Snow and ice on roofs – icicles and climate change

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SUMMARY:
Snow and ice is a typical winter problem. Snow accumulates on roofs and icicles can hang at the eaves. 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 and their geometry is described. The spacing between icicles is explained. To get icicles to grow we need melting water comes either from solar radiation or heat loss from buildings. Two cases with icing on roofs are shown. Rules for reducing the risk for snow and ice problems on roofs are described. The effect of climate change on icicles is discussed.

1. Introduction

Snow and ice on roofs is occurring during the winter. This gives a many problems 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. Icicles have killed people. That had happen in Sweden. According to the law is the owner of the building responsible for prevention of sliding of snow and ice from the building. 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 legal cases and examples of contracts with firms for snow and ice removal. A short evaluation of risk is mentioned.

The problem with icing and icicles on roof is a complex problem involving architecture, meteorology, glaciology and building physics (Nielsen A 2005). The architect decides the layout of the building and the type of roof and its geometry. 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. The glaciology describes the physics behind ice and snow. The building physic is involved as heat air and moisture transfer is involved.

2. Model and results

Icicles 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 water temperatures above the freezing point to develop 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.

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.

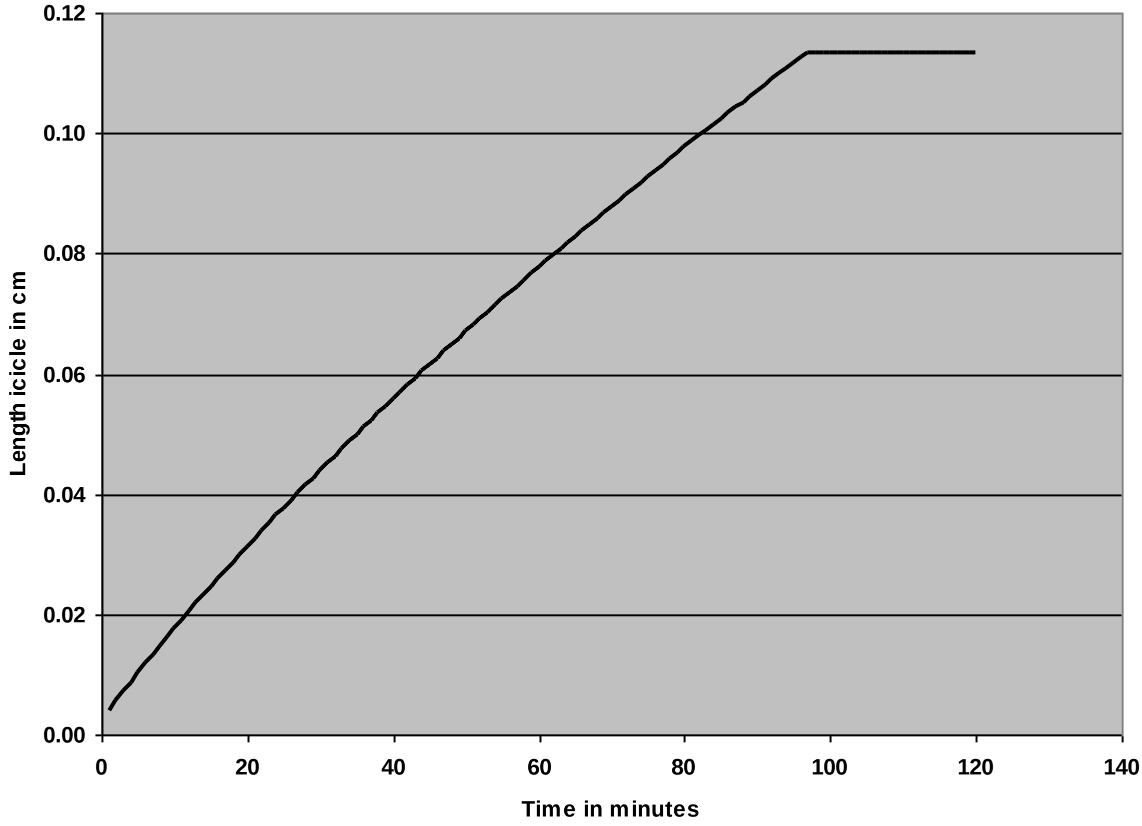

FIG. 1: Example of calculation of icicle growth with an outdoor temperature of –10 C.

