Sliding temperatures of ice skates

S. C. Colbeck, L. Najarian, and H. B. Smith

Citation: American Journal of Physics **65**, 488 (1997); doi: 10.1119/1.18576
View online: https://doi.org/10.1119/1.18576
View Table of Contents: https://aapt.scitation.org/toc/ajp/65/6
Published by the American Association of Physics Teachers

Sliding temperatures of ice skates

S. C. Colbeck
U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755-1290

L. Najarian and H. B. Smith
Women in Science Program, Dartmouth College, Hanover, New Hampshire 03755

(Received 10 June 1996; accepted 5 December 1996)

The two theories developed to explain the low friction of ice, pressure melting and frictional heating, require opposite temperature shifts at the ice-skate interface. The arguments against pressure melting are strong, but only theoretical. A set of direct temperature measurements shows that frictional heating is the dominant mechanism because temperature behaves in the manner predicted by the theory of frictional heating. Like snow skis, ice skates are warmed by sliding and then cool when the sliding stops. The temperature increases with speed and with thermal insulation. The sliding leaves a warm track on the ice surface behind the skate and the skate sprays warm ejecta.

I. INTRODUCTION

Pressure melting is still commonly used by physicists as a qualitative explanation of skating although Bowden and Hughes[1] suggested some time ago that the pressure under a skate blade could not be high enough to cause pressure melting. The basic problem is that the melting temperature of ice is too weakly dependent on pressure. Colbeck[2] further developed the arguments against this mechanism, explaining that the melting temperature must be reduced to below the ambient temperature to account for heat flow to the melting interface. The other mechanism, frictional heating, provides a direct source of heating at the interface, the conversion of mechanical energy into thermal energy. Colbeck also argued against pressure melting, stating that the pressures required would be above the failure stress of ice, that pure water cannot coexist with ice below about -20 °C at any pressure, and that, if pressure melting is the dominant process, the water films could be only about 0.08-μm thick.

Evans *et al.*[3] found that, at an ambient temperature of -11.5 °C, highly conductive copper had a high coefficient of friction, which they explained by high heat conduction from the interface. This strongly supported the theory of frictional heating because, if pressure melting dominated, the interface temperature should have been below the ambient and a more conductive slider should have favored more heat conduction to the interface. While these arguments against pressure melting are useful, a simple temperature measurement at the sliding interface would allow us to identify the dominant mechanism.

We would like to measure the pressure or thickness of the water film directly, but only a temperature measurement is practical and definitive. The theory of pressure melting requires that the melting temperature at the interface be below the ambient temperature. The theory of frictional heating, on the other hand, requires that rubbing raises the temperature at the interface, and causes heat flow into both the ice and skate blade. Thus if pressure melting is the dominant mechanism, the temperature at the interface must decrease during skating, whereas if frictional heating is the dominant mechanism, the temperature at the interface must increase upon the onset of motion, and then decrease to the ambient temperature when motion ceases.

II. EXPERIMENTAL PROCEDURE

Temperature measurements are easier to make with skis than with skates because thermocouples can be easily installed in the plastic bottoms of the skis and are not easily damaged. The thermal signal from a ski is smoother than from a skate because the snow surface is softer than ice, the pressures are lower, and the ride is smoother due to the greater length of a ski.

Installation of a thermocouple in a skate is difficult because of the need to penetrate the hard steel with a small hole. Success was achieved only after the skate blade was annealed in a small area at the bottom of the blade. The skate, shown in Fig. 1, was an old hockey-style skate that was ground flat to obtain an apparent contact length of 150 mm and a width of 3 mm. The wire pathway was established by drilling an access hole across the width of the skate blade and then a connecting hole upwards from the blade bottom; this provided a continuous path between the bottom and the side of the blade. The thermocouple was epoxied into the pathway while it protruded slightly through the blade bottom and then the bottom was ground to give a smooth running surface with the thermocouple visible at the bottom but flush with it. The wire was secured to the skate blade mounts and the leather shoe, and then connected to a data logger carried by the skater in a small ''fanny pack.'' Data acquisition and management were done in the same manner as with skis, e.g., Colbeck.[4] The tests were performed both indoors under controlled conditions and outdoors on a pond where normal skating was possible. The main advantage of being indoors was that we could achieve a lower, controlled temperature.

