<td>9</td>
<td>16/02/2017</td>
<td>3</td>
<td>2</td>
<td>1.8</td>
<td>50</td>
<td>450-490</td>
<td>-7.42</td>
<td>68 1.47 45 (M) 20 (M) 0 (S) 20 (S)</td>
</tr>
</tbody>
</table>

*it means the panel was clear before starting to heat the panel.
Figure 4.6 shows the temperature variation in the PV panels during the heating process for the test number 9 on 16/02/2017. This figure only shows the temperature readings of thermocouples 3 (x/L=0.5) and 5 (x/L=0.86) representing the upper and lower half of the panel respectively (Figure 4.2). This day was chosen for further analysis since most of the possible snow removal cases (snow melting and snow sliding) happened on this day. The snow removal process was started at 9:30 in the morning. Panels at all tilt angles (30, 45 and 55 degrees) were heated using the resistance film heater (Figure 4.3, Figure 4.4, and Figure 4.5). One panel at a tilt angle of 45° was also heated by reversing current through the panel while the panel frame at the bottom edge
was removed to ease the snow sliding process on this panel (Figure 4.4). It was observed that the snow cover was melted from the panels at 30 and 45° tilts when using the resistance film heater. Additionally, the snow cover slid off the panel at the tilt angle of 45° when a reverse current forced through the panel (the frame effect on snow removal will be discussed in the next section).

It was observed that the panel at a 55° tilt angle was almost clear before any heating on that day. In Figure 4.6, the temperatures of the panel at a 55° tilt increased faster than the other panels. There were two reasons for a faster melting process: 1) since the melting process started in the morning on that specific day, the angle between the solar rays and the panel surface normal was smaller for the panel at tilt angle of 55° than the panels at 30 and 45 degrees. It resulted in more solar heating for the panel at 55° tilt compared to the other panels. 2) The snow cover thickness on the panel at 55° tilt was less than the other panels as it was observed that increasing the panel tilt angle decreased the snow accumulation on the panel (Table 4.3).

As expected, during the melting process, the panel surface temperature remained close to the melting point (0°C) until the snow layer melted or slid off the panel. As the thermocouples were located between the insulation and the heater on the back of the panel, the temperatures recorded during the melting process was indicated a temperature of 2°C on the back of the panel which was in contact with the heater rather than 0°C on the front surface which was in contact with the mixture of water and snow. It was also noted that when the panel was clean of snow, the temperatures increased rapidly.

In addition, comparing Figure 4.6 a and b reveals that the panel temperature at the lower half remained constant (at 2°C) longer than the upper half of the panel, i.e., the upper half of the panel was clear of snow cover before the lower half, since the snow cover slid off from the upper half to the lower half of the panel. This effect is evident from the photo of panel temperatures shown in Figure 4.7.
a) Temperature recorded by thermocouple 3 representing the upper half of the panels

b) Temperature recorded by thermocouple 5 representing the lower half of the panels (The panel at 45 degree with reverse current had only thermocouple placed at the center of the panel which represents the upper half of the panel. This panel did not have a thermocouple at location T5 to represent the lower half of the panel.).

**Figure 4.6** The temperature variation of the panels at tilt angles of 30, 45 and 55 degrees are shown during the heating process for test number 9 on 16/02/2017. The conditions for this test (No. 9) were: test date=16/02/2017, panel tilt angle= 30, 45 and 55 degrees, ambient temperature= -7.42°C, relative humidity= 68%, solar radiation= 450 to 490 W/m², snow density= 50 kg/m³, and wind speed=1.47 m/s. The panel temperature remained approximately around the melting point until the snow layer melted or slid off the panel, then the panel temperature started to increase rapidly. The upper half of the panel was cleaned faster than the lower half since the snow cover slid down from the upper half to the lower half.
Upper half of the panel was clean while the lower half was still covered by snow.

Figure 4.7 Temperature of the panels at all angles (30°, 45° and 55 degrees) showing that the upper half of the panel increased in temperature faster than the lower half because of snow sliding from the upper half to the bottom of the panels.
Figure 4.7 shows the temperature distribution on a panel heated by using the electrical resistance thin film heater at different periods of time during the snow melting. As expected, the average panel temperature increased with time. Since thermocouple 1 (at x/L=0.14) was mounted on the junction box on the back of the panel and was exposed to the ambient air, the trend for this thermocouple is slightly different from the others. This figure shows that the panel temperature at the middle (x/L=0.5) increased faster than the temperature of the lower section of the panel (x/L=0.86) for all tilt angles, i.e., the upper half of the panel was clean while the lower section of the panel was still covered by snow. This pattern can be seen in Figure 4.4. It was observed that when the snow cover slid down the panel, the panel frame at the bottom prevented the snow layer from sliding completely off the panel. It should be noted that for the panel at 55° tilt in Figure 4.7.c, the panel was clean in 90 minutes resulting in a sudden temperature increase after 90

Figure 4.8 Ice bridges formed between the panels and the snow cover. The panel temperature in the section which is not in contact with the snow cover (under the ice bridge) increased rapidly. If the ice bridge collapsed on the surface, the panel temperature would drop again.
minutes.

According to these observations, it could be beneficial if the panel had two separate heaters, one each for the upper and lower halves, to prevent heat loss from the upper half of the panel when it is clean while the lower heater can continue heating the panel until the panel surface is completely clean.

For some cases, the panel temperature increased suddenly while the panel was still covered by snow (Figure 4.8.a). To investigate the reason, a small-scale experiment was conducted in a freezer to control all parameters during the snow melting. The snow melting process was repeated with a small glass panel (0.3 m by 0.3 m) heated by a resistance film heater bonded on its back surface. It was observed that in some cases, an ice bridge formed on top of the panel resulting in a local increase in panel temperature (Figure 4.8.b and c). In effect, the local melting and draining of water from the region resulted in an air-filled cavity that insulated the panel surface. Since the heat flux did not vary, a rapid increase in panel temperature occurred at the region below the ice bridge. This is of concern as higher temperature gradients may induce thermal stresses that may result in panel or heater failure over time. It also explains the situations reported by some other researchers regarding snow sliding off the panels at panel temperatures above 25°C rather than 0°C (on that study, the panels were heated by using the solar radiation (Becker et al., 2008)).

4.3.2 The effect of PV panel frame detail

As seen in Figures 4.6 and 4.7, the upper half of the panel became clear faster than the lower half. It was also observed that the snow cover on the upper half of the PV panel slid down as a water film formed on the panel surface, but it did not slide off entirely due to the frame thickness at the bottom edge of the panel and water refreezing at the edge of the panels. Figure 4. shows this situation where sliding snow was caught on the edge of the frame that was higher (2mm) than the panel’s glass surface. This also caused icicles and an ice dam to form on the frame. This process led to more extended periods of snow coverage on the lower half of the panel.
The icicle formation can be explained by modeling the snow cover as a porous media (Calonne et al., 2012). The snow cover absorbs the melted snow and retains water until it is saturated with water. To quantify this characteristic, previous researchers defined a “permeability” for snow. It can be treated as a coefficient of Darcy’s law (the basic law governing the flow of fluids through porous media) (Calonne et al., 2012). Darcy’s law defines permeability, $k \text{ (m}^2\text{)}$, as the property of snow that controls the ease with which a fluid, typically air or water, can move through the snow as follows (Calonne et al., 2012).

$$ v = \frac{-k}{\mu} \Delta P $$

(4.2)

where $v$ is the fluid flux (discharge per unit area m/s), $\mu$ is the fluid viscosity (Pa·s), and $\Delta P$ is the total pressure drop. It shows that how quickly water can flow through the snowpack based on water viscosity and the pressure drop. The pressure drop can be defined based on gravitational force and snow thickness.

By heating the snow cover on a panel, the snow cover will be melted at the interface between the glass and snow. The melted snow near the panel surface becomes liquid water that is absorbed by capillarity action into the snow layer. This process continues until the snow layer becomes saturated and liquid water begins to drain through the snow cover. Since the panels are tilted, once the snow cover is saturated, the melted snow will drain the snow cover from the bottom edge. If the ambient temperature is lower than 0°C, this will lead to the freezing of run-off water to the frame and icicles will form. Freezing at the frame impedes the drainage of meltwater and causes an ice dam to form at the bottom of the panel. Figure 4, compares the melting process after snow saturation between panels with and without a frame at the bottom. The icicles and ice dams formed on the bottom edge of the panel frame prevented the snow cover from sliding off the panel.
It was noted that since the panel had an aluminum frame at the bottom, if the ambient temperature was lower than the melting point for the snow (0°C), and the frame was not heated, the frame temperature was less than 0°C and it would act as a cooling fin for the panel. It caused the meltwater to freeze to the frame. As a result, in terms of snow removal from PV panels, using frameless panels can be beneficial.

Figure 4.9 Partial snow cover at the bottom of a panel due to the frame effect. The shape of snow cover reveals that the snow on the upper half of the panel slid down and was impeded from sliding off at the bottom edge due to the frame effect.

Figure 4.10 Photo of icicles formed at the bottom of a PV panel with the frame compared to the panel without frame for the 45° tilt angle. The ice dam and icicles impeding the snow cover from shedding.
4.3.3 Heating area effects

As mentioned, only 80% of the panel was covered with heaters since it was not possible to cover the area to the sides and top of the junction box with the film heater. As it can be seen in Figures 4.3, 4.4 and 4.5, the snow cover was primarily melted in the area directly heated. This illustrates that heat conducting from the heated section of the panel to the unheated section was not sufficient to melt snow on the unheated portion of the panel surface. This was expected due to the relatively low conductivity and thickness of the glass cover. As even partial snow cover can shut down a panel, it appears that partially heating a panel may not be effective. Consequently, the whole surface of a panel should be heated to clean the snow cover effectively.

4.3.4 Heating by reversing current through the panel

During this study, three factors related to the use of thermal heating as a means of removing snow cover from PV panels have been identified. These are: 1) the effect of the panel frame at the bottom edge of the panel that can prevent the snow cover from sliding off the panel, and 2) refreezing the meltwater to the frame and formation of ice dam and icicles, and 3) the limit to the thermal conduction through the panel which was not sufficient for partially heating the panel, i.e., the whole surface of a panel should be heated. To address these issues, as mentioned in the methodology section, the lower edge of the frame was removed from one of the panels at a 45° tilt, and a Sorensen XFR 150V-8A DC power supply was used to heat the panel by forcing the reverse current (235 W/m²) through the module (Figure 4.4).

As shown in Table 3, for most of the test cases, snow sliding did not occur except for the panel at a 45° tilt angle without the frame at the bottom (which was heated by forcing reverse current through it) and the panel (with frame) at the highest tilt angle (55°). The snow cover slid off the panels with heaters on a single test day (No. 8 on 13/02/2017). On that day the snow thickness was more than 11 cm.
4.3.5 Required energy for snow removal

Figure 4.9 compares the measured snow-cover mass with the equivalent snow-cover mass per unit area calculated based on the heat flux supplied by the electrical heater, $q$, ambient temperature, $T_{amb}$, and the measured time required for snow removal, $t$, as presented in Table 3. This figure also shows the snow-cover mass based on the predicted time required for snow removal using the numerical method presented in Chapter 3. The snow-cover mass represents the mass of snow covering a PV panel surface per unit area and varies with snow density and thickness. The equivalent snow-cover mass, $m_e$, is the mass of a snow cover that the heater could melt during the recorded melting time (or predicted melting time using the model presented in Chapter 3), $t$, for each test. The energy required for snow removal is proportional to the snow-cover mass. To have consistency between the results, the test case No. 6 is not shown in Figure 4.9, since it was a day with freezing rain and snow. The snow-cover mass per unit area, $m$, was calculated based on the measured snow thickness ($h_i$) and density ($\rho_s$) as follows.

$$m\, (\text{kg/m}^2) = h_i \times \rho_s \quad (4.3)$$

Then using the ambient temperature ($T_{amb}$), specific heat ($C_p$) and latent heat of fusion for snow ($h_{fg} = 334 \text{ kJ/kg}$), the equivalent snow-cover mass per unit area, $m_e$, was calculated as:

$$m_e = \frac{q \times t}{C_p(0 - T_{amb}) + h_{fg}} \quad (4.4)$$

Figure 4.9 shows that for the test cases where the snow cover was primarily melted (rather than sliding from the panel), the measured snow-cover mass, the equivalent snow-cover mass based on measured melting time (Table 4.3 Listing of the snow removal experiments conducted during this study and a summary of the tests conditions and results) and the equivalent snow-cover mass based on the melting time predicted by using the presented numerical method (Chapter 3) are in a good agreement. The slight difference for some of the test cases could have been caused by the heating effect of the incident solar radiation during the test period. Test cases with snow sliding resulted in a substantially lower equivalent snow-cover mass (case No. 8).
also shows that the numerical method proposed in this study can predict snow removal from a tilted panel properly.

Figure 4.9 shows that for test case No.4 (\(T_{\text{amb}} = 1^\circ \text{C}\), relative humidity= 91%, solar radiation= 10 to 50 W/m\(^2\), snow density= 360 kg/m\(^3\), and wind speed=0.6 m/s), the measured snow-cover mass was significantly more than the equivalent snow-cover mass. As the ambient temperature was higher than zero, the snow cover was already melting before the heaters were activated. As a result, the measured snow density was higher than the actual snow density since the snow cover had absorbed a portion of the meltwater causing an overestimation in the snow density and consequently the snow-cover mass.

Comparing Figure 11 a, b and c reveals that increasing the panel angle decreased the required time for snow removal (and consequently the equivalent snow-cover mass according to Eq. 4.4) since panels installed with higher angle had a lower snow accumulation on them (Table 4.3).

Figure 4.10 shows the energy provided for melting the snow cover as a function of the snow-cover mass for several test cases. It also shows the theoretical energy required for melting snow before and after considering the incident solar radiation (Eqs. 4.5-6). Without considering the solar radiation, Eq. (4.5) calculates the theoretical energy required \((E)\) for melting the snow covering a panel with the mass of \(m\) (kg/m\(^2\)). If the heater with 180 W/m\(^2\) power were used to provide the energy, the required time would be \(t=E/180\) (s). Considering the Albedo (Al) of 0.8 for the snow cover (Andrews and Pearce, 2013; Warren, 1982), the available solar energy for melting snow during this period \((i)\) would be \(t \times (1-Al) \times G_T\) where \(G_T\) is the total measured incident solar radiation. Equation 4.6 shows the difference between the available solar radiation and the theoretical energy required for melting the snow cover. Dash lines on Figure 4.10 show the energy required for melting the snow cover after the reduction of the incident solar radiation contribution.

\[
E \left( \frac{kj}{m^2} \right) = m \times h_{fg}
\]  

(4.5)
\[ E_{\text{solar}} = E - \frac{E}{180} \times ((1 - A1) \times G_T) \]  (4.6)

If the experimental data is above the theoretical line on Figure 4.10, it shows that the energy provided by the heaters was more than the theoretical energy required as calculated by Eq. (4.5) (solid line in Figure 4.10). This situation could happen when the snow-cover was frozen to the panel. Conversely, if the experimental data are below the theoretical line in Figure 4.10, it shows that the energy provided by the heaters was less than the energy required for melting the entire snow-cover from the panel. There were three reasons for such a situation: 1) the snow-cover slid off the panel, 2) The rest of the required energy was provided by the sunlight as shown by the dash lines calculated by Eq. (4.6), 3) the ambient temperature was more than zero resulting in melting the snow-cover, or a combination of all these situations.
b) Panels at a 45 degree tilt angle

c) Panels at a 55 degree tilt angle

Figure 4.9 Comparing the snow-cover mass per unit area with the equivalent snow cover-mass per unit area calculated based on the heater heat flux (180 W/m²), ambient temperature and the melting time (eq. 4.4) for the experiments presented in Table 4.3 except test case No. 6 as it was a freezing rain and snow. The required energy for snow removal is proportional to snow-cover mass.
Snow sliding occurred. \( T_{\text{amb}} \) was above zero (1°C) and snow was already melting.