Figure 1 is a calculation of the length of the icicles under constant water flow rate and constant outdoor temperature of –10 C. The length-growing rate will decrease with time as surface area increases. The icicle stop to grow in length after 97 minutes as the water flow is all freezing on the surface of the icicles – no water reach the tip. The icicle will still increase in weight and in diameter. The figure will look the same, if the water flow just stopped after 97 minutes but a figure showing the diameter or weight would have shown the difference.

3. Icicle geometry

In most literature and in the previous simulation we have assumed, that the icicles are cone shaped. This is found not to be correct. A paper by Short M, Baygents J and Goldstein R from 2006 has described the growing of an icicle and the expected geometry based on a free-boundary problem. The energy balance between the icicles is defined by the thin layer of water flowing on the surface of the icicle and a thermal boundary layer of warmer air rising around the icicle. Setting up the energy balance and rewriting the equations will describe the geometry of the icicles as a formula (1) with the dimensionless variables A and B.

$$A = 4/3*(B^{0.5}+2)*SQRT(B^{0.5}-1) \qquad (1)$$

A is a dimensionless radius and B is a dimensionless length.

The theoretical formula will described the form of icicles as seen in figure 2. It has a convex carrot like form. This can be compared with the conical form with the same total volume. The carrot like form gives a larger radius in the lower part of the icicle and a smaller radius in the upper part. An effect of this is that the strength is less for real form, as the area is smaller at the top of the icicle. This expression for the icicle form has been compared with natural icicles and is found to fit very well with their geometry.

Stalactites in limestone caves – has a striking resemblance with icicles with a convex carrot like form. They are generated by another physical process from precipitation of calcium carbonate. The mathematical description of this process gives the same formula (1) as for icicles. This explains why icicles and stalactites are so similar in form.

