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Temperature effects of black versus white polyethylene bases for snow skis

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Abstract

Basal temperatures of skis were measured to assess the impact of color on basal energy balance. The skis were identical except one had a black base and the other had a white base. The black-based ski ran at higher temperatures than the white-based ski, even when only diffuse sunlight was reaching the snow surface. Heat production calculations suggest that solar radiation absorption at a ski base can contribute significantly to the production of the meltwater film on which skis glide. Since ski-base color affects the energy balance of the base, color should affect ski friction.

Keywords: Snow; Skis; Friction

1. Introduction

The basic processes responsible for the low coefficient of friction for snow are well known (e.g., Colbeck, 1994a) but remain a subject of interest because of the intensively competitive nature of ski racing. Anything that produces a small reduction in friction could be significant. Buhl et al. (2001) looked at the effects of temperature and load on ski friction while Moldestad (1999) investigated the effects of structure. The differences in the heat production of black versus white ski bases is investigated here as a possible way of affecting snow friction.

The bases of sliding skis and ice skates warm by frictional rubbing and the heat generated by this rubbing creates a meltwater film that provides lubrication. The film is essential for easy sliding to occur, but too much melt water can cause capillary drag (Colbeck, 1997). Thus there is a limited range of meltwater lubrication where the frictional characteristics of skis are optimized for any given set of conditions. At low temperatures any source of heat should reduce friction since it would help compensate for heat loss by conduction into the cold snow and/or ski. At high temperatures, when the snow is already wet, further meltwater production is unnecessary and, in fact, heat production should be avoided as much as possible; too much meltwater produces capillary drag. Thus it seems possible that white skis would offer

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advantages at high temperatures by reducing meltwater production while black skis would offer advantages at low temperatures by increasing meltwater production. This might be true even if only the ski bases are white or black.

Temperature measurements on the bottoms of skis have consistently shown that ski bases warm during motion. Higher weights and faster speeds produce more frictional heating and the basal temperatures rise accordingly. However, skis also respond directly to the presence or absence of solar radiation. Skating skis ran at lower temperatures when the skier passed through shaded areas of a track (Colbeck, 1994b). While that may have been due to either a lack of direct solar radiation absorption on the ski base or simply that the snow in the shade was colder, thermocouples (TC) at the base of a ski did respond instantly when that section of the ski was shaded from, or exposed, to the sun. At an elevation of 2500 m with a dry atmosphere, the incoming solar radiation was sufficiently strong to cause the basal temperature of a ski to rise instantaneously to 0 °C upon exposure to the sun. This effect was first noticed on skis with a fairly light-colored base; these skis responded quickly and predictably when they were shaded or exposed around the area of the TC, even though the TC was on the bottom of the ski and in contact with snow. It was clear that solar radiation was reaching the base of the ski after being scattered in the snow, thus suggesting that black ski bases might increase heat production while white ski bases might reduce it. This effect is investigated here by measuring the basal temperatures of black and white ski bases.

2. Ski measurement methods

K2 made a pair of GS-Race skis especially for this study. The skis were identical, except one had a very black base and the other had a very white base. The black base was IMS P-Tex Electra 4000 with graphite and the other was a clear IMS-Tex 2000 base, which was back-painted white. Both were high-molecular weight, sintered polyethylene bases widely used by the ski industry. One TC was inserted into each ski directly under the foot of the skier where the heat production due to frictional heating is the greatest and the relative effect of solar heating should be minimized. The TCs were placed in holes drilled vertically through each ski and then set in place with epoxy colored to match the ski base. Thin TC wires were used to reduce heat conduction and the TC wires were covered with insulation where they emerged on the upper surface of the skis. The TC junctions were flush with the surface of the base for direct contact with the snow.

There are a number of factors that could produce differences between the two skis aside from their different albedos. Graphite is added to polyethylene to produce black bases and this could change the hardness, electrical, thermal, and therefore the frictional characteristics of the ski base. Colbeck (1995) has shown that white ski bases did not accumulate electrical charges on packed ski runs although electrical charges did accumulate in deep powder snow. If graphite increases the thermal conductivity of the base there should be more heat loss through conduction, which would reduce the temperature at the base of a black ski as compared to a white ski. However, the results of the calibration measurements given later show a negligible difference. While these material properties and processes are important, it is only the thermal responses of the ski bases that are considered here.

