Understanding Snow Adhesion and Mechanisms of its Removal from Photovoltaic Modules

Abdel Hakim Abou Yassine[1], Navid Namdari[1], Behrouz Mohammadian[1], Reza Rizvi[2], Hossein Sojoudi[1]

[1]*Department of Mechanical Industrial and Manufacturing Engineering, The University of Toledo, Toledo, OH, USA*
[2]*Department of Mechanical Engineering, York University, 4700 Keele St BRG 437, Toronto, ON M3J 1P3, Canada*

AbdelHakim.AbouYassine@rockets.utoledo.edu, Navid.Namdari@utoledo.edu, Behrouz.Mohammadian@utoledo.edu, Reza.Rizvi@lassonde.yorku.ca, Hossein.Sojoudi@utoledo.edu

Abstract— **Snow accumulation on photovoltaic (PV) modules creates mechanical stress on them and significant economic loss by preventing solar power generation. Here, snow adhesion to various surfaces of interest (i.e. glass and aluminium) and its mechanism of removal is studied under various heat transfer modes. A snowphobic coating (details of which is not provided) is developed and installed on of small glass/aluminium surfaces resembling PV modules to facilitate snow removal. Artificial snow with controlled liquid water content (LWC) is formed using a snow gun that mixes air and water in different pressure and ratios. The LWC of the created snow is monitored using a surface-mountable sensor. The effects of free convection and shortwave radiation on snow removal are studied. Under free convection, the aluminium/glass surface with the coating allowed snow removal 23 hours earlier than the control bare sample. Under shortwave radiation, the coating resulted in 6 hours faster snow removal. This work paves the path for facilitating snow removal from PV modules, enabling their full power generation throughout the year.**

Keywords—*: Photovoltaic modules, Snow shedding, Liquid water content, Snowphobic surfaces, Artificial snow*

I. Introduction

Accumulation of atmospheric icing on surfaces causes significant economic and safety problems for energy production services[1, 2], aviation[3], ground transportation systems[4, 5] and many other fields. Snow is one of the most common atmospheric icing precipitation that is a mixture air, water, and ice. Snow accumulation on photovoltaic (PV) modules can cause up to 100% of the expected yield monthly losses[6].

The PV deployment capacity have been rising significantly throughout the years, where it increased in the U.S. alone from 1000 MW to 14000 MW during 2010-2019 [7]. Due to this rise in the PV market, several experimental and numerical studies have been analysed to calculate energy losses due to accumulation of snow on PV modules, seeking to establish active/passive snow mitigation strategies. For example, snow accumulation have caused up to 90% monthly losses on PV modules in Colorado and Wisconsin[8]. Another study has shown that the yearly losses due to snow accumulation can reach up to 4.4% in Northern California[6].

Due to the significant losses that are caused by snow accumulation on PV modules, passive/active snow removal strategies have been developed. Hydrophobic, superhydrophobic, and hydrophilic coatings have been used to passively facilitate snow removal from the PV modules[9]. However, it has been determined that these coatings are not fully efficient in mitigating snow removal from the PV modules, and in some scenarios, they delayed snow removal by natural means such as convection heat or solar irradiation[10, 11]. Another passive method that has been developed is vented insulation [12] which causes a rise in the module's surface temperature and improves snow melting; however, this method reduces the power generation efficiency during the summer.

Due to lack of efficient passive snow removal strategies, active methods have been utilized. Thermal heating [13] has been used to actively remove snow from the PV modules, which was found to be ineffective for full snow removal. At freezing temperatures, the bottom frame of the modules prevent snow from sliding and icicle form at those frames. The bottom frame is typically made of on which snow adheres more strongly, when compared to snow adhesion to glass, which is covering mostly of module's surface [14].

In this study, we facilitate snow shedding from a PV module using a snowphobic coating, details of which is not provided due to proprietary reason. A snow gun is used form artificial snow inside a walk-in freezing room and a surface-mountable sensor is used to measure the liquid water content (LWC) of the produced snow. Several experiments are performed to study the effectiveness of the coating on snow removal under various conditions (i.e., convection and/or radiation). Up to 24 hours faster snow removal is observed when utilizing the coating. The results of this study will help to improve power generation efficiency of PV modules installed in cold regions.