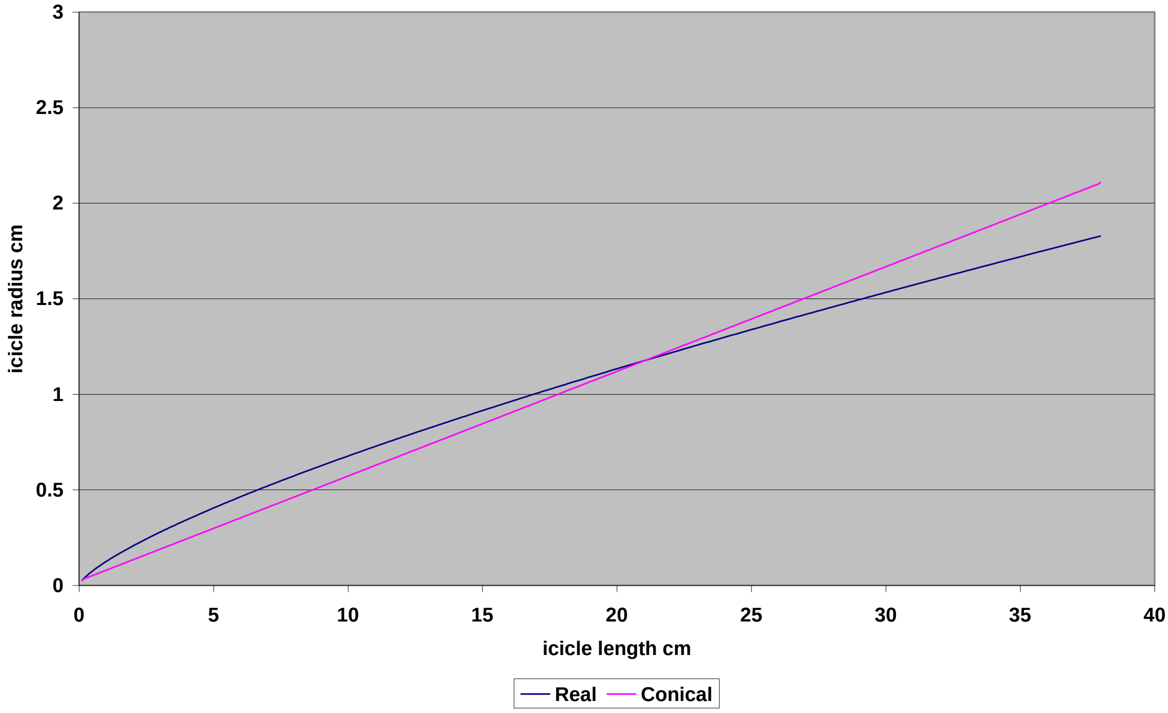

FIG. 2: Comparing simplified icicle form – conical – with the real curve (formula 1).

4. Icicle distance

If we look at icicles at for instance a gutter we will in many cases see that there is a number of icicles with a regular spacing. This spacing is actually determined by the spacing of the water droplets from which they form. The assumption is that first is formed a water film under the solid material and then the water will generate water droplets hanging down from the water film. The distance between the droplets will mostly depend on a balance between surface tension and gravity. Makkonen and Fujii (1993) assume that the weight of the water at a point on the profile is equal to the vertical component of the surface tension force. Using a differential equation for this condition can be solved with zero-order Bessel function of the first kind, covering the domain from zero to the next point where the function has zero slope. This gives a drop radius of 1.06 cm. The spacing between adjacent droplets will be twice this value or 2.13 cm. Using another theory from de Bruyn (1997) gives a value 2.47 cm. This has been compared with measurements of icicles in actual freezing condition and the value is mostly between 1.6 and 3 cm, which include the two theoretical values.

The distance between icicles is interesting for calculation of melting water flow from a roof. The area for each icicle will be 2-3 cm wide and with a length as the roof. The catch area will be larger or smaller depending on the roof type. If we look at hip roof as seen in figure 3 we can see that the catch area is lower near the roof corner at a hip. Larger catch areas for corners with a valley is seen in picture 3. The result is that an icicle in a corner with a valley will typical be larger than others as the water flow will continue for a longer time. Based on the geometry of the roof is it possible to note areas with a higher risk for generation of large icicles. This will typical be at the end of valleys if we do not have a downpipe in the corner. But inside the downpipe is also a risk as the water can freeze in the pipe, so that melting water cannot drain away.

The theory expects that the droplets are generated on a horizontal surface. If the surface is sloping, then the water will run to the lower end of the slope or a point with a scratch. A scratch will probably be able to stop the water so much that it can generate an icicle at this point. Gutters will typical have a slope to drain the roof water to the downpipes. The icicle will most likely by at the lower end. The problem is that the water will freeze in the gutter. Then the water flow stops and we can get icicles hanging from the ice at the top of the gutter.

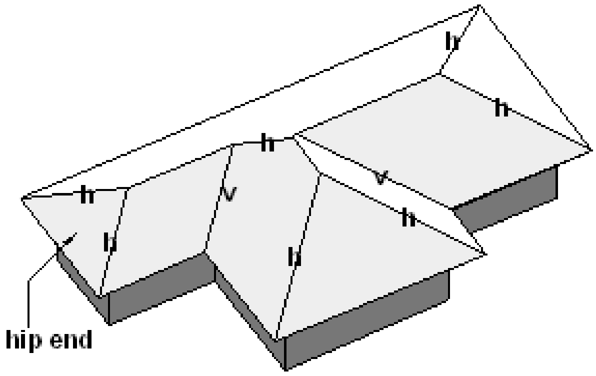

FIG. 3: Hip roof, where "h" is a hip a and "v" is a valley (Wikipedia picture by Bill Bradley)

5. Practical cases

The previous chapter explains that icicles can be generated with a spacing of 2-3 cm. Figure 4 shows an case with many similar spaced icicles. It is from a freezing rain period where raindrops freeze on surfaces, as seen on the very steep roof and the tree in the background. These icicles are very similar with a length of 20 cm and will not give serious risks of damages when they fall down.

