Snow, ice and icicles on roofs – physics and risks

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SUMMARY*:*
Snow and ice is a typical winter problem. Icicles can hang at the eaves of roofs. The downfall of icicles can kill people. To prevent that we need to look at architecture, meteorology, glaciology and building physics. The physical theory for growth of icicles is described. The conditions for downfall of icicles are discussed. To get icicles to grow we need melting water from snow either from solar radiation or from the building heat loss. Two cases with icing on roofs show that ventilation in cold roofs is important to prevent the snow from melting. Heat cables can be used to prevent freezing of the melting water. Examples of problem areas in roofs are described. Finally we give some guideline to predict when we have growth of icicles and when the risk is high for downfall of icicles depending on climate conditions and the building.

1. Introduction

A typical winter problem is snow and ice on roofs. This can give a lot of problems that are related to building physics. An example is icing and generation of icicles on the roof edges. Icicles hanging from the eaves look nice but are a serious problem as they can fall down and hit people walking beneath. The impact of a falling icicle can in the worst case kill people. Such incidents have happen in Sweden and Norway. According to Swedish law, it is the owner of the building who is responsible for prevention of sliding of snow and ice from the building.

Figure 1. Building with icicles in Narvik. No pedestrian area below.

The Swedish Association of Buildings Owners (Fastighetbranchens Utviklingsforum) has made a report (Snö och is på tak 2004) about the problems of snow and ice on roofs. It describes some law cases and examples of contracts with a firm to remove the icicles, when they form in the winter. It is very helpful for the building owner as a basis for reducing the risk of snow and ice problems but it only sketches the physics behind the problem. A better solution is to prevent or at least reduce the risk by a better knowledge of icicles and how and when they form.

The problem with icing and icicles on roof is a complex problem involving architecture, meteorology, glaciology and building physics. The architect decides the layout of the building and the form of roof used. The architectural solution can reduce or increase the risk of icicle generation. The meteorology comes in, as we must know the weather that will permit the icicles formation and the periods with high risk for downfall of icicles. The glaciology has the information on the physics behind ice and snow. The building physic is important as heat air and moisture transfer in buildings is involved.

2. Traditional roofs

We can divide roofs in two types cold (ventilated) roofs and warm (non-ventilated) roofs. In warm roofs, it is normal to have internal drainage with downpipes in the building. This solution has no, or very little risk for icicles. Freezing of the melting water on the roof can still be a problem. Ventilated roofs introduce a ventilated gap or roof space to prevent moisture problems and to keep the surface of the roof cold. These roofs are in most cases sloped. The drainage is external to gutters along the eaves and to downpipes. The result is a high risk of icicles if the melting water freezes for instance in the gutter.

3. Icicles

Freezing of dripping water or melted snow forms icicles as in figure 1 and 2. It is found not only at roofs, but also in nature from trees, waterfalls, fences and so on. The form on the icicles is shaped as a cone or a spike with the thick end at the top. They are all different in details depending on the local conditions, as snow crystals are also unique. The source of the icicles is liquid water, so we need to have temperatures above the freezing of the water to generate the icicles. A water source at the root of the icicle will make a liquid film on the surface of the icicles that will cover the entire icicle if the flux of water is not very small. The thickness of the liquid film is 40-100 μm. To get the icicle to grow the air temperature must be below 0 C. When the icicle grows the latent heat from freezing must be taken from the ice-water interface. The heat loss rate from the surface to the surrounding will control the growth rate of the icicle. In cold temperatures, the freezing will go faster but also the humidity, wind speed and solar radiation is important. The heat loss from the surface to the air is mainly by thermal convection and by evaporation. Radiation to the surrounding is of minor importance and heat conduction in the interior of the icicle is negligible. When the water flow down the surface of the icicle parts of it will freeze. However, if the water supply is large enough a water drop will be formed at the end of the icicles. This drop grows until it reached a certain size around 5 mm in diameter and then falls and a new drop will be formed.