To determine differences between the two skis due to differences in the basal materials or the thermocouples, the skis were calibrated in two ways. First, they were placed bottom-to-bottom and wrapped in insulation. The TCs were read for 12 h and, after a transient period, they tracked room temperature overnight with the white ski reading consistently higher by about 0.08 °C. This shows that the TCs could be read accurately to better than 0.1 °C, but that there was a small difference between them. Second, ski runs were made well after sunset since even small amounts of diffuse sunlight on a cloudy day seemed to affect the skis. Four runs were made on a gentle slope where the skier poled to accelerate and one run on a steeper track where the skier was accelerated by gravity. The results from the later run are shown in Fig. 1, but only for that portion of the test where the skis were moving steadily. Both skis warm, but there is some noise due to snow surface roughness and shifts in how the skier carried his weight. There is a difference between the white base and the black base, which was worn on the right side. On average the black base was 0.1 °C

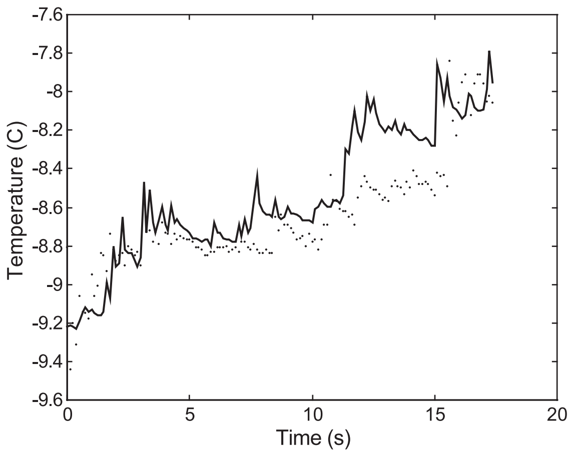

Fig. 1. Ski-base temperatures versus time during a run at night. The black base (solid line) ran, on average, 0.10 °C warmer, apparently because the skier favored his right leg.

warmer than the white base, the opposite result from what was found when the skis were calibrated indoors. This difference probably arose because the skier strongly favored his right leg.

Four runs were made during darkness on the gentler slope where the skier could keep the skis as flat as possible and the skis were alternated left-to-right on subsequent runs. These results show that the ski on the right side carries more of the skier's weight and is more strongly heated. These conclusions about loading and heating are consistent with earlier work (Colbeck, 1994a). In two of these four runs the black base was on the right foot and ran, on average, 0.02 °C warmer. In the other two runs, the white base was on the right foot and ran, on average, 0.07 °C warmer. Thus the results of both the indoor and outdoor calibrations suggest that the white base reads a higher temperature, but these results are ignored for two reasons. First, the results give a consistent pattern, but there was a lot of noise in the signal from the four test runs on the gentle slope. Second, although including these calibration results would strengthen the ultimate conclusions, the effect would be very small.

2.1. Ski measurements with sunshine

The ski-glide tests were done on two slopes in New Hampshire, USA, during the months of February and March when there was a continuous snow cover, temperatures were below freezing, but the sun was 2–3 months past the winter solstice. The steeper slope was about 130 m long with a rapid drop in the first 10 m where the skier accelerated, a slight drop in the next 70 m where the skier maintained speed, and then a flat run out. Except to start, the skis were never lifted off of the snow and only gentle shifts in direction were necessary. The temperatures of the skis are shown in Fig. 2 as they cool toward the outdoor temperature, about −4.5 °C at 1130 h. The skier was standing still on the skis facing the sun. Although the bases were facing downward, the black base was considerably warmer than the white base. This can only be due to the difference in absorption of solar radiation by the bases since the tops of the skis were identical and the skis were at the same temperature when brought outdoors. The difference is so great that the skier felt a significant amount of drag due to capillary adhesion on the black base, but none on the white base.

