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Passive Snow Repulsion: A State-of-the-art Review Illuminating Research Gaps and Possibilities

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Abstract

Building integrated photovoltaics (BIPV) are becoming more common every day. They are used everywhere, from the cabin in the mountains to the modern apartment building, and with more common use, strengths and weaknesses begin to reveal themselves more and more. In the regions of the world experiencing a colder climate, ice and snow coverage presents a challenge to productivity, BIPV resilience and longevity. Mechanically clearing snow and ice wears down the installations more quickly and may present a hazard to the people carrying out the clearing. Several research studies have been presented regarding the passive repulsion of ice and frost, while the repulsion of snow remains largely unexplored. This study aims to concisely present a review of what has been published in the field regarding snow repulsion and illuminate the research gaps and thus pave the way for future research. The snow aspect is illuminated by employing strategies previously applied to icephobicity research. A special emphasis is put on the comparison between microstructured, nanostructured and hierarchically structured surfaces as these constitute the basis of most icephobic (pagophobic) strategies.

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Keywords: Snow; Icephobic; Snowphobic; Frigophobic; Pagophobic; Chionophobic; Building integrated photovoltaics; BIPV; Microstructure; Nanostructure; Hierarchical structure; Review; State-of-the-art

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1. Introduction

Removing snow and ice from building integrated photovoltaic (BIPV) installations is a necessary step to maximize electricity production through the winter months in regions that experience significant snowfall. This is an activity that can be accompanied by a risk of personal injury (e.g. from falling off a slippery roof) and of damaging the modules with various tools. A BIPV solution with a surface that passively sheds snow would effectively eliminate this risk and ensure continuous production throughout the year. Also, the risk of irreversibly damaging an integrated part of a building envelope is potentially expensive to rectify, making the passive clearing of snow and ice that much more important.

A lot of recent work has been carried out in the field of passively de-icing surfaces [1–5] and the terms icephobic and pagophobic were invented to describe these surfaces. Passive snow repulsion or shedding, however, is a largely unexplored area. In this study, possible strategies are explored and recent research reviewed in order to illuminate challenges and future research opportunities. In keeping with scientific tradition, snowphobic surfaces will hereafter be referred to as chionophobic surfaces (chion = snow (Greek)).

2. Ice versus snow

While significantly different phenomena, ice and snow accumulation are intimately related. As reviewed in a previous study [6], ice will commonly accumulate via a liquid stage whether it be glace, frost or rime. This makes the successful application of a superhydrophobic surface, a realistic potential solution. Snow differs from ice in that it is comprised of an agglomeration of snow crystals, liquid water and air; all in varying relative quantities. This gives snow a wide range of physical characteristics depending on composition and ambient conditions. Snow crystals also come in a great variety of morphologies, ranging from simple hexagonal prisms to the more famous dendritic forms [7–10] (*see figure 1*). This further adds complexity to the range of physical behaviour snow can display.

Snow has been defined by Sojoudi et al. [3] as "dry" at temperatures below -1°C to -2°C and "wet" above the same. The same definition was previously made by Glenne et al. [11] but with a limit at 5°C and Pfister et al. [12] observed a limit of snow cohesion at -3°C. This implies some ambiguity as to what can be defined as "wet" and "dry" snow. A more stringent treatment could be as a continuum of compositions containing air, water and snow crystals (*see figure 1*). Each continuum will, however, only be valid for one crystal morphology and can be strongly affected by the level of inter-crystal bonding of the snow.