Figure 2. Icicles at roof eaves

Numerical models for icicle growth have been made by Makkonen (1988) and Maeno et al 1994.The model shows that the growth rate of an icicle under constant conditions is strongly time dependent. The elongation rate increases with time under fixed atmospheric conditions and water supply rate. This is mainly do to the increasing freezing area of the icicle as it get bigger and the decreasing drip rate. The grow rate in the width will decrease in time as the heat transfer coefficient decreases with increasing icicles diameter. Under fixed conditions will the growth rate increases until there is no drip and length growth stops. At that time is all the supply water collected by the icicle. The model suggests no upper limit for the size of an icicle if conditions for growth exist. In practice several factors limit the icicle size. If the water supply is high, the icicle will grow slowly and is unlikely to grow big. If the water supply is low, the icicle will soon stop to elongate as no flow reach the icicle tip. Very big icicles can therefore form under conditions in which the water supply rate is first small and then increases. This explains the formation at roofs where the flow rate is low in the morning and increases during the day from heat loss from the building and/or solar radiation on the snow covered roof surface to increase the snow melting water rate as the icicle grow.

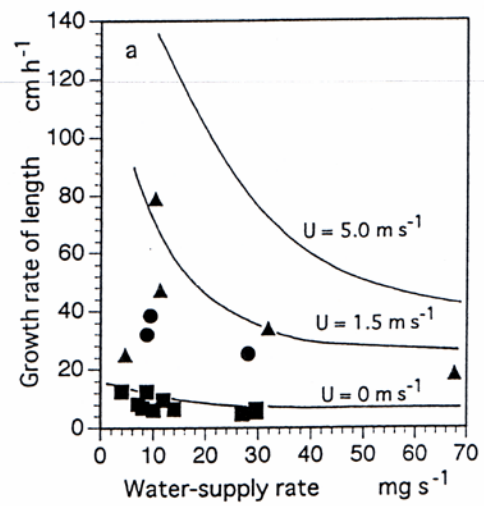

Fig. 7. Growth rates of icicles versus water-supply rate at a temperature around −10°C. a. Length, b. Diameter. ■: $U=0\ m\,s^{-1}$, ●: $U=1.5\ m\,s^{-1}$, ▲: $U=5.0\ m\,s^{-1}$. The curves are calculated rates in conditions $T=-10°C$, $R=75\%$, and $U=0$, 1.5 and 5.0 $m\,s^{-1}$.

Figure 3. Icicles growth – model (lines) and measurements (points) from Maeno et al 1994

The results of simulations and measurements on the length growth rate of icicles in Maeno et al 1994 are seen in figure 3. The conditions are –10 C, 75% RH and wind speeds of 0, 1.5 and 5 m/s. The growth rate increases very much with higher wind speeds because of the cooling from the airflow around the icicle. The growth rate can be 10 to 40 cm/hour. The measurement gives a lower effect of wind speed than from the theory. The water supply rate is important with the highest growth rate at a low water supply. The physical model shows that the conditions are important to reduce the risk from icicle generation. We cannot change the climate but we can try to control the melting of the snow and we can also design the roof so that icicle downfall does not give risk for pedestrians. The conclusion is that the worst case is low temperature, high wind speed and a water supply rate of 10 milligram/s. An estimate for the time to build an icicle of 0.5m with 2 kg ice is 5 hours and for 1 m with 20 kg of ice is 10 hours. The 1 m icicle will be dangerous if it falls from large height.

Risk analysis of falling icicles is seldom performed. Tool for such risk analysis involves environmental wind tunnels and numerical simulations as well as statistical analysis. The paper of Delpech and Leininger 2004 looks on icing from rain on structures especially cables.

4. Falling icicles

Having gutters along the street, where pedestrian walk, will always give a risk for falling icicles. A solution can be to have some type of garden along the façade of the building with a width of approximately 2 m, if the overhang is not more than 50 cm. Then the icicle will fall in the garden. Pedestrians must not walk in the garden area in the winter. A problem can then come from doors in the façade, but they have to have an overhang, which can protect against icicles. An alternative solution is to have doors at the gable end and no traffic along the length of the building. This solution is not easy to use for existing buildings in many towns where the building is placed along the pedestrian lane. In these cases we have to look on other possibilities to reduce the risk.

