

THOMAS THIIIS\*, ALMERINDO D. FERREIRA\*\*, MARKUS MOLNAR\*,  
ARNOLD V. ERICHSEN\*

## CHARACTERIZATION OF SHEAR STRESS DISTRIBUTION ON A FLAT ROOF WITH SOLAR COLLECTORS

### CHARAKTERYSTYKA ROZKŁADU NAPRĘŻEŃ STYCZNYCH NA PŁASKIM DACHU Z KOLEKTORAMI SŁONECZNYMI

#### Abstract

In the search for new renewable energy sources, photovoltaic systems and solar thermal collectors have become more common in buildings. With increased efficiency and demand for energy, solar power has also become exploitable at higher latitudes where snow is a major load on buildings. For flat roofs, one usually expects approximately 80% of the snow to be eroded off the roof surface. Installing solar panels would change this since the flow pattern and wind conditions on the roof are affected by their presence. This study shows the erosion of sand particles from underneath solar panels of various configurations associated with different wind velocities. The pattern of erosion is used to determine the relative friction velocity,  $u_{REL}$ , of the wind on the roof. This value is the friction velocity on the roof relative to the friction velocity on a flat roof without solar panels. The experiments, conducted in a wind tunnel, show that the area where  $u_{REL}$  is 0 and where it is expected that sand and snow will accumulate in case of an upwind particle source and decrease with increasing distances between roof and solar panel. It is also shown that a larger gap between the solar panel and roof surface creates larger erosion zones, where  $u_{REL} > 1$  for both wind directions. Since the erosion is closely linked to the air flow under the solar panels, and that higher air velocity increases the erosion, it is likely that a larger solar panel, extending higher into the free air flow would be desirable to avoid snow accumulation on a flat roof with solar panels. If the solar panel has large enough dimensions, the solar panels can be used as a deflector to decrease snow accumulation on flat roofs. With solar panels of the size in the current experiments, a building with a length smaller than the equivalent of  $x/L = 0.3$  would have  $u_{REL} > 1$  on most of the roof surface and would thus likely have a lower snow load than an equivalent flat roof without solar panels.

*Keywords: wind engineering, wind tunnel, snow load, environmental actions, wind erosion*

#### Streszczenie

Wraz ze zwiększoną efektywnością i zapotrzebowaniem na energię, energia słoneczna stała się możliwa do wykorzystywania w większych szerokościach geograficznych, gdzie śnieg jest głównym obciążeniem budynków. W przypadku płaskich dachów, można się spodziewać, że 80% śniegu jest zwiwiane z jego powierzchni. Po zainstalowaniu paneli słonecznych, sytuacja ulega zmianie, gdyż przepływ powietrza i warunki wiatrowe na dachu zmieniają się. Praca przedstawia erozję ziaren piasku spod paneli słonecznych, w różnych układach, przy różnych prędkościach wiatru. Forma erozji jest wykorzystywana do wyznaczania względnej prędkości tarciowej,  $u_{REL}$ , wiatru na dachu, względem dachu bez paneli. Doświadczenia w tunelu aerodynamicznym wskazują obszar, gdzie  $u_{REL} = 0$  i gdzie piasek i śnieg będą się zbierać w przypadku źródła ziaren w napływie i zmniejszać się wraz ze wzrostem odległości między dachem i panelem słonecznym. Większy odstęp między panelem i dachem przyczynia się do zwiększenia obszarów erozji, gdzie  $u_{REL} > 1$ , dla obu kierunków wiatru. Ponieważ erozja jest silnie związana z przepływem pod panelami, a większa prędkość powietrza powoduje wzrost erozji, prawdopodobne jest, że większy panel słoneczny, sięgający wyżej w przepływie powietrza, jest pożądany, aby uniknąć gromadzenia się śniegu na powierzchni dachu. Jeśli panel ma wystarczająco duże wymiary, może zostać wykorzystany do zmniejszenia gromadzenia się śniegu na dachu. W przypadku paneli słonecznych w rozmiarach użytych w badaniach, budynek o długości mniejszej niż  $x/L = 0,3$  ma  $u_{REL} > 1$  na większości powierzchni dachu i będzie charakteryzować się mniejszym obciążeniem śniegiem, niż na odpowiednim dachu bez paneli słonecznych.