Figure 4.10 The required energy for melting snow vs. the snow-cover mass per unit area. Each symbol represents a test case. The required energy for melting snow for each test case is shown in the left axis and the measured melt time for heater heat flux of 180 W/m² in the right axis. The solid line shows the theoretical required energy (TRE) for melting snow without considering any solar radiation. Dash lines show the required energy for melting snow after considering a certain value of solar radiation available to assist the snow removal process (albedo effect of 0.2 was considered for all cases (Andrews and Pearce, 2013; Warren, 1982)).
a) Mass of snow cover versus equivalent mass accounted for the heater powers (180 W/m²) and available solar radiation

b) Provided energy by the heaters (180 W/m²) and available solar radiation based on the snow-cover mass

c) Provided energy by the heaters (180 W/m²) and available solar radiation based on the equivalent snow-cover mass accounted for these parameters as well as ambient temperature

**Figure 4.11** The correlation for the provided energy for melting snow on each test based on the available solar radiation and the heater power (180 W/m²) for the actual snow-cover mass per unit area and the equivalent snow-cover mass calculated based on the ambient temperature, the solar radiation and the heater power for each test (Eq. 4.7).
To consider the effects of both available solar radiation ($G_\tau$) and ambient temperature on the required energy for snow melting, a new equivalent snow-cover mass per unit area was calculated accounted for these parameters as follows.

$$m_{et} = \frac{(q + (1 - Al)G_\tau) \times t}{C_p(0 - T_{amb}) + h_{fg}}$$

(4.7)

This equivalent mass, $m_{et}$, is the mass of a snow cover that the heaters (180 W/m$^2$) and available solar radiation together could melt during the recorded melting time, t, for each test.
presented in Table 4.3. Figure 4.11a shows that this equivalent mass, \( m_{et} \), is in a good agreement with the actual snow-cover mass, \( m \), except for the test cases in which the snow cover was frozen to the panel or snow sliding occurred. In addition, Figure 4.11 b and c show the provided energy by the heater and solar radiation for melting snow as a function of the actual snow-cover mass and the new equivalent snow-cover mass, \( m_{et} \). The proposed correlation can be used to estimate the required energy for melting the snow cover on the panels.

It should be noted that since the wind speed was low (less than 1 m/s) for all of the experiments, the convective heat transfer from the snow cover surface was negligible compared to the solar radiation and the heater heat flux; however, for strong wind situations, it can be an effective factor.

Figure 4.12 compares the melting time between panels at 45 degree tilt angles: the panel with the electrical resistance heater versus the panel with an imposed reverse current through the PV cells. For “new snow” (mass per unit area less than 150 kg/m²) the required time for snow removal was almost the same for both panels since the main snow removal mechanism was melting snow. For “new snow”, the snow cover weight could not overcome the friction force between the snow cover and the panel surface to slide off even for the panel without the frame. For “settling snow” and “wind-toughened snow” covers (mass per unit area more than 150 kg/m²), snow slid off the panel without a bottom-frame while snow remained on the framed panel (the snow types categories are adopted from the Ross (1995) study, where the snow was categorized based on the density). Consequently, modifying the frame or using frameless panels may be helpful in terms of snow shedding for some types of snow cover.

4.3.6 Case Study

To illustrate the impact and potential benefit of implementing the previously described snow melting procedure, a hypothetical case study was considered. Specifically, the net energy production of a 16.3 m² PV array (i.e., 10 panels each of 1.63 m²) was calculated based on the
time of the day snow melting was implemented such that the panel was completely clear of snow-cover. The assumptions considered for this case study are as follow.

- A roof-top PV system with a total array area of 16.3 (m²) located in Toronto, Canada was considered.
- The panels characteristics were $P_m = 295$ W, $V_{mp} = 32$ V, $I_{mp} = 9.2$ A, $V_{oc} = 39.6$ V, $I_{sc} = 9.6$ A.
- The calculation was performed for two typical sunny (winter) days after a snowfall (i.e. January 1st and February 22nd were chosen from typical meteorological year (TMY) weather data).
- The hourly system production was calculated based on the method explained by Gilman (2015) using the Simple Efficiency Module Model.
- It was assumed that there is no PV output before the panels were completely clear of snow.
- The total output of the system during the days considered is presented in Table 4 assuming that the system was clear of snow before sunrise.

The energy required for snow removal ($E_{heater} = q \times RTS$) was calculated based on the results from test case number 7 (Table 3) depending on the panel tilt angles (i.e., $E_{heater}=4.9$, 2.9 and 2.4 kWh for panels at 30°, 45° and 55° tilt angles respectively).

**Table 4.4 The output of the hypothetical system assuming that the PV panels were clear of snow as calculated for two typical winter days from TMY weather data**

<table>
<thead>
<tr>
<th>Day</th>
<th>System output at 30° tilt angle (kWh)</th>
<th>System output at 45° tilt angle (kWh)</th>
<th>System output at 55° tilt angle (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1st</td>
<td>8.6</td>
<td>9.8</td>
<td>10.3</td>
</tr>
<tr>
<td>February 22nd</td>
<td>16.5</td>
<td>17.9</td>
<td>18.3</td>
</tr>
</tbody>
</table>
As mentioned, based on the time of the day snow melting was implemented, the net energy produced by the panel, $E_{net}$, represents the energy captured during the remaining portion of the day minus the energy expended in melting the snow-cover, i.e.,

$$E_{net} = \int_{t_{clear}}^{t_{snow}} E_{PV} dt - E_{heater}$$

(4.8)

where: $t_{clear}$ is the time of the day that snow melting is completed, $t_{snow}$ is the time of day sunset occurs, and $E_{heater}$ is the energy expended for melting the snow. Assuming the day in question is clear from sunrise to sunset, then the relative benefit of completing snow melting by a specific time of day can be calculated as the fraction of the clear sky energy $E_{cs}$ that is available, accounting for the energy used for snow melting as

$$FE_{CS} = \frac{E_{net}}{E_{cs}} = \frac{\int_{t_{clear}}^{t_{snow}} E_{PV} dt - E_{heater}}{\int_{Tsunset}^{Tsunrise} E_{PV} dt}$$

(4.9)

In this case, the value of $FE_{CS}$ should be higher than 0 to justify implementing the snow melting protocol. Figure 4.13 shows $FE_{CS}$ calculated versus time of day that snow clearing is completed assuming different solar array tilt angles. The benefit of snow melting is reduced as it is implemented later in the day. Comparing Figure 4.13 a and b shows that the benefit of using snow removal system is greater for days with longer day-time hours (e.g., February 22nd compared to the January 1st); however, even for January 1st, Figure 4.13 shows that if the panels were cleaned before the noon, the net energy factor would still be above zero.

As well, removing the previous evening’s snow cover prior to sunset will minimize the impact of the snow cover on the following day’s output. For instance, it can be seen that if the panels were clean before sunrise (at 6:00 and 7:00 AM in Figure 4.13 a and b), the 66% (for January 1st) and 84% (for February 22nd) of the total possible production of the system could be achieved for panel tilt angle of 45°; while without using the thermal snow removal system, the panels would
be potentially covered by snow the entire day (Andrews et al., 2013b; Ross, 1995). It is expected with the recent advances in local weather forecasting, maximization of net PV array output accounting for snow removal energy consumption will be possible.

Beside the net energy benefit of using the snow removal system, some other factors should also be considered for the system to be financially beneficial. For instance, the capital cost of implementing the snow removal system (which will vary depending on the chosen method), the value of energy produced by the system, the cost of electrical energy from the electrical grid, and the local climatic conditions (snowfall rates and frequency, solar resource and ambient temperatures, etc.). A comprehensive study of the cost-benefits of implementing snow melting protocols would provide valuable information for PV system integrators and operators.
Figure 4.13 The ratio of the net energy production of a PV system (located in Toronto CA) from sunrise to sunset during a sunny day after snowfall to the maximum energy production of the system on that day. At each hour of the day, it is assumed that the panel was covered by snow before that time the panel was clean of snow after that time. The required energy for snow melting was subtracted from the system production at each time to find the net energy production. The required energy for snow removal was calculated based on the results from test case number 7 depending on the panel tilt angles (E_{heater}=4.89, 2.93 and 2.45 kWh for panels at 30°, 45° and 55° tilt angles respectively).
4.4 Conclusion

In this paper, the use of a thermal method for snow removal from PV panels was investigated. Nine panels were mounted at 30, 45 and 55° tilts (three panels at each angle). One of the panels at each set had a heater on the back. In addition, the frame for one of the panels at 45 degree was modified, and the panel was heated by imposing reverse current through the PV cells instead of using the heater. The results revealed that:

1. During the melting process, the meltwater freezing on the frame was the major factor for stopping the snow cover from sliding off the PV panels. At the ambient temperature less than 0°C, formation of ice dam and icicles can occur on the bottom edge of a PV panel preventing the snow cover from sliding off. As a result, using frameless PV panels for areas with significant snowfall can be beneficial for owners and operators based on net energy delivery.

2. It was observed that for some cases, the panel temperature increased suddenly while the panel was still covered by snow due to the formation of an ice bridge on top of the panel. This resulted in a local increase in panel temperature. This is of concern as higher temperature gradients may induce thermal stresses that may result in panel or heater failure over time. It also explains the situations reported by some other researchers regarding snow sliding off the panels at panel temperatures above 25°C rather than 0°C.

3. It was observed that the snow cover slid off from the upper half of the panel and stayed at the lower half until it was melted due to the formation of an ice dam and icicles at the bottom edge. According to these observations, it could be beneficial if the panel had two separate heaters, one each for the upper and lower halves, to prevent heat loss from the upper half when it was clean while the lower heater could continue heating the lower half of the panel.
4. Covering only below the junction box of a panel with the heater was not an effective method for snow removal since the heat conduction through the panel glass was not sufficient to conduct heat from the heated area to the unheated parts of the panel. As a result, snow melting occurred only in the heated region. For heating snow removal method, it is recommended to heat the entire surface of the panel.

5. To address the frame and heating area issues, a reversed electrical current was forced through the PV cells for one of the panels at 45° tilt, and the bottom frame was removed. The snow slid off this panel in most of the experiments, while snow sliding did not occur for other panels with the heater (the snow slid off the other panels only when snow accumulation was more than 11 cm). It is recommended for the owners to use frameless PV panels if they need to install the PV panels in a region with significant annual snowfall.

6. Based on the measurements and observations, it may be concluded that imposing reverse current through PV cells with a modified frame can be a more beneficial and practical method for snow removal from PV panels compared to using a heater. It should be noted that the amount of reverse current should not exceed the panel capacity to avoid any possible damage to the panel.

7. It was observed that for freshly fallen snow covering a panel, even if a frameless panel was used, the main snow removal mechanism would be snow melting. Since the snow cover weight could not overcome the friction force between the snow cover and the panel surface to slide off even for the panel without the frame.

8. The hypothetical case study showed that using the thermal snow removal system can be beneficial for a PV system depending on the start time for removing snow from the panel. If there is no snowfall during the day, it is recommended to remove the snow before sunrise.
Acknowledgements

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Chapter 5

The effect of insulating a photovoltaic solar panel on its performance during the summer

Abstract

In this paper, the effect of having insulation mounted on the back of a PV panel during summer has been investigated. The main reason for such insulation is the need for snow removal from the panel during the winter. During the winter, using a heating snow removal system with insulation can expedite and reduce the energy consumed by the snow removal process; however, during the summer, it can increase the panel temperature, and it reduces the energy production of the panel. Therefore, a modified insulation system has been proposed to reduce the negative effect of having insulation during the summer. This approach was implemented on thermal solar panels but has not been adopted for use on PV panels. For this study, two PV panels were installed at the slope angle of 45 degree. One of the panels had the insulation on the back and the other panel was remained uninsulated to serve as a reference panel. The current-voltage (I-V) and power-voltage (P-V) curves of both panels were measured under several natural conditions including solar radiation and wind speed. The proposed insulation layer was equipped with two vents at the very top and bottom of the panel, and was painted black on the side facing the panel. The insulation was mounted below the back of a PV panel producing the air channel of approximately 3 cm depth. In the summer, natural convection through the vents and radiation heat transfer between the panel and the insulation help to control the panel temperature. On the other hand, during the winter, closing the vents maximizes the effect of the snow removal system. The effect of solar radiation and vent configurations on the panel output were studied to find the optimum configuration for the vents. A numerical simulation was also conducted to investigate
the effect of other parameters: the wind speed, panel tilt angle and the surface emissivity of the insulation. The results showed that the proposed method could control the panel temperature and minimize the adverse effect on the PV panel electrical output. Using the proposed insulation on the back of the PV panel with the vents can cause approximately 50% less energy loss as compared to the case that the insulation did not have any open vent, while still minimizing the energy required for snow removal in the winter period.

Keywords: Photovoltaic solar panels, Snow removal, Panel insulation, temperature distribution, efficiency

5.1 Introduction
Photovoltaic (PV) systems are a clean energy option for supplying power. The output of PV modules depends on the environmental and weather conditions. One of the examples happens during the winter, when snow and ice can accumulate on PV panels, reducing their electrical output for extended periods of time. Previous studies have indicated that annual losses related to snow accumulation and ice-buildup effect on a PV system can be as high as 0.3% to 15% depending on the orientation, tilt angle of the PV modules and meteorological factors (Andrews et al., 2013b, 2013a; Becker et al., 2008; Marion et al., 2005; Townsend and Powers, 2011). As a result, determining and reducing these effects can improve the performance of PV systems installed in regions that experience notable annual snowfall.

Since PV panel manufacturers are not interested in mechanical techniques due to the high risk of damaging the panels, heating the panel can be considered as a snow removal option. Regardless of the method used for heating the panel, using proper insulation is crucial for having an efficient heating process. However, while there is a positive effect of mounting insulation on the back of a PV system for more efficient heating in the winter to remove snow, the insulation
can increase the panel temperature during the summer as well. Since higher panel temperature reduces PV efficiency, there is a trade-off between the adverse effect of the insulation during the summer and its positive effect for removing snow from the panel during the winter. In addition, PV panel manufacturers are not interested in using seasonal insulation since it is neither practical nor economical, particularly for large solar fields.

As a result, to determine the effect of insulating a photovoltaic panel on its performance, two main factors should be investigated: 1) the effectiveness of a heating snow removal method with an insulation for a PV system during the winter, and 2) the effect of the snow removal system, particularly the insulation effect, on the PV panel performance during the seasons without snowfall.

Several researchers have studied the snow effect on a PV system performance. Since higher snow precipitation in an area leads to higher annual snow loss for a PV system, there is a range of snow loss presented in the literature for different regions. For instance, in Germany, Becker et al., (2008) reported snowfall losses in the range of 0.3 to 2.7% using 6 years of data from the New Munich Trade Fair Center (1999 to 2006). This value is significantly less than 13 to 26% presented for Truckee California by Townsend and Powers (2011). It should be noted that the average monthly or yearly snowfall in Munich is not comparable with the average snowfall in North America. For instance, in 2011 the average monthly snowfall for Munich was less than 30 cm (Becker et al., 2008), while in Truckee, California the average was 5 m of snow per year. It shows how the impact of snowfall on the PV system performance depends on the meteorological factors (especially the amount of snowfall).

Considering the significant effect of snowfall on PV systems and the manufacturer concerns about not damaging the panels, various active and passive heating snow removal systems have been proposed in the literature (Ross, 1995; Van Straten, 2017; Weiss and Weiss, 2016). Most of these methods need proper insulation to operate correctly; however, before designing a heating
snow removal system with the insulation, the effect of insulation on the panel temperature and consequently on the panel performance during seasons without snowfall should be determined. As a result, the primary goal of this study is to determine the effect of insulating a PV panel on its performance during the summer. Several solutions have been examined to reduce the insulation effect on the panel performance during the summer while it is still beneficial during the winter for snow removal.

The main influence of having insulation on a PV system will be reflected on the panel temperature. The effect of the operating temperature on a photovoltaic module is well documented. Three parameters play major roles on the PV performance: open circuit voltage $V_{oc}$, short circuit current $I_{sc}$ and maximum electrical power $P_{m}$. The increase of the panel temperature decreases both the open circuit voltage and the maximum power, while the short-circuit current may not change significantly by the panel temperature (Andrews, 2015; Zondag, 2008). As a result, to determine the effect of insulating a PV panel, the panel temperature and its electrical characteristics ($V_{oc}$, $I_{sc}$, and $P_{m}$) should be monitored during a regular sunny day while it is insulated.

