AN IMPROVED NUMERICAL METHOD FOR PREDICTING SNOW MELTING ON PHOTOVOLTAIC PANELS

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ABSTRACT

Large scale photovoltaic power generating systems are being increasingly used in Canada. Unfortunately in Canada in winter snow accumulation on the PV panels can lead to very significant decreases in the power generated by such systems. One approach is to heat the panels causing melting of the snow or sliding of the snow layer off the panel. An improved numerical model of the melting of a snow layer on a heated panel has therefore been developed. 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. Results have been obtained using this model for various depths and densities of snow cover and compared with available experimental data and with results given by an earlier numerical method. This comparison shows that the current model more accurately predicts melt time and water run-off rates than the previous model. This is especially true when the surface heat flux rates are low which is important for PV panels.

INTRODUCTION

One of the most efficient methods of directly converting sunlight into electricity is photovoltaic cells. While PV panel systems are not presently a major contributor to the total annual electrical power supply needs of the world, in recent years the lifetime generation cost of the electricity from PV panel system has became comparable with the cost of electricity generated by conventional sources, i.e., grid parity has been achieved [1-4]. It has in fact been shown that depending on the location, the cost of solar PV generated electricity has already dropped below that of conventional sources [5, 6].

The main problems 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 which lower the conversion efficiency of the panel [7]. In cold regions like Northern United states and some parts of Canada, losses associated with snow cover of the PV panels are of great importance, strongly affecting the PV cells output during the winter when, there is a high demand for electrical power. The problem is severe as even partial snow cover on PV modules may significantly reduce the output of a complete string of PV panels [8].

Several numerical and experimental studies have been carried out to clarify the effect of snow covering on PV panel output. The first such study was undertaken by Brench [9] in 1979 to determine the losses due to snow covering of the panel. However, owing to some reliability issues more than 50% of the data obtained in the study was discarded. Using 6 years of data obtained from 1999 to 2006 at the New Munich Trade Fair Center, Becker et al. [10] showed approximetly 3% annual snow losses for that site which had an average 30 cm annual snow precipitation. However, the effect of snow on the PV system performance located in Truckee, California with an average 5 m (200 in) of snow per year was approximetly 15% on an annual basis. Monthly losses during winter ranged up to 80%, 90% and 100% of expected yields for 39^{o}, 24^{o} and 0^{o} panel tilt angles respectively [11]. The significant losses associated with snow coverage losses of PV systems shows the necessity of a deicing system to keep the PV cell industry competitive with conventional resources in cold regions. Ross(1995) [27] and Andrew et al. (2013) [26] tried to use a passive melting system which was based on the reflection of light onto the rear surface of the modules and the use of a surface coating on the panel but found that there was no appreciable improvment of snow removal from the panel.

Past studies therefore indicate that a more effective method of PV panel snow removal needs to be developed. In order to do this a more accurate simulation method for such a deicing system is required to evaluate the performance of any proposed thermal deicing system in order to increase the chances of the system being successful. Although no research studies have been undertaken to numerically evaluate deicing systems for PV panels, some researchers tried to predict the effect of snow on PV panel output. Considering some effective key parameters for snow removal of PV systems, Townsend and Powers [11] proposed a generalized monthly snow loss model calibrated using their experimental measurements. More recently, Marion et al. [12] developed a similar model for the prediction of PV system performance losses from snowfall. They considered two causes for snow to remain on the PV module: frictional forces and freezing of the snow layer on the PV module. Based on these studies, it is clear that one of the feasible methods for the deicing of PV systems is to heat the panel and in particular to use heating from the rear surfaces of the panels.

The first step required in order to evaluate the practical possibility of using such a system is to simulate the system numerically. Although snow melting models have been proposed by Liu et al. [14] and Rees et al. [13], none of these is applicable for snow melting on PV panels. The reason is that all the previously proposed methods for predicting snow melting have been for horizontal surfaces (such as an asphalt pavement), while most PV panels have a degree of inclination which affects the melting process. In addition, the heat and mass transfer mechanisms involved in the snow melting process are complex and require treatment of phase change phenomena. As a result, the main goal of this study is to propose a new snow melting model for inclined surfaces which enables the evaluation of the performance of thermal deicing systems for PV panels.

A discussion of the methodology and numerical methods used in the model will first be given and then the results obtained using this model will be presented and compared with available experimental results.