FIG. 4: Icicles at the eaves after a freezing rain period (Wikipedia photo by Jonathan Zander)

Figure 5 is a case with an old house with much icing on the roof. The house has a low thermal insulation level and a high heat loss trough the roof. In this case there are heavy icing in the gutter along the façade and in some places icicles are hanging from the ice in the gutter. The icing in the gutter is less in front of the dormers as the catch area is less here. The dormers will increase the water flow and the icing on both sides of the dormers. This building has two types of risk scenarios. The first is that icicles can fall down, when the temperature rises. The second is that ice above or in the gutter on the lower part of the roof can break loose for instance from snow sliding of the upper part of the roof. This can give a more serious risk that larger ice trunks can fall down. For this building is it necessary to keep people and cars away from the façade of the building. It is recommended to insulate the roof to reduce the risk of icing. The insulation does not totally prevent snow sliding, so using snow guard is a good solution.

FIG. 5: An old house with icicles at the gutter filled with ice (photo Anker Nielsen)

6. Reducing the risk for snow and ice problems on roofs

The previous article Nielsen A, 2005 discussed when icicles will be grow and when they will fall down and not so much the design of the roof. Design methods has previous been discussed in Buska J and Tobiasson W, 2001. This is special important in areas with much snow in the winter. In most cases will the snow load on roofs be lower than on the ground, as some of the snow will be blown away or slide from the roof.

A possible solution is to use a flat roof with internal downpipes and a parapet along the perimeter. The problem with a flat roof will always be the waterproofing. A minimum slope must be used. There is a risk for icing around downpipes. This can give water dams that are not drained. If the flat roof is watertight then it will avoid many of the snow and icing problems on a sloped roof.

Another possibility is to have so steep a roof that the snow would fall of. To get that the slope has to be more than 60-75 degrees and then it is more like a wall. In most practical cases we have to have sloped roofs with a slope of 20-45 degrees. The melting water from a snow layer will run from the ridge to the eaves. A long distance from the ridge to the eaves will increase the risk for icicles. At valleys we will get more melting water and a higher risk for icicles. The melting water will typically run down in the gutter and could freeze here. If the freezing continues the ice-layer will reach over the top of the gutter and onto the lower part of the roof as seen in figure 5. Snow guards as described in Byggforsk A525.931 in the lower part of the roof will stop snow slides. In case of icing as in figure 5 can the snow guard also hold back part of the icing as ice can be expected both in front and behind the guard. This will reduce the possible size of ice falling down. It is very important that the mechanical strength is high for the fastening of both the gutters and the snow guard. They must not fall down in case of a snow slide on the roof. They must be able to withstand the full load of the snow and ice on the roof.

The surface of the roofing material will influence the risk for snow slides from the roof. A roof with a low sliding resistance as a metal roof will have a high risk for sliding snow. A rougher surface as for instance an unglazed tile roof will have a lower risk.

The length of overhang with the eaves is important for the function of the roof. A narrow overhang can cause icing on the walls. A wide overhang may generate larger icicles. Practical recommendation is an overhang with minimum 30 cm and maximum 60 cm.

Different obstacles on the roof can change the snow sliding and water flow pattern. This can be from dormers, ventilation boxes and chimneys. They can work as snow guards in some places but most likely will they direct the water and snow to adjacent areas. These areas will have a higher risk for icicles. Chimneys, ventilation ducts and other obstacles should be placed near the ridge of the roof as this reduces the risk for being damaged. A plumbing ventilation duct can in worst case be bend by sliding snow.

Roof windows are not a good thing in areas with much snow, as the snow will melt on the window. The result is a higher risk of icicles at the eaves below the window. It is also a risk for snow slides from the roof surface above the window. The best solution is to use dormers with a vertical window.

Electric heating cables can be used in gutters to prevent the freezing of melting water. They can also be used to drain ice dams behind ice blocks in the gutter for instance in valleys. Using electric heating cables is not a good method as the energy cost will be high specially if the effect is not controlled by temperature. Only heat in freezing weather.