Although there are some studies regarding the effect of insulating a PV-thermal (PV/T) panel on its temperature (He et al., 2006; Yin et al., 2013), there is no specific study in the literature about the effect of insulation on PV panel’s temperature and consequently its performance. As a result, in this study, a goal is to determine to what extent taking advantage of insulating the back of a PV panel for melting snow during the winter affects the PV performance during the summer, and how this effect can be reduced.

In this study, the approach consists of adding an insulation layer to the back of the panel. A proposed configuration for the insulation layer was also considered. A venting channel between the PV panel and the inward facing surface of the insulation was considered to facilitate natural convective heat transfer from the panel. The air flow through the vent channel was controlled by
thermostatically controlled vents located at the top and bottom of the panel. A well-instrumented
PV panel with that insulation was installed at the tilt angle of 45° to the horizontal. To allow a
comparison, a second panel was installed at the same slop without any insulation to serve as a
reference panel. The I-V and P-V curves of each panel were measured as well as panel
temperature at different time periods and solar radiation intensities. The effect of vent size on the
panel performance is also investigated. The results for panels with and without insulation are
compared and the power reduction for the insulated panel is reported as compared to the
reference panel. Numerical simulations were also conducted and validated by the experimental
data to perform a parametric study on the effect of wind speed, panel tilt angle and surface
emissivity of the insulation on the panel temperature.

5.2 Methodology

To experimentally study the effect of insulation on a PV panel performance, two PV solar
panels were used. The panel characteristics are presented in Table 5.1. The performances of the
panels were compared before mounting the insulation to ensure that both panels were identical.
The I-V (current vs. voltage) and P-V (power vs. voltage) curves of both panels are given in
Figure 5.1. The difference between curves is less than 1%. As a result, one of the panels was used
without any insulation as the reference panel, and a Polyisocyanurate foam insulation with a
thickness of 10 mm and R-value of 0.54 (m²C/W) was mounted on the back of the other panel
(Figure 5.2).
Table 5.1 The panel characteristics at standard test condition (1000 W/m², Cell Temperature 25°C)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (P_m)</td>
<td>180 W± 3%</td>
</tr>
<tr>
<td>Maximum Power Voltage (V_mp)</td>
<td>36.80 V</td>
</tr>
<tr>
<td>Maximum Power Current (I_mp)</td>
<td>4.90 A</td>
</tr>
<tr>
<td>Open Circuit Voltage (V_oc)</td>
<td>44.20 V</td>
</tr>
<tr>
<td>Short Circuit Current (I_sc)</td>
<td>5.35 A</td>
</tr>
<tr>
<td>Normal Operation Cell Temperature (NOCT)</td>
<td>47 ± 2°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1581 × 809 × 40 mm</td>
</tr>
</tbody>
</table>

Figure 5.1 Comparison of the I-V (current vs. voltage) and P-V (power vs. voltage) curves of two panels before mounting the insulation on the back of one of the panels for two different solar radiation intensities. The panels’ performance is identical within 1%.
A 3 cm air gap between the panel and the insulation on the back was used along with two openings located at the top and bottom of the insulation to enhance the passive air cooling through the channel (Figure 5.2 and Figure 5.3). The inside surface of the insulation (facing the panel) was painted black with an emissivity (ε) of 0.90. It is reported in the literature that such a coating can increase the heat transfer rate from the panel by more than 10% depending on the temperature (Hussain and Harrison, 2015). The panels were installed on a mounting rack at an inclination of 45° in the Solar Calorimetry Lab of the Department of Mechanical and Materials Engineering of Queen’s University, Kingston, Canada.

If the vents are open during the summer, they can enhance natural convective heat transfer from the panel. Once the panel is heated by the solar radiation, the air between the panel and the insulation will be heated and exit by natural convection. Cool fresh air will enter the channel from the bottom vent enhancing the heat removal process. In addition to the natural convection, as mentioned, the black coating on the back of the insulation enhances the radiation heat transfer between the panel and the insulation. Considering the construction restraints, several vent sizes were examined to find the best configuration for the vents. The mechanical valve used for the upper vent (which closes the vent during the winter for snow melting) had the maximum opening of 3 cm. As a result, the upper vent size was fixed to 3 cm due to the mechanical limitation (Hussain and Harrison, 2015). Two vent sizes of 3 cm and 6 cm were tested for the bottom vent. For one of the experiments, a 3 cm vent was added at the center of the panel. In addition, the case with both vents closed was also examined.
Six OMEGA thermocouples (Type T) were mounted on the back of each panel (Figure 5.3) as well as one thermocouple on the inside surface of the insulation. To ensure good contact between the panel and the thermocouples, a Polyimide Film with a silicone pressure sensitive adhesive (which are designed for thermocouples) was used to attach each thermocouple to the surface. To ensure that the surface temperature measured by each thermocouple is accurate, thermal tape and black paint were also used on top of the silicone adhesive. The ambient temperature was recorded using another thermocouple mounted on the rack. A Kipp and Zonen CMP21 pyranometer was used to measure solar radiation in the plane of PV surface. UMB Smart Weather Sensor was used to measure the wind speed. A natural Instrument SCXI Data Acquisition (D/A) unit, with a built-in cold junction compensation, was utilized to record the thermocouples’ temperature using National Instrument LabView software. All experimental measurement instrumentation are listed in Table 5.2.
Table 5.2 The measurement facilities used in this study

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>OMEGA Co.</td>
<td>Type T</td>
<td>Copper/Constantan thermocouples type T (0.5 mm dia.)</td>
</tr>
<tr>
<td>Weather station, (wind speed)</td>
<td>UMB Smart Weather Sensor</td>
<td>WS600</td>
<td>This station has an integrated ultrasonic wind sensor for high accuracy wind speed and direction measurement as well as instruments for relative humidity and pressure measurements.</td>
</tr>
<tr>
<td>Global solar radiation at 45 degree</td>
<td>Kipp &amp; Zonen</td>
<td>CMP21</td>
<td>Mounted in the plane of the PV module to measure incoming global solar radiation with a 180° field of view.</td>
</tr>
<tr>
<td>Natural Instrument data logger</td>
<td>Natural Instrument</td>
<td>SCXI</td>
<td>Used to record the temperature data measurements and for other instruments including weather station and pyranometer.</td>
</tr>
</tbody>
</table>
Figure 5.3 Schematic figure of the insulated panel and thermocouples location as well as inlet and outlet vents located at the bottom and top of the panel. Another thermocouple was located on the inside surface of the insulation at the same location as the highlighted thermocouple in the picture.

5.2.1 Uncertainty analysis

The uncertainty associated with the temperature measurements was calculated based on the calibration uncertainty $u_{\text{cal}}$, accuracy $u_a$, standard deviation of the mean $\sigma_m$ and resolution of the DAQ (Figliola and Beasley, 2015; ISO 9806 Standard, 1994). The thermocouples were calibrated using a thermostatic bath in the range of 0-100°C. The calibration uncertainty was ±1°C. The thermocouple wires were also routed toward the bottom edge of the panel to avoid disturbing the flow passing through the channel. The DAQ device recorded data at 10Hz and stored the mean value every 1 sec. In this study, the temperature measurements were recorded during the steady-state conditions by averaging the data every 30 seconds. The maximum standard deviation was
±1.1°C. This deviation could result from the sudden changes in the wind speed, the solar radiation or other environmental parameters. The DAQ accuracy and resolution were 0.5°C and 0.001°C respectively.

As a result, the temperature measurement uncertainty was:

\[ u_{total} = \pm \sqrt{u_{cal}^2 + u_a^2 + \sigma_m^2 + Res^2} = \pm 1.6°C \]  

(5.1)

5.3 Mathematical Modeling

Numerical simulations were also conducted in parallel with the experiments to study the effects of some parameters such as the panel tilt angle, surface emissivity and ambient wind speed which varied during the outdoor tests. The heat transfer from the PV panel was simulated under the same environmental and boundary conditions as existed in the experiments to compare the predicted temperature distribution over the panel with the experimental results. Since the fluid dynamics are governed by the conservation equations for mass, momentum and energy, the continuity equation, momentum equations and energy equation were solved under the following assumptions using Fluent 15 (Fluent, 2016):

1- The flow was steady, approximately 2D at the center of the air channel and fully turbulent since the Rayleigh number was higher than 10^9 (Incropera and DeWitt, 1990).

2- The effects of wiring, dust and water vapor on the flow were negligible.

3- The Boussinesq approximation was used to predict the buoyancy force while the other air properties were assumed to be constant (Wilcox, 1993).

4- The ambient conditions were steady, and the variation of the inlet air temperature entering the channel behind the panel was negligible during the test.
5.3.1 Governing equations

The Reynolds Averaged Navier Stokes (RANS) equations were solved along with the energy equation by using Fluent 15. In addition, the k-ε RNG turbulence model was utilized to model the turbulent flow around the panel. It has been shown that the k-ε model predicts natural convection more accurately than most of the turbulence models including k-ω or SST k-ω (Hussain and Harrison, 2015).

To consider the radiation exchange between the insulation and the panel, a radiation transport equation (eq. 2) was solved using the discrete ordinates radiation model (DO). Since this model does not perform ray tracing, a finite number of vector directions associated with discrete solid angles is considered in the global Cartesian system (x,y,z).

\[
\frac{dI(\hat{r}, \hat{s})}{ds} + (\alpha + \sigma_s)I(\hat{r}, \hat{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{2\pi} I(\hat{r}, \hat{s}) \phi(\hat{r}, \hat{s}) d\Omega
\]  

(5.2)

The details of the model are available in the (Fluent, 2016).

A Coupled algorithm (Fluent, 2016) was used for the velocity-pressure coupling to get a converged solution. The governing equations were solved so that the absolute normalized residuals for all cells became less than 10^{-6}.

5.3.2 Grid study and computational domain study

The density of the mesh near the wall was determined based on the near-wall modelling strategy by using the y+ characteristic parameter. The enhanced wall treatment (Fluent, 2016) was utilized to calculate the velocity and temperature at the first cell adjacent to the wall. To examine the mesh independence of the numerical results, three mesh densities were investigated. In addition, three computational domain sizes were examined to study the domain independence of the model.
5.3.3 Boundary conditions

The boundary conditions were set to match the experimental situations in which the experiments were conducted as much as possible (environmental parameters such as wind speed, sky temperature, and solar radiation). The back and side walls of the air channel were assumed to be adiabatic (the insulation in the experiments). The constant heat generation was used for the panel based on the measured solar radiation. The absorption coefficient was assumed to be 0.85 for the panel (assuming no PV conversion as there was no electrical output during the experiments) (Brogren et al., 2001; Hegazy, 2000; Mattei et al., 2006). In addition, the no-slip boundary condition was imposed for all walls. The outer boundary was assumed to have a relative atmospheric pressure of 0 Pa and temperature of 294K based on the sky temperature (Duffie and Beckman, 2013). Low turbulence and steady-state conditions were assumed for the outside of the

Figure 5.4 Domain size and mesh density around the panel. Three different domain sizes and mesh densities were examined for the numerical simulations to ensure the independence of the numerical results from the domain size and mesh density.
computational domain, and the turbulent intensity of $10^{-3}$ and turbulent kinetic energy of $10^{-5}$ were used. To simulate the experimental cases with wind, constant velocity boundary conditions were considered for the outer boundary depending on the wind direction.

5.4 Results and Discussions

The experimental and numerical results are presented and compared in this section to investigate the effects of several factors such as the vents’ configuration and size, tilt angles of the panel, wind speed and surface coating of the insulation on the panel temperature and performance.

5.4.1 Experimental results

To study the effect of an insulation layer on the PV panel performance, as mentioned, several effective parameters have been considered in this study. The first parameter is the size and configuration of the inlet and outlet vents.

5.4.1.1 The effect of the size and configuration of the vents

Figure 5.5 compares the I-V and P-V curves for different vent sizes and configurations. An attempt was made to conduct the tests for different vent configurations in similar environmental conditions to minimize the effect of other factors. The solar radiation and averaged wind speed were approximately $I=985 \pm 20 \text{ W/m}^2$ and $U=2 \text{ m/s}$ for all of the cases presented in Figure 5.5. Since the wind speed was slightly changing during the tests, the wind speed was averaged in 10 minutes ($\pm 5^\circ\text{C}$) around the time that the panel performance measurement was conducted. The results show that increasing the vent size decreased the power loss ($P_m$) for the insulated panel as compared to the reference panel without the insulation. Larger vent size increased the heat transfer rate from the back of the panel resulting in the lower panel temperature. Consequently, since the PV panels operate more efficiently at the lower temperature, the maximum output power ($P_m$) of the insulated panel with the larger vent size did not drop significantly as compared
to the reference panel. Increasing the inlet vent size (more than 6 cm) was not practical due to the increase of mechanical complexity; because it would need a larger valve to close it during the winter.

Figure 5.5 Comparing I-V and P-V curves of panels with and without insulation for different vent sizes at top, bottom and center of the insulation. The solar radiation at the time of these experiments was approximately $I=985 \pm 20 \text{ W/m}^2$. The panel performance is the lowest when there is no vent, and the performance is the highest for the configuration of “Top vent= 3 cm, bottom vent= 6 cm”. Adding another vent at the center of the insulation did not show a significant improvement for the panel performance.
Figure 5.5 shows that adding a vent at the center did not improve the heat transfer rate significantly as compared to the case with only two vents on the top and bottom of the insulation; while it would need another mechanical valve to close the vent during the winter. In this case, although fresh air entered from both bottom and center of the channel rather than only bottom vent, the existence of the center vent decreased the total mass flow rate through the channel due to the reduction of the buoyancy force. When the fresh air entered the center vent, the difference between the air density at the inlet and outlet of the channel decreased. It resulted in lower mass flux and subsequently lower heat transfer rate from the panel. Consequently, considering the mechanical difficulties for closing the vents, the results show that using two vents at the top and bottom of the insulation with sizes of 3 cm and 6 cm respectively gave the best result.

Table 5.3 also summarizes the effect of vent size on maximum power, short circuit current, and open circuit voltage. Reducing the vent size caused an increase in the panel temperature, and consequently decreased the open circuit voltage (and maximum power), while the short circuit current is slightly increased. The results were consistent with the results presented in the literature regarding the effect of increasing the panel temperature on the open circuit voltage and the short circuit current (Nagano et al., 2003; Skoplaki and Palyvos, 2009; Tiwari and Sodha, 2006a, 2006b; Tobías et al., 2003).

Table 5.3 The effect of vent size on the insulated panel performance as compared to the uninsulated reference panel (I=985 ± 20 W/m²) (negative percentage shows increment for the insulated panel as compared to the reference panel)

<table>
<thead>
<tr>
<th></th>
<th>T-vent = 3 cm</th>
<th>T-vent = 3 cm</th>
<th>T-vent, M-vent = 3 cm</th>
<th>T-vent = 0 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-vent=3cm</td>
<td>B-vent=6cm</td>
<td>B-vent=6cm</td>
<td>B-vent=0cm</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>4.13%</td>
<td>2.24%</td>
<td>1.76%</td>
<td>5.39%</td>
</tr>
<tr>
<td>$I_{sc}$ (A)</td>
<td>-0.60%</td>
<td>-0.39%</td>
<td>-0.77%</td>
<td>-3.63%</td>
</tr>
<tr>
<td>$V_{mp}$ (V)</td>
<td>5.29%</td>
<td>3.27%</td>
<td>2.85%</td>
<td>8.52%</td>
</tr>
<tr>
<td>$I_{mp}$ (A)</td>
<td>3.16%</td>
<td>1.34%</td>
<td>0.80%</td>
<td>1.12%</td>
</tr>
<tr>
<td>$P_m$ (W)</td>
<td>8.29%</td>
<td>4.57%</td>
<td>3.62%</td>
<td>7.49%</td>
</tr>
</tbody>
</table>
Figure 5.6 Comparing temperature distribution on panels with and without insulation for different vent sizes at the top, bottom, and center of the insulation. The solar radiation at the time of these experiments was approximately $I=985 \pm 20\, \text{W/m}^2$. The panel temperature is the highest when there is no vent.

Figure 5.6 compares the temperature distribution for the panels with and without the addition of insulation. The solar radiation and wind speed were approximately $I=985 \pm 20\, \text{W/m}^2$ and $U=2\, \text{m/s}$ for all of the test cases presented in Figure 5.6. The panel temperature increased from the bottom to the top of the panel for both panels; however, the rate of increment and temperature gradient were greater for the panel with the insulation. Comparing the cases with different vents sizes and configurations shows that the highest temperature difference between the insulated and
uninsulated panels was for the case with closed vents. By opening the vents, the panel temperature was significantly reduced beyond the case with closed vents.