METHODOLOGY

A snow melting model, based on the use of appropriate heat transfer equations and appropriate initial and boundary conditions, that can be used to evaluate the performance of a thermal snow melting system on PV panels when the panel is uniformly heated from its rear surface is presented in this section. Previously proposed snow melting models tried to consider the transient nature of weather conditions during a storm since they were designed to predict snow melting on different types of pavements over longer periods of time than here being considered. Accordingly these models are optimized for predicting the long-term performance of the system, multi-year predictions based on the use of hourly data often being used [14, 13]. Using these models for the prediction of snow melting on a PV system can lead to inaccurate results because the desired melt time for a PV deicing system is at most a couple of hours which is of the same order as the accuracy of these existing models; and because PV panels are usually set at an angle to the horizontal which affects the melting process whereas existing models all assume melting is occurring on a horizontal surface.

Owing to the fact that they were concerned with long term simulations, it was necessary for previous models to deal with boundary conditions that were representative of a wide variety of weather conditions. In the present model, although different conditions are considered, it is not necessary to consider several very different weather conditions in one simulation since changes in the weather conditions in a period of a few hours (1 to 3 hours at most) are normally not very significant especially as a PV panel deicing system is supposed to work after storms have ended.

Following the classification described by Rees et al. [13], the possible surface conditions for a PV system will be as follows:

- Clean surface: the surface is free of ice and liquid and its temperature may be above or below the freezing point (0 ^{0}C).
- Dry snow: here the surface temperature is below the freezing point and it is covered by dry snow and free of liquid. Under these circumstances, the snow is treated as a porous matrix of ice.
- Slush only: here the surface temperature is at the freezing point, the snow layer is saturated by liquid water and water penetrates the porous matrix from the bottom to the upper surface.
- Dry snow and slush: a combination of a dry snow layer at the top and slush at the bottom of the snow layer.

Rees et al. [13] and Liu et al. [14] also considered hoarfrost and solid ice as other possible surface conditions. In the present model these are treated by regarding them as involving dry snow with different snow densities.

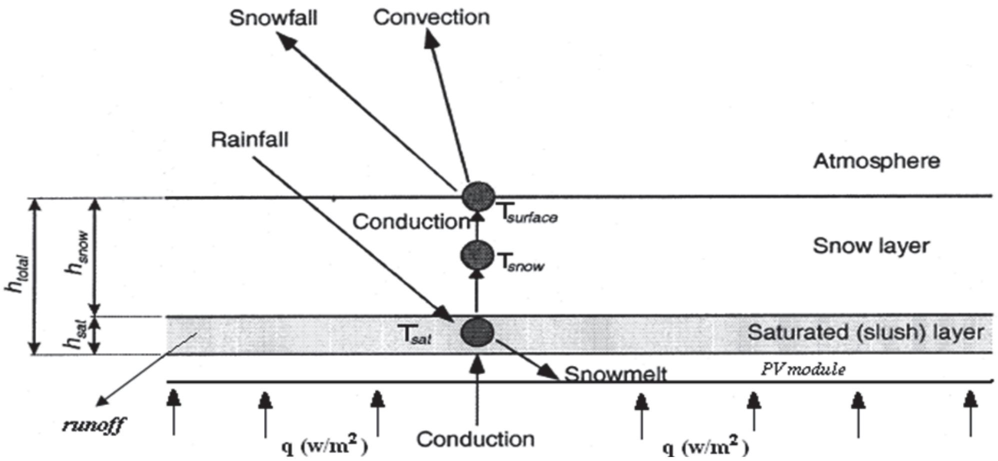


Figure 1: Heat transfer in the three-node snowmelt model

One of the most important aspects of the simulation of snow melting is the specification of the surface condition. It is not only necessary to consider the current surface temperature but it is also necessary to consider the prior snow precipitation and the snow layer height. However, in contrast to the simulation of pavement snow melting, it is not necessary in the simulation of PV panel snow melting to worry about the current snow precipitation since the PV melting system would normally only be utilized after the snow-fall had ceased and when relatively clear sky conditions exist (usually at early morning). However one of the most challenging aspects of PV snow melting compared to pavement snow melting is the energy consumption of the system. For pavement melting system cost is usually not the first priority because the safety of the roads is much more important. In contrast with PV panel snow melting, energy consumption and cost are the first priorities since the snow melting is being used to increase the efficiency of PV system.