It is very important to have a well-insulated and ventilated roof to reduce the heat loss from the building to the roof. The ventilation with outdoor air will keep the attic temperature low, so the snow melting is reduced until it melts from non-freezing outdoor temperatures.

7. Climate Change

Climate projections from climate models point to a warmer climate with an intensified hydrological cycle in the future (Nielsen A., Kjellstrom E and Sasic Kalagasidis A., 2007) But, such changes are already observed both globally and regionally. In Sweden, for instance, the last 10-15 years have been mild and wet compared to previous periods. The trend in the recent Swedish warming is in line with climate change scenarios. The climate projections include changes in both average conditions and in the frequency and magnitude of extreme events. Climate model experiments can be done with coupled atmosphere-ocean general circulation models (AOGCMs). These models are applied with different external climate forcing factors as changing greenhouse gas concentrations or changes in solar intensity etc. The response of the climate system to changes in forcing factors depends on the climate sensitivity of the AOGCM. According to the climate change scenarios described in the previous mentioned paper, the future climate in northern Europe can be summarized as warmer with an increase in the mean average yearly temperature of 1.8C to 4.0C to year 2100. This is particularly true for wintertime conditions when retreating snow cover amplifies the warming at high latitudes. Also, precipitation is expected to increase in all of northern Europe in these scenarios for the winter. Summer temperatures are also projected to increase, but precipitation will increase only in northernmost Scandinavia while decreases in precipitation are projected for most of Europe.

As the formation of icicles is a complex process, it is not trivial to judge what impact climate change may have on their occurrence. In a warmer climate, the snow season and the amount of snow will decrease in most areas, which will favour diminishing the problems. The number of days when the temperature is critical, i.e. going from below to above 0C, will be lower in the southern part of Scandinavia but higher in the north, as seen in figure 6. More information in: Nielsen A., Kjellstrom E and Sasic Kalagasidis A., 2007. This indicates that the problems with icicles will not disappear and may even be worse in some areas, but the risk can be higher or lower depending on the climate scenarios. More simulations with different climate scenarios will be made to evaluate the risks.

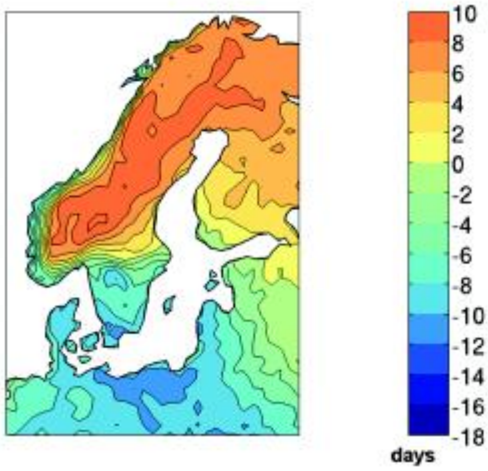

FIG. 6: Change in the number of days when the temperature crosses 0^oC in Scandinavia during winter (December, January and February). Shown is the average change for 2041-2070 compared to 1961-1990.

8. Conclusions

A well-insulated and ventilated roof will reduce the heat loss from the building and reduce the risk for icicles on the roof. Designing the roof for snow and ice is important in areas much snow in winters. Keep the roof geometry simple and take away as much as possible of obstacles on the roof.

The geometric form of icicles (carrot-like) has been described in Short M, Baygents J and Goldstein R 2006. Theoretical evaluation on spacing of icicles on a horizontal surface is presented. The distance is 2-3cm. This is important for calculation of water flows to each icicle on a roof.

Two practical cases are discussed.

A preliminary evaluation of scenarios for climate projections in Sweden to year 2100 shows a warmer climate and more precipitation. This will influence the risk for problems with snow and ice on roofs. The indication is that problems with icicles will not disappear and may even be worse in some areas. Future simulations with different scenarios will give a better risk evaluation.

9. Acknowledgements

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