After the skis cooled to a stable temperature, the skier skied down the slope. Fig. 3 shows that the black base ran at a higher temperature for the entire run. The ski bases had not cooled to the ambient air temperature because of solar heating of the entire ski. With the onset of motion at about 27 s in the figure, both ski bases cooled by passing over cooler snow. At about 35 s the energy generated by frictional heating and solar radiation absorption was sufficient to overcome

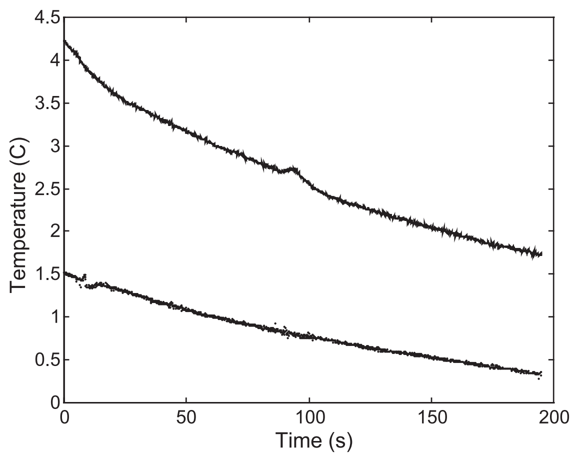

Fig. 2. Ski-base temperatures versus time as the skier stood facing the sun. The black base (solid, upper line) was warmer as the skis cooled.

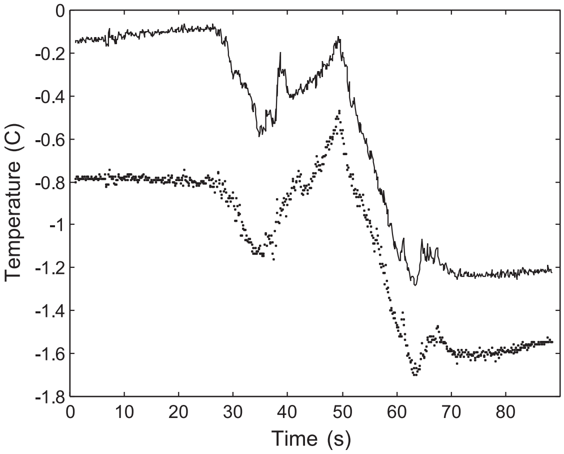

Fig. 3. Ski-base temperatures versus time during a run. The black base (solid line) was on the side toward the sun during glide. When glide started at about 27 s, both ski bases cooled by passing over cold snow. At about 35 s the heat generated by frictional heating and solar radiation absorption was sufficient to overcome that cooling effect and the skis began warming. The ski run ended at about 49 s and both skis cooled, as the skier stood motionless on cold snow but in the sun.

that cooling effect and the skis began warming, as normally happens in a ski run (e.g., Colbeck, 1994a, 1994b). The ski run ended at about 49 s and both skis cooled, as the skier stood motionless on cold snow, but in the sun. The skis eventually began to warm and continued to do so until data acquisition ended. During this run the sun was on the right of and behind the skier, crossing the skis at and angle of about 45°. Thus the black base, which was worn on the right foot, might have had an advantage since the right leg of the skier shaded a short section of the white base. Accordingly, the skis were switched and the run repeated immediately.

Fig. 4 shows that the same result occurred but, with the white base on the right, sunny side of the skier, the difference between the two skis was not as great. It is possible that this reduction occurred mostly because the area of the ski containing the black thermocouple was shaded by the skier's right leg, at least during part of the run.

The same run was repeated on a clear day with an ambient air temperature of −9.5 °C, but at 1640 h when there was no sunshine directly on the snow. Thus the solar radiation incident on the snow was the diffuse sky component, which can still be a significant energy source, about 10% of the direct solar radiation on this very clear day. The skis responded in a similar manner, but the solar effect is less. Before the onset of motion, the black base was warmer than the white base, but the difference was not as great as it was when direct solar radiation reached the surface. Once the skier started to move, the skis warmed immediately and, while the black base was generally warmer than the white base, the difference is greatly reduced. Once motion stopped the white base cooled a little more than the black base. Thus, with purely diffuse solar radiation, there is a difference based on color, but the difference is reduced.