*Słowa kluczowe: inżynieria wiatrowa, tunel aerodynamiczny, obciążenie śniegiem, oddziaływania środowiskowe, erozja eoliczna*

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\* Department of Mathematical Science and Technology, Norwegian University of Life Sciences, Norway.

\*\* ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Portugal.

## 1. Introduction

Solar radiation is a form of power that is being increasingly utilized. The increased popularity is connected to the improved efficiency of photovoltaic systems and the decrease in production costs. In the search for new renewable energy sources, the solar thermal collector has also become more frequent in buildings. Common for these two principles are that they need large areas facing the sun to have adequate effect. Since these systems are generally light weight, this has led to installations on top of flat roofs. This brings the systems out of the public space and uses areas that otherwise would have been unused. One drawback of placing solar panels on roofs is that they become exposed to higher wind speeds than if placed on the ground. This has been investigated thoroughly and there are now several guidelines on wind loads on solar panels, e.g: NVN 7250 [10] and BRE Digest 489 [2].

With increased efficiency and demand for energy, solar power has also become exploitable in higher latitudes where snow is a major load on buildings. Snow load on roofs is usually a combination of a drift load and a balanced load [7]. Usually, the drift load consists of the snow that is accumulated in sheltered areas of the roof and the balanced load that is calculated as the fraction of the ground snow load which is not eroded by wind. For flat roofs with no drift load, this fraction ranges from 70% for a wind exposed roof, 84% on a normally exposed roof to 96% for a sheltered roof. The corresponding fractions in the Eurocode are 64% for an exposed roof, 80% for a normal roof and 96% on a sheltered roof.

When placing obstructions to the wind flow on a flat roof, such as solar panels, there will also be sheltered zones where snow can accumulate in snow drifts. The snow load standards describe how to calculate snow loads around such obstructions if they are continuous all the way down to the roof. This usually constitutes a considerable extra snow load. However, if the solar panels could be mounted with an air gap between the roof and the obstruction, this is likely to create a speed increase under the panel. This will prevent snow drift accumulation, thus reducing the snow load. This effect was studied by Tabler [13] in connection with snow fences, which have the function of collecting snow to avoid problems on roads and infrastructure. However, solar collectors are located close together and the aerodynamic effects of the closely grouped solar collectors are different than in the case of snow fences. Tabler [12] also describes so-called deflectors the purpose of which is to deflect wind to avoid snow accumulation. Additionally, Thiis et al. [14] investigated the use of deflectors on buildings to reduce problems with snow accumulation.

Being a granular material, the physics of snow transport has several similarities to the physics of sand particles. One important physical feature of snow erosion is the threshold friction velocity. This is the friction velocity, exerted by the wind on the snow surface, below which snow transport ceases [11]. Viegas and Borges [15], and also Ferreira [4], have used the erosion technique to determine the relative wind exposure of an area. Such technique consists of a thin layer of sieved and calibrated sand that is exposed to gradually larger wind speeds. The eroded contours are recorded using a digital video camera, for later image treatment. Using such an experimental technique, areas of larger exposure, i.e., of higher friction velocity, can be quickly identified.

Sand has been used as granular material for determining snow accumulation. Zhou et al. [16] has analyzed three different materials and concludes that silica sand of diameter 0.2 mm gives good results in reproducing full scale accumulation patterns of snow drifts on a multilevel roof in a wind tunnel using a model with a height of 240 mm.

This study aims to analyze the wind exposure of a flat roof surface equipped with several configurations of solar collectors. Both the distance between the roof and the solar collector and the spacing between the collectors are investigated. Since the erosion is an important mechanism in determining the snow load on roofs, this might be a support in developing future provisions for snow load codes. The equipment and method used is similar to what was used in Ferreira [4].