III. RESULTS

Only simple tests were run because of the noisy character of the data due to the rough ice and the short length of the skate. These tests fall into several distinct categories: motionless, steady speed, normal skating, and insulated blade.

A. Motionless

As shown in Fig. 2, the temperature decreased when the skate was pressed against the ice on the pond and increased when the load was removed. This might be interpreted as a decrease in the melting temperature with an increase in pres-

Fig. 1. Instrumented skate showing the flat bottom and thermocouple wire. The thermocouple wire enters a small hole in the side of the blade and connects to the thermocouple which is at the bottom of the blade.

sure when weight was applied. However, the temperature changes were probably just due to better thermal contact with the ice when the skate was pressed against it. From the Clausius–Clapeyron equation, the area of the blade, and the weight of the skater, the pressure required to reduce the melting temperature to the extrapolated value of the exponential decay ($r^2=0.999$), -7.48 °C, could be achieved only if the true contact area between the blade and the skate were only 1.4% of the area of the flat part of the blade. If pressure melting–regelation had occurred, the contact area would have increased with time, thus reducing the pressure and

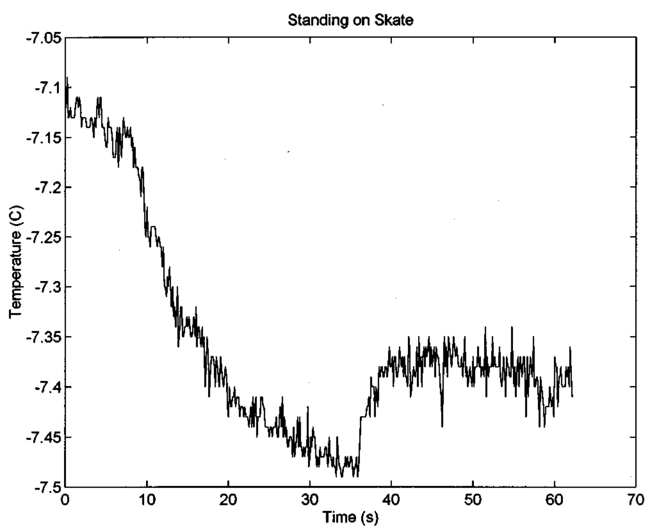

Fig. 2. Skate-bottom temperature versus time. The temperature drops when the skater first places her weight on the skate and then increases to a plateau when most of the weight is removed at about 35 s. These temperature differences are probably just due to better thermal contact when the skate is weighted.

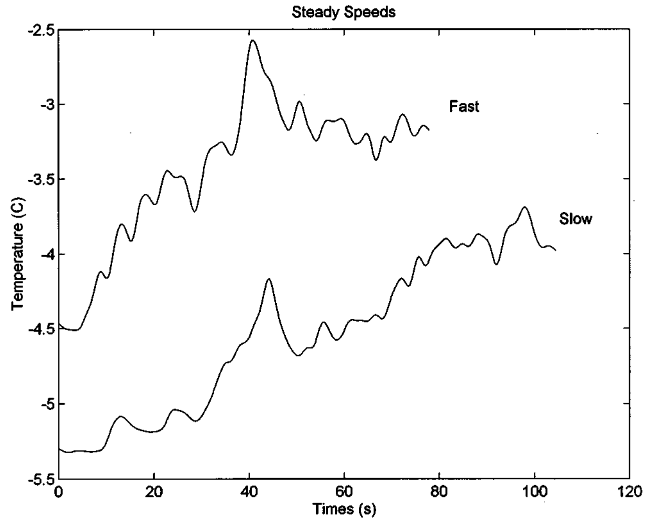

Fig. 3. Skate-bottom temperature versus time at two speeds. The ice temperature was about -5.3 °C, as shown for the first 9 s before the slow run started. The temperature reached a higher plateau during the faster run. The data were smoothed to show the plateaus.

increasing the melting temperature. Because this did not happen, pressure-melting regelation could not have occurred while the skater was standing still.