Based on the discussion given above it may be concluded that knowledge of the current heating flux and surface temperature are not sufficient to define the current surface conditions. Consequently a rule-based approach has been adopted in formulating the heat and mass balance. Several parameters play key roles in this approach. These include the surface temperature, the mass of ice and water, the heating flux and the weather conditions. As was done by Liu et al. [14], the weather boundary conditions used in the present model are those found in standard weather records. These include ambient wet and dry bulb temperatures, wind speed, cloud cover fraction, and solar fluxes. In the current modeling, due to the importance of the snow height, the rate of precipitation and the snow height consequently are adopted from available experimental data not based on weather records data files. However, considering data files for calculating snow height may not affect the results significantly.

Numerical model development

Snow is a porous material composed of ice crystals, air, and water vapor. During the melting process from the lower surface of the snow layer (PV panel), a portion of the snowmelt is retained and partly saturates the snow [14]. Thus, two distinct layers exist in the snow-layer on the PV panel. These are the dry snow layer at the top and the slush layer (which is saturated with water) at the bottom. Depending on the boundary conditions, different combinations of these layers may cover the PV modules including dry-snow, slush and ‘snow-slush’. In the ’snow-slush’ layer it has been observed [16, 15] that as snow melts, the thickness of this layer increases until a maximum thickness is reached [17, 18, 16]. This maximum thickness is determined by the point at which capillary and gravity forces are in balance.

At the beginning of the simulation the panel and the snow cover are in a sub-freezing condition. This condition is termed ‘dry snow’. Following the heating of the panel from the bottom (Fig. 4), the panel surface temperature increases up to $0^{o}C$ at which point snow melting starts. When melting occurs, as mentioned above, a portion of the snowmelt is retained and partly saturates the snow leading to the formation of a slush layer at the bottom of the snow cover. This condition is termed ‘snow-slush’ with a dry snow layer existing at the top and a slush layer occurring at the bottom of the snow cover. With more heating of the panel a thicker slush layer forms so that only a relatively thin layer of fully saturated snow and liquid exists. This condition is termed ‘slush only’. It is worth noting that the slush layer thickness will not increase after it reaches the equilibrium thickness in which the capillary and gravity forces are in balance. The run-off rate is increased to the melt rate after this point.

In the present model, the snow melting process starts from ‘dry snow’ followed by ‘snow-slush’ and then ‘slush only’ conditions and ends up with a ‘clear surface’ condition. Three nodes (with specific assumptions on each of them) are considered in the snow layer in calculating the conduction heat transfer rate through slush and dry snow layers. The existence of the dry snow layer is essential in the modeling because the insulating effect of the dry snow layer can be significant [19]. The slush layer is assumed to remain relatively thin and to be isothermal and saturated since it is a mixture of ice and water [14, 15, 13]. Figure 4 shows a schematic of the configuration used in finding the heat transfer rate under the ’snow-slush’ condition.

A number of assumptions are made in the model including:

- The dry snow layer is homogeneous and porous. According to the specific types of snow crystals, it is believed that the dry snow can be treated as a porous media [20, 14]. In addition, by defining an effective thermal conductivity, it is possible to avoid consideration of the small effect of directional thermal conductivity [19].
- The slush layer is isothermal at melting point of water 0^{o}C because it is a mixture of ice and water.
- Melting of snow occurs only at the PV module surface. The reason is that it is assumed that the ambient temperature during the simulation is below the freezing point with the result that no snow melting can occur as a result of convective heat transfer from the snow edges or surface.
- The snow melting process is treated as a one-dimensional process and therefore the lateral heat and mass transfer between the adjacent snow and slush layers is not accounted for. Since the slush layer is isothermal, mass transfer from one cell to another one does not have any effect on the heat transfer. As a result, the major purpose for solving the mass transfer equation in the slush layer is to calculate the amount of run-off water which is calculated separately using Darcy’s law in the present model. In addition, assuming there is a thin layer of snow with a low heat transfer conductivity over the modules and assuming that the ambient temperature remains constant during the simulation, it may be concluded that the dry snow layer is isothermal [19, 14, 13].