As a final test of the differences due to ski-base color, a run was taken on the gentler track. The white base was worn on the right side of the skier, which gave it four advantages. First, the sun was on the right. Second, the skier carries more weight on his right side. Third, the skier turned gently to his left by weighting his right leg. Fourth, in the calibration tests the white-based ski read slightly higher. Nevertheless, in this run the black-based ski ran 0.4–0.6 °C warmer than the white-based ski as shown in Fig. 5. As the skis began moving at 0 s, the white-based ski warmed faster due to frictional rubbing, presumably because its lower temperature gave it a higher coefficient of friction. This preferential heating reduced the temperature difference to about 0.4 °C at

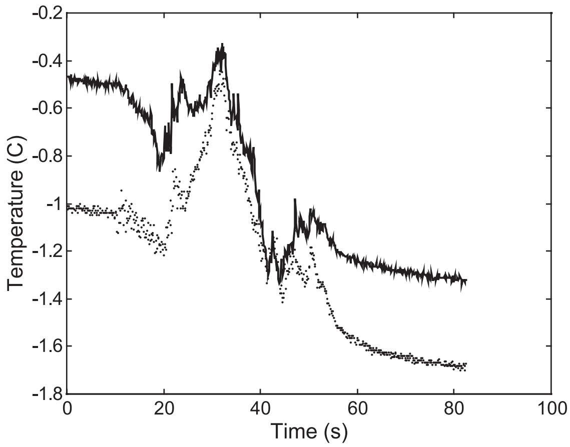

Fig. 4. Same ski run as shown in Fig. 3 except white base (dots) on side toward the sun. The difference between the skis was not as great during glide, although the black base was still warmer. Glide started at about 10 s, the skis cooled initially but started warming at about 19 s. Motion ceased at about 32 s.

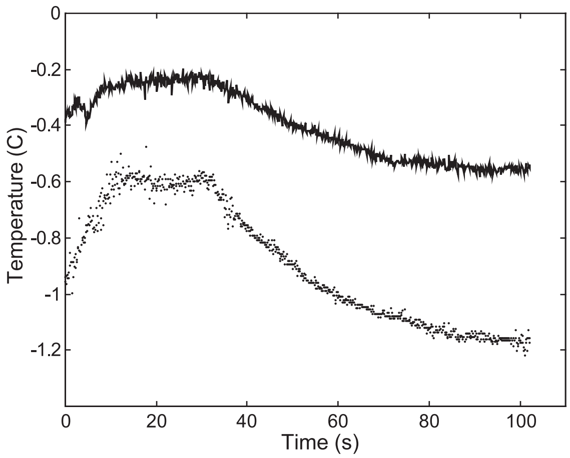

Fig. 5. Ski-base temperature versus time during a run on a gentle slope. All factors, except ski-base color, favored the white base, but the black base (solid line) was still warmer. Motion began at 0 s and ceased at about 30 s.

30 s when motion ceased. As the skier stood still and the skis cooled, the temperature difference increased again.

3. Discussion

It is clear that black bases run at higher temperatures than white bases and this effect should be measurable during all daylight hours, even during overcast conditions, since diffuse solar radiation still penetrates the snow surface. The effect is less on a cloudy day, in the shade, and when the ski run is sloped away from the sun. While snow albedo is virtually independent of sun angle when the angle is within 50° of the perpendicular to the slope, less radiation will penetrate the snow at greater angles, i.e., when the sun is at a low angle to the slope (Wiscombe and Warren, 1980). This would be especially important at higher latitudes during the darker months of the year.

The solar contribution to ski-base heating can be put into perspective by calculating the heats produced by frictional rubbing and solar radiation absorption. Frictional heat production is simply speed times normal force times the coefficient of friction. Thus for a coefficient of friction of 0.02 and a weight of 400 N per ski, heat production would be 320 W per ski at 40 m/s. This might be a reasonable number for a DH ski at high speed, whereas a Nordic skier might, on average, generate 32 W per ski. Accordingly, we take these as the approximate range of interest.