While these arguments are based on the theory of pressure-melting regelation and not just the temperature observations, they are unnecessary anyway in view of the results reported next.

B. Steady speed

The rate of heating should increase proportionately with speed and load, and thus a variable speed, constant load run provides a good test of the concepts behind the theory of frictional heating. The first of these tests was done with a second person pushing the skater at steady speeds and then quickly stopping to let the skates cool. Figure 3 shows typical responses where the ''slow'' test was done at a slow walk on the pond and the ''fast'' test was done at a brisk walk. The slow test was done first, so the initial temperature of -5.3 °C was a good measure of the ambient ice temperature and the onset of motion at about 9 s is evident in Fig. 3. When motion began, the temperature rose slowly and was just reaching a plateau when the skater was stopped. After this test ended, the fast test was started before the skate cooled back to the ambient temperature, but, with the onset of more rapid motion, the skate warmed more rapidly to a plateau of about -3.2 °C.

For snow skis these plateaus were always below the melting temperature, probably because only about 4% of the ski was in actual contact with snow, and therefore the thermocouple was in contact with cooler air most of the time. However, with skates the fractional contact area appears to be much higher. Melting must occur to achieve these low levels of friction, and yet the measured temperatures never approached 0 °C. We believe that we were not measuring a true surface temperature, but rather measured the average temperature of the thermocouple over its vertical length, while only the lower tip was in contact with the water film. There

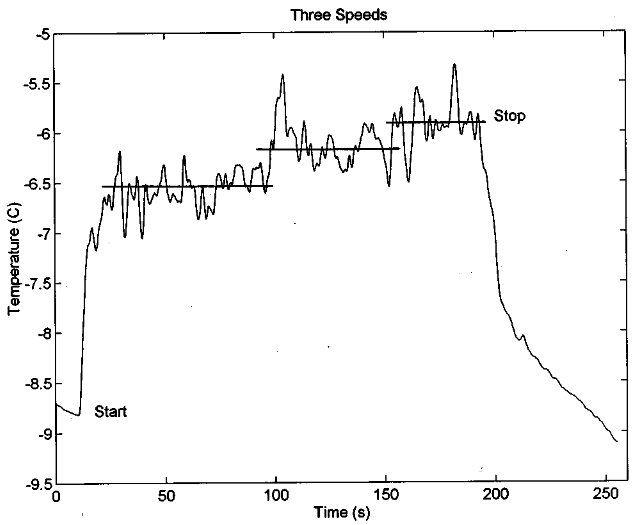

Fig. 4. Skate-bottom temperature versus time for three speeds in succession. The skate was cooling before motion started and then cooled rapidly once motion stopped. The temperature reached progressively higher plateaus as speed increased to higher levels. The data were smoothed to show the plateaus.

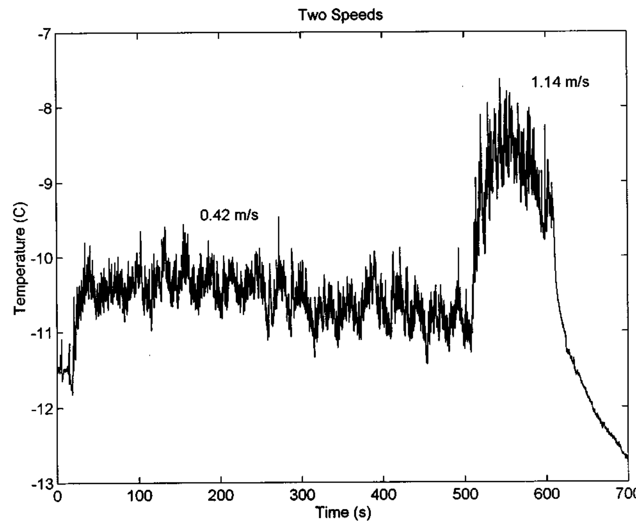

Fig. 5. Skate-bottom temperature versus time at two speeds in a cold room. The skater was pushed around a fixed circle at about a constant speed, which was then suddenly increased before she was suddenly stopped. However, it appears that the speed decreased slightly during both runs.

was heat flow up the length of the thermocouple toward the shoe, which cooled the thermocouple and reduced its average temperature.

