Thermal Patterns in the Snow: Icicles as Indicators of Heat Loss

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The Physics Teacher, Vol. 46, March 2008

On Dec. 27, 2006, we drove with our children and their families to a cabin we rented on the grounds of the "YMCA of the Rockies" in Estes Park. (Co), for a few days of winter relaxation and recreation. On the night the 27th a snowstorm dropped over half meter of new snow, creating a beautiful winter wonderland. For the next couple of days the Sun shone brightly but the temperatures staved well below freezing, so the combination of time and temperature cooperated to produce some spectacular thermal patterns in the snow on the roofs of the buildings. In the following days I walked a great deal, using my new digital camera to photograph these evolving thermal patterns, a subject that first fascinated me more than 30 years ago.[1,2] This time the thermal patterns were dramatically complemented by the presence of icicles.

Fig. 1. South face of an unheated cabin (12/31/06) with most of its roof snow intact. To the right and left of the porch, at the lower edge of the sloping roof closest to the camera, is a narrow strip of the bare roof a few centimeters wide (A). This is evidence of the developing South Eave Effect. Notice that the strip of bare roof does not extend completely to the corners of the roof at the far right and far left. At each corner, a point of snow extends down to the extreme tip of the corner of the roof (B). These two corners will not receive as much convected warm air as the adjacent parts of the eaves, because these corners extend to the right and left of the front wall of the cabin, which is heated by the Sun.

Physics

For icicles to form along the lower edge of a sloping roof when there is snow on the roof, there must be thertnal energy flowing to the snow to cause the snow to melt. To melt a kilogram of snow requires 3.34 X 10^5 joules, which is the latent heat of fusion of water. After snow is melted, the meltwater runs down to the lower edge of the roof -where, if there are no gutters, it drips to the ground. If the air temperature is well below freezing, the melt-water will not leave the edge of the roof but will freeze in place, and as more ineltwater reaches the lower edge of the roof, icicles will form. As the process continues, the icicles can become spectacular in size and number. When the melt-water freezes, the water gives tip the latent heat of fusion in the form of heat, which is lost to the cold outside air. The melting snow, flowing melt-water, and freezing icicles constitute a mechanists that takes heat energy from the inside to the outside of the building. A second source of enerf1y that can cause snow to melt is the energy in sunlight incident on the top layers of the snow on the roof. To the extent that snow is melted by heat flow from the interior of the building, the presence of icicles is visual evidence of thermal energy being wasted.

South Eave Effect and North Eave Effect

The eaves are the projecting overhanging parts of the roof beyond the wall of a building. In these cabins, the rafters supporting the roof may be 2x4's on which is nailed a single lavcr of 1.9-cm wood onto which the waterproof roofing is fastened. In the Northern Hemisphere, the south wall of the building (and to a lesser extent, the cast in the morning and west wall in the afternoon) will receive direct sunlight, which will warm the wall, creating an updraft of warm air near the surface of the wall. This warm air rises to the underside of the overhanging eaves where it heats the underside of the eave, melting snow that was on the top surface of the cove. This updraft of warm air tends to create a warm environment at the eaves, which may inhibit the formation of icicles on the south eaves. Let us refer to these collectively as the South Eave Effect. The north face of the building gets no direct sunlight during the middle of the day, so there is no heating of the wall and no consequent updraft of warm air. The temperature of the underside of the north eave will then be close to the ambient outside air temperature, and snow on the top surface of this eave will experience little melting. Let's call this the North Eave Effect. The "north" and "south" effects will be reversed for buildings in the Southern Hemisphere.
The accompanying photographs were taken a few days after the snowstorm.

Thermal Patterns and Icicles

Figure 1 shows the south face of a cabin that was unoccupied and unheated. Consequently, the snow on the roof of this cabin has been modified only by the incident solar energy. No icicles are visible. A small dark band of bare roof, perhaps 10 cm wide, is visible at the very lower edge of the roof to the right and left of the porch. This is an example of the South Eave Effect.