## 2. Method

The experimental tests were conducted on the wind-tunnel installed in the Industrial Aerodynamics Laboratory – University of Coimbra. The test chamber of the wind-tunnel is 5m long, no roughness elements were used to control the boundary layer thickness and shape due to its relatively short length. The approaching wind and turbulence profiles, measured upstream, have the shapes shown in Fig. 1. The wind profile can be fitted by a power law ( $u/U_0=(z/\delta)^\alpha$ ), where  $\alpha = 0.11$  and  $\delta = 0.4$  m [6],  $U_0$  is the undisturbed wind speed, and  $\delta$  the boundary layer thickness. The turbulence intensity ( $i$ ) can be assumed as being close to 15%.

The tests were conducted using the sand-erosion technique [15], for which a 1 mm layer of sieved and calibrated sand is exposed to gradually larger wind speeds. The sand used has a prevailing grain diameter equal to 0.5 mm, to which correspond a threshold shear velocity,  $u_{*0}$ , of approximately 0.33 m/s [5]. Each wind speed was maintained for 120 seconds, which was the observed time interval necessary to define the eroded contour. The contours were recorded continuously using a digital video camera for later image treatment. Although the video was recorded continuously, just the contour images, each one of them defined after 120 s of constant wind speed, are shown in section 3. Using such an experimental technique, the areas of larger exposure were quickly identified.

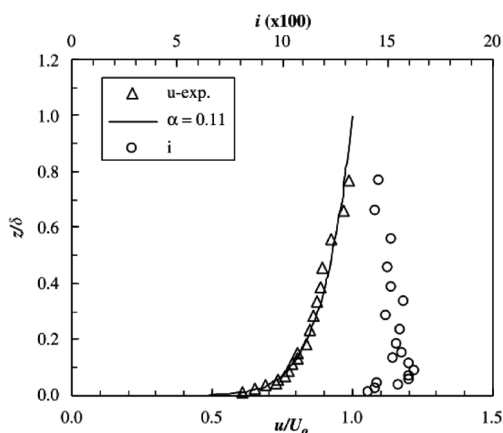


Fig. 1. Streamwise mean velocity component ( $u$ ) and turbulence intensity ( $i$ ) profiles, measured at the center of the wind tunnel test chamber ( $z$  – vertical coordinate;  $U_0$  – undisturbed wind speed;  $\delta$  – boundary layer thickness) [6]

The building model used in this study represents a typical three-story building with solar collectors installed on its roof. It is made at 1:25 scale with dimensions  $H \times W \times L = 30 \text{ cm} \times 120 \text{ cm} \times 60 \text{ cm}$ , as shown in Fig. 2. The model solar collector has a height of 75 mm and a thickness equal to 8 mm. This represents a solar collector of approximately 2 meters in height and a thickness of 20 cm.

The distances between the roof and the solar collectors varied from 8 mm to 16 mm and 24 mm, corresponding to approximately 20 cm, 40 cm and 60 cm in full scale. The angle of the solar collectors, relatively to the horizontal, was set at  $70^\circ$ , assuming a relatively high latitude. In this study, the undisturbed wind direction was set as perpendicular to the longest side of the model and thus, also to the solar panels. Both a positive inclination (solar panel leaning against the wind) and a negative inclination were tried. The combinations of 2, 3 and 5 rows of solar panels were tested. In the case of 2 rows of panels, panels no. I and V were used. The case of 3 rows used panels no. I, III and V, whereas the last case included all the rows of solar panels. A total of 19 different experiments were accomplished including the reference case without panels.

