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Temperature below a gliding cross country ski

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Abstract

The temperature of snow under skating skis was studied with infrared sensors at four positions and three different velocities. To have an indication of causes and consequences of the heating the friction coefficient with a linear tribometer and the pressure distribution were measured as well. The friction increased with velocity. The highest temperature increase was measured 440 mm from the ski end at the highest velocity of 10 m/s. Temperature increase at position 1550 mm was independent of velocity. Friction coefficient, pressure distribution and temperature measurements showed a high reliability and allowed to create a model to explain the temperature profile along the ski.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: snow, ski, friction, snow-temperature

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1. Introduction

In cross country skiing, the friction coefficient between ski and snow is one of the most important material factors. The friction between ski and snow during gliding produces heat, which is dissipated in the ski and the snow. The heating of the snow can lead to the formation of a thin melt water film (Bowden, 1953). According to Kietzig et al. (2010) the thickness of this film is essential for the type of friction between the two surfaces. The thickness of the water film depends on parameters like snow temperature, liquid water content of the snow, normal force, material (different specific heat and thermal conductivity coefficients), structure of the surface etc. and also varies along the length of the ski. Colbeck et al. (1994) suggest that the water film increases from ski tip to ski end. Ambach and Mayr (1981) were able to measure a several micrometers thick water film by using a comb-shaped capacitor. The capacitor was positioned at the end of the ski. Colbeck et al. (1991) measured the temperature with thermocouples at 4 positions at the ski base. Bäurle et al. (2006) measured the snow temperature right after a sliding object (length = 4 cm) with an infrared camera. However, no work could be found in which the temperature on the snow surface was measured along the ski. A knowledge on the heat development at the snow surface under the ski could be helpful for a better understanding of the melt water development. Therefore, the aim of this study was to measure the temperature of the snow surface under the ski while sliding. To have an indication of causes and consequences of the heating, the friction coefficient and the pressure distribution were measured as well.

2. Method

2.1. Measurement of the snow temperature under the ski

Four infrared temperature sensors (MLX90614ESF, Melexis, Belgium; accuracy +/-1°C in a range of -40 to 60°C) were used for the temperature measurements of the snow. The signals were recorded by an 8 bit microcontroller with a sample rate of 10 Hz. The sensors were positioned in drilled holes, which were slanted to prevent snow from getting stuck in the holes (Fig. 1a). A pair of Fischer RCS N17 skating skis (length 187 cm, stiffness hard) with the same structure without wax were used. Both skis had one hole on the left and one on the right side, so any interference between the holes was avoided (Fig. 1b).

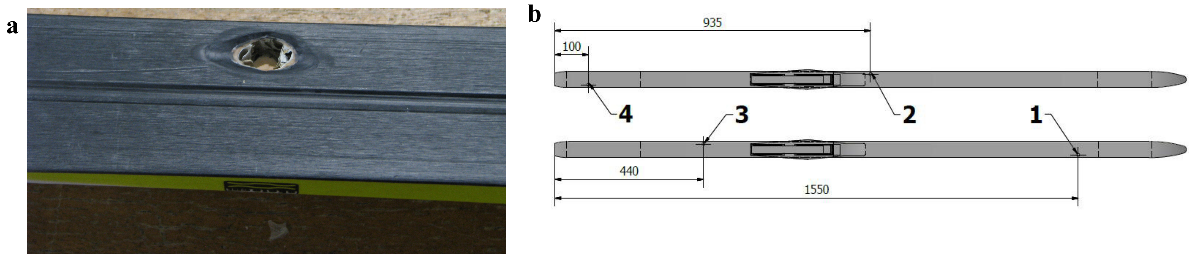

Fig. 1. (a) A drilled and slanted hole for a temperature sensor; (b) positions of the 4 temperature sensors on the skis

2.2. Linear tribometer

The skis were tested under laboratory conditions with the linear tribometer of the Centre of Technology for Ski and Alpine Sports. This linear tribometer basically consists of a 23 x 0.8 m trough for snow or ice and a guidance beam on which a ski, mounted on a measuring sledge, can be moved by a high torque electro motor. After acceleration, the ski slides with a constant velocity. A vertical force was applied to the ski by two spring-loaded bars. Horizontal and vertical forces were measured with load cells (U9B, 5 kN and 0.5kN, HBM, Austria). The velocity of the sledge was measured with an inductive length measuring system (LMK-132.Z-0-1-6 and LMB-130.2, AMO, Austria). The snow was produced by a snow lance in a neighboring room at -19°C to -14°C. This snow was filled into the trough, pressed and stropped with a preparation car. Additionally, every track was prepared by 20 runs with a skating ski. The density of the snow was determined by measuring the weight of a 5 dm³ snow volume. The free water content was measured with a hygrometer (Hygro O11, Doser, Germany). The grain size analysis was based on a snow picture taken on a 1x1mm squared background (mean value of eight measured grain sizes). Each ski was tested on a separate track 5 times at velocities of 2, 5 and 10 m/s on freshly produced, very fine grained and on old, coarse grained snow. Due to a two minutes break between the runs both snow and skis reached the initial temperature.