Icicles fall when the weight of the icicle exceeds the strength of the icicle. When does this occur? The problem is complex, but the temperature is expected to be above 0 C. A typical winter day we will have freezing during the night and above freezing during the day and possible solar radiation. In the freezing temperatures during the night and in the morning will the risk be low. When the temperature goes up risk will increase from the influence of both the increasing amount of melting water and solar radiation. My evaluation is that the risk is low in the morning and will increase during the day. The highest risk will be in the afternoon in days without solar radiation. If we have solar radiation the risk will increase and will depend on the orientation and slope of the roof. If we have solar radiation on the roof surface before 12 will the risk increase in the late morning.

5. Snow melting

The results from the calculations of growth rate of length, figure 3, were that the worst case was a low water supply rate. We have two mechanisms for melting the snow – heat loss from the building and solar radiation. We will start looking on the melting from solar radiation. If we have a solar radiation of 1 kWh/m^2 we will be able to melt around 2 kg/m^2hour or 599 milligram/sm^2 if we assume that 80 % of the radiation is reflected. If we compare the melting rate in figure 3 and chapter 3 with the rate from solar melting we will find that most of the water will drip from the tip of the icicle. The risk will be that the water flow will get the icicle to fall. The melting water of a temperature of 0-1 C warms the root of the icicle and the supporting structure for instance a gutter. Close to 0 C is the adhesion strength of ice and the structural strength quite low. The result is a great risk of heavy icicle breaking up, if the melting water supply is high. The estimated water supply will depend on the catch area of the icicle and that includes the length of the roof. A longer roof will give a higher water supply. If the roof is of metal the snow will have a tendency to slide down and the top part of the roof will be without snow. As we will have radiation on this part of roof then it is important to remember that here only 30 % of the radiation will be reflected. The result is a high surface temperature on the metal plates. As metal is a good heat conductor the heat will flow into the metal under the snow. The result is an increase in the snow melting and a higher water flow. The conclusion is that solar radiation will increase the water flow to the icicles and increase the risk for falling icicles.

6. Snow on roofs

We can calculate when the snow thickness is so high that the snow begins to melt because of the heat loss from the building. Calculations for glass roofs were made in handbook for glass roofs Dreier et al 1985 and Nielsen 1988. Table 1 shows the calculation for different U-values for new snow density 100 kg/m3 and old snow 300 kg/m3. The indoor temperature is 20 C and the outdoor temperature is –10 C. The snow density is important and the U-value of the roof important. For glass roof were the minimum thickness is very low, will the snow start to melt very fast and in that case slide down the roof. In the design book we have shown that it is very important that we have space for the sliding snow. For a normal roof is the minimum thickness so high that melting from below is of minor importance at this temperature –10 C. For lower outdoor temperatures and/or higher indoor temperature will the melting from the heat loss from the building be important.

Table 1. Minimum snow thickness giving melting from the building heat loss

U-value W/m2K	Glass 3.0	Glass 1.9	Roof 0.3	Roof 0.2	Roof 0.15
New snow	0.5 cm	1 cm	8 cm	12 cm	16 cm
Old snow	2.5 cm	4.5 cm	37 cm	56 cm	75 cm

7. Case – icing on a large roof

In the winter 1987, The Norwegian Building Research Institute got information on icing problems on a large roof as described in Juul and Böhlerengen 1990. The roof had a U-value of 0.25 W/m^2K, a length of 16 meter and a slope of 20 degrees. The roof surface was metal. The roof was made as ventilated roof with an air gap of 48 mm. The size of the icicles was very large from 2 to 4 m from the roof to the ground. The heat loss though the roof should not be able to melt so much snow if the indoor temperature are 20 C. An inspection on the site and later discussions with the manager of the heating system showed, that the technical installation room below the roof had a temperature of up to 40 C in the winter. The warm air was also blown in under the roof with a temperature above 20 C. The conclusion was that the high temperature under the roof would melt much of the snow on the roof. The ventilation gap was also too small to get an air temperature in the gap around 0 C. Theoretical calculations by Nielsen found in the report showed that the air gap should be 15 cm in a roof with 16 m length. The solution was first to increase the insulation of the technical room so the heat loss was reduced and increase the size of the ventilation air gap in the roof. In this case the icicles were placed so that the risk for personal damage was minimal.