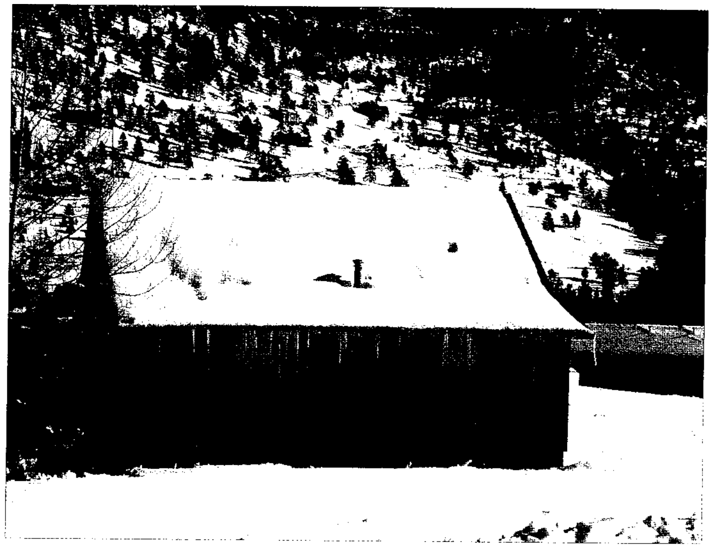

Fig. 2. West face of a cabin (12/31/06). The South Eave Effect is seen clearly on the south edge of the roof at the right.

One does not see the South Eave Effect on the near edge of the porch roof because the porch roof shades part of the front wall of the cabin, reducing the production and upward convection of warm air that would otherwise melt snow on the roof of the porch.

This photo is a record of the effect of the solar input by itself. This is the baseline picture against which the other pictures must be compared.

The snow on the roof of the cabin in Fig. 2 appears to be readonably uniform in thickness, which suggests insulation in the form batts of insulation such as fiberglass on the underside of the roof. There are a few scattered dimples in the snow, which suggest a random pattern of faults in the placement of this insulation. Understandably, the snow is melted around the sheet metal stovepipe. We can see the South Eave Effect developing on the right side of the roof. The few icicles suggest that there has been some melting of the snow from a combination of heat flow from the interior plus solar energy input on the roof.

In Fig. 3 we are looking at a heated cabin that faces approximately east. At the left edge, a narrow strip of bare roof is the result of the South Eave Effect. The snow appears to be of full thickness on the left half of the roof and on the roof of the porch. The snow appears to be at full thickness on the right (north) cove. This is a dramatic example of the North Eave Effect. Why is the snow almost all melted away on the right half of the roof? When you enter the typical cabin such as this from the porch, you enter the living/diningroom, which is the right part of the building in the photo. The bedrooms are in the left part of the building. The living roots has an open cathedral-stele ceiling, which allows the warm air in the living roots to convert upward and heat the underside of the roof boards, melting snow on the roof. The warm interior air tends to collect at the peak of the interior space