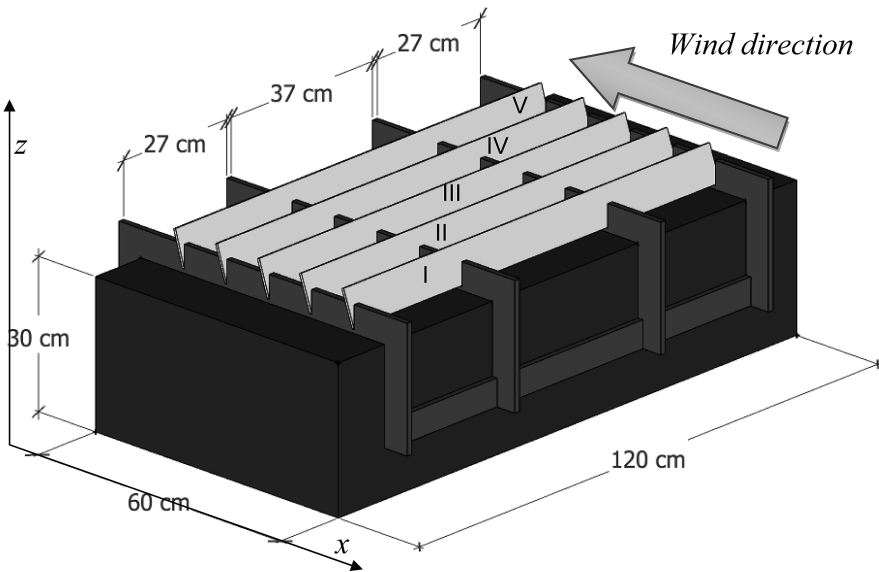


Fig. 2. Model with five rows of solar panels and negative inclination

In the post processing of the data, the erosion on the building model without solar panels was used as a reference to normalize the data. Since friction velocity is directly proportional to velocity following the logarithmic wind profile close to the boundary, it is possible to determine the relative friction velocity at which sand erodes,  $u_{*REL}$ , as given by Eq. (1):

$$u_{*REL} = \frac{u_{e0}}{u_{ePANEL}} \quad (1)$$

where  $u_{e0}$  is the undisturbed velocity in the wind tunnel, upwind the model at roof height without solar panels at which sand erodes on a specific part of the roof and  $u_{e\text{PANEL}}$  is the velocity at the same spot with solar panels mounted.

### 3. Results and discussions

The post processing of the pictures taken during the wind tunnel erosion experiment involved combining various pictures of erosion contours, each one corresponding to a different undisturbed wind velocity, into one picture for each configuration. The area from which sand was eroded was colored with a different color for every wind velocity. Fig. 3a shows the erosion pattern on the reference case without any solar panels mounted and Fig. 3b shows one example of the erosion pattern for the configuration of five rows of solar panels with an 8 mm gap between the solar panel and the roof and a negative inclination towards the wind. As mentioned in section 2, silica sand ( $\rho_p = 2650 \text{ kg/m}^3$ ), with a prevailing grain diameter equal to 0.5 mm, was used in these experiments as a modelling particle. The corresponding threshold friction velocity ( $u_{*t}$ ), as given by Eq. (2), where  $\rho$  is air density, and  $A = 0.1$  [1], is approximately equal to 0.33 m/s.

$$u_{*t} = A \sqrt{\frac{(\rho_p - \rho)}{\rho} g d} \quad (2)$$

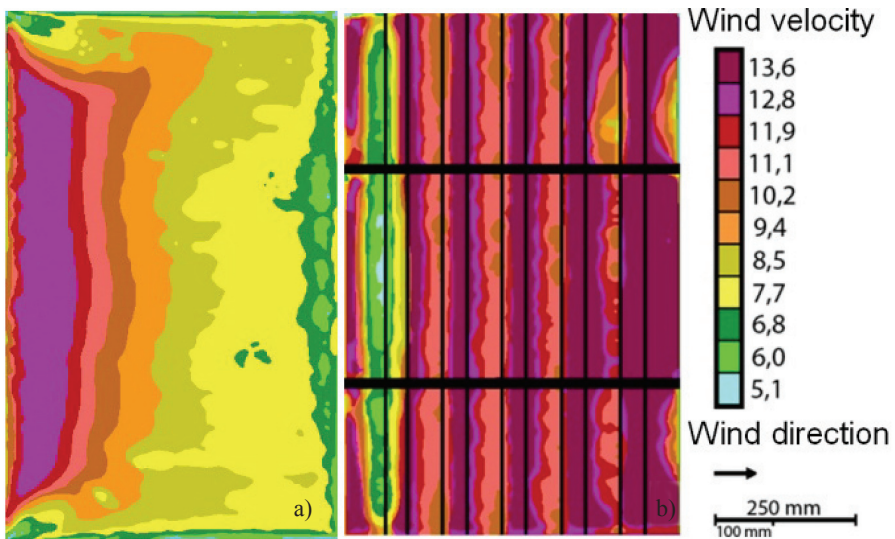


Fig. 3. Erosion pattern at different velocities, a) reference case without solar panels, b) 5 rows of solar panels, 8 mm gap, negative inclination towards the wind (wind from left to right)