8. Case - ventilated roofs

The importance of ventilation of cold roof is also confirmed in research from the United States (Tobiasson et al 1998 and 1999) at Cold Region Research and Engineering Laboratory (CRREL). Measurements on buildings and cold room studies indicate that the outside design temperature for sizing natural or mechanical ventilation systems to avoid problematic icings at roof eaves should be –5.5 C. In that case the attic temperature should be –1 C. When it is colder outside, ventilating with outside air is increasingly effective, and when it is warmer, icings at eaves seldom grow. The amount of fresh air needed to minimize icings is related to the size and slope of the roof, the temperature in the heated building below, and the thermal resistance in between. In big open attics, essentially all of the resistance to airflow is created at inlet and exhaust openings. In cathedral ceilings, the resistance to flow up the narrow airways is also an important consideration. Design aids are developed to make the task of sizing inlet and exhaust openings and, in the case of cathedral ceilings and the airway height.

An interesting result is here that icicles seldom occur in the temperature range 0 to –5 C. From the Maeno calculations and measurement is the length growth rate at –4 C around 3 cm/h, but the water supply rate must be less than 5 milligram/s. The risk of generating large icicles must be small in that temperature range as the growth is low. The water supply rate from melting water can be so high that it will melt icicles.

9. Heater cables

Use of electric heater cables is necessary in some cases to be sure that the melting water can run of without freezing. This will reduce the risk of generation of icicles. Typical use is for cold ventilated roof with external gutters. The cables are placed in gutters and downpipes. In some cases we will still get icicles, as the heat effect is too low or the cables has been moved by snow and ice so the effect is reduced in certain areas. Design rules for gutter systems and glass roofs are found in Hugdal and Nielsen 1991. In that case is the problem more sliding of snow from the sloped glass as the snow will slide when melting is starting in the bottom of the snow layer. The result is reduced snow load on glass roofs and that is now part of the international standard for snow loads on buildings. The electricity cost of using the heater cables can be very high, if you do not have some kind of control system to turn of the heat off when it is not needed.

10. Snow guards

To avoid snow slides it is normal to have snow guards on roofs (Byggforsk 1996). The slide happens when the snow melt on the underside of the snow layer. This is the same condition we have described in chapter 6 to 8 as either outdoor temperature above O C or heat loss from the building or solar radiation. The roof slope and the roofing material defined if snow guards must be used. Metal roof as in figure 4 is an example of a roof type where snow guards are necessary. A problem with many snow guards is that they are not strong enough or the snow can slide above or under it. Snow slides can also get icicles to fall down from the mechanical load of the sliding snow. More about snow guards is found in the reference. If the snow guards work then the problem will come from the melting of the snow and the risk of getting icicles on the roof.

11. Problem areas

If we look at practical cases can we get icicles along the gutter at the roofs eave as seen in figure 1. This will happen with overhanging eaves, which is cold because there is no warm building below. But certain details have a higher risk, that is typical at the downpipes because they freeze and then we get melting water freezing at the top. This can be seen in figure 1 and 3. Another typical problem area is the valley between two roofs, especially at the base. Valleys are a difficult area to ventilate and we also have more melting water in this area. This gives a high risk of icicles. Small gables can be placed on the roof above the doors to prevent icicles. The problems are that we now move the problem to the valleys between the gable and roof.

Figure 4. Complex roof geometry in Gothenburg.