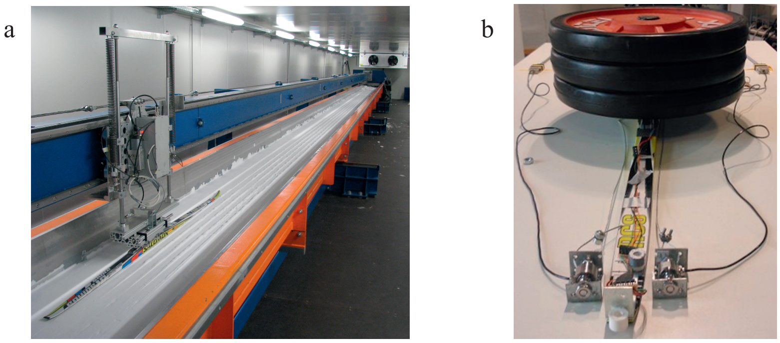

Fig. 2. (a) Linear Tribometer with the measuring sledge; (b) Experimental setup of the pressure distribution measurement

The snow temperature was -8°C and the normal force was set to 650 N (around the weight during gliding on one ski).

2.3. Pressure distribution measurement

To measure the pressure distribution, the ski was loaded with three 20 kg weight plates positioned on the top of the binding. A fixed plastic sheet was pulled along the ski between a table and the ski (Fig. 2). The pulling force was measured by two load cells (U9B, 5 kN, HBM, Austria). The position of the plastic sheet was recorded by a magnetic length measurement system (EMIX3 and EMAX-000-D0110, Regatronic, Austria, resolution 0.01 mm). Assuming that the coefficient of friction between table, sheet and ski is constant, because the structure of the ski surface is constant along the ski, the pressure distribution can be determined. The test was carried out twice.

2.4. Data analysis

The friction coefficient μ was calculated by dividing the mean horizontal force by the vertical force. Out of the 5 measurements per speed, the trials two to five were used to calculate the mean friction coefficient and the standard deviation. The temperature increase ΔT was defined as the difference from the maximum temperature T_{max} of the sliding phase to the mean temperature T_{mean} (-1.5 s seconds before the start until the start) (Fig. 3).

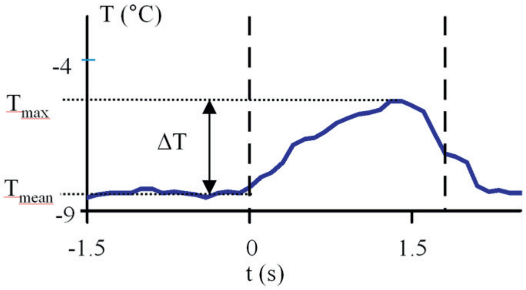

Fig. 3. Measured temperature course of a sensor during a sliding test. The vertical dashed lines indicate start (0 s) and end (1.8 s) of the sliding phase.

3. Results

The characteristic values of the old, coarse grained snow and the new, fine grained snow are listed in Table 1. Except of the grain size these two snow types were very similar.

Table 1: Mean and standard deviation of the snow properties of the two snow types

	new snow	old snow
Snow temperature (°C)	-8.3 ± 0.3	-8.7 ± 0.3
Density of the snow (kgm^{-3})	490 ± 30	466 ± 17
Diameter of one snow grain (mm)	0.15 ± 0.04	0.35 ± 0.06
Water content (%)	17 ± 3	20 ± 3

The pressure distribution of the Fischer RCS1 ski is shown in Fig. 4. The vertical, dashed lines display the position of the temperature sensors. The ski mainly had contact on two pressure areas, whose maxima are at 54 and at 141 cm, measured from the end of the ski. The mean difference between the two tests was under 1.5% in relation to the measured values.