Such a threshold velocity ensures that, according to Kind [9], the flow field in the tests is fully rough, as:

$$\left( \frac{u_{*f}^3}{2g\nu} \right) \approx 120 \geq 30 \quad (3)$$

The use of such sand particles makes certain that saltation of these high density particles ( $\rho_p / \rho \geq 600$ ), is dynamically similar to those of real snow in air, even though this implies abandoning the Froude-number similarity requirement, as discussed by Kind and Murray [8]. For a thorough discussion on the similarity requirements, the references of Kind [9] and Zhou et al. [16], e.g., are recommended.

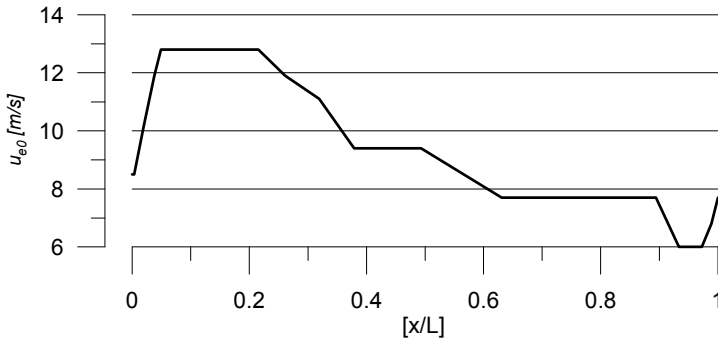


Fig. 4.  $u_{e0}$  distribution on the flat roof model without solar panels, along the symmetry plane parallel to the wind direction

Fig. 4 shows  $u_{e0}$ , the undisturbed velocity in the wind tunnel upwind the model at roof height at which sand erodes on a specific part of the flat roof without panels, along the longitudinal symmetry plane. (The Fig. 4 is the result of multiple wind tunnel runs with different wind velocities and is in fact the wind velocity along the symmetry plan in Fig. 3a).

The relative friction velocity was calculated along the symmetry plane, parallel to the wind direction. A value of  $u_{*REL} = 1$  indicates the same friction velocity on the roof surface as is the case of the roof without solar panels. A value of  $u_{*REL}$  larger than unity represents a higher friction velocity on the roof with panels (for the same undisturbed wind speed); therefore, a larger potential for erosion of sand/snow. Conversely,  $u_{*REL} < 1$  reveal areas where the potential for erosion is lower than in the case of no solar panels. Values of 0 indicate areas where no sand is eroded even at the highest wind velocity tested (equal to 13.6 m/s). Therefore, areas of  $u_{*REL} = 0$  correspond to locations where it is likely that snow will accumulate in the course of snowfall coinciding with wind. The solar panels will then cause snow drifts on top of the roof which might be larger than in the case of the roof with no solar panels. Fig. 5 shows  $u_{*REL}$  distributions for the 9 experimental cases with negative inclination and Fig. 6 shows  $u_{*REL}$  for the other 9 corresponding cases with positive inclination. A low value of  $[x/L]$  indicates an upwind position.