A critical point in the simulation is to distinguish whether the surface is covered with ‘slush only’ or ‘snow and slush’. Liu et al. [14] assumed that the slush layer thickness had already reached the equilibrium thickness which is an adequate assumption for annual simulation but not for PV panel snow melting simulations. As a result, in the present model, the total thickness of the snow layer (dry snow and slush layer) is compared with the thickness of the saturated snow (slush). Consequently, two coupled transient mass balance equations should be solved to calculate the mass of ice and retained water. The problem is that these equations are coupled with the PV module heat balance equation. Furthermore, the way in which the phase change modeling contributes to this modeling increases 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. [13].

The difference between the present model and that developed by Rees et al. [13] is that they used a simple heuristic approach to estimate the amount of runoff. In the Rees et al. model in order to approximate the effect of water being retained in the snow due to capillary action, the runoff was limited to 10% of the melt rate until the saturated layer is 2 in. thick [13]. The runoff rate is then increased to the melt rate after this point to prevent more water being retained. While this type of modeling may be adequate for a horizontal surface, this method may not be adequate for PV panels because these panels are usually tilted relative to the horizontal. To address this difficulty in the present model the Darcy’s law equation is used to calculate the amount of run-off which can move through the snow. Using Darcy’s law allows the velocity of water flowing through pore spaces on the snow layer to be calculated thus allowing the run-off rate to be determined.

In this model, five primary equations have been considered. These include a mass balance for the solid ice, a mass balance for liquid water, and a heat balance for each node. The mass balance on the snow is given by:

$$\frac{dm_{snow}}{dt} = \dot{m}_{snowfall} - \dot{m}_{melt} \quad (1)$$

where

$\dot{m}_{snowfall}$ = snowfall rate per unit area = (kg/s·m^2);

$\dot{m}_{melt}$ = melting rate per unit area= (kg/s·m^2);

$\dot{m}_{melt}$ = mass of snow per unit area (kg/m^2);

t = the time (s).

The mass balance on the liquid is given by

$$\frac{dm_{liq}}{dt} = \dot{m}_{melt} - \dot{m}_{runoff} \quad (2)$$

where

$\dot{m}_{runoff} =$ rate of runoff (kg/s·m^2);

$\dot{m}_{melt} =$ mass of liquid water per unit area (kg/m^2).

To estimate the amount of runoff, Darcy' law is used:

$$v = -\frac{K}{\mu}\frac{dp}{dx} \quad (3)$$

where

K= snow permeability (m^2);

μ =kinematic viscosity of water ($Pa \cdot s$).

The permeability of snow is the property of snow that controls the ease with which a fluid, typically air or water, can move through the snow [20]. 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 the permeability of snow [20].

The driving force or pressure gradient (*dp/dx*) is calculated based on the portion of liquid water weight which is acting parallel to the PV panel surface (Fig. 2):

$$\frac{dp}{dx} = m_{liq} g \, sin\theta / L \quad (4)$$

where

θ= Tilt angle of the panel

L= The lengh of the panel in x direction (m)

Then using the pressure gradient (*dp/dx*), Darcy's law and slush layer thickness, the fluid velocity (*v*) will be calculated (Eq. 3). The rate of runoff water per unit area can then be computed using:

$$\dot{m}_{runoff} = \rho_{water} VA \quad (5)$$

where

V= velocity of water flowing in slush layer (m/s);

$\rho_{snow} =$ density of snow (kg/m^3);

A= cross section area of slush layer (m ^{2}).

In order to calculate the slush layer height and the heat balance on the snow, it is necessary to find total height (h_{total}) of snow-slush layer, this being given by:

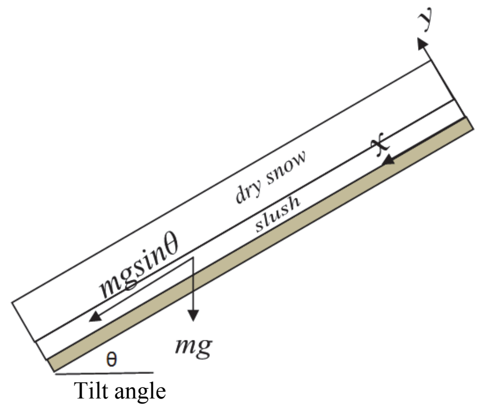


Figure 2: Coordinate system used in the model

$$h_{total} = \frac{m_{snow}}{\rho_{snow}} \quad (6)$$

where

$m_{snow} =$ total mass per unit area (kg/m^2);