II. Experimental Setup

All experiments are performed inside a walk-in freezing room (**Fig. 1**) that can reach temperatures as low as -20 ℃. The freezing room goes through a resting time every 6 hours (**Fig. 2(d), Fig. 3(d)**), where the room temperature increases for 10 minutes, and then decreases after that to the set temperature. A snow gun (**Fig. 1**) is developed to form artificial snow by mixing water from a faucet and compressed air. An air compressor (10 Gal. 2.9 HP, California Air Tools) is used to increase the air pressure supplied to the snow gun, which is then mixed with water to create a water-air mixture of 98% with a flow rate of 0.27 g/s. Pressurized air (300 kPa) and room-temperature water are supplied through two inlets, which are then mixed together. The water-air mixture is then released from the snow gun through a converging nozzle at the outlet, after which dispersed water droplets convert into artificial snow due to the room's low air temperature. The snow gun is placed 3 meters away from two samples that are made of 15.3 x 15.3 cm^2 PV glass with an aluminium frame attached to the bottom, each resembling a small portion of a PV module. The samples are angled at 25° from the horizontal. A camera (purchased from FDT) is used to monitor the real-time footage of the indoor experiments. The real-time snow LWC and surface temperature measurements on the glass samples is done using a surface mountable LWC sensor [15]. The measured LWC and surface temperature values are collected using a data acquisition (DAQ) system (CR1000, Campbell Scientific).

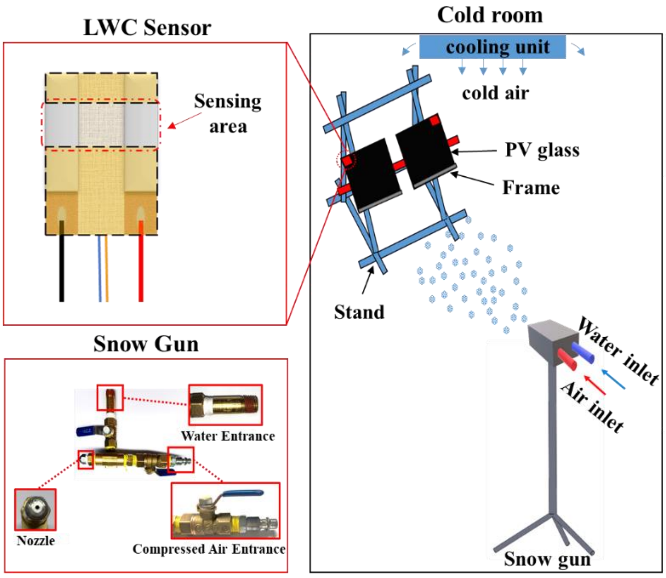

Fig. 1 A schematic of the indoor snow experiments inside a walk-in freezing room, showing the formation of artificial snow using a snow gun. A sensor is installed on the glass surface of each sample to monitor the LWC of snow during its accumulation and removal.

III. Results

Several indoor experiments are performed to study the effectiveness of coating on snow removal from the PV modules. Snow removal is studied under two heat transfer modes of free convection and shortwave radiation. The free convection experiments are executed by setting the freezing room temperature to 0°C (after snow formation and accumulation), while the shortwave radiation experiments are carried out using a halogen lamp to simulate solar radiation.

A. *Snow Removal During Convection*

An average thickness of 42 mm of snow is first accumulated on the two samples (bare/control and coated) as shown in **Fig. 2(a)**. To simulate prolonged snow melting, an ice layer is formed at the glass-snow interface by taking the samples with the accumulated snow on them outside of the freezing room for a couple of minutes where the temperature outside the freezing room was 23°C. This enabled slight melting of snow and formation of more liquid water at its interface with the substrates. The samples are then placed inside the freezing room for 3 hours at a - 6°C temperature to freeze the liquid water layer at the interface, transform it into an ice layer. Ice formation at the interface can cause the snow/ice layer to remain on PV modules for many days due to ice having a significantly stronger adhesion to surfaces than snow [16]. After that, the freezing room temperature was set to 0 °C (**Fig. 2(d)**) to simulate free convection. After 7.3 hours from starting the free convection (**Fig. 2(b)**), the coated sample experienced complete snow/ice shedding. This is due to reduced adhesion of the snow/ice to the coated sample. In addition, snow melting begins slowly and progresses, forming a liquid layer at its interface with substrate that leads to its sliding. However, the same accumulated snow remained on the bare/control substrate for 30 hours until it was removed (**Fig. 2(c)**) due to gradual melting and few jumps in air temperature since the freezing room routinely undergoes a resting time every 6 hours (**Fig. 2(d)**) which facilitated snow removal from the bare substrate. This indicates around 23 hours earlier removal of the snow due to the coating.

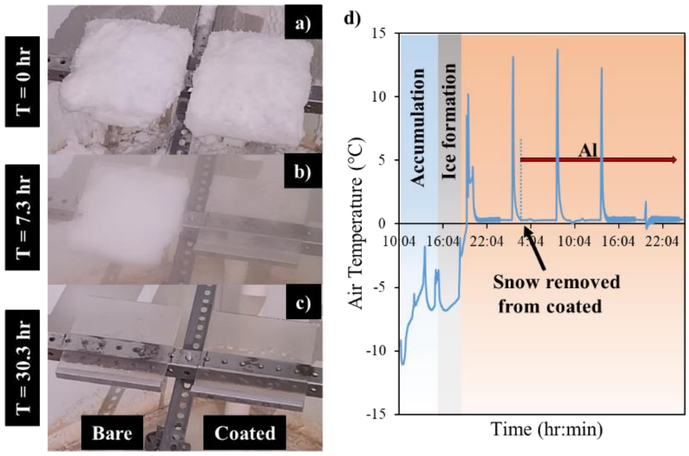

Fig. 2 The coating improved snow removal during free convection. a) Shows 42 mm thick snow accumulated the samples (Time of T = 0). b) Shows snow removed/detached from the coated sample (in right) after T = 7.3 hours. c) Shows snow melted from control/bare sample (in left) with significant delay at T = 30.3 hours. d) Plot of air temperature vs. time during snow accumulation and removal.