It is also possible that pressure reduced the melting temperature to the observed plateau, but because the plateau depends on speed, this seems very unlikely. Furthermore, a pressure-melting temperature of −3.2 °C would require a fractional contact area of only 1.7% under these conditions. This seems very unlikely because of the large contact areas visible in the thermal-infrared images of the ice shown later.

Figure 4 shows temperature measurements at three speeds in succession on the pond. The skate was still cooling when motion started and, for these particular conditions, the blade warmed very rapidly at first. This rapid warming may be due to the higher coefficient of friction at this lower ambient temperature. At the slowest speed the skate reached a plateau of about −6.5 °C, at the medium speed the skate quickly reached a plateau at about −6.2 °C, and at the fastest speed it rose to about −6 °C. Upon stopping, the skate cooled as the thermal energy was conducted away. All of this behavior reinforces the concepts behind frictional heating: first, the initial rise in temperature with the onset of motion, second, the temperature increase with speed, and third, the exponential-like decay when motion stopped.

A more carefully controlled set of runs was done indoors in a cold room with the skater being pushed around an ice sheet. The skater held one end of a rope, which was anchored in the center of the ice, and she was pushed in a circle around the pivot at two speeds in succession. The initial speed was a very slow walk at an average speed of 0.42 m/s for about 480 s. Then the speed was increased suddenly to 1.14 m/s for another 160 s. These results are shown in Fig. 5, where it can be seen that the temperature rose to a plateau of about −10.6 °C at the slower speed and then to about −8.7 °C at the faster speed. The ice temperature was −13.4 °C, so the temperature rise for the slower speed was 2.8 °C and for the faster speed was 4.7 °C. The temperature did not rise proportionately with speed because heat loss from the interface increased with interface temperature, and the temperature cannot exceed the melting point at any speed.

C. Normal skating

The skating cycle gives rise to a distinctive signal in Nordic-style skating skis, which are snow skis used with the cyclic motion of ice skates. With the skis, every individual cycle of the skater can be characterized by rapid warming when the ski glides on the snow and an exponential-like decay when the ski is lifted into the air.[4] Ice skating on the pond gave a similar cycle, but the time series shown in Fig. 6 is noisier, probably because the skate is much shorter than

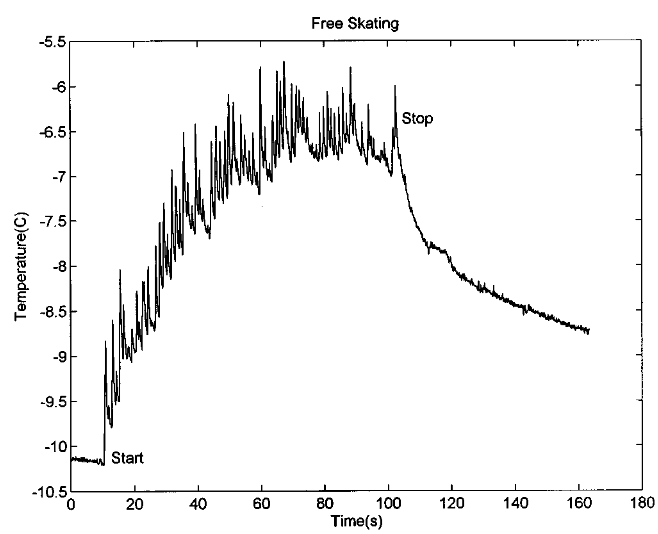

Fig. 6. Skate-bottom temperature versus time for normal skating. Each cycle of glide and lift gives a very distinctive pattern of sudden temperature increase followed by exponential cooling.