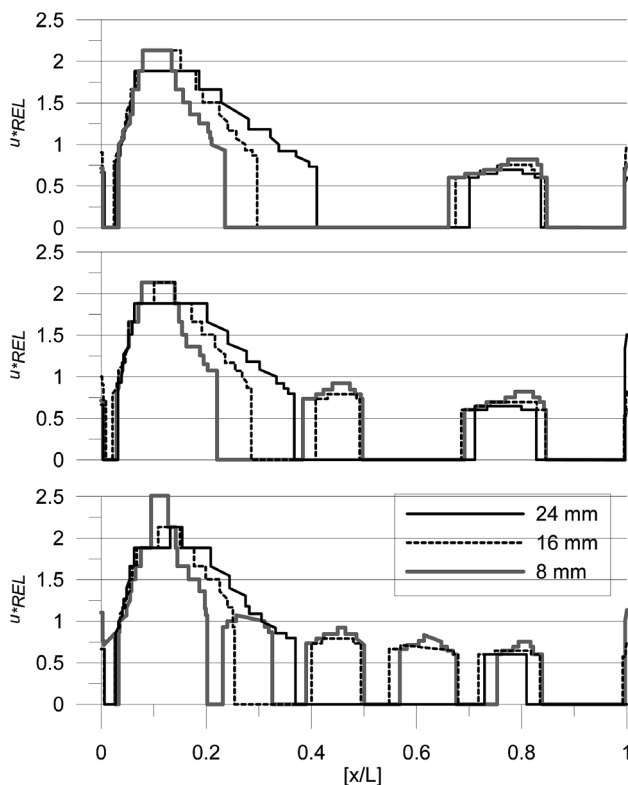


Fig. 5. Relative friction velocity for the experiments with solar panels with negative inclination: a) 2 panels; b) 3 panels; c) 5 panels

Generally, it can be seen from those two figures that the solar panels induce areas of increased relative friction velocity, but also some sheltered spaces where  $u_{*REL}$  is 0. From Fig. 5a it can be seen that an increased distance between the roof and the solar panel has two main effects. The most visible effect is that the area of erosion increases close to the most upwind panel; conversely, the eroded region is slightly decreasing around the downwind panel. The other effect is that  $u_{*REL}$  is slightly reduced in the case of the largest gap between roof and solar panels. The first is due to the Venturi effect creating the velocity speed-up below the solar panel. As the panel is moved vertically, more air is forced to flow between the roof and the solar panel – this promotes erosion and increases the size of the eroded zone. The most upwind solar panel is creating a zone with  $u_{*REL}$  larger than unity for a distance of approximately  $0.3 [x/L]$  downwind from the solar panel when the gap is at its largest distance from the roof. As the zone increases,  $u_{*REL}$  decreases slightly. However, the zone where there is no erosion and accumulation is expected to be relatively large. Comparing Fig. 5a to Fig. 6a (where the inclination of the solar panels is positive, i.e., the solar panel is leaning towards the wind), it is possible to see that a positive inclination creates a higher  $u_{*REL}$  and that the zone with  $u_{*REL}$  larger than unity extends up to  $0.6 [x/L]$  when the gap is at its highest. This is likely because the positive inclination is funneling air under the panels.

At the maximum distance between the panel and the roof, it also seems that the flow pattern around the downwind panel is different from the case with a gap distance of 16 mm. When the gap is at its largest, no erosion was observed experimentally underneath the downwind panel. However, it should be highlighted that erosion occurs under that panel at a 16 mm panel to roof distance and increases at an 8 mm distance. A similar tendency is visible in Fig. 5b which illustrates three rows of solar panels and negative inclination; there is no erosion underneath the center solar panel when the distance between the panel and the roof is at its maximum and erosion occurs at the smaller distances. Except for the erosion underneath the center panel, these measurements are quite similar to the case with two rows of solar panels. In Fig. 6b, the positive inclination causes the erosion zone to extend beyond the center row of solar panels in the cases of distances equal to 16 and 24 mm. However, the area where  $u_{REL} > 1$  is quite similar to the case with two rows of panels. This is also the case when five rows of solar panels are used; the area of relative friction velocity higher than unity is approximately equal for all experiments of same wind direction when the gap is 24 mm, Fig. 6c. In such cases, the sand is eroded from most of the roof. This is in contrast to cases with a negative inclination and a 24 mm gap, shown in Fig. 5c, where the five rows of solar panels gives approximately the same erosion pattern as in the case of tree and two rows. With smaller distances, there is local erosion underneath the solar panels.