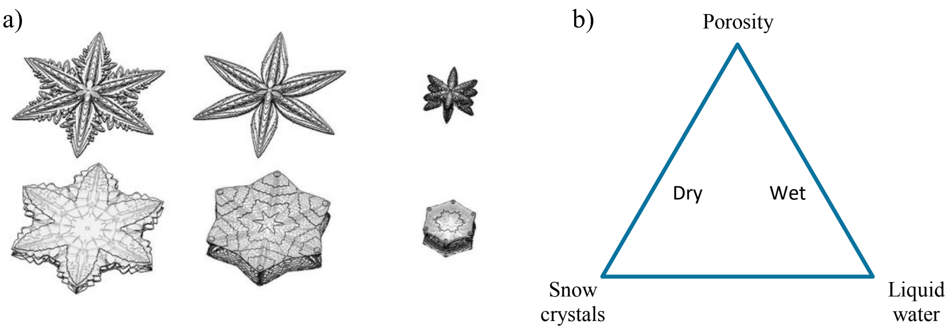

Fig. 1. (a) Snow crystal morphology examples as shown by Kelly et al. [10]; (b) Suggested compositional view of snow depicted as a ternary diagram, yielding a more dynamic definition of "wet" and "dry" snow. (The figure may appear to suggest the existence of porous water, which is incorrect. It is merely a representation of the coexistence of the three components)

3. Snow repulsion and shedding strategies

Snow crystals can have several hundred different types of morphologies depending on the thermodynamic conditions in the atmosphere at the time of their formation [8, 9]. This can make it very difficult to accurately predict the behaviour of snow in the general sense. In a previous study [6], strategies for preventing icing and the passive removal of ice were reviewed, but strategies catering specifically to the removal of snow and prevention of snow accumulation were largely omitted. In the following subsections, the most promising pagophobic strategies are reviewed with regards to chionophobicity and superhydrophobicity is given a special emphasis as the foremost promising pagophobic strategy.

3.1. Using superhydrophobic surfaces against snow

Similar to the accretion of ice, snow accumulation can be assumed to be aided by the onset of frost on a surface. Frost effectively alters the apparent surface exposed to the natural elements, to a rough, cold surface that is ideal for the adhesion and growth of ice, and likely snow as well. This speaks to the advantage of using a pagophobic strategy to achieve chionophobicity as well.

The porous nature of snow allows it to act as a thermally insulating material with thermal conductivity between about 0.04 W/mK [13] and 0.9 W/mK [14, 15] depending on snow density, water contents etc. This allows it to trap heat beneath even a very thin layer of snow. Andrews et al. [13] argue that this, in combination with the optical transparency of a thin snow layer, might be able to accumulate heat like a greenhouse, melting the inner most snow layer. The liquid water would then act as a lubricant at the interface to aid the snow in sliding on the underlying surface.

An obvious limitation of this strategy is the severely reduced transmission of solar radiation through thick layers of snow. At 2 cm of snow, the reduction is approximately 80% and at 10 cm, the reduction is 96% [13]. In locations that experience significant snowfall, the heating effect might be severely reduced, or even negligible, following a heavy snowfall event. It has, however, been shown that a superhydrophobic surface aids dry snow sliding off a surface and reduces the adhesion strength of both wet and dry snow. Unfortunately, the sliding of wet snow is not facilitated. Instead, a hydrophilic surface has been shown to accomplish this [16].

A potential explanation of this behaviour is the sliding lubrication of a water film formed at the interface by the attraction of the hydrophilic surface, whereas this film is rejected by the superhydrophobic surface, leaving the dry snow crystals in contact with the surface and thus hindering the sliding behaviour. The lowered adhesion of both kinds of snow to the superhydrophobic surface, could be explained by the lack of surface wetting lowering the adhesive bonding between any water contents and the surface. Very dry snow would naturally lack this adhesive effect, and could possibly be further aided by the reduced surface exposure offered by a nanostructured surface and/or the repelling effect between water molecules and a fluoropolymer.

3.1.1. Structured surfaces

There are, broadly speaking, three types of structured surfaces commonly associated with superhydrophobicity and pagophobicity. Microstructured, nanostructured and hierarchical surfaces. In the case of ice- and frost prevention and removal, the nanostructured and hierarchical structures have shown the most promise while microstructured superhydrophobic surfaces suffer from complete loss of pagophobicity at the onset of frost accretion within the structure [17].