Similarly, the height of the saturated layer can be calculated from the mass of liquid using:

$$h_{sat} = \frac{m_l}{\rho_{liq} n_{eff}} \quad (7)$$

where $n_{eff} = 1 - \rho_{snow}/\rho_{ice}$ is relative density and the height of the dry snow layer can be found by using, $h_{snow} = h_{total}$ - h_{sat} . h_{sat} Will increase until the maximum height of this saturated layer (MSLH) is reached [15]. The runoff rate is then increased to the melt rate after this point to prevent more water being retained. Using h_{snow}, the mass per unit area (kg/m^2) of the dry snow layer can then be found using:

$$m_{snow} = \rho_{snow} h_{snow} \quad (8)$$

These mass balance equations are coupled to the energy balance equations by the melt rate. Aside from the heated PV panel, some other heat sources can affect the heat balance of the snow layer including shortwave (solar radiation) and longwave radiative heat fluxes as well as convective heat transfer from the snow surface. Since the best time to start snow melting for PV panels is before sunrise (to enable us to use the solar radiation during the day), in the first step of simulation, solar radiation is not considered (it will be taken into account in a later modified version of the present model). As a result, the energy balance for the snow layer is as follows:

$$m_{snow}C_p \frac{dT_{snow}}{dt} = q_{cond.snow} - q_{conv.} - q_{rad_{LW}} \quad (9)$$

where $q_{cond.snow}$ and longwave radiative heat flux $q_{rad_{LW}}$ are given by:

$$q_{cond.snow} = \frac{k_{snow}}{0.5h_{snow}}(T_{slush} - T_{snow}) \quad (10)$$

$$q_{rad_{LW}} = \varepsilon\sigma\left(T^4_{surface} - T^4_{sky}\right) \quad (11)$$

where

k_{snow} =thermal conductivity of snow (w/(m.K));

T_{slush} =slush layer temperature (^0C);

T_{snow} =temperature of the snow node (^0C);

ε =the emissivity of snow,

σ =the Stefan-Boltzmann constant (5.670373$\times 10^{-8}$ (W/m^2k^8))

To estimate the thermal conductivity of snow (*k*), attempts have been made to relate variations of the effective thermal conductivity for different snow types to the density of the snow [20, 21, 22]. The values of k_{eff} were fitted to snow density by Calonne et al. [19] leading to $k_{eff} = 2.5 \times 10^{-6}\,\rho^2 - 1.23 \times 44910^{-4}\rho + 0.024$. In addition, Yen [22] mentioned that k_{snow} is not sensitive to temperature for snow with a density of approximitly 100 kg/m^3 and a temperature between 250 to 280 K. The sky temperature T_{sky} is here computed with the algorithm proposed by Martin and Berdahl [23]. Finally, to find the rate of melting, the energy balance for the slush layer is utilized leading to the following:

$$\dot{m}_{melt}h_{if} = q_{cond.module} - q_{cond.snow} \quad (12)$$

where h_{if} is the latent heat of fusion (*kj/kg*) for snow. The boundary condition between the slush layer and the PV surface can define the rate of heat flux through the PV modules ($q_{cond.module}$) required to melt snow. This will be dicussed in the following section.

Boundary Conditions

As mentioned above, the snow melting process is treated as a one-dimensional process and the lateral heat and mass transfer between the adjacent snow and slush are therefore not considered in the calculations.

The boundary conditions include two inter-faces: ‘snow-ambient air’ at the top, and ‘snow-PV surface’ at the bottom.For the interface between snow and air, convective heat flux is considered giving:

$$q_{conv} = h_c \times \left(T_{surface} - T_{air}\right) \quad (13)$$

where h_c is convective heat transfer coefficient (W/m^2) which is assumed to be given by the correlation given by Incropera and Dewitt [24]. $T_{surface}$ and T_{air} are the snow surface and the air temperature respectively.

In order to use the heat balance (Eq. 12) at boundary between the snow layer and the PV panel (‘snow-PV surface’ boundary), the rate of heat flux through the PV modules is required. The finite-difference method has been used to solve the two dimensional heat conduction equation (Eq. 14) that describes the temperature distribution within the PV module.

$$\frac{\partial T}{\partial t} = (\alpha)\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] \quad (14)$$

where *x* and *y* are parallel and normal to module surface respectively (Fig. 1), and α refers to 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 question that may come to the mind is why 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 heater at the bottom can be changed. In the present simulation a constant heat flux is assumed over the entire module surface.