The data presented in Figure 5.6 and Table 5.3 shows that using the vents could reduce the adverse effect of insulation on the panel temperature by approximately 50% during the experiments. For instance, for the cases with 6 cm vent at the bottom, the highest temperature difference between the insulated and uninsulated panels was less than 8°C resulting in approximately 4-5% reduction in the maximum power $P_m$ at noon (with the highest solar radiation); while the temperature difference for the case with closed vents was around 16°C resulting in approximately 7-8% reduction in $P_m$.

To enhance the heat transfer from the insulation, the effect of mounting, six aluminum fins 1.5 m long and 2 cm high, at the back of the insulation was also investigated; however, it did not show a significant effect on the panel temperature. The result is shown in Figure 5.7. The temperature difference between the insulated and uninsulated panels and the power reduction is approximately the same as the case without the fins shown in Figure 5.6. Adding more fins may improve the heat transfer rate, but this may not be economical. In addition, fins were not mounted on the back of the panel because PV manufacturers do not like attaching fins to the back of the panels.

5.4.1.2 The effect of the solar radiation

The second parameter which can change the insulation effect on the PV performance is the solar radiation. If panels do not track the sun, the effect of the insulation may vary with the incident solar radiation during the day. As a result, the effect of the insulation on the panel temperatures and performances was examined at several solar radiations.

Figure 5.8 shows the temperature distribution for the insulated and uninsulated panels at different solar radiations. The averaged wind speed for all of the test cases was between 3 and 3.5 m/s. The higher solar radiation led to higher temperature differences between the insulated and
uninsulated panels; however, the highest temperature difference was less than 10°C. Since PV panel performance decreases with the temperature increment, the higher solar radiation leads to lower efficiency for the insulated panel as compared to the uninsulated panel. 

shows the percentage of reduction of the short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power (P_{m}) for the insulated panel as compared to the reference panel at different solar radiations. Both open circuit voltage (V_{oc}) and maximum power (P_{m}) had more reduction at higher solar radiation, while there was no significant change for short circuit current (I_{sc}) between the insulated and reference panels. The results have an agreement with the effect of temperature on PV panel performance reported in the literature (Zondag, 2008). It should be noted that since Table 5.4 presents the percentage decrease between the insulated and uninsulated panels for I_{sc}, V_{oc}, and P_{m} at a certain solar radiation, the results basically show the effect of panel temperature on these parameters (I_{sc}, V_{oc} and P_{m}) at a certain solar radiation (not the effect of solar radiation on I_{sc}, V_{oc} and P_{m} of a single panel).

Table 5.4 The percentage (%) of reduction between the insulated panel (Top vent= 3 cm, bottom vent= 6 cm) and the reference panel at different solar radiations for the short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power point voltage (V_{mp}), maximum power point current (I_{mp}) and maximum power (P_{m})

<table>
<thead>
<tr>
<th></th>
<th>I=668 W/m²</th>
<th>I=818 W/m²</th>
<th>I=1006 W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{oc}(V)</td>
<td>1.92%</td>
<td>2.33%</td>
<td>2.67%</td>
</tr>
<tr>
<td>I_{sc}(A)</td>
<td>0.0%</td>
<td>0.00%</td>
<td>0.50%</td>
</tr>
<tr>
<td>V_{mp}(V)</td>
<td>3.40%</td>
<td>3.67%</td>
<td>4.96%</td>
</tr>
<tr>
<td>I_{mp}(A)</td>
<td>1.63%</td>
<td>1.63%</td>
<td>1.49%</td>
</tr>
<tr>
<td>P_{m}(W)</td>
<td>4.98%</td>
<td>5.24%</td>
<td>6.38%</td>
</tr>
</tbody>
</table>
a) 6 aluminum fins which were 1.5 m long, 2 cm high and 0.5 mm thick were mounted on the back of the insulation

Figure 5.7 Comparing temperature distribution and I-V curves between panels with and without the insulation with six fins. Fins are 1.5 m long and 2 cm high at the back of the insulation. The vents configuration is “Top vent= 3 cm, bottom vent= 6 cm”. The averaged wind speed was U≈3 m/s. The solar radiation at the time of this experiment was approximately I=968 ± 20 W/m².
Figure 5.8 Comparing temperature distribution between panels with and without the insulation at different solar radiations. The vents configuration is “Top vent= 3 cm, bottom vent= 6 cm”. The averaged wind speed for all cases was $U=3 - 3.5$ m/s. The higher solar radiation leaded to higher temperature difference between the insulated and uninsulated panels.

5.5 Numerical results

Figure 5.9 compares the measured temperature distributions on the back of the PV panels with and without insulation with the results given by the numerical simulations. The numerical simulations are in good agreement with the experimental data, especially for the insulated panel which is the main focus of our simulations. The slight difference for the panel without the insulation can result from the 3D effects and wind variation in the flow field around the uninsulated panel and the averaged boundary conditions used for the steady-state simulations.
the insulated panel has a channel on the back of the panel, the 3D flow field effect on the 2D simulations along the centerline of the panel is less as compared to the uninsulated panel. In addition, as mentioned, the measured wind velocity and ambient temperature (especially wind speed) were slightly changing during the tests, therefore, the 10 minute averaged wind speed and ambient temperature were used as a representative of the steady state boundary conditions.

As shown in Figure 5.10, the rapid temperature increase at the bottom of the insulated panel was due to the air circulation inside the frame on the back of the panel (Figure 5.10.b) as well as the stagnation point on the front surface resulting in higher temperature. After the circulation, the air entering directly in the panel through the inlet vent decreased the panel temperature rapidly. The panel temperature increased as the air flowed through the channel until it reached the outlet vent. The increase rate of the panel temperature is observed to decrease from the bottom to the top of the panel as heat loss to the environment increases.

Figure 5.9 Comparing the experimental temperature distributions on the back of the panels with and without insulation with the results given by the numerical simulations. The vent sizes were as top vent = 3 cm, bottom vent = 6 cm. The insulation surface emissivity and wind speed were $\varepsilon = 0.9$ and $U=1$ m/s for the simulations.
5.5.1 Parametric analysis

In this section, a sensitivity analysis for the panel temperature was carried out based on changing the following parameters: the PV installation tilt angle to the horizontal, the surface emissivity of the insulation and the wind speed.

5.5.1.1 Panel installation tilt angle

Three simulations at three different tilt angles were performed in the range from $20^\circ$ to $60^\circ$. The vent sizes were the same for all three simulations (top vent = 3 cm and bottom vent = 6 cm), and the insulation surface emissivity and wind speed were considered to be the same as the validation case ($\varepsilon = 0.9$ and $U = 1\, \text{m/s}$). The temperature distribution of the panel is compared for tilt angles of $20^\circ$, $45^\circ$ and $60^\circ$ in Figure 5.11.

Figure 5.10 Streamlines and velocity distribution around the panel and inside the frame ($\varepsilon = 0.9$ and $U = 1\, \text{m/s}$). The flow field around the inlet vent of the channel is magnified on the picture on the right. It shows that there is a circulation zone at the very bottom of the panel.
It will be seen that increasing the tilt angle from 20° to 45° decreased the average temperature by approximately 3°C, while the increase from 45° to 60° decreased the average temperature by only 1°C. Increasing the panel tilt angle increased the buoyancy force inside the channel, and consequently higher natural convective heat transfer from the panel resulted in lower average temperatures. Although the optimal tilt angle for PV panels depends on the site latitude and some other parameters, the results show that for the proposed insulation scheme with vent channel, higher tilt angle leads to lower average panel temperature.

### 5.5.1.2 Surface emissivity of the insulation

The effect of changing the insulation emissivity was also studied, and the results are given in Figure 5.12.a. The effect of surface emissivity on the panel temperature was studied numerically under the following conditions: top vent = 3 cm and bottom vent = 6 cm, the panel tilt angle and wind speed were 45° and U=1 m/s.

Figure 5.12.a shows that increasing the insulation emissivity (by painting the insulation) can decrease the panel temperature. The average temperature increase was 3°C for changing the emissivity from 0.9 to 0.3. The temperature reduction was mostly due to the radiation heat transfer from the panel to the insulation. In addition, as the higher emissivity means higher absorption for the insulation, it increases the insulation temperature. As a result, the higher temperature difference between the air and the insulation leads to more effective natural convection from the insulation, thereby lowering the PV panel temperature.

### 5.5.1.3 Wind speed

The other parameter which can affect the panel temperature is the speed of wind blowing over the panel. The numerical simulations have therefore been conducted for different wind speed (U) situations for the same panel configuration, i.e., vent sizes were: top vent = 3 cm and bottom vent
= 6 cm as well as the panel tilt angle of 45° and the insulation surface emissivity of ε=0.9. Figure 5.12.b shows that changing the wind speed blowing to the panel can change the panel temperature significantly. Changing the wind speed from 1 m/s to 3 m/s decreased the panel temperature by approximately 10°C. This significant change shows the effect of wind speed on the panel temperature; however, changing the wind speed from 3 m/s to 5 m/s just lowered the panel temperature by approximately 5°C.

Once the wind speed is 1 m/s, the convective heat transfer mechanism from both front and back surfaces of the panel is mixed free-forced convection as Gr/Re² ≈ 1 (Incropera and DeWitt, 1990). As the heat transfer mechanism in the flow field changes from the mixed convection to the forced convection, the panel will be cooled down more effectively, mostly through the front surface exposed to the wind. Increasing the velocity from 1 to 3 m/s changes the flow field from mixed free-forced to the only forced convective heat transfer. Although more velocity increment (from 3 to 5 m/s) increases the heat transfer from the panel (around 5°C temperature decrease for the panel surface), the inflection point of changing the flow field from the mixed to the forced convection causes more change for the panel temperature (around 10°C) (Figure 5.12.b).

Figure 5.11 The effect of changing the tilt angle on the panel temperature. The vent configuration was as top vent = 3 cm and bottom vent = 6 cm (ε=0.9 and U=1 m/s). Increasing the panel tilt angle decreases the overall panel temperature.
Comparing snow loss for PV panels during the winter with the effect of insulation on the panel output during the summer

The experimental results revealed that using the proposed insulation can control the panel temperature by taking advantage of the enhanced natural convection and the radiation heat transfer between the panel and the insulation. The proposed method can keep the panel temperature increase less than 10°C on average as compared to a panel without the insulation. In addition, the power reduction was less than 5% at the highest solar radiation at noon while lower solar radiation during the rest of a day caused less reduction in the power generation. As a result, the average daily energy loss due to the proposed insulation will be less than 5% during the summer. The temperature increase less than 10°C and power reduction less than 5% is promising for using this type of insulation during the winter for snow removal from the panel.

According to the literature, the annual snow loss for a PV system can vary from 0.3% to 26% depending on the location, panel tilt angle and meteorological factors. The energy loss of 5% due to the insulation shows that using the insulation for a PV system with snow loss less than 5% is
not recommended. As a result, using a thermal snow removal method with insulation can be practical for a PV system with a higher rate of snow loss (e.g., <5%); however the effectiveness of the thermal snow removal system, the additional price for mounting the system and the associated pay-back period should also be considered. Moreover, the type of a PV system can be important. For instance, a building integrated PV system may be already insulated by the walls as compared to a rack mounted PV panel. As a result, using the proposed system for snow removal may be more practical and economically reliable for certain types of PV system.

5.6 Conclusion

In this paper, the effect of mounting insulation on the back of a PV panel during the summer was studied. Two similar PV panels were compared: one with the insulation on the back and the other one without insulation. Adding back insulation to the PV panel with a novel venting scheme was evaluated that limited panel temperature during high ambient temperature and solar radiation. The inward surface of insulation in the venting channel was also painted black to increase the radiation heat transfer and improve natural convection. The temperature distributions and the energy production of the panels were compared under several natural outdoor conditions. In addition, a numerical model was used for further investigation of the effect of the panel tilt angle, the insulation surface emissivity, and the wind speed. The results revealed that

1- Using 6 cm vent at the bottom and 3cm vent at the top of the insulation would limit the panel temperature increase to 10°C as compared to the panel without the insulation. It was also shown that using the proposed insulation with vents would result in approximately 50% less reduction in maximum PV output as compared to mounting the insulation without any vents.

2- Keeping the panel temperature increase less than 10°C led to only 5% power loss at noon (the highest solar radiation). The average daily energy loss was less than 5%.
3- Although the optimal tilt angle for PV panels depends on the site latitude, the numerical simulations showed that higher tilt angles led to increased natural convective heat transfer in the venting channel resulting in lower average panel temperatures.

4- The numerical simulation revealed that the high emissivity coating on the insulation surface could decrease the panel temperature by 3°C resulting in lower energy loss due to the insulation in the summer.

5- Changing the surrounding wind speed from 1 m/s to 3 m/s decreased the panel temperature by approximately 10°C. It shows the significant effect of wind speed on the panel temperature, however, changing the wind speed from 3 m/s to 5 m/s just changed the panel temperature by 5°C.

6- The maximum average daily energy loss of 5% due to the insulation showed that using the insulation for a PV system in a region with the energy loss of 5% or more due to snow can be useful. However, the effectiveness of the snow removal method and additional cost for mounting the system should also be considered.

**Acknowledgements**

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Abstract

Increased concern related to the climate change is driving the development and implementation of green sources of energy including photovoltaic-thermal (PV/T) systems. This PV/T technology potentially increases the PV cell performance by decreasing the panel temperature, and using the extracted heat to warm up a fluid (usually air or water). The continuous decline of the cost of PV/T panels has increased the number of systems installed around the world including regions with cold climates and significant annual snowfall. A key challenge, however, is dealing with the effects of snow and ice buildup on the panel surfaces. In this paper, a method is proposed to remove snow from PV/T panels by circulating hot fluid through the back of the panel. To evaluate the method, outdoor tests were conducted under natural conditions. Two PV/T panels were installed adjacent to each other at a tilt angle of 45 degree to the horizontal. These PV/T panels were not initially insulated on their back surfaces. Therefore, to accurately measure the heat flux required for melting snow, one of the panels was insulated from the back and the other one was left uninsulated to serve as the reference panel. The insulated panel was connected to a heat exchanger and was heated after each snowfall event by circulating hot fluid through its absorber plate bonded to the back surface. The reference panel remained uninsulated and empty, with no fluid circulation. The surface temperature of each panel was measured during the snow removal process. Solar radiation, ambient temperature, and wind speed were also measured during each test. Comparing the results for the insulated and uninsulated panels showed that this method can clean the panels in a short period of time. The
results of this study were also compared with the results given by a numerical model presented in the literature for snow removal from PV panels using a thermal method. In addition, an improved configuration for the back absorber plate of a PV/T panel was proposed to enhance the snow removal process. Finally, a non-dimensional number was also defined to show the ratio of the energy consumption for snow removal to the energy produced by the panel after the snow removal based on the daily panel production.

Keywords: Photovoltaic-Thermal panel, Snow melting, Snow sliding, Heat flux

6.1 Introduction

Solar energy is the most widely available source of “green” energy (Tse et al., 2016). Solar thermal and photovoltaic systems are the most well-known technologies among all solar technologies developed during the last decades (Daghigh et al., 2011; Hamid et al., 2014; Hasan and Sumathy, 2010; Lee and Tong, 2012; Mojumder et al., 2017; Parida et al., 2011; Skoplaki and Palyvos, 2009; Society, 2005). Recently, hybrid photovoltaic/thermal (PV/T) technology has received more attention due to its high thermal and electrical performances. This technology potentially increases the PV cell performance by decreasing the panel temperature and uses the extracted heat to warm up a fluid (usually air or water) (Florschuetz, 1979; Wolf, 1976).