Of these, the hierarchical surface has the potential advantage of reducing the effectively exposed surface area. This minimizes thermal conduction and friction, while allowing for the capturing of air beneath a falling water droplet, possibly allowing it to bounce on the surface without being pinned in a Wenzel state [1, 4]. A potential drawback of the hierarchical structure could be the physical hindrance of snow crystals from the micro-scaled structures. It is a possibility that dendritic crystals, for instance, get caught in some structure designs and hinder successful repulsion and sliding. Well controlled experiments could potentially elucidate this matter and present further possibilities of chionophobicity surface designs.

The strictly nanostructured surface could potentially serve as a compromise. It might lack the extra apparent surface reduction of a hierarchical surface, but has the advantage of increased smoothness. It might also offer a simplified production more suitable to large scale production. One could also imagine a hierarchical surface with preferential directionality in an obvious sliding direction, similar to the three-dimensional structures produced by Kako et al. [16].

3.1.2. Liquid infused surfaces

Liquid infused surfaces (LIS) still remain unexplored as chionophobic alternatives. Though they hold great promise as pagophobic surfaces, the liquid surface that so effectively retards frost formation and ice accretion [18] could potentially counteract the desired repulsion of snow by adhesive effects between the snow crystals and the liquid surface. By strategically selecting the lubricating liquid, however, this issue could be addressed and with sufficient experimentation, it might hold an important key to the successful repulsion of snow.

A related surface design is the slippery liquid infused porous surface (SLIPS) [19, 20]. The strategy of these closely resemble that of LIS surfaces but attempt to counteract the depletion of lubricating liquid by infusing it into the underlying material, allowing it to act as a lubricant buffer while counteracting depletion. There has been significant research conducted on these surfaces with respect to pagophobicity but not with respect to chionophobicity.

3.1.3. Smooth surfaces and hybrid surfaces

Other superhydrophobic approaches to pagophobicity include the use of smooth fluoropolymers, like polytetrafluoroethylene (PTFE) [21] or the hybridization of polydimethylsiloxane (PDMS) material with the SLIPS strategy [5]. These have shown very promising results as pagophobic materials and are interesting candidates for testing as chionophobic surfaces.

A more recent development, magnetic slippery surfaces (MAGSS), has been the application of a ferromagnetic superhydrophobic liquid to a magnetic surface, magnetized in a pattern to raise the liquid in a way that resembles that of a microstructured surface [22]. This surface has the advantage of self-healing and frost repulsion seen in LIS and SLIPS while being simultaneously smooth and structured. This allows for a reduction of exposed apparent surface area and, consequently, reduces the thermal conduction and friction. If this can be viewed as a passive surface could be debated, but it should not consume any of the electricity generated by the BIPV installation if permanent magnets are utilized.

3.2. Balancing repulsion of both wet and dry snow

The adhesion and sliding of snow on superhydrophobic and hydrophilic surfaces was evaluated by Kako et al. [16]. Both were found to be advantageous under different circumstances. The superhydrophobic surface was found to prevent adhesion of both wet and dry snow while facilitating the sliding of dry snow. The hydrophilic surface, on the other hand, was found to facilitate sliding of wet snow. This was then followed up by experiments where hybridized surfaces with both hydrophobic and hydrophilic elements were tested, showing, as could be expected, a behaviour close to the weighted average of the surface distribution [16].

These experiments have one significant point of critique, however. They used synthetic replacement for natural snow, consisting of water suspended porous glass beads. While this may simulate the viscosity quite accurately, the particle interactions with the surface and between the glass beads may not correctly simulate that of natural snow. The surfaces prepared for these experiments might behave quite differently when exposed to natural snow.