Model Implementation

Based on a consideration of Eqs. 6 and 12, it will be seen that the ’snow-PV surface’ boundary condition and subsequently the energy balance for the snow layer are coupled with the model of conductive heat transfer in the module. There are a number of ways to deal with this coupling but in the present model, several steps have been introduced that are designed to increase the accuracy of the solution as compared to that of other snow melting models [14, 13]. In the first step, based on the initial conditions, the conduction heat transfer equation is solved in the snow layer and the PV module until the interface temperature between the snow and the module reaches 0^{o}C. In the next step, the surface temperature is fixed at the freezing point of water when snow is melting on the surface. The heat flux conducted through the module calculated at the last time step is passed to the snow melting model to determine the snow melting rate leading to the slush layer growth until the whole layer becomes slush (no dry snow layer). In addition, there is another option in the code which enables the user to consider cyclic heating (melting and freezing subsequently).

RESULTS AND DISCUSSION

The first stage of the work was to evaluate the code by comparing the results given by the code with available experimental results. Several studies have been performed for snow melting on horizontal surfaces such as pavements and some building roofs. However, thus far, no quantitative experimental studies have been performed for snow melting on a tilted surface. As a result, in the present paper the code will be validated using available experimental data for horizontal surfaces. Some experiments involving snow melting on tilted surfaces are presently being undertaken and a comparison of these results with those predicted by the code will be made in the future.

Hockersmith [15] performed a set of snow melting experiments using artificial snow. An environmental chamber was used to make the snow and to simulate the weather conditions during freezing conditions. The snow melting process was investigated using a heated horizontal plate mounted inside a Plexiglas tube with a hole at the bottom for measuring run-off water. The amount of run-off water from the plate and the snow height during melting were recorded for different heat flux cases. Other conditions were kept constant during all the heat flux test cases considered including keeping the chamber temperature at 2°C and the humidity ratio around 80%. The density of snow was measured before each experiment was undertaken. Hockersmith [15] generated numerical results for the conditions existing during these experiments and compared the experimental and numerical results.

The present numerical model has been run for conditions matched those existing in the Hockersmith experiments. The inputs to the model were the initial snow height and temperature, the snow density, the ambient temperature and the heat flux. Since a convection coefficient of 1.5 W/m^2C and a thermal conductivity of 0.3 W/m^2C for snow were used by Hockersmith [15] in his model, the same values have been used in present model. To check the uncertainty in the numerical results that could be associated with the uncertainties in the assumed thermal conductivity value, the thermal conductivity was changed $+20\%$ and -20% from the value of 0.3 *W/mK* used in obtaining the model results. These changes in the thermal conductivity value caused changes in the predicted melt time of less than 1 minute. The effect of changing the convective coefficient ($+20\%$ and -20%) on the predicted melt time was also studied and it was found to be +7 and -36 minutes uncertainty.

The predicted snow height and water run-off for all of the heat flux cases considered are compared with the experimental data in Figure 5. The largest differences between the experimental and numerical snow heights will be seen to occur during the last hour of the melt experiment. It is mentioned in the report on the experiment that the deceleration of snowmelt rate during last hour of the test may be described as 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 [15]. However, it will be seen that by solving the conductive heat transfer equation in the snow and slush layers as is done in the present model, the agreement between the numerical and experimental results has been improved compared to that achieved using the Hockersmith [15] model.

In addition to examining the adequacy of the assumptions of the model and the uncertainties in the results predicted by the model, the uncertainties in the experimental results was also evaluated to determine if the differences between the numerical and the experimental results could be partly the result of experimental uncertainties. Two of the significant experimental uncertainties were the result of the sampling time and the result of the inhomogeneous melting of the snow [15]. Several methods were employed to estimate the inhomogeneity in the snowmelt experiment and the corrected experimental melt times were compared with the results given by both the old and the new numerical methods these results being shown in Table 1. The maximum difference between the results given by the present model and the experimental results is 7%. Given the experimental uncertainties discussed above, this amount of error is acceptable.