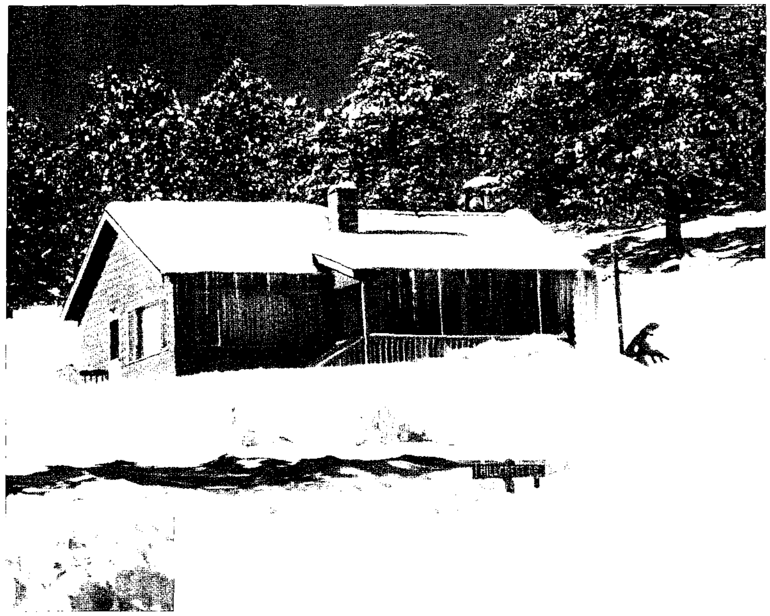

Fig. 3. East face of a cabin (12/30/06). The South Eave Effect is starting to develop on the left of the roof, and the piled up snow on the overhanging north eave at the right is a demonstration of the North Eave Effect.

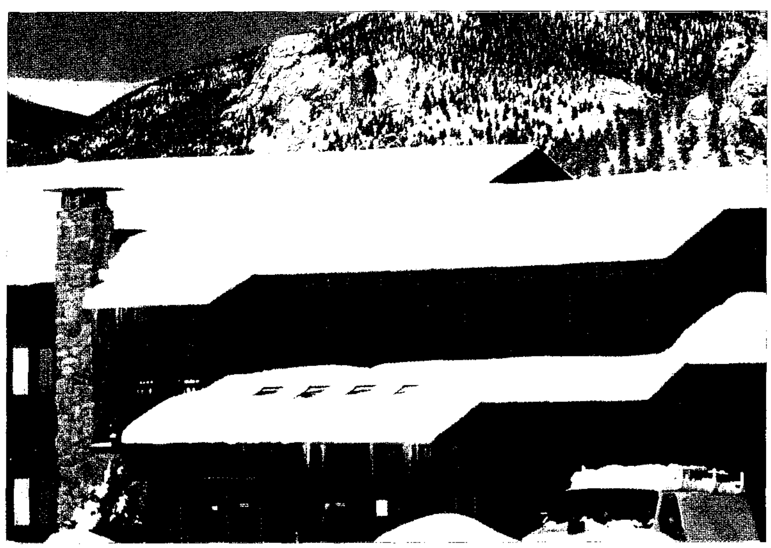

Fig. 4. The snow appears to be rather uniform in depth over the large south-facing roof of this apparently new lodge (12/30/06). However, heat has escaped through the four skylights to melt completely all of the snow that fell on them.

so that there is a thermal gradient of increasing inside air temperatures as you go up to the peak of the roof. As a result, one would expect the outside snow to be thinnest at the peak of the roof, indicating the gradient of the inside air temperatures. Indeed, the snow appears to be completely melted on a very narrow strip at the highest part of the roof. The bedroom space has a horizontal flat drywallceiling, which isolates the warm air in the bedrooms from the air in the triangular space above the ceiling and under the roof. There may be thermal insulation over the drywall. The combination of isolation and insulation reduces the heat flow from the bedroom ceiling into the cooler space above the ceiling and under the roof, so relatively little snow has been melted froth the roof over the bedrooms. The temperature of the underside of the porch roof is probably the temperature of the outside ambient air, so there is little melting of the snow on the porch roof. Notice that there are icicles along the edge of the porch. Most of their water probably came from thermal conduction through the roof over the living room. The icicles on the left edge of the roof arise probably from a combination of heat loss through the roof over the bedrooms and solar input from the afternoon Sun.

Figure 4 shows the south side of a large building with what appears to be a uniform covering of snow except for the four skylights in the lower roof. Skylights tend to have poor insulating qualities. It would be interesting to estimate the outward flux of energy, lost through a skylight for 24 hours and compare it with the inward flux of solar energy during a 24-hour period to see which is larger.