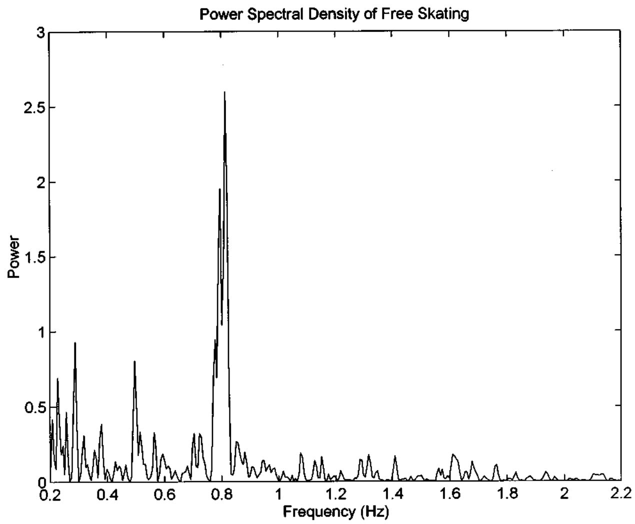

Fig. 7. Power versus frequency for the skate-bottom temperatures shown in Fig. 6. The skater established a highly regular pattern of four skating cycles every 5 s.

the ski. The power spectrum of this run is shown in Fig. 7, where the skater's frequency is 0.8 Hz, or four skating cycles every 5 s.

Compare the results from the two tests done in close succession under the same conditions and shown in Figs. 4 and 6. Figure 4 depicts the results achieved by pushing the skater, whereas the results in Fig. 6 come from normal skating. The skate did not warm up as quickly and achieved a lower plateau during normal skating in spite of the higher speed. We assume this is because the skate was raised into the cold air only during the normal skating cycle.

D. Insulation

Figure 8 shows the results of two runs made indoors in quick succession at the same speed where the skate blade was thermally insulated for the first run but bare for the second. The insulation was applied by gluing a thin, molded sheet of flexible insulation around the skate from the boot all the way down the blade. Only the glide surface of the blade was exposed, while all of the metal above the ice was placed in the insulating envelope. This reduced heat loss to the cold air and therefore reduced heat loss from the skate/ice interface by conduction upward through the metal. Accordingly, the interface temperature increased significantly, more energy was available for melting, and we assume the friction was lowered. As expected, the insulation reduced the rate of cooling once motion ceased. Both decay curves are described well by exponential functions with r^2 greater than 0.9999; the decay constants, 0.057 s^{-1} for the insulated run and 0.063 s^{-1} for the bare run, show that the insulation reduced the rate of cooling by about 10%.

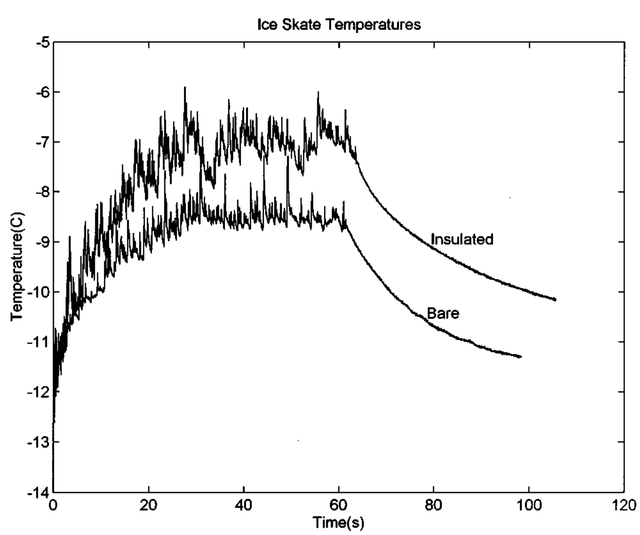

Fig. 8. Skate-bottom temperature versus time for two runs at the same speed done in close succession. The skate was thermally insulated during the first run, but the insulation was removed before the second run. When insulated, the skate warms to a higher temperature and cools more slowly once stopped.

E. Infrared images

A thermal-infrared camera was used indoors to examine the track behind the skate, which was also warmed by frictional heating. In real time, the infrared image on the video screen clearly showed the decay of a warm streak on the ice surface after the skate passed. Although viewing the video itself is very informative, suitable still images could not be produced for presentation here.

During some passes there were spots on the track that were preferentially warmed, presumably high spots, showing that the ice surface was not smooth and that the load was not carried uniformly. These were warmer and took longer to cool than the rest of the track. However, in all images, the entire length of the track was at least partly warmed, indicating that there was contact over nearly the entire track. We could conclude that the pressures were higher at the distinct warm spots and that pressure melting could have occurred there, but contact did not appear to be limited to those spots. Also, they were observed as warm spots due to a concentration of frictional heating, and not cold spots where pressure melting was occurring.