Table 1: Melt time [15] comparison with numerical methods

Heat Flux (w/m^2)	Exp. melt time (min)	Old model (min)	Current model (min)	Error of current model
234	730	705	774	6%
311	575	520	560	3%
468	445	415	433	3%
633	305	275	284	7%
780	235	230	235.8	0.3%

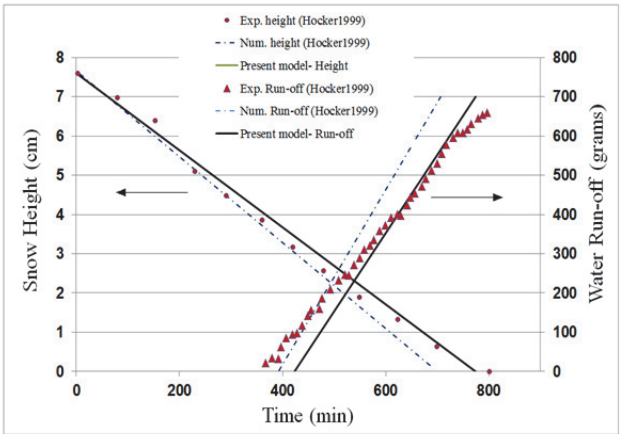
Table 2: Comparing numerical result from code with experimental data by Chen et al. [25] for snow melting on asphalt pavement

Pavement type	Melting time (min) Exp.	Melting time (min) Num.	Error
Asphalt AC50	217	209	4%
Asphalt CAC50	309	246	20%

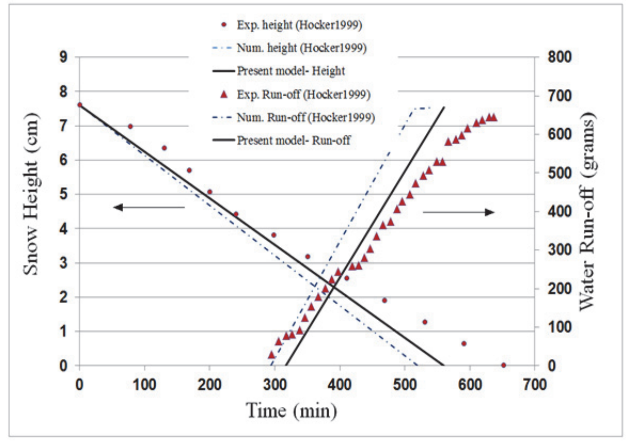
A comparison of the melt times predicted by the present model with experimental results [25] for snow melting over two different types of pavement are presented in Table 2. It should be noted however that it is not clear what the value of the snow density in this experiment is. It is worth noting that the improvements included in the current model have significantly increased the accuracy of the predictions of melt time and water run-off especially in low heat flux rate cases which is particular important for predicting the performance of PV panels because it is not economical to use high heat flux rates with such panels.

Regarding melt water runoff, from the experimental results, a time delay for the water to runoff was noticed. It was determined that during this early period of melting, the melt water was wicked up into the pores of the snow to form a slush layer and did not run off the plate (for flat plate only). In the current model, the maximum height of this saturated layer (MSLH) is taken to be 3 ± 0.7 cm, based on the experiments [15] and model accuracy. The water runoff is determined numerically based on Darcy's law as a function of heat flux untill MSLH is reached. The runoff rate is then increased to the melt rate after this point to prevent more water being retained. During the last minutes of the melting experiment (where there is the most discrepancy between numerical and experimental results), the amount of water runoff is affected by crowning effects, surface roughness, surface tension of water and orientation. Again the present model predicts water runoff more accurately than the other one, especially in low heat flux rates.