The building in Fig. 5 is one of the lodge buildings whose roof has an exquisite snow pattern. We are looking at the north side of the building, so we see the North Eave Effect of thick snow along the north (lower) edge of the roof. We see the same effect on the cove to the right, probably because trees or other buildings are keeping the afternoon Sun from striking much of this west wall. There seems to be little or no insulation in the roof as is indicated by the four large rectangular sections of the roof ors which the snow is almost completely melted. This melting has given rise to the dense curtain of icicles on the near edge of the roof. The roof sections are identified by four lines of snow running up the roof. These lines of snow most cerrtinly identify the position of four major structural roof beams, which, because of their mass and thickness, provide some insulation to reduce locally the outward beat flow. This pattern is almost like an x-ray of the roof structure. The fifth section to the left of the left beam seems to have more snow than the sections to the right, suggesting the possibility of some insulation under that section of the roof.

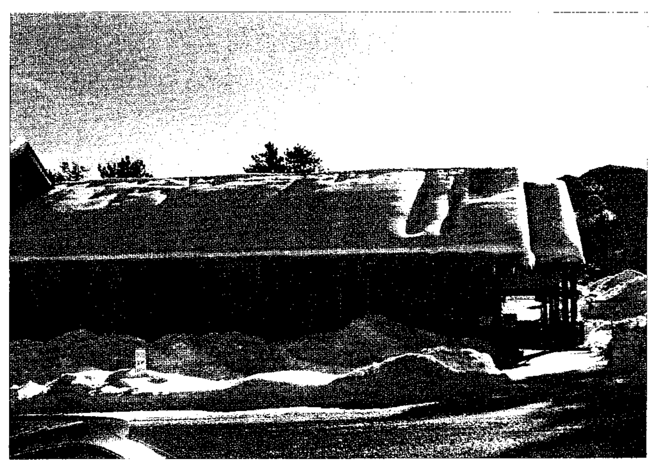

Fig. 5. Looking southeast at the north roof of a lodge building. This roof appears to be a superhighway for the escape of heat from the interior of the building. The large thickness of snow on the lower edge of the roof and on the right (west) edge are examples of the North Eave Effect (12/31/06).

Fig. 6. East facing roof of a lodge building (1/1/07). Barely visible at the lowest edge of the narrow porch roof on the right edge of the building are two very small curved strips of bare roof. Electric heating tape has melted the snow here to keep icicles from forming above the pedestrian walk.

The roof of the main part of the building to the left seems to have more snow on the lower part of the roof, indicating that it is probably insulated. It is not clear why there is a large irregular area to the right of the Chimney that is free of snow. Wind can scuplt the snow on roofs, so this could be the result of winds. Because of the different patterns on the two parts of the building, one wonders if the right wing, with all the heat loss, was constructed some time after the construction of the main part of the building to the left, with the roof insulation being different in the two constructions.

Figure 6 shows another lodge building with a great deal of snow remaining on the roof. There is all irregulat pattern along the ridge of the roof suggesting random irregularities in the placement of insulation on the underside of this part of the roof. Near the right edge ofthe roof are two long well-defined channels where the snow is largely melted. These suggest that no insulation was placed in the two spaces between adjacent roof rafters. Farther to the right, the snow onl the upper part of the space between rafters is largely melted while the snow on the lower part of this channel is largely intact. Insulation may have been left out of this part of tlhe roof. To the left, and not very clearly visible, are a couple of more channels where the snow is partially melted, indicating poor insulation between adjacent rafters.

In Fig. 7 wearc looking at the south face of the swimming pool building. From the outside, the eave structure of this building can be seen to be different from that of the cabins or lodges. We see a long vertical fascia ruining horizontally along the south edge of the roof. The fascia probably has a horizontal soffit underneath that encloses a dead air space under the cove. The rising outside air, heated by the sunlight incident on the south wall, is prevented by the soffit from reaching and heating the underside of the cove, so snow remains here in something similar to the North Eave Effect. The same strip of unpelted snow is seen on the west cove at the left. It is not clear what happened to the melt-water from the snow that was originally on this south half of the roof. It is probable that the fascia was kept sufficiently warm by the Sun that the melt-water dripped to the ground without forming icicles. The near complete absence of snow oil the main roof seems to scream out, "Here's an enormous leak! Do something!" But the clinching evidence for the heat leak is seen in Fig. 8, which shows the north face of the building. We see a continuous sheet of icicles between one and three meters long, some of which reach almost to the ground!