PV/T collectors produce more energy per unit surface area than side-by-side PV modules and solar thermal collectors (Tabook et al., 2014). Thus, PV/T systems are appropriate for applications with limited available surface area. For instance, PV/T panels have been integrated into building design with novel control methods to cut off the high-level use of fossil fuels by buildings (He et al., 2014; Zeng et al., 2015). Various researchers have summarized the PV/T technology development history for different applications (Chow, 2010; Hasan and Sumathy, 2010; Kumar et al., 2015; Society et al., 1997; Zhang et al., 2012).
Due to the continuous decline of the cost of solar systems, PV and PV/T systems have received more attention across the world, including those countries with cold climates and significant annual snowfall such as Canada, Germany, Japan, etc (Branker et al., 2011). As such, in 2009 nearly three-quarters of photovoltaic resources (PV or PV/T) were installed in countries that experience some amounts of snowfall (Prices, 2010).

A major issue for using PV and PV/T systems in snowy climates is the effect of snow on energy production of the system. If the panel is covered by snow, long shut-down periods may occur while waiting for mild weather. Although there is no research study about the snow effect on PV/T module performance, there are several studies in the literature regarding energy loss due to the snow for PV systems.

Townsend and Powers, (2011) studied the effect of snow on a PV system performance located in Truckee, California with an average 5 m (200 in) of snow per year. The recorded monthly snow losses ranged up to 80%, 90% and 100% of expected yields for 39°, 24°, and 0° tilt angles respectively. In addition, on an annual basis, losses were found to be 13%, 17%, and 26% for a low profile system of 39°, 24°, and 0° tilt angles respectively. Other researchers measured monthly energy losses as high as 90% and annual losses from 1% to 12% for Colorado and Wisconsin (USA), the New Munich Trade Fair Centre in Germany, and Kingston, Ontario, Canada locations (Andrews et al., 2013b; Becker et al., 2008; Heidari et al., 2015; Marion et al., 2013, 2005).

These studies reveal the impact of energy losses due to snow on PV systems. In terms of PV/T systems, if the panel is covered by snow, both electrical and thermal productions of the panel will be affected. Based on these studies, it is reasonable to assume that the snow effect on the electrical energy production of PV/T systems will be as significant as for PV systems. It is also important to note that in the case of PV panel, even partial snow cover of the panel can stop all
electrical production of the system; while for a thermal solar panel (or PV/T panel), heat production may still be possible at a reduced rate.

Thermal snow removal systems for PV panels have been discussed in the literature (e.g. Weiss and Weiss, 2016). Based on those studies, the authors present the idea of circulating hot air or water through a PV/T panel to trigger the snow shedding process from the panel. Some PV/T manufactures have also claimed that circulating hot water through the panel can melt snow and result in higher performance in snowy climates (Dean et al., 2015); however, they did not provide any scientific proof for their claim.

The PV/T panel design can also alter the snow effect on the system performance. Some PV/T panels are insulated from the back to improve the thermal efficiency of the panels which can expedite the snow melting on the panel as well. On the other hand, some other PV/T panels are designed to perform without any insulation on the back of the panel which can increase energy consumption for snow removal from that panel. In addition, if the insulated PV/T panels were chosen for snowy climates, higher panel temperatures could be experienced during summer periods that could negatively affect the electrical performance of the panel.

Various studies have examined the effect of insulation on PV/T panel performance (Mohammed et al., 2013; Tripanagnostopoulos et al., 2002). The results were not consistent between these studies and depended on the experimental situations and the PV/T panel design used for the study. Some studies reported a 2 to 3% reduction of electrical performance (Tripanagnostopoulos et al., 2002) due to insulating the panel; while another study showed 6 to 7% increase for the thermal performance of the panel with no significant effect on the electrical performance after insulating the panel (Mohammed et al., 2013).

As a result, this paper presents the results of an experimental study focused on deicing of a PV/T panel by circulating hot working fluid through the back of an insulated panel. In particular, the snow melting mechanisms were investigated to quantify how much energy the proposed
method requires to remove snow from a panel. The experiments were conducted outdoors under natural weather conditions. Specially prepared and instrumented PV/T modules were mounted at a 45 degree tilt angle. An unheated and uninsulated PV/T panel was used as a baseline sample. In addition, the effect of meteorological factors on snow removal, e.g., solar radiation, ambient temperature, wind speed, etc. were measured. The surface temperature of the panels was compared during the melting process. The experimental results are also compared with the results given by a numerical prediction model for snow removal from PV panels presented in the literature.

6.2 Methodology

Two PV/T panels were installed next to each other at the tilt angle of 45 degree to the horizontal. The panel characteristics are listed in Table 6.1. The PV/T panels were not originally insulated on the back. Therefore, to measure the heat flux required for melting snow accurately, one of the panels was insulated from the back using Polyisocyanurate foam insulation board with a thickness of 20 mm and RSI value of 0.99 (m²C/W). The other panel was not insulated to serve as the reference panel (Figure 6.1).

Table 6.1 The PV panel characteristics at standard test conditions (solar radiation 1000 W/m², Cell Temperature 25°C)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Monocrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (P₀)</td>
<td>270 W</td>
</tr>
<tr>
<td>Maximum Power Voltage (Vₘₐₙ)</td>
<td>31.8 V</td>
</tr>
<tr>
<td>Maximum Power Current (Iₘₐₙ)</td>
<td>8.5 A</td>
</tr>
<tr>
<td>Open Circuit Voltage (Vₒc)</td>
<td>39.1 V</td>
</tr>
<tr>
<td>Short Circuit Current (Iₒc)</td>
<td>9 A</td>
</tr>
<tr>
<td>Maximum operation pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Stagnation temperature</td>
<td>74.7°C</td>
</tr>
<tr>
<td>Volume of heat transfer fluid</td>
<td>1.7 L</td>
</tr>
<tr>
<td>Dimensions</td>
<td>167.7×99×4 cm</td>
</tr>
</tbody>
</table>
6.2.1 Measurement facilities and instrumentation

The instrumentation used for this study is listed in Table 6.2. A 50-50% mixture of ethylene-glycol and water (with the freezing point of approximately -20°C) was pumped to the panel using a 27 Watt circulation pump. This mixture was used to avoid freezing the working fluid inside the panel during the night. The reference panel remained uninsulated and empty, with no fluid circulation. The working fluid in the panel was heated by passing it through a counter-flow heat exchanger. The other pass of the heat exchanger was connected to a hot water boiler providing a constant temperature, hot water supply (Figure 6.2). The experimental apparatus was installed on a roof top at Queen’s University (Kingston Ontario, CA).

![Image](image.png)

**Figure 6.1** The panel with hot fluid circulation on the back was insulated using Polyisocyanurate foam insulation board with a thickness of 20 mm and RSI value of 0.99 (m²C/W), and the reference panel was uninsulated. Three thermocouples (type T) were located on the front surface and one thermocouple attached on the back of each panel.

To measure the panel temperature, three type T thermocouples were placed on the front surface of each panel. One thermocouple was also attached to the back of the panels (Figure
The input and output temperatures of the working fluid were also measured using two type T thermocouples mounted inside the piping system. The thermocouples were calibrated using a reference temperature bath in the range of -15 to 40°C. A national instrument SCXI 1303 data logger was used along with LabView monitoring system to record the data at 0.25 Hz. The snow density was also calculated by measuring the weight and volume of a sample snowpack.

Table 6.2 The measurement facilities used in this study

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Manufacturer</th>
<th>model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>OMEGA Co.</td>
<td>Type T</td>
<td>0.5 mm diameter Copper/Constantan type T thermocouples were used.</td>
</tr>
<tr>
<td>Weather station, (wind speed, ambient temperature, and pressure)</td>
<td>ACURITE weather station</td>
<td>WS600</td>
<td>Included a wind sensor for wind speed and direction measurement as well as instruments for barometer measurements.</td>
</tr>
<tr>
<td>Global solar radiation at 45° tilt</td>
<td>Kipp &amp; Zonen</td>
<td>CMP21</td>
<td>It was mounted on the plane of the panels at 45° tilt angle (located mid height) to measure incoming global solar radiation with a 180° field of view.</td>
</tr>
<tr>
<td>National instrument data logger</td>
<td>National instrument</td>
<td>SCXI 1303</td>
<td>It was used to record the measurements and read signals from the other instruments. The DAQ recorded data at 0.25Hz.</td>
</tr>
<tr>
<td>I-V and Power-V curves</td>
<td>Solmetric PV analyzer</td>
<td>PVA-600</td>
<td>Provided I-V traces at specific intervals.</td>
</tr>
</tbody>
</table>

A Kipp and Zenon SMP21 Pyranometer was used to record solar radiation during the experiments. An ACURITE weather station was also utilized to record the ambient temperature and the wind speed.
6.2.2 Experiment procedure

After each snowfall event, an experiment was conducted. Before starting the system, the snow thickness on each panel was measured, as well as, the snow density. In addition, the boiler was started before the test to store hot water in an insulated storage tank at a specific temperature. It provided a constant temperature hot water supply for the duration of the experiment.

Once the hot water supply reached 30°C, the pump which was controlling the PV/T heating cycle was started to heat the panel. The subsequent snow removal process was recorded using both temperature measurements and video recordings. Pictures of the panels were taken at regular intervals depending on the experiment situation. The panel temperatures, solar radiation, ambient temperature and wind speed were also measured. The panel was heated until 90% of the panel surface was free of snow-cover, e.g., the very top and bottom of the panel was excluded. It is worth noting that the absorber plate did not cover precisely 100% of the panel back surface. The impact of this are described in the following section. A schematic of the experimental setup is shown in Figure 6.2, and the instruments used to heat the panel are shown in Figure 6.3.

![Figure 6.2 Schematic of the experiment’s setup and apparatus used in this study. The panel on the right was not connected to the loop to serve as a reference panel.](image-url)
6.3 Results and discussion

Figure 6.4 shows the snow removal process for one of the experiments. In the case shown, 90% of the panel surface area was cleaned after 16 minutes. It was observed that most of the snow cover was melted; however part of the snow cover slid off from the upper part to the lower part of the panel, and it was stopped there by the bottom edge of the frame. The obstacle effect of the frame was also observed in another study (Weiss and Weiss, 2016). In addition, since the snow cover thickness was less than three centimeters for all the tests (Table 6.3), it is expected that if the snow cover was thicker, it would be more likely that the snow cover weight would overcome the frame effect and slide off the panel.
Table 6.3 Listing of the snow removal experiments conducted during this study and a summary of the test conditions and results ($q_f$ is the fluid heat flux to the panel and RTS is the required time for snow removal)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>Snow density (kg/m$^3$)</th>
<th>Snow thickness (cm)</th>
<th>$T_{amb}$ (°C)</th>
<th>Wind speed (m/s)</th>
<th>Relative humidity (%)</th>
<th>$q_{sun}$ (W/m$^2$)</th>
<th>$q_f$ (W/m$^2$)</th>
<th>RTS (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13/01/2018</td>
<td>N/A</td>
<td>2</td>
<td>-9</td>
<td>0.83</td>
<td>52</td>
<td>630</td>
<td>660</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>30/01/2018</td>
<td>103</td>
<td>2</td>
<td>-8</td>
<td>2.5</td>
<td>66</td>
<td>229</td>
<td>1020</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>07/02/2018</td>
<td>157</td>
<td>1.8</td>
<td>-5</td>
<td>2.77</td>
<td>88</td>
<td>119</td>
<td>864</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>07/02/2018</td>
<td>157</td>
<td>1</td>
<td>-6</td>
<td>2.22</td>
<td>81</td>
<td>60</td>
<td>926</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>10/02/2018</td>
<td>158</td>
<td>1.5</td>
<td>-4</td>
<td>2.22</td>
<td>90</td>
<td>22</td>
<td>902</td>
<td>14</td>
</tr>
</tbody>
</table>

As mentioned, only 90% of the panel was clean shortly after heating the panel; while the other 10% of the panel surface was covered by snow for a longer period of time (even sometimes for a full day). Figure 6.5 shows that the hot water piping on the back of the PV/T panel only covered 90% of the panel area allowing the spots at the upper and lower parts of the panel to be covered by snow for a longer time.

The working fluid entered the panel from the bottom to heat the bottom part of the panel more quickly as it may impede the snow shedding from the panel. In test cases shown in Table 6.3, however, the snow sliding did not occur, and the snow cover was melted. In case of snow melting, entering fluid from the top or bottom may not affect the time and energy required for snow removal from the panel.

Attempts were made to clean the upper and lower parts of the panel by heating the panel for more extended periods of time; however, it was not successful due to the relatively low thermal conductivity of the PV panel in the transverse direction. It shows that as expected the relatively low thermal conductivity of the glass cover of the panel was not sufficient to conduct heat from the heated part of the panel to the lower and upper parts of the panel. Another study reported a
similar result regarding the low thermal conductivity of the glass for the PV panels (Rahmatmand et al. 2018). In addition, as it can be seen in Figure 6.5, the aluminum plate of the absorber plate is extended to the upper and lower regions, but its heat transfer was not sufficient to melt the snow cover above these regions. As a result, it was noted that once the section of the panel which was heated directly by the absorber plate on the back was clean, it would not be economical to heat the panel longer.

Figure 6.4 Photos of snow melting sequence, shown as a duration of time through the heating process. The PV panel shown on the right was heated by circulating hot fluid through the back of the panel. The adjacent panel was the unheated reference panel. The conditions for this test (No. 3) were: test date=07/02/2018, panel tilt angle= 45°, ambient temperature= -5°C, relative humidity= 88%, averaged solar radiation= 119 W/m², snow density= 157 kg/m³, Initial snow cover thickness= 1.8 cm and wind speed=2.77m/s.
6.3.1 Heat sources

There were three main sources of heat in our experiments: the incident solar radiation, the radiation with the sky and the hot fluid circulation through the back of the panel. To calculate the heat flux from the fluid to the panel the following equation was used:

\[
q = \dot{m} \times c_p \times \left( T'_\text{inlet} - T'_{\text{transition-time outlet}} \right)
\]

(6.1)

where \( \dot{m} \) is the working fluid mass flow rate (kg/s), and \( T'_\text{inlet} \) and \( T'_{\text{outlet}} \) are the fluid temperatures entering and exiting the panel.

Figure 6.5 The area covered by the absorber plate on the back of the panel. The heated area affects the snow melting on the front surface of the panel. The fluid is only circulated through the region shown inside the rectangular shape. The aluminum plate of the absorber plate is extended to the upper and lower regions, but its heat transfer is not sufficient to melt the snow above these regions.
Since the heating process of the panel was transient and the inlet and outlet temperatures of the fluid entering and exiting the panel were changing during the experiment (Figure 6.6), a Lagrangian method was used to find the difference between the inlet and outlet temperatures of the fluid. Using the fluid flow rate, \( \dot{m} \), passing through the panel, the Transition Time was calculated. The Transition Time is the time difference between the fluid entering the panel and exiting. The temperature difference was calculated as the difference between the fluid inlet temperature at a specific time and the outlet temperature at a Transition Time later. The average heat flux during each test is estimated by using Eq. 6.1 (Table 6.3). Figure 6.6 shows the inlet and outlet temperatures of the working fluid for one of the experiments.

![Figure 6.6](image)

**Figure 6.6** The inlet and outlet temperature of the fluid entering and exiting the panel for test No. 2: test date=30/01/2018, panel tilt angle= 45 degree, ambient temperature= -8°C, relative humidity= 66%, averaged solar radiation= 229 W/m², snow density= 103 kg/m³, initial snow cover thickness= 2 cm and wind speed=2.5m/s.
Figure 6.7 shows the solar radiation during one of the experiments. The solar radiation was averaged during the snow removal period which was usually much less than the panel heat flux. The average solar radiation heat fluxes and the fluid heat flux are listed in Table 6.3 for each experiment.

The radiation between the sky and the snow cover on the panel was calculated based on the estimated sky temperature and the snow cover temperature (Duffie and Beckman, 2013). This heat source was considered in the numerical simulation in section 6.3.3.

Figure 6.7 The solar radiation distribution during test No. 2: test date=30/01/2018, panel tilt angle= 45 degree, ambient temperature= -8°C, relative humidity= 66%, averaged solar radiation= 229 W/m², snow density= 103 kg/m³, initial snow cover thickness= 2 cm and wind speed=2.5m/s.
6.3.2 Snow removal time

Table 6.3 presents the experimental results of the conducted experiments. It can be seen that the heated panel was clean after 16 minutes for all of the experiments with the fluid heat flux of approximately 900 W/m²; while it was observed that the unheated panel was covered by snow the entire day.