There were warmed ejecta sprayed beside the track. It is not known if the ejecta were liquid droplets or warmed ice shards although meltwater spray was observed by Tusima and Yosida.[5] As is normal in ice skating, a pile of ice debris was visible around the track.

IV. DISCUSSION AND CONCLUSIONS

The first quantitative theory of ice friction was provided by Evans *et al.*,[3] who suggested that, above a temperature of -2 °C, pressure melting would contribute by reversing the temperature gradients in the ice and skate. It is important to note that our conclusion about the applicability of frictional heating is valid only in the temperature range where our measurements were made. If pressure melting does contribute to the generation of meltwater production at temperatures between -2 and 0 °C, then insulating the skate blade would not be advantageous. While insulation reduces the heat loss when the ambient temperature is below the interface temperature, it would reduce heat gain when the ambient temperature is above the interface temperature.

Without further measurements at higher temperatures, we can draw some tentative conclusions using both theory and the observations made here. The infrared images showed nearly complete contact in the track, and thus we infer that the contact area was nearly 100% of the actual area of the skate blade, even when there were hot spots in the track. Given the weight on and area of the skate, the pressure-melting temperature should have been about $-0.054\,°C$, which suggests that pressure melting can be ignored entirely.

While much of what we know about the kinetic friction of ice is based on theory, the simple temperature and thermal-infrared measurements reported here allow some important interpretations of the theory. The observed temperatures are never as high as the melting temperature because of problems associated with making true surface-temperature measurements, but they prove that frictional heating is the dominant mechanism accounting for meltwater production.

The rate of heating should increase proportionately with speed and load, and repeated tests with different speeds showed that the skate behaved as the theory of frictional heating predicted. The skate warmed with the onset of motion, the temperature plateau increased with speed, and the skate cooled exponentially once motion ceased. The normal skating cycle gave a distinctive signal where every individual cycle of the skater showed rapid warming during glide and an exponential-like decay when the skated was lifted into the air. Thermally insulating the skate to reduce heat loss showed that skates run at higher temperatures when insulated. That suggests that insulation increases the amount of energy available for generating meltwater and therefore should lower the coefficient of friction.

Thermal-infrared imagery showed the decay of a warm streak on the ice surface after the skate passed. During some passes there were warm spots on the track, presumably high spots, indicating that the ice surface was not smooth and that the contact pressure varied along the track. Warm ejecta were spread beside the track but it is not known if the ejecta were liquid droplets or warm ice shards, or both.

The basic ideas behind the theory of Evans *et al.*[3] were substantiated, although their suggestion that pressure melting may contribute above a temperature of $-2\,°C$ seems unlikely. Pressure melting could make at least a partial contribution at or very close to the melting temperature, where the melting temperature might be below the ambient temperature.

ACKNOWLEDGMENTS

We thank Roger Berger, Jim Lacombe, and Greg Pedrick for helping us obtain the infrared images. Reviews by Cathy Jones and Jim Lacombe were very helpful. Reviews by the editor, Dr. Robert H. Romer, and an anonymous reviewer were also very helpful. This work was supported by Physical Properties of Snow Covers AT24-SC-S01 at CRREL and WISP at Dartmouth.

[1] F. P. Bowden and T. P. Hughes, ''Mechanism of sliding on ice and snow,'' Proc. R. Soc. London, Ser. A **172**, 280–298 (1939).

[2] S. C. Colbeck, ''Pressure melting and ice skating,'' Am. J. Phys. **63**, 888–890 (1995).

[3] D. C. B. Evans, J. F. Nye, and K. J. Cheeseman, ''The kinetic friction of ice,'' Proc. R. Soc. London, Ser. A **347**, 493–512 (1976).

[4] S. C. Colbeck, ''Bottom temperatures of skating skis on snow,'' Med. Sci. Sports Exer. **26**, 258–262 (1994).

[5] K. Tusima and Z. Yosida, ''The melting of ice by friction,'' Low Temp. Sci. A **31**, 34–43 (1969).