Another problem is from a complex geometry (figure 4) of the roofs as is typical in towns with flats in the roof. The slope is 70 degrees on the lower 3 m of roof to get as much space as possible under the roof. The upper part of the roof has a much lower slope. Accumulation of snow on the upper part of the roof can very easily freeze and generate icicles that can fall down on the lower roof and further on to the ground. The picture shows an icicle at the corner of the elevated top roof with a ventilator on the roof. This part is probably a technical room with a higher indoor temperature. The melting snow then freezes at the eave at this part of the roof and produce the icicle seen in the picture. In the street below are warning signs – risk of snow and ice falling.

Roof windows can also be a problem in areas with much snow. The snow will melt on the window and then the water will freeze on the insulated roof below. In areas with much snow in the winter is the rule of thumb is not to use roof windows but make an attic with a vertical window.

12. Conclusions - risk conditions for icing

From this investigation into the problems related to icicles and icings of roof we could give some guidelines.

Rules of thumb for the growth of new icicles:

- No snow on roof – no icicles.
- For air temperatures above 0 C – no icicles.

- For air temperatures from 0 to –5 C is the growth rate low and can be 0 with much melting water.
- For air temperatures below –5 C can icicles grow. Lower temperature gives higher growth rates.
- Increased wind speed will increase the growth rate.
- No melting water – no growth of the icicle.
- Low melting water flow gives a high growth rate.
- High melting water flow gives a lower flow rate and could melt part of the icicle.

Rules for the risk for downfall of icicles:

- For air temperatures of 0 C and above – high risk.
- For air temperatures from 0 to –5 C – normal risk. Reduced strength of ice.
- For air temperatures below –5 C – low risk.
- Higher wind speed increases the risk.
- Low melting water flow – risk depending of the temperature but the melting water will increase the risk.
- High melting water flow – higher risk than for the air temperature alone as the strength will be reduced.
- Solar radiation on roof with snow above icicles – increased risk as we get more melting water.

Building related rules that can reduce the risk of icicles downfall and or that somebody is hit.

- Use internal downpipes and roof with slope from the perimeter of the building.
- Place the entrance at the gable end where the risk is low.
- Use an overhang above the entrance doors to absorb falling icicles.
- Use a garden along the façade, so the icicle falls here and not on the street.
- Never have higher indoor temperatures than 21 C in room under the roofs.
- Extra insulate technical room – free heat from installations can increase the risk.
- For ventilated roofs keep the temperature in the ventilation gab below –1 to stop melting. Can be done by increased natural ventilation or mechanical ventilation.
- Gutters and downpipes are always risk areas and heat cable can be a solution to keep the water running without freezing.
- Icicles very often builds at downpipes as the water freezes in the lower part so this is a risk point.
- The base of valleys between roof parts is a high-risk area as the ventilation is difficult to make and much water comes in a small area.
- Insulated roof areas below a roof window can be a risk area.
- Glass roofs give much melting water and sliding snow.
- In complex roofing geometry can icicles be generated in part of the roof and then fall down on other roofs.
- Always check if icicles can fall from a roof down on a glass roof – high risk.

As always these guidelines will depend on the type of the building, the geometry, the construction and the technical insulation, so some point is more important than other in a real case. We expect to continue work in this area and present a computer model as assistance in the evaluation of the risk for downfall of icicles. We know that in some winters we do have many periods with icicles and in others few. It depends on the local climate. The Swedish Meteorological and Hydrological Institute SMHI should be able to predict weather periods with risk for icicles generation as it is done for winter road conditions. If icicles are generated it will depend on snow conditions and the building types and the use of them.

Better knowledge about icicles can reduce the risk of personal and material damage from downfall of icicles. For pedestrians the dangerous time is in the afternoon after a cold night with freezing temperatures. Then the snow on the roof will melt and if the sun is also shining is the risk high. It is difficult to look up, but if you see a frozen area on the pavement and see water is dripping then do not walk over that area. If an icicle is above then there is a high risk of downfall from the combination of high temperature and much melting water.

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