Figure 6.8 compares the temperature distributions of the heated panel and the reference panel for one of the experiments. During the melting process, the temperature of each panel section (top, center, and bottom) remained constant approximately around the melting point of snow (0°C) until the snow layer melted or slid off that section of the panel. Figure 6.8 shows that the panel temperature at the lower half, T3, was close to the melting point of snow longer than the upper half of the panel, T1, i.e., the upper half of the panel was clean while the lower half is still covered by snow.

The upper part of the panel was clean more quickly than the lower part as the snow cover was observed to slide down from the upper part to the lower part of the panel. In most cases, the snow sliding was stopped by the bottom edge of the panel frame. This is consistent with the finding of Weiss and Weiss, (2016). They observed that the bottom edge of the frame was one of the reasons which prevented the snow cover from sliding down the panel completely.

In addition, as shown in Figure 6.5, the piping system on the back of the panel did not cover the very top and bottom of the panel. As a result, the unheated snow cover at the very bottom of the panel can be another reason for preventing the snow cover from sliding off the panel completely. To address this issue, it is recommended that panel manufacturers modify their design to ensure they heat all of the panel area, especially at the very bottom of the panel.
Figure 6.8 Comparing the surface temperature of the heated panel and reference panel at different locations
6.3.3 Numerical modelling

A numerical model was proposed by Rahmatmand et al. (2018) (see Chapter 3) to predict the snow removal from photovoltaic solar panels using the heating method. The model predicts the time required for snow removal from a panel based on the incident solar radiation, an external heat flux (e.g., circulating hot fluid to the back of the panel in this study), and the weather conditions as inputs. The model considers the snow-cover on a panel as a combination of a slush layer and a dry snow layer on the top. During the heating process, part of the meltwater (water) is wicked by the dry snow and a slush layer forms. The dry snow layer thickness decreases until all of the snow cover on the panel is a slush layer. The total time for removing the dry and slush layers from the panel is calculated as the required time for snow removal. The model is described briefly below. The details of the model are presented by Rahmatmand et al., (2018).

6.3.3.1 Inputs for the numerical model

For each test, the weather conditions presented in Table 6.3 were used as model inputs for initial snow cover thickness and density, ambient temperature, relative humidity, incident solar radiation and external heat flux due to hot fluid circulation through the back of the panel. Three main heat sources (i.e., incident solar radiation, external heat source and radiation with the sky) were considered in the model as follows:

1) External heat source: as mentioned, since the model needs a heat flux rate as the external heat source, the averaged heat flux from the hot fluid to the panel calculated in section 6.3.1 was used in the numerical model;

2) Incident solar radiation: the averaged incident solar radiation during each test was used as the solar heating source;

3) Radiation with the sky: the model calculates the sky temperature using the relative humidity and ambient temperature and then using the calculated snow-cover temperature and sky temperature, the radiation exchange with the sky will be computed.
6.3.3.2 Comparing the numerical data with the experimental results

Table 6.4 compares the predicted snow removal time by using the numerical method with the measured snow removal times during the experiments. The predicted snow removal times are in good agreement with the experimental time. The slight difference (between 8 to 9%) for some of the cases resulted from partial snow sliding from the panel for those tests. This was not considered in the numerical method. As mentioned, although the bottom frame of the panel impeded the snow cover from sliding off the panel completely, it was observed that for some tests, part of the snow cover slid off the panel and then stopped sliding until it was melted. Since the amount of snow cover sliding off the panel was negligible compared to the total snow cover amount, snow sliding was not considered in the numerical prediction.

Table 6.4 Comparing the predicted required time for snow removal (RTS) predicted by the model presented by Rahmatmand et al. (2018) (Chapter 3) with the measured time during the tests in this study

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>Snow density (kg/m³)</th>
<th>Snow thickness (cm)</th>
<th>T_{amb} (°C)</th>
<th>q_{sun} (W/m²)</th>
<th>q_{f} (W/m²)</th>
<th>Measured RTS (min)</th>
<th>Predicted RTS (min)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>30/01/2018</td>
<td>103</td>
<td>2</td>
<td>-8</td>
<td>229</td>
<td>1006</td>
<td>10</td>
<td>10.9</td>
<td>9%</td>
</tr>
<tr>
<td>3</td>
<td>07/02/2018</td>
<td>157</td>
<td>1.8</td>
<td>-5</td>
<td>119</td>
<td>1025</td>
<td>16</td>
<td>17.3</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>(11:50AM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>07/02/2018</td>
<td>157</td>
<td>1</td>
<td>-6</td>
<td>60</td>
<td>1070</td>
<td>10</td>
<td>10.1</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>(4:30 PM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10/02/2018</td>
<td>158</td>
<td>1.5</td>
<td>-4</td>
<td>22</td>
<td>1037</td>
<td>14</td>
<td>13.3</td>
<td>5%</td>
</tr>
</tbody>
</table>

To further estimate the effect of a range of environmental conditions which did not happen during the experiments, the numerical model was used to calculate the snow removal time for some combinations of input variables (environmental conditions). The range of -20-0°C was considered for ambient temperature ($T_{amb}$). The snow density ($\rho$) was changed between 50 to 300 kg/m³. The snow cover height ($H_s$) variation was 1 to 10 cm. The solar radiation ($q_{sun}$) and hot
fluid heat flux \((q_f)\) were changed between 0-700 W/m\(^2\) and 500-1200 W/m\(^2\) respectively. To account for the effect of all input variables on the required time for snow removal (RTS), the variable of \(R_t\) was defined which has the dimension of time.

\[
R_t = \frac{\rho H_s C_p T_{amb}}{(q_{solar} + q_f)}
\]  

(6.2)

where \(R_t\) represents all of the input variables for the numerical model: snow density \((\rho)\), snow cover height \((H_s)\), ambient temperature \((T_{amb})\), solar radiation \((q_{solar})\) and hot fluid heat flux \((q_f)\). As the numerator of eq. (6.2) has the dimension of kJ, and the denominator has the dimension of W, \(R_t\) will have the dimension of time. As a result, \(R_t\) represents the time required for solar radiation \((q_{solar})\) and the hot fluid heat flux \((q_f)\) to increase the snow cover temperature to 0°C assuming that the snow cover is initially in equilibrium condition with the ambient.

Figure 6.9 shows the relation between \(R_t\) and RTS for different environmental conditions mentioned above if the entire snow layer covering the panel is melted. Increasing \(R_t\) (including the increase of snow density, snow cover height and lower ambient temperature) increases the RTS. On the other hand, as expected, increasing the magnitude of the heat sources (lower \(R_t\) value) decreases RTS. A linear fitting to the data is also presented in Figure 6.9 providing an equation for quick estimation of the required energy and time for melting snow on a panel based on the environmental conditions.
To decide whether the snow removal method is beneficial for the system, the energy production of the panel after removing snow should be compared with the energy required for cleaning the panel. The energy production after the snow removal process depends on the time in which snow removal from the panel occurred. For instance, if there was a snowfall event between the sunset and sunrise (during the evening or night) and the panel was cleaned before the sunrise in the following day, the panel would be ready to function during the entire next day. On the other hand, if the snow was shed from the panel during the daylight, the panel could only function the

Figure 6.9 The variation of $R_t$ defined in equation (6.2) versus the required time for snow removal from a panel. $R_t$ represents the effect of snow cover density and height, ambient temperature and the heat sources on the time required for snow removal (RTS) from a panel if the entire snow cover is melted. The dotted line shows the best linear fitting to all data.

6.3.4 Non-dimensional number for PV panel snow removal

To decide whether the snow removal method is beneficial for the system, the energy production of the panel after removing snow should be compared with the energy required for cleaning the panel. The energy production after the snow removal process depends on the time in which snow removal from the panel occurred. For instance, if there was a snowfall event between the sunset and sunrise (during the evening or night) and the panel was cleaned before the sunrise in the following day, the panel would be ready to function during the entire next day. On the other hand, if the snow was shed from the panel during the daylight, the panel could only function the
rest of the day after the snow removal. In both situations, without the snow removal mechanism, the panels would be covered by snow for the entire day or even a couple of days after the snowfall (Andrews et al., 2013b; Ross, 1995).

To compare the energy production of a system after the snow removal process with the energy required for cleaning the panel, the net energy production of the panel, $E_{net}$ is defined based on the time of the day snow melting was implemented. This represents the energy captured during the remaining portion of the day minus the energy expended in melting the snow-cover, i.e.,

$$E_{net} = \int_{t_{clear}}^{t_{snow}} E_{PV} dt - E_{heater}$$

(6.3)

where: $t_{clear}$ is the time of the day that snow melting is completed, $t_{snow}$ is the time of day sunset occurs and $E_{heater}$ is the energy expended for melting the snow. Assuming the day in question is clear from sunrise to sunset, then the relative benefit of completing snow melting by a certain time of day can be calculated as the fraction of the clear sky energy $E_{cs}$ that is available, accounting for the energy used for snow melting as

$$FE_{CS} = \frac{E_{net}}{E_{cs}} = \frac{\int_{t_{clear}}^{t_{snow}} E_{PV} dt - E_{heater}}{\int_{T_{sunrise}}^{T_{sunset}} E_{PV} dt}$$

(6.4)

In this case, the value of non-dimensional number of $FE_{CS}$ should be greater than 0 to justify implementing the snow melting protocol.

To estimate the time, RTS, and energy, $E_{heater}$ required for snow melting, the following equation can be used based on Figure 6.9.

$$RTS = 1.572 \times R_t$$

$$E_{heater} = RTS \times q$$

(6.5)

This correlation shows a relation between $RTS$ and $R_t$ representing the weather conditions and available heat sources for snow removal. It should be noted that this equation only assumes the snow melting (i.e., snow sliding is not considered).
6.3.4.1 Case study

$FE_{CS}$ more than 0 is the minimum condition to have an energy efficient thermal snow removal from a PV system as this number does not consider the installation cost of a thermal snow removal system, maintenance of the system, etc. To show how non-dimensional number $FE_{CS}$ can be used for a PV (or PV/T) system, a hypothetical case study has been performed for a simple roof mounted 16.3 m$^2$ PV array (i.e., 10 panels each of 1.63 m$^2$) located in Toronto, Canada at 45° tilt angle with the horizontal (considering a PV/T system instead of a simple PV system will increase the $FE_{CS}$ values as the thermal output of the panel should also be considered in estimation of the net energy production of the system). The assumptions considered for this case study are as follow.

- A roof-top PV system with a total array area of 16.3 (m$^2$) located in Toronto, Canada was considered.
- The panel characteristics were $P_m = 295$ W, $V_{mp} = 32$ V, $I_{mp} = 9.2$ A, $V_{oc} = 39.6$ V, $I_{sc} = 9.6$ A.
- The calculation was performed for several typical sunny (winter) days after a snowfall according to the typical meteorological year (TMY) weather data for Toronto, Canada.
- The snow cover thickness and density were assumed to be 3 cm and 175 kg/m$^3$ respectively. Ambient temperature was assumed to be constant -5°C during the day.
- The hourly system production was calculated based on the method explained by Gilman (2015) using the Simple Efficiency Module Model.
- It was assumed that there was no PV output before the panels were completely clear of snow.
The energy required for snow melting was calculated based on the 1000 (W/m²) heating power (the same power as the experiments), and the time required for snow melting was also estimated by using Eq. (6.5).

The total output of the system during the days considered is presented in Table 4 assuming that the system was clear of snow before sunrise.

**Table 6.5 The output of the hypothetical system assuming that the PV panels were clear of snow as calculated for four typical winter days from TMY weather data**

<table>
<thead>
<tr>
<th>Day</th>
<th>January 1st</th>
<th>February 14th</th>
<th>March 6th</th>
<th>December 3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>System output at 45° tilt angle (kWh)</td>
<td>9.8</td>
<td>15.4</td>
<td>19.8</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Figure 6.10 shows the variation of $FE_{CS}$ with the snow removal time for several typical winter days from TMY weather data for Toronto, Canada. The incident total solar radiation during these days is shown in Figure 6.10b. For the typical days shown in Figure 6.10, it can be seen that the benefit of using the snow melting mechanism was usually reduced as the snow removal occurs later in the day. Some small peaks in the graphs were caused by periods of relatively high solar radiation at that time which reduced the energy required for snow removal at that time (Eq. 6.5) and consequently increased $FE_{CS}$.

Figure 6.10 also shows that the benefit of using the melting mechanism is much more for the days at February and March (as compared to the January and December), as there is more available solar radiation to generate power because of the effect of the azimuth and zenith angles of the sun. For January and December, although it is still beneficial to use the snow removal system early in the day in terms of energy consumption, as $FE_{CS}$ does not consider the capital cost.
of implementing the snow removal system and associated cost, snow melting from the panel may not be beneficial in terms of the total cost of the system during these months.

In summary, in terms of the net energy production of the system, it can be seen that for all of the days shown in Figure 6.10, when the panels were cleaned approximately before the noon, the $FE_{CS}$ value would be higher than 0, i.e., the thermal snow removal from the panels can be beneficial.

Figure 6.11 compares the $FE_{CS}$ value for different snow cover thicknesses on January 1st. It can be seen that if the snow cover is 4 cm thick or more, the $FE_{CS}$ values would be less than 0 for the entire day. It shows that removing the snow cover from the system using the thermal method may not be economical depending on the snow-cover thickness. This situation happens for snow-cover thicker than 4 cm in January provided that the entire snow layer should be melted. It is clear that if the snow cover slid down the panel, $FE_{CS}$ would be easily more than zero. As a conclusion, the $FE_{CS}$ value depends on the system characteristic and weather conditions. It is expected with the recent advances in local weather forecasting, maximization of net PV array output accounting for snow removal energy consumption will be possible.
Variation of $FE_{CS}$ defined by equation (6.3) with the time of day snow removal is completed. For each day, it was assumed that the panels were covered by snow from the snowfall during the previous days. At each hour, the $FE_{CS}$ value was calculated provided that the sun came out on that hour (the sky was fully covered by the cloud before that hour), and the system can function during the rest of the day after removing the snow. The first data point for each day shows the $FE_{CS}$ value if the snow is removed before the sunrise. The test conditions assumed to be the ambient temperature= -5°C, snow cover thickness= 3 cm, snow cover density=175 kg/m$^3$. 

Solar radiation distribution on the 45 degree panel surface

Figure 6.10 Variation of $FE_{CS}$ defined by equation (6.3) with the time of day snow removal is completed. For each day, it was assumed that the panels were covered by snow from the snowfall during the previous days. At each hour, the $FE_{CS}$ value was calculated provided that the sun came out on that hour (the sky was fully covered by the cloud before that hour), and the system can function during the rest of the day after removing the snow. The first data point for each day shows the $FE_{CS}$ value if the snow is removed before the sunrise. The test conditions assumed to be the ambient temperature= -5°C, snow cover thickness= 3 cm, snow cover density=175 kg/m$^3$. 

Solar radiation distribution on the 45 degree panel surface
Conclusion

The rapid decline of the PV and PV/T panels cost leads to vast installation of these systems across the world including some areas with significant snowfalls. The primary issue for using PV and PV/T systems in snowy climates is the effect of snow on energy production of the systems. The snow cover on panels can cause long shut-down periods. In this study, a method was proposed for snow removal from PV/T panels by pumping hot fluid to the back of the panels. After analyzing the experimental and numerical results, it was concluded that:

1. This method can clean the panels in a short period of time depending on the available heat sources.
2. Heating a PV/T panel using circulating hot fluid through the back of the panel is a transient process, and a Lagrangian method is used to calculate the average heat flux.

Figure 6.11 Comparing the $F_{ECS}$ value for different snow cover thickness for January 1st. The test conditions assumed to be ambient temperature= -5°C and snow cover density=175 kg/m³.
3. The piping system design on the back of the panel can affect the snow removal from the panel. Since the piping system on the back of the panel did not cover the very top and bottom of the panel, it took much longer time to clean those sections of the panel compared to the center of the panel.

4. Due to the relatively low thermal conductivity of PV cell encapsulated and the glass cover of the panel, the PV panel cannot rapidly conduct heat from the heated section of the panel to the unheated sections of the panel which are not exposed to the absorber plate with hot fluid from the back directly.

5. A non-dimensional number ($FE_{cs}$) is defined to represent the ratio of panel net energy production during a day after the snow removal to the maximum panel production during the day. If $FE_{cs}$ is greater than zero, it shows that the snow removal mechanism can be economical.