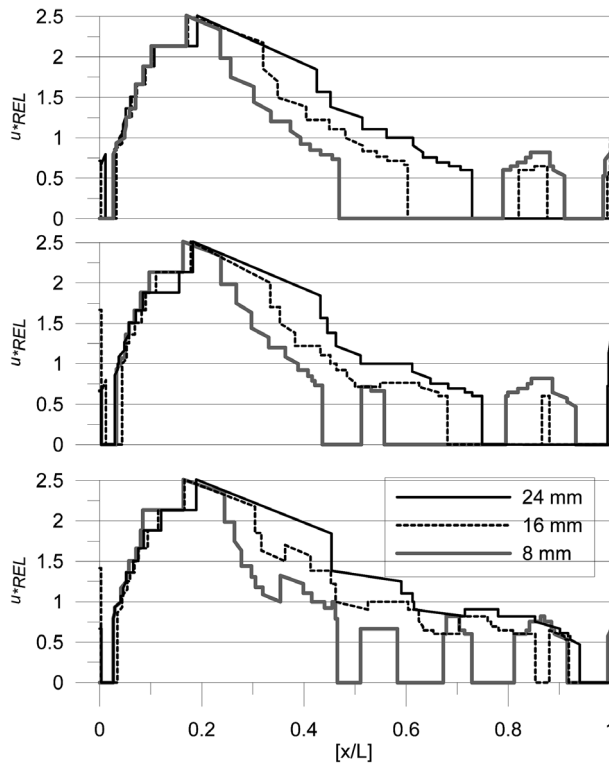


Fig. 6. Relative friction velocity for the experiments with solar panels with positive inclination: a) 2 panels; b) 3 panels; c) 5 panels



The areas where the relative friction velocity is 0 most likely correspond to locations where sand or snow would accumulate if there was an upwind particle source present. If these areas are too large, it might facilitate accumulation of significant snow loads in real cases. It is therefore desirable to avoid having such zones on a roof. Based on the present experiments, it can be assumed that a larger gap between the solar panel and roof surface promotes larger erosion zones where  $u_{*REL} > 1$  for both wind directions.

However, snow particles are different from sand in the sense that snow particles make interparticulate bonding within hours to days after a snow fall. This means that if snow falls in calm conditions and is then subjected to such metamorphosis, the snow surface will not erode easily. This might block the gap between the solar panel and the roof surface thus reducing the erosion of the snow surface.

The measurements indicate that elevating the panels increases particle erosion. Specifically, Fig. 5c shows that the elevated solar panel configuration creates airflow that also erodes the sand around panel number II. It is likely that this effect, partly caused by extending the solar panel into a height with a higher wind velocity, causes more air to pass underneath the panel. One way of increasing this effect further would be to make larger panels which would increase the air flow under the solar panel. It is likely that, if local accumulation of snow drifts is a problem, it would be preferable to have one large solar panel instead of several smaller ones.

Assuming that there is little change in the general wind pattern if the length  $L$  of the building is reduced, one might assume that if the length  $L$  had been smaller than the equivalent of  $x/L = 0.3$ , the whole roof would be more exposed to wind than the reference case; thus, they would have a lower snow load than a roof without solar panels. Above this length,  $u_{*REL}$  is larger than unity for both wind directions. The experiments concern only two wind directions. It is shown that negative inclination gives relative friction velocity lower than unity under all but the most upwind solar panel indicating that this is unfavorable compared to a roof without solar panels. Other wind directions might give even more unfavorable snow loading conditions – this has to be considered.

### 3. Conclusions

This study shows the erosion of sand particles placed underneath solar panels of various configurations associated with different wind velocities. The pattern of erosion is related to the relative friction velocity,  $u_{*REL}$ , of the wind on the roof. Locations where sand was not eroded were set to  $u_{*REL} = 0$  and those are areas where it is likely for sand or snow to accumulate if there is an upwind particle source present.

The experiments show that the area where  $u_{*REL} = 0$  decreases with an increasing distance between the roof and the solar panel. It is also shown that a larger gap between the solar panel and roof surface leads to larger erosion zones where  $u_{*REL} > 1$  for both wind directions.

Since the erosion is closely linked to the air flow underneath the solar panels, and that higher air velocity increases the erosion, it is likely that a larger solar panel extending higher into the free air flow would be desirable to avoid snow accumulation on a flat roof with solar panels.

If the solar panel has large enough dimensions, the solar panels can be used as a deflector to decrease snow accumulation on flat roofs. With solar panels of the size used in the current experiments, a building with a length smaller than the equivalent of  $x/L = 0.3$  would have  $u_{*REL} > 1$  on most of the roof surface and thus, would most likely have a lower snow load than on an equivalent float roof without solar panels.

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