In addition to balancing the repulsion of wet and dry snow, there remains the need to repel frost and ice accretion as well. As the optimal strategies for each might differ, it could be that a compromise must be made. In such an event, it might be beneficial to tune the compromise to each application and location. A façade mounted BIPV solution might have a greater need for pagophobicity while a roof mounted BIPV system might have a greater need of strategies beneficial to chionophobicity.

3.3. Building integration for optimization of snow shedding

An advantage of BIPV installations is the great variety of integration that can be utilized. Photovoltaic (PV) panels can be applied on facades, roofs, ornamentations, in windows and so on. In urban locations with tall buildings situated in close proximity, the more advantageous placement might be on the roof, as this minimizes the shading. For such applications it might be possible to tailor the surface of the PV modules for the reduced sliding angle.

For buildings situated in a more spacious manner, it might be advantageous to place the BIPVs on the façade or incorporate them in the windows. This could be advantageous, not only to the shedding of snow and ice by the vertical surface, but could actually generate more energy in winter than roof mounted BIPVs [23]. Owing to the increased albedo effect of a snowy country, the façade could, despite the less optimized solar radiation angle, capture more solar radiation in the winter.

There might also be an angle, optimized for each location depending on expected albedo effects, at which a façade or roof might enjoy the maximized effect of both radiation angle and albedo effects while allowing for maximized sliding effect. This would then have to be considered from a net annual production standpoint to optimize the production economy of the installation and, as a result, the economy of the building.

Integration of PVs into buildings should thus start in the early stages of building design, as an integral part of the functionality of the building. This ensures sufficient power generation for the desired purposes, allows for a perfect fit of BIPV modules to building standards and the financial aspect of the installations is given more transparency to the commissioning party.

4. Future research opportunities

As mentioned previously, the superhydrophobic strategies applied to pagophobicity would be very interesting to evaluate with respect to chionophobicity. A comparison of the dry strategies (structured surfaces and fluoropolymer surfaces) to the wet strategies (LIS and SLIPS) would also be a very interesting aspect to have elucidated. It should, however, be performed with as realistic snow as can be managed, in order to deconvolute the effects of different snow types and different ambient conditions.

The mentioned combination of superhydrophobic and hydrophilic surfaces would also be of interest to further develop. Different geometries with different materials and strategies could be employed and focused in a way that optimizes the geometries to the applied surface orientation and application.

Another possibility for the future is the albedo effect. Acquiring quantitative evidence of how much this effect the energy production under different circumstances and possibly determining a method for predicting it, would be of great importance to future building integration strategies.

Aspects that have not been mentioned above, that would be of great interest to research further, include the following:

- Assess the thermodynamic albedo effects of a black backside of free-standing PV systems. It has been mentioned by Ross et al. [24] as a potential solution for freestanding PV installations.
- For each surface evaluated, there should be a minimum angle for snow sliding that can be calculated. This should also be combined with a comparison between snow types and ambient conditions.
- A closer assessment of the sintering and melting behaviour of snow would be interesting as this could potentially affect the sliding behaviour of snow in a significant manner.
- Avalanches have been studied for many years in the hopes of better understanding and predicting where and when they will occur. This research could potentially be adapted to the sliding of snow on engineered materials like roof tiles and façade mounted BIPVs.

5. Concluding remarks

Building integrated photovoltaic (BIPV) installations in countries with significant precipitation in the form of snow, experience a loss of energy production due to the physical obstruction of solar radiation by snow. The efficient removal of this snow remain a largely unexplored, yet very important, area. Herein, a concise summary of possible research topics and opportunities is presented along with a summary of existing research presented on the topic.

It appears evident that there is a wide range of topics to be studied and the benefits of a successful future strategy should be a strong motivator for funding the research. The field is closely related to pagophobicity with potential applications in areas like aeronautical, nautical and automotive industries, besides the significance to the growing BIPV industry. As such, chionophobicity could be of significant interest to these same industries as well as building segment manufacturers in general.

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