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Chapter 7

Conclusions and Further work

In the previous chapters, a detailed discussion of the proposed thermal methods for snow removal from PV panels and a numerical model to predict the snow removal process was carried out. Here, we summarize the most important findings. This will be followed by ideas for possible extensions to improve the outcomes of this thesis.

7.1 Important findings of this study

The solar photovoltaic market is rapidly expanding as costs decrease, driven by the decreasing capital and operating costs of these systems. This market expansion includes regions with significant annual snowfall. A key challenge to the wide-scale implementation of solar photovoltaics in cold climates like Canada is dealing with the effects of snow and ice buildup on the panel surfaces. PV panel output depends on ensuring that obstructions such as snow and ice do not shade solar panel surfaces. In most cases, even partial panel coverage will significantly reduce or stop electrical production. Although several experimental and numerical studies have been performed to study the effect of snow on annual and monthly PV systems performance, there currently is no practical mechanism to remove snow-cover from PV surfaces. A few research studies regarding snow removal methods for PV systems (including surface coating (Andrews, 2015) and passive heating (Ross, 1995)) provided valuable information, but they did not present practical solutions. As mechanical removal of snow from PV arrays has also been rejected by plant operators due to the fragile nature of the glass panels, active heating of the panels can be a promising solution. The objective of this thesis was to present methodologies and tools to model an active thermal snow removal mechanism for PV panels which will allow further expansion of the PV market in regions experiencing noticeable annual snowfall.
Considering an active thermal snow removal mechanism for PV panels, Chapter 3 presented a numerical model for predicting thermal snow removal from a PV panel using the experimental data of snow sliding from a small scale PV panel. This model can predict snow sliding or snow melting on horizontal or tilted panels, as the previous models presented in the literature cannot predict the snow sliding from a tilted panel. The model was validated against available experimental data. The model relies on the use of improved definitions of the boundary conditions and improved models of heat and mass transfer in the snow and slush layers. In terms of tilted panels, the meltwater drainage rate from a tilted panel was predicted by treating the snow cover as a porous media and using the governing equation for porous media, i.e., Darcy's law. In addition, an empirical correlation was proposed for calculating the required energy and time for snow sliding from tilted panels based on the conducted experiments. This model can provide valuable information for a PV system owner/operator to decide whether or not active thermal snow removal mechanism is beneficial for the system, before implementing the mechanism to the system.

To validate the numerical model and examine a real prototype of the proposed thermal snow removal system, outdoor tests were conducted with full-scale PV panels under natural conditions and the results were described in Chapter 4. Specially prepared and instrumented PV modules were mounted at various tilt angles. Two heating methods were investigated: 1) electrical heating by a resistance thin film heater installed on the back of the PV panel, and 2) electrical heating due to the application of reverse current through the PV cells. The results of these investigations presented in Chapter 4 showed that heating a PV panel, especially through imposing reverse current through the panel, can effectively remove snow. However, the same issue of the small-scale model was observed for the full-scale panels. The meltwater freezing on the frame was the primary factor for stopping the snow cover from sliding off the PV panels. It caused the formation of an ice dam and icicles as well as ice bridge on top of the panel. This resulted in a
local increase in panel temperature below the ice dam. This is of concern as higher temperature gradients may induce thermal stresses that may result in panel or heater failure over time. As a result, using the frameless panel was recommended for snowy climates.

The thermal snow removal method proposed in Chapter 4 had an insulation on the back of the panel improving the performance of the heating process. However, insulating the panel can reduce the panel performance during the summer, and seasonal insulation for the panels is not economical. As a result, Chapter 5 presented the effect of mounting insulation on the back of a PV panel during the summer. To minimize the negative effect of back insulation (i.e., that increases the panel temperature) a special vented cooling channel was proposed and evaluated. The vent would close in winter periods but open in the summer thereby limiting the PV panel temperature during a regular sunny day by taking advantage of improved natural convection and radiation heat transfer from the panel. The proposed insulation had two vents at the very top and bottom of the panel and was painted black on the side facing the panel. In the summer, natural convection through the vents and radiation heat transfer between the panel and the insulation help to control the panel temperature. Conversely, during the winter, closing the vents maximizes the effect of the snow removal system. The effect of solar radiation and vent configurations on the panel output were studied experimentally, while the effect of wind speed, panel tilt angle and the surface emissivity of the insulation surface on the panel temperature were studied numerically. The results showed that using this method could control the panel temperature in a way that the maximum power loss at noon, with the highest solar radiation, was less than 5% while it was double for an insulated panel without any vents and modifications.

In addition, the numerical simulations showed a noticeable effect on panel temperature by changing the wind speed around the panel. Changing the wind speed from 1 m/s to 3 m/s decreased the panel temperature by approximately 10°C. The effects of changing the panel tilt angle and the black coating of the insulation on the panel temperature were less than 3°C.
After proposing a proper snow removal mechanism for photovoltaic panels, another thermal snow removal method was examined for removing snow from photovoltaic-thermal panels presented in Chapter 6. These types of panel (PV/T) have the ability to circulate a fluid through the back of the panel which can be used to remove snow from the panel as compared to the electrical heating for PV panels proposed in Chapter 4. A set of outdoor experiments was conducted using specially instrumented PV/T panels mounted at 45 degree tilt angle. When the panel was covered by snow, hot fluid was circulated through the back of the panel to melt the snow cover. The required time and energy for snow removal were recorded as well as other environmental factors: incident solar radiation, wind speed, relative humidity and ambient temperature. The experimental results showed that this method can clean a panel in a short period of time. It was observed that as the piping system on the back of the panel did not cover the very top and bottom of the panel, it took much longer time to clean those sections of the panel compared to the center of the panel. As a result, for using PV/T panels in snowy climate regions, it was recommended to the manufacturer to modify the piping system on the back of a PV/T panel in a way that it covers more surfaces area of the panel surface.

In addition, to compare the required energy for snow removal from a panel with the output of the panel after cleaning the panel, a non-dimensional number, $FE_{CS}$, was defined. $FE_{CS}$ is the ratio of the net energy production of the panel after the snow removal to the potential energy output of a clean panel (without the snow cover) during a day. A case study was performed for a roof-top system installed in Toronto, Canada, and it was shown that depending on the environmental conditions, snow removal from a PV system could be beneficial for the system in terms of net energy.
7.2 Future work

This thesis has demonstrated new methods of modeling, analyzing and optimizing possible thermal snow removal mechanism for PV systems. There are multiple extensions to this work which can increase its accuracy and applicability to the broader PV community.

7.2.1 Standard tests for imposing current through a panel

One of the main concerns of the PV manufacturers is the long-term effect of thermal snow removal mechanism on PV panels. Some standard tests like Hot-spot endurance test and Thermal cycling (CEI/IEC 1215, 2005) can examine the endurance of a PV panel under imposed reverse current through the shaded cells or repeated changes of temperature; however, they cannot adequately represent the effect of a thermal snow removal mechanism on a PV panel. There are routine tests for certification of PV panels.

Hot-spot endurance test determines the ability of the module to withstand hot-spot heating effect, e.g., solder melting or deterioration of the encapsulation. This defect could be provoked by cracked or mismatched cells, interconnect failures, partial shadowing or soiling (CEI/IEC 1215, 2005). In this test, the module will be exposed to a certain radiant source and then one or a couple of cells will be shadowed, and the dissipated heat and panel temperature will be monitored. Also, the mechanism of heating the cell is similar to the reversing current through the cell, it is not precisely the thermal snow removal method. As a result, investigating new tests to examine the endurance of a module under imposing reverse current directly can enable the PV manufacturer to be aware of the effect of the proposed mechanism for snow removal on the panel’s warranty.

In addition, the thermal cycling test determines the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperature (CEI/IEC 1215, 2005). In this test, the module will be located in a chamber, and it will be subject to cycling
between several module temperatures. Again, although this test can examine the endurance of a panel for rapid change of the panel temperature, some additions or modifications regarding thermal cycling induced by snow removal mechanism may be required to ensure the manufacturers about the long-term effect of the proposed method.

7.2.2 Panel frame design

In this study, it has been shown that imposing the reverse current through PV cells can provide enough energy for snow removal from PV panels if the panel frame is designed in a way that it does not impede the snow shedding. However, the frame of the panel will also influence the endurance of the panel against the thermal stresses. As a result, more experimental studies under different natural conditions with framed and frameless panels are recommended to study the frame effect on the panel performance and life-cycle.

These investigations require a large number of facilities and instrumenting, but will be valuable to determine the long-term and short-term effects of the proposed snow removal method, and will be a useful tool to encourage module manufacturers to consider adding this snow removal system to their products being used in cold climate regions.

7.2.3 Snow removal research network

Overall, this study has shown that snow shedding from a PV panel depends on multiple variables, not all of which were controlled in this study. This thesis also presented a broadly applicable methodology for assessing thermal snow removal from distributed PV systems. However, these investigations were limited due to the relatively small geographic scope of the collected data. It is recommended to collect more information from a variety of climates and years, as well as, more controlled laboratory experiments, in order to derive statistically significant correlations for the creation of a robust thermal snow removal model. A snow removal research network has been proposed to facilitate the capture of this additional data.
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180


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Appendix A

Calibration of Sensors and Uncertainty Analysis
To increase the accuracy of experimental measurements, key instrumentation was calibrated by comparison with available reference instruments or by comparison against fundamental measurements. In particular, the thermocouples used to measure panel temperature and input and output fluid temperatures to the PV/T panel and the flowmeter used in the PV/T panel loop were calibrated as described below.

A.1 Calibration of Flowmeter

A liquid turbine flowmeter (model FT-4 8NEXW) was used to determine the mass flow rate through the PV/T panel to calculate the heat transfer rate from the fluid to the panel. In a turbine flow meter, fluid entering the meter first passes through an inlet flow straightener that reduces its turbulent flow pattern. Fluid then passes through the turbine, causing the turbine to rotate at a speed proportional to fluid velocity. As each turbine blade passes through the magnetic field generated by the meter's magnetic pick-up, an AC voltage pulse is generated. These pulses provide an output frequency that is proportional to volumetric flow. An OMEGA flow signal conditioner (model FLSC-45) was used to translate output frequency to an analog output. LabVIEW, ver. 7, was used to capture and display measured flow rates in real time. The unit's original calibration was based on water rather than propylene glycol so it was calibrated by direct comparison with gravimetric flow rate measurements covering the range of flow rates used for the experimental investigation (Cruickshank, 2009).

To conduct the calibration, the flow from the PV/T panel loop was directed into a reservoir such that the flow could be diverted into a measurement beaker. The average flow rate was determined by measuring the time interval required to accumulate a fixed volume of fluid. This procedure was repeated for flow rates ranging from 0.5 to 3 L per minute and the standard error associated with each sequence of flow measurements was determined.

Figure A.1 shows the results of the calibration. The error bars shown in Figure A.1 are representative of the error associated with the measurement of the flow meter using the sensor.
The magnitude of the error bars was determined based on the one standard deviation of the reading of the flow meter for 5 minutes with 0.25Hz. A linear regression analysis performed on the data shows that the instrument’s original calibration was approximately 3% lower when compared to the gravimetric measurements performed on the propylene glycol-water mixture. The bias error for the measurements was assumed equal to zero (i.e., the regression curve was assumed to go through 0). A residual plot of the errors is shown in Figure A..2. The dashed lines mark the 95% confidence interval (i.e., 20 to 1 odds or 2STD). Based on this analysis, it was assumed that the flow rate could be determined to within ±0.185 (L/min). Consequently, a value of ±0.185 L/min was chosen as the uncertainty associated with the flow measurements (see Section A.3).

![Figure A. 1 Measured flow rates using the turbine flow meter against the gravimetric flow rates. The dotted line is a linear regression analysis with the assumption of zero bias error (going through the 0).](image)

$y = 0.968x$
$R^2 = 0.9645$
A.2 Calibration of thermocouples

Temperature measurements were made with Type T thermocouples and recorded on the computer-based data acquisition system. A national instrument SCXI 1303 data logger was used along with LabView monitoring system to record the data at 0.25 Hz.

To assess the accuracy and precision of the thermocouple temperature measurements, all thermocouples used for measuring panel surface temperature and the inlet and outlet temperature measurement of the working fluid of the PV/T panel were calibrated by comparison against a precision reference thermometer (PRT). The Guideline thermometer was independently calibrated to an accuracy of ±0.012°C for 95% confidence interval (Guideline Certificate of Calibration, 2007). For the calibration, each thermocouple was immersed in a calibration temperature bath.
(EXTECH, Model 7312) and the calibration occurred within the range of 0 to 80°C. Figure A.3 shows the bath used for calibrating the thermocouples.

The results of calibrating the input and output measurements of the fluid entering and exiting the PV/T panel are presented in Figure A.4. The error bars shown in Figure A.4 are representative of the error associated with the measurement of the temperature sensor. The magnitude of the error bars was determined based on the one standard deviation of the reading of the thermocouple for 5 minutes with 0.25Hz. A third order polynomial was fitted to the data by the method of least-squares.

The third order polynomial was used to correct the thermocouples reading. The accuracy of all the temperature sensors was increased to ±0.35°C for 95% confidence interval or two Standard deviations. The thermocouples error was plotted in Figure A.5. The dashed line in the figure is the 95% confidence interval (2 Standard deviations). As a result, a value of ±0.35°C was chosen as the uncertainty associated with the temperature measurements to calculate the heat flux transferred from the fluid to the PV/T panel (see section A.3).

![Figure A.3 Thermocouple from the test apparatus was immersed into the calibration temperature bath through the guideline.](image)
a) Temperature error of the inlet thermocouple reading before correction for fluid entering the panel

\[ y = -2E^{-0.05}x^3 + 0.0014x^2 - 0.0102x + 0.3356 \]

\[ R^2 = 0.6961 \]

b) Temperature error of the outlet thermocouple reading before correction for fluid exiting the panel

\[ y = -3E^{-0.05}x^3 + 0.0015x^2 - 0.0122x + 0.8037 \]

\[ R^2 = 0.707 \]

Figure A.4 Calibrating the input and output measurements of the fluid entering and exiting the PV/T panel. The magnitude of the error bars was determined based on the one standard deviation of the reading of the thermocouple for 5 minutes with 0.25Hz. A third order polynomial was fitted to the data by the method of least-squares to correct the data.
Temperature error (°C)

Inlet temperature (°C)

a) Temperature error of the inlet thermocouple reading after correction for fluid entering the panel

b) Temperature error of the outlet thermocouple reading after correction for fluid entering the panel

Figure A.5 Thermocouple readings’ error after correction. The dash lines are the 95% confidence interval for each thermocouple
A.3 Propagation of Measurement Uncertainty

The propagation of measurement uncertainty is defined as the way in which uncertainties in individual variables affect the uncertainty in the results (Kreith, 1999). To propagate the random error of measured quantities $x_i$ to a derived quantity $z$, if the variables $x_i$ are independent, the variance formula is a standard formula among engineers and scientists to calculate error propagation (Kline and McClintock, 1953; Moffat, 1985). As mentioned in the previous section, by assuming a 95% confidence interval (2×STD), an estimated uncertainty can be calculated for each variable based on the standard deviation of the measurements (2×STD).

Therefore, the result $Z$ of an experiment is assumed to be calculated from a set of $n$ independent variables, e.g. $x_1, x_2, x_3$, i.e., $Z=f(x_1, x_2, ..., x_i)$. If the estimated uncertainty associated with the variable $x_i$ is $S_{x_i}$, then the estimated uncertainty for the derived quantity, $S_z$, can be calculated as follow (Kline and McClintock, 1953).

$$S_z = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 S_{x_1}^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 S_{x_2}^2 + \left(\frac{\partial f}{\partial x_3}\right)^2 S_{x_3}^2 + \cdots} \tag{A.1}$$

A.3.1 Uncertainty in the Heat Transfer Rate

The heat transfer rate from the working fluid to the PV/T panel can be calculated as

$$Q = \dot{m}C_p(T_{in} - T_{out}) \tag{A.2}$$

Where $\dot{m}$ is the mass flow rate of the fluid; $C_p$ is the specific heat of the heat transfer fluid, and $T_{in}$ and $T_{out}$ are the inlet and outlet temperatures of the panel, respectively.
If $S_Q$ is the uncertainty in a calculated variable $Q$ such that $Q = \dot{m}c_p(T_{in} - T_{out})$ then

$$s_Q = \sqrt{\left(\frac{\partial Q}{\partial \dot{m}}\right)^2 s_{\dot{m}}^2 + \left(\frac{\partial Q}{\partial c_p}\right)^2 s_{c_p}^2 + \left(\frac{\partial Q}{\partial T_{in}}\right)^2 s_{T_{in}}^2 + \left(\frac{\partial Q}{\partial T_{out}}\right)^2 s_{T_{out}}^2} \quad (A.3)$$

Where $\frac{\partial Q}{\partial \dot{m}} = c_p(T_{in} - T_{out})$, $\frac{\partial Q}{\partial c_p} = \dot{m}(T_{in} - T_{out})$, $\frac{\partial Q}{\partial T_{in}} = \dot{m}c_p$, $\frac{\partial Q}{\partial T_{out}} = -\dot{m}c_p$.