B. *Snow Removal During Solar Radiation*

Similar to previous set of experiments, dry snow (LWC of ~ 6%) with an average thickness of 43 mm of was accumulated on two samples (bare/control and coated) to examine effectiveness of the coating on snow removal during solar radiation. To simulate the effect of shortwave radiation on snow removal, a halogen lamp with a type T bulb was placed about 1.5 meters from the tested samples. Also both substrates (bare/control and coated) were painted black to increase their absorption of radiation, which increases the surface temperature during snow removal. The average irradiance received by the samples was measured using DBTU1300 solar power meter (purchased from Amazon) to be 123 W/m^2, and the freezing room temperature was set at -5°C (**Fig. 3(d)**), mimicking harsh winter ambient conditions. Initially, snow starts to melt from the top surface due to shortwave radiation emitted by the halogen lamp, where its LWC increased from ~ 6% to ~ 30%, which was followed by formation of icicles at the bottom frame of each sample. This phenomenon occurs at subzero temperatures and is explained by modelling snow as a porous media[17], in which the water content of snow increases until reaching a saturation level. Since the modules are tilted, liquid water will drain the snow cover from the bottom aluminium frame, which freezes at outdoor temperatures below 0 °C, forming icicles [13]. After 22.5 hours (**Fig. 3(b)**) of shortwave radiation, snow and ice present at the bottom area of the coated sample shed once its LWC increased due to slow melting, but this change wasn't detected by the sensor since snow wasn't present on the top area of the glass sample. This change in LWC of snow translates to reduction in its adhesion strength that leads to its shedding from the surface. However, the snow/ice layer remains for additional 6 hours on the bare/control substrate until it gradually melts. This difference is considerable and indicates effectiveness of the coating on snow/ice removal even at subzero temperatures (- 5°C).

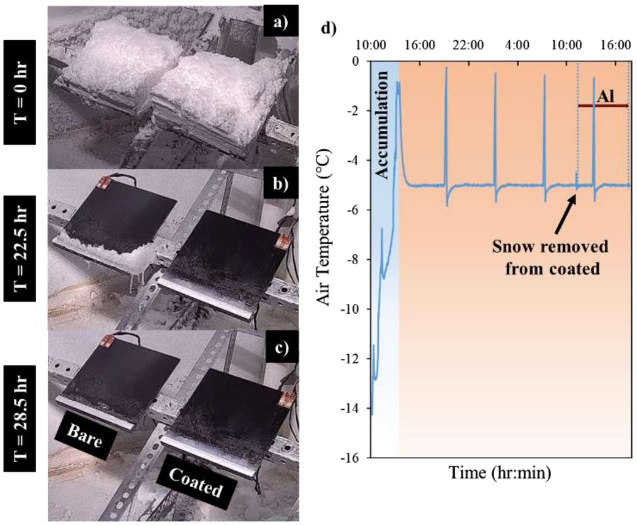

Fig. 3 Coating impact on snow removal under shortwave radiation. a) Snow with thickness of 43 mm and LWC of ~ 6% accumulated on bare and coated samples (Time of T = 0 hr). b) Snow removed from the coated sample at time of T = 22.5 hours. c) Shows snow removal from bare sample at time of T = 28.5 hours. d) Plot of air temperature vs. time during snow accumulation and removal.

IV. Conclusions

In this study, we examined effect of coating on snow removal from surfaces made of glass with aluminium frame resembling PV modules. The snow removal was studied during two heat transfer modes of convection and shortwave radiation. Using a snow gun, artificial snow was formed on two identical samples (glass with Al frame) inside a freezing room. To study the effect of convection on snow removal, the freezing room temperature was set to 0°C, where the coated sample allowed 23 hours earlier snow removal when compared to the bare sample. The effect of radiation was studied by using a halogen lamp at subzero temperatures. A weak irradiance was received by the glass surfaces (123 W/m^2) that caused slow snow melting from both surfaces, allowing formation of icicles at the bottom of each. The coated sample enabled 6 hours in advance snow removal, while the snow on the bare sample gradually melted. This study provide means to fully utilize power generation capacity of PV modules installed in areas with natural snow precipitation during winter seasons. Future studies will focus on examining effectiveness of these coatings on PV modules under natural snow and durability studies on the coatings.

Acknowledgment

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