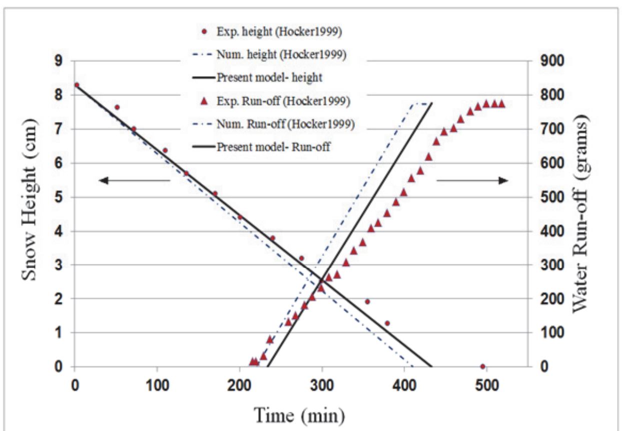
The results reveal that melting of the whole layer of snow by heating alone requires the consumption of too much time and energy especially with a low heat flux rate when up to 6 to 7 hours is required for melting. A method that could possiblely be used in conjunction with heating should therefore be found to slide the snow layer off the panel possibly before the snow layer is fully melted. Tilting of the PV panel may be a possible solution but more investigation of the effect of tilt angle is required. An experimental study of the effect of tilt angle on snow removal is being undertaken. In summary, one can classify the snow-melting process into three distinct stages. In the first stage, the melt water is wicked up through the snow due to capillary pressure, until the pressure due to the weight of the fluid offsets that of the capillary pressure (reaching MSLH in the code). The second stage of snowmelt is characterized by the onset of significant run-off water [15]. During the second stage, the snow thickness continues to decrease and water runs off since there is no place for excess water to be stored and therefore must run off the panel. The last stage is characterized by the absence of dry snow, i.e., by the existence of the 'slush only' situation. The original snow crystals are no longer present and have joined together to form larger ice crystals. Water continues draining from the plate until all of the snow has melted.



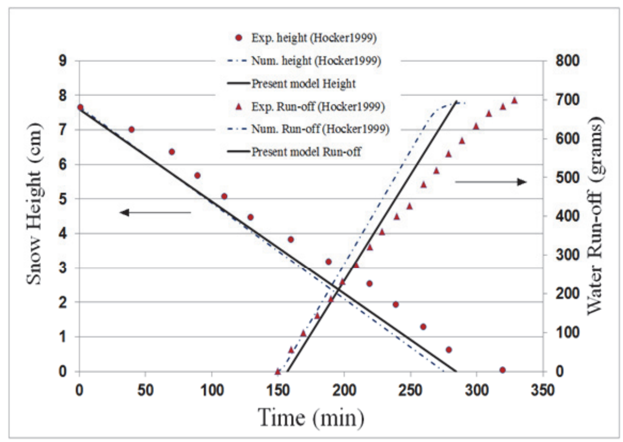
a) 234 W/m²



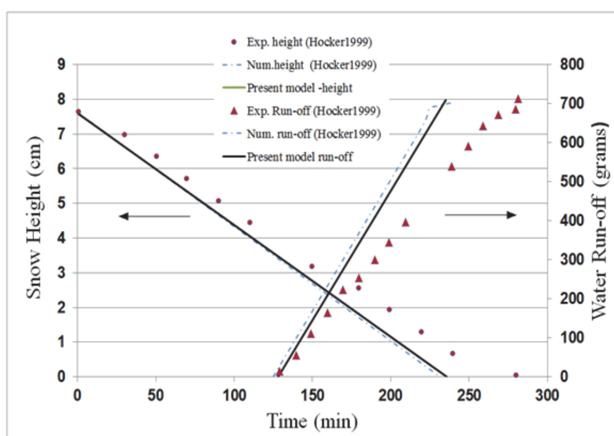
b) 311 W/m²



c) 468 W/m²



d) 633 W/m²



e) 780 W/m²

Figure 3: Comparison between model and experimental snow height and water run-off

CONCLUSIONS

The widespread use of solar power around the world in general and North America in particular has encouraged researchers to seek an effective method of snow-removal or deicing of PV panels during the snowy season. As the cost of solar PV has already dropped below that of conventional sources of electrical power, one of the main issues arising in the use of this technology to compete with conventional electrical power sources is the losses associated in particular with partial shade and snow cover. The first step in the evaluation of potential deicing systems for PV panels is to numerically simulate the performance of the proposed system. As a result, this paper proposes a modified snow melting model for PV panels. 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 and slush layers on the panel. A comparison of the results given by this model with available experimental results and with results given by an earlier numerical method reveals that:

1. Solving the conductive heat transfer equation in snow and slush layers in the current model has improved the results compared to those given by the earlier model.
2. Experimental uncertainties especially during the last hour of the snow melting experiments makes a full evaluation of the model somewhat difficult.
3. Melting of the whole layer of snow using the back heating method here proposed requires too much time and energy, and a method should be developed to slide the snow layer off the panel in conjunction with panel heating or without any heating. Tilting the panel to try to accomplish this needs to be investigated but more studies of this and of other snow removal methods needs to be undertaken so that an economical solution to the snow removal problem can be found.

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