There is much more uncertainty in the calculation of the solar effect, but its upper limit can be calculated easily as the solar constant (1370 W m^{-2}) times the area of the ski. For the K2 skis used in the measurements that is about 212 W per ski. This value only applies to a perfectly black ski base facing the sun at the top of the atmosphere and it has to be reduced for atmospheric effects, radiative scattering within the snow, and the albedo of the ski bases:

1. The atmospheric effects are dependent on altitude, since at higher elevations the incoming radiation passes through less air. The effect is also dependent on humidity, cloudiness and aerosols. For these reasons much stronger solar effects are seen during ski measurements in Utah than in New Hampshire. Certainly these effects would be smaller at higher latitudes during the darker times of the year. In New Hampshire, atmospheric effects reduce the solar radiation reaching the snow by at least 25%, whereas in Utah the reduction would generally be less.
2. The all-wave albedo, integrated over the solar spectrum, of fresh snow can be as large as 0.9. The albedo decreases as the snow ages, but for dry snow values are still in the range of 0.75–0.85 (Warren, 1982). These large albedos indicate that a considerable amount of solar radiation is emerging from the snowpack, radiation that may be absorbed by the base of the ski. Since snow is a highly scattering medium there is considerable horizontal transport of radiation and we expect the self-shadowing effect of the ski to be relatively small. However, our calculations neglect self-shadowing and therefore represent a maximum bound on the amount of solar heating.
3. The albedos of black and white sheets of polyethylene were measured with a spectral photometer over most of the solar spectrum, between of 400 and 1000 nm. The albedos were found to average about 0.9 for the white sheet and about 0.02 for the black sheet. These measurements were made with the sheets held in the air against a white background and, when placed on a ski, the background of the white sheet could affect

its albedo since light penetrates it readily. Thus, when a white sheet is bonded to a ski, it should be bonded to a white background or back painted white to get this high reflectance. The black sheet, on the other hand, would not be affected by its substrate since light does not penetrate it well.

The solar heating effect in New Hampshire on very clear days is calculated assuming that the solar irradiance at the surface (F_r) is one-half of the solar constant, the base area (A) is 0.1515 m^2, the black base's albedo (α) is 0.02, and the white base's albedo is 0.9. The solar heating (Q_r) of the ski is

$$Q_r = \alpha F_r A$$

Accordingly, the black base would have been heated at about 94 W and the white base at about 2 W; the black base was about 45 times more absorptive than the white base. Thus switching from a white base to a black base could increase the production of heat by about 91 W per ski, which is more than twice the frictional heat production calculated for a skier moving at 4.5 m/s and more than one-fourth of the heat production calculated for a skier moving at 40 m/s. Although the solar effect may have been overestimated, it does explain why the black-based ski ran at significantly higher temperatures than the white-based ski, which shows that ski-base color is important. Even if the solar effect has been overestimated by an order of magnitude, its effect is still significant, especially for a Nordic skier.

The K2 skis used were identical except for the color of the bases. While the effect might have been greater if all surfaces of the ski had been entirely black or white, vertical heat conduction within a ski is generally small, so heating the base directly might be more effective than relying on heat conducted downwards from the upper surface. However, the use of all-black or all-white skis should be considered.

Based on the results reported here, it appears that black ski bases can offer advantages, or disadvantages, over white bases, depending on the situation. At low temperatures where heat production should be maximized to overcome conductive heat loss, black bases run at higher temperatures, apparently because of solar radiation absorption. While scattering significantly depletes the radiation as the light moves through snow, the heat produced by solar radiation absorption on a black ski base could be more than the heat produced by frictional rubbing at lower speeds. At higher speeds this heat source could still contribute significantly to the energy production needed to produce meltwater. White bases absorb much less solar energy and should offer advantages at high temperatures where too much meltwater is present and capillary drag increases ski friction.

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