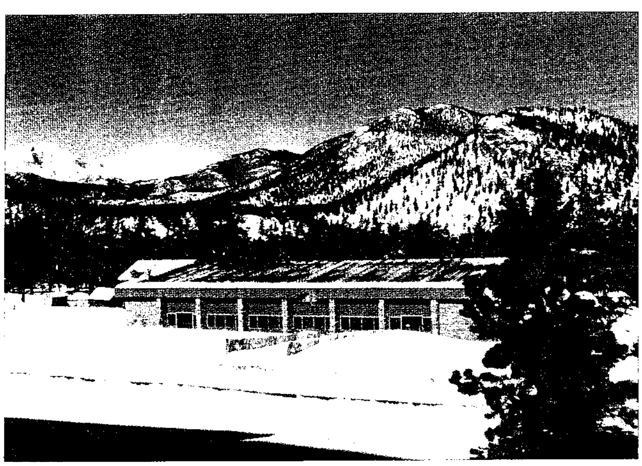

Fig. 7. South side of the swimming pool building (12/31/06). (12/31/06). The roof is sheet metal and almost all of the snow is gone.

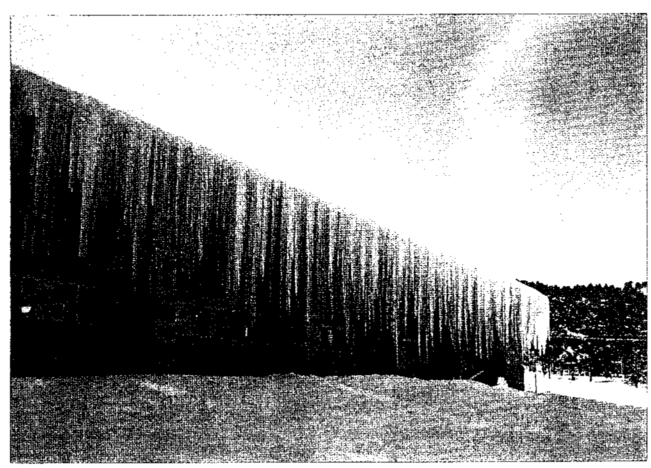

Fig. 8. North side of the swimming pool building

Heat Transfer to Form Icicles

How much beat loss is represented by the ice in Fig. 8? The latent heat of fusion of water is 3.34X 10^5 J/kg, or 9.3 X 10^{-2} Wh/kg, or 93 kWh per ton of ice. If electric resistance heating is the source of the energy lost through the roof of the building and if the electric rate is $0.11 per kWh, then every ton of icicles represents a cost of about $10. If one estimates that the icicles are cones with a base (top) radius of 6 cm and a length of 2 m, then the volume of each is 7.5X 10^{-3} m^3 and the mass of each icicle is about 71kg. Otte can estimate that there are about 3X 10^2 icicles, so the total mass of ice visible ill the photo is a little over two tons, representing approximately 180 kWh of electric energy or a cost of about $20. The icicles represent the heat loss during the limited time it took to melt the snow off the roof. But after the snow is gone, the heat loss and the high energy costs continue.

Conclusion

Simple observation of thermal patterns in the snow on roofs of buildings is a low-tech, non-intrusive way of seeing and documenting the details of wasteful heat loss. Identifying and taking corrective steps to reduce this energy loss is becoming more important each year as growing demand and limited supplies are causing increases in the price of energy.

Physics is much more broad and universal than the exercises done in laboratories with high-tech gear and computers. Physics is central to the functioning of the real world. After a snow storm, almost every building roof has a story to tell. If one can learn to look, one can see interesting examples of physics every clay. I am ashamed to admit how many years it took the to realize this simple fact. We must help make our students aware that beautiful, elementary, and useful physics can be seen ill everyday experiences.

Acknowledgment

I wish to thank an anonymous referee for very helpful comments.

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