As such, the relative uncertainty in the heat transfer rate measurement, $S_Q/Q$, can be calculated using a sample set of measurements, Table A.1. The uncertainty values of flow and temperature (i.e., $s_{\dot{m}}$ and $s_T$ respectively) used in this analysis are based on values obtained from the sensor calibration analysis described in Sections A.1 and A.2. The relative uncertainty of the specific heat value, $s_{c_p}$, was estimated based on a $\pm 5^\circ$C range of tabulated specific heat values.

**Table A.1 Uncertainty in heat transfer rate measurements for tests conducted on the PV/T panel.**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>$s_{\dot{m}}$ (L/min)</th>
<th>$s_{c_p}$ (J/kgK)</th>
<th>$s_{T_{in}}$ (C)</th>
<th>$s_{T_{out}}$ (C)</th>
<th>$S_Q/Q$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>30/01/2018</td>
<td>±0.185</td>
<td>±0.025</td>
<td>±0.32</td>
<td>±0.35</td>
<td>5.9%</td>
</tr>
<tr>
<td>3</td>
<td>07/02/2018 (11:50AM)</td>
<td>±0.185</td>
<td>±0.025</td>
<td>±0.32</td>
<td>±0.35</td>
<td>5.7%</td>
</tr>
<tr>
<td>4</td>
<td>07/02/2018 (4:30 PM)</td>
<td>±0.185</td>
<td>±0.025</td>
<td>±0.32</td>
<td>±0.35</td>
<td>6.1%</td>
</tr>
<tr>
<td>5</td>
<td>10/02/2018</td>
<td>±0.185</td>
<td>±0.025</td>
<td>±0.32</td>
<td>±0.35</td>
<td>4.7%</td>
</tr>
</tbody>
</table>
Appendix B

Sample numerical code
function [RTS]=time(input1)
[ii,NN]=size(input1);
for gh=1:ii
    Ta=input1(gh,1);
    H=input1(gh,2);
    rho_snow=input1(gh,3);
    q_BC=input1(gh,5);
    q_sun=input1(gh,4);
    RH=input1(gh,5);
    theta=input1(gh,6);

    %Glass Properties"
    rho_glass=2600;       %[kg/m^3]
    k_glass=0.8;          %[w/m-k]
    Cp_glass=840;         %[j/kg-k]
    alpha_g=k_glass/(rho_glass*Cp_glass);
    LL=1;

    %Snow properties"
    %rho_snow=158;        %[kg/m^3]
    k_snow=2.22362*(rho_snow/999)^(1.885);  %[w/m-k]
    Cp_snow=2100;         %[j/kg-k] bejan heat transfer
    alpha_s=k_snow/(rho_snow*Cp_snow);
    %H=0.015;              %[m] Initial height
    H2=H/2;
    rho_ice=920;
    rho_water=999;
    hif=334000;           %J/kg
    k_per=10^(-7);        % divided by 1000
    miu=1.787;            % divided by 1000
    k_m=k_per/miu;

    %Panel properties
g=9.81;  \quad \%[m/s^2]
\theta=30;\quad \%[\text{degree}]
H_{cri}=0.05;
Albedo=0.8;
Al=1-Albedo;

%Air properties"
h_{conv}=13; \quad \%[w/m^2-k]
\%Ta=-4; \quad \%[T]
Ta=Ta;
h_{conv2}=24; \quad \%[w/m^2-k]
T_{box}=5;
\%RH=88; \quad \%\text{relative humidity}
T_{dp}=243.04*(log(RH/100)+((17.625*Ta)/(243.04+Ta)))/(17.625-log(RH/100)-((17.625*Ta)/(243.04+Ta)));
\%[C]
T_{dp};
hour=17; \quad \%\text{melting start time from midnight}
T_{sky}=(Ta+273.15)*(0.711+0.0056*T_{dp}+0.000073*T_{dp}^2+0.013*cos(15*hour*pi/180))^{(1/4)};
T_{sky};
N1=0.9; \quad \%\text{Cloud cover}
T_{sky}=(Ta+273.15)*((1-0.35*exp(-10*1007/(Ta+273.15)))*(1+.0035*N1^2))^{(1/4)};
T_{sky};
%Numerical parameters"
Nx=10; \quad \%\text{Number of nodes in the X and Y directions.}"
Ny=3;
d_x=1/(Nx+1); \quad \%\text{Grid spacing}"
L=0.003; \quad \%\text{Glass thickness}"
d_y=L/(Ny+1);
Time=12000; \quad \%[sec]
d_t=0.2; \quad \%\text{Time step}"
niter=Time/d_t;
A=(rho_glass*Cp_glass*d_y/2+rho_snow*Cp_snow*H2/2);
t2;
x=0.1; \quad \%\text{Percentage of runout}
sigma=5.67*10^{-8}; \quad \%\text{tefan-Boltzmann constant [W?m^2?K^{-4}]}\n
%Define Boundary condition for inside layer of slab
\%BC=1; \quad \%\text{constant temperature}
\[ T_{\text{constant}} = 5; \]

\[ \text{BC} = 2; \quad \% \text{Constant heat flux} \]

\[ \% \text{BC} = 3; \quad \% \text{Convective Boundary condition} \]

\[ \% \text{Heating power (heater and sun)} \]

\[ \% q_{\text{BC}} = 1137; \quad \% [\text{w/m}^2] \]

\[ \% q_{\text{sun}} = 22; \quad \% [\text{w/m}^2] \]

\[ \text{Albedo} = 0.8; \]

\[ \% \---------------- Part 1 (Before freezing point) \---------------- \]

\[ \% \text{Main Program} \]

\[ \text{flag1} = 1; \]

\[ \% \text{Initial condition} \]

\[ T_{\text{ref}} = -4; \]

\[ T_{\text{snow}}(1: \text{Nx}+2, 1) = T_{\text{ref}}; \]

\[ T(1: \text{Nx}+2, 1: \text{Ny}+2, 1) = T_{\text{ref}}; \]

\[ T_{\text{surf}}(1: \text{Nx}+2, 1) = T_{\text{ref}}; \]

\[ T_{\text{iter}}(1) = 0; \]

\[ \% \text{Constant Temp. Boundary condition} \]

\[ \text{while} \ (\text{flag1} == 1) \]

\[ T_{\text{iter}}(t) = (t-1) \times d_t; \]

\[ \% T_{\text{old}}(:,0,:) = T(:,0,:); \]

\[ \% T_{\text{surf}}(:,0,:) = T_{\text{snow}}(:,0,:); \]

\[ \% T_{\text{surf}}(:,0,:) = T_{\text{surf}}(:,0,:); \]

\[ \text{if} \ \text{BC} == 1 \]

\[ T(:,1,t) = T_{\text{constant}}; \]

\[ \text{end} \]

\[ \text{for} \ i = 2: \text{Nx}+1 \]

\[ \quad \text{for} \ j = 2: \text{Ny}+1 \]

\[ \quad \quad T(i,j,t) = (\alpha_g \times d_t / d_x^2) \times (T(i+1,j,t-1) + T(i-1,j,t-1) - 2 \times T(i,j,t-1)) \]

\[ \quad \quad \quad \quad \quad + (\alpha_g \times d_t / d_y^2) \times (T(i,j+1,t-1) + T(i,j-1,t-1) - 2 \times T(i,j,t-1)) + T(i,j,t-1); \]

\[ \quad \text{end} \]

\[ \text{end} \]

\[ \% \text{Boundary condition in x direction} \]

\[ T(\text{Nx}+2,:,t) = T(\text{Nx}+1,:,t); \]

\[ T(1,:,t) = T(2,:,t); \]
if BC==2
    T(:,1,t)=q_BC*d_y/k_glass+T(:,2,t);
end

%Interface between Snow and glass
T(:,Ny+2,t)=d_t/A*(T(:,Ny+1,t-1)*k_glass/d_y+T_snow(:,t-1)*k_snow/H2... 
    -(k_snow/H2+k_glass/d_y)*T(:,Ny+2,t-1)+Al*q_sun)+T(:,Ny+2,t-1);

%Snow layer and surface
q_sky=sigma*(T_sky^4-(T_surf(Nx/2,t-1)+273.15)^4);
T_snow(:,t)=(alpha_s*d_t/H^2)^2*(T(:,Ny+2,t-1)+T_surf(:,t-1) ... 
    -2*T_snow(:,t-1)+T_surf(:,t-1)+q_sky)+T_surf(:,t-1);
T_surf(:,t)=(d_t/(rho_snow*Cp_snow*H2/2))... 
    *(h_conv*Ta+T_snow(:,t-1)*k_snow/H2-(k_snow/H2+h_conv)*T_surf(:,t-1)+q_sky)+T_surf(:,t-1);

if (T((Nx+2)/2,Ny+2,t)<0)
    flag1=1;
else
    flag1=0;
end
q_slab(:,t)=-k_glass*(T(:,Ny+2,t-1)-T(:,Ny+1,t-1))/d_y;
t=t+1;

fprintf('Time required for reaching 0: %f [min] \n',T_iter(t-1)/60);

% ___________________Part 2 (deicing-P1)______________________________

H_ice(1:Nx+2,1:t-1)=H;
H_sat(1:Nx+2,1:t-1)=0;
h_if=hif;
md_mlt(1:Nx+2,t-1)=0;
md_run(1:Nx+2,t-1)=0;
m_ice(1:Nx+2,1:t-1)=rho_snow*H;
m_liq(1:Nx+2,1:t-1)=0;
u_run(1:Nx+2,1:t-1)=0;
flag=1;

while (flag==1)
    T_iter(t)=(t-1)*d_t;
\[ T(:,Ny+2,t-1) = 0; \]

% Snow layer and surface\]
\[ \text{H}_{\text{ice}1} = \text{H}_{\text{ice}}(5, t-1)/2; \]
\[ q_{\text{sky}} = \sigma(T_{\text{sky}}^4 - (T_{\text{surf}}(Nx/2, t-1) + 273.15)^4); \]
\[ T_{\text{snow}}(:,t) = \alpha_s d_t / \text{H}_{\text{ice}1}^2 \times (T(:,Ny+2,t-1) + T_{\text{surf}}(:,t-1) - 2 \times T_{\text{snow}}(:,t-1) + T_{\text{snow}}(:,t-1)); \]
\[ T_{\text{surf}}(:,t) = \frac{d_t}{\rho_{\text{snow}} \times C_p_{\text{snow}} \times \text{H}_{\text{ice}1}/2} \times (h_{\text{conv}} \times Ta + T_{\text{snow}}(:,t-1) \times k_{\text{snow}} / \text{H}_{\text{ice}1} - (k_{\text{snow}} / \text{H}_{\text{ice}1} + h_{\text{conv}}) \times T_{\text{surf}}(:,t-1) + q_{\text{sky}}) + T_{\text{surf}}(:,t-1); \]

% Interface between Snow and glass
\[ q_{\text{slab}}(:,t-1) = -k_{\text{glass}} \times (T(:,Ny+2,t-1) - T(:,Ny+1,t-1)) / d_y; \]
\[ q_{\text{snow}}(:,t-1) = -k_{\text{snow}} \times T_{\text{snow}}(:,t-1) / \text{H}_{\text{ice}1}; \]
\[ \text{for } i=1:Nx+2 \]
\[ \text{md_mlt}(i,t) = (q_{\text{slab}}(i,t-1) + Al * q_{\text{sun}} - q_{\text{snow}}(i,t-1)) / (h_{\text{if}}(h_{\text{if}} - C_p_{\text{snow}} \times T_{\text{snow}}(i,t))); \]
\[ \text{end} \]

% Snow and Slash layers height
\[ \text{for } i=1:Nx+2 \]
\[ u_{\text{run}}(i,t) = k_m \times (m_{\text{liq}}(i,t-1) \times g \times \sin(\theta \times \pi/180) \times 2/3); \]
\[ \text{md}_{\text{run}}(i,t) = \rho_{\text{water}} \times u_{\text{run}}(i,t); \]
\[ \text{end} \]
\[ \text{if } (H_{\text{cri}} > H_{\text{sat}}(Nx/2,t-1)) \]
\[ \text{md}_{\text{run}}(:,t) = 0; \]
\[ \text{end} \]

\[ m_{\text{ice}}(:,t) = m_{\text{ice}}(:,t-1) - d_t \times \text{md}_{\text{mlt}}(:,t); \]
\[ m_{\text{liq}}(:,t) = m_{\text{liq}}(:,t-1) + d_t \times (\text{md}_{\text{mlt}}(:,t) - \text{md}_{\text{run}}(:,t)); \]
\[ H_{\text{total}}(:,t) = m_{\text{ice}}(:,t) / \rho_{\text{snow}}; \]
\[ n_{\text{eff}} = 1 - (\rho_{\text{snow}} / \rho_{\text{ice}}); \]
\[ H_{\text{sat}}(:,t) = m_{\text{liq}}(:,t) / (\rho_{\text{water}} \times n_{\text{eff}}); \]
\[ H_{\text{ice}}(:,t) = H_{\text{total}}(:,t) - H_{\text{sat}}(:,t); \]

% Slab heat transfer
% Constant Boundary condition
\[ T(:,Ny+2,t) = 0; \]
\[ \text{for } i=2:Nx+1 \]
for j=2:Ny+1
    T(i,j,t)=(alpha_g*d_t/d_x^2)*(T(i+1,j,t-1)+T(i-1,j,t-1)-2*T(i,j,t-1))
    + (alpha_g*d_t/d_y^2)*(T(i,j+1,t-1)+T(i,j-1,t-1)-2*T(i,j,t-1))+T(i,j,t-1);
end

%Boundary condition
T(Nx+2,:,t)=T(Nx+1,:,t);
T(1,:,t)=T(2,:,t);
if BC==2
    T(:,1,t)=q_BC*d_y/k_glass+T(:,2,t);
elseif BC==1
    T(:,1,t)=T_constant;
end

% denom=tan(theta*3.14/180+atan(H_total(Nx/2,t)/LL))^(0.28)*(rho_snow*H*9.81*1/1000)^(0.13);
% nomi1=(q_BC/1000+q_sun*(1-Albedo)/1000)^(0.26);
% nomi2=(rho_snow*H*(Ta)*2.09)^(0.13);
% RTS_m=(-3.9287*denom+5.3009)*nomi2/nomi1)^ (1/0.26); &&
T_iter(t)<RTS_m
    if (T_iter(t)<Time && H_cri>H_sat(Nx/2,t) && H_ice(Nx/2,t)>0 && T_snow(Nx/2,t)<=0 )
        flag=1;
    else
        flag=0;
    end
end
t=t+1;

q_sky=sigma*(T_sky^4-(T_surf(Nx/2,t-2)+273.15)^4);

df=T_surf(Nx/2,t-2);

T_step1=T_iter(t-1);
m_ice(2,t-3);
q_slab(2,t-2);
h_conv*Ta;
q_sky
q_sun;
\[ T_{\text{total}} = (T_{\text{step}} + m_{\text{ice}}(2,t-3)\cdot h_{\text{if}}/(q_{\text{slab}}(2,t-2)+h_{\text{conv}}\cdot T_a+q_{\text{sky}}+A_{\text{l}}q_{\text{sun}}))/60; \]

\%RTS(gh,1)=T_{\text{step}}/60; sliding
RTS(gh,1)=T_{\text{total}};  \%melting
RT(gh,1)=T_{\text{total}};

fprintf('Time required for the first step (melting snow): %f [min] \n', T_{\text{total}}/60);
end