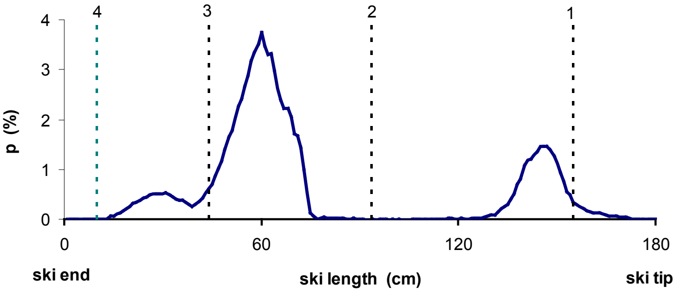

Fig. 4. Pressure distribution p of Fischer RSC1 ski. Positions of temperature sensors are indicated by the dashed lines 1-4.

The temperature course during a run with 10 m/s on new snow is shown in Fig. 5. With the start of the acceleration (t = 0 s), the temperature increased rapidly, and stayed constant after the top-speed was reached (t ~ 0.6 s). During breaking (t ~ 1.7 s), the temperature fell and reached the initial value after the ski stopped (t = 2 s). The high correlation between velocity and temperature is also shown in this figure.

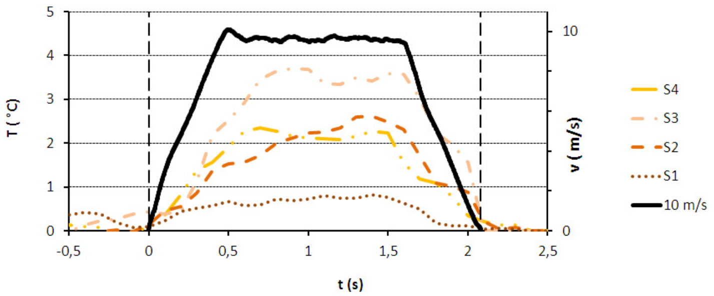

Fig. 5. Snow temperature, measured by the sensors 1-4 on the old snow and velocity of the ski slide. The vertical dashed lines indicate the start and the end of the movement.

Mean values and standard deviations of the friction coefficient µ of the two skis on the two different types of snow at different velocities are shown in Fig 6. The differences of the friction coefficients between ski 1 and ski 2 were small for all velocities tested. The friction coefficient increased with increasing velocity for new and old snow. The friction was higher for 2 and 5 m/s for old snow than for new snow.

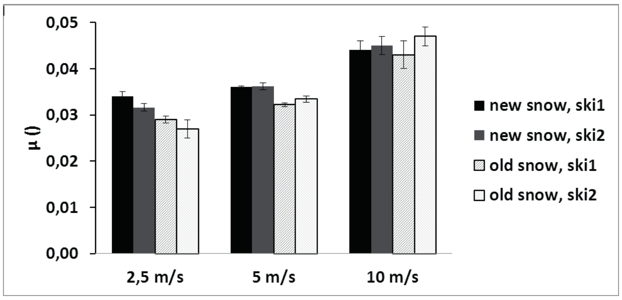

Fig. 6. Mean and standard deviation of the friction coefficients measured with the linear tribometer.

Fig. 7 shows the temperature difference ΔT, measured by the infrared temperature sensors, at different positions and at different velocities. The temperature difference ΔT is around 1°C at all velocities for sensor 1 and increases up to 4°C at 10 m/s for sensor 3 located at the end of the second pressure area (Fig. 4).

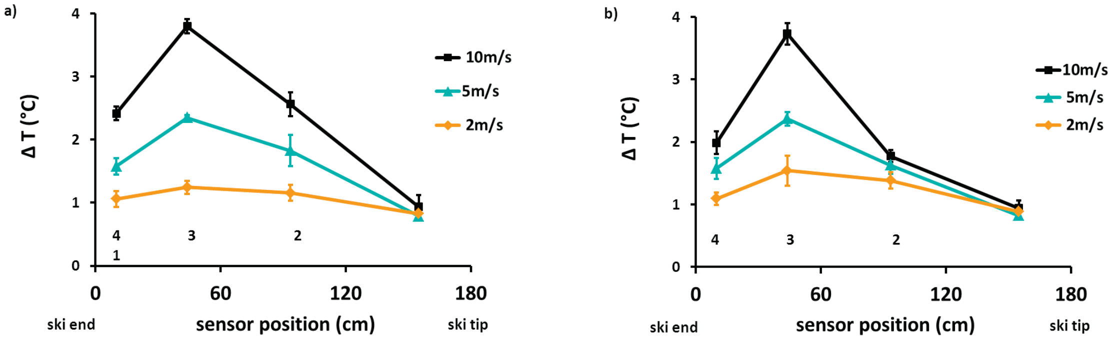

Fig. 7. Temperature difference ΔT as a function of the sensor positions. The sensors are labelled with the numbers 1-4. (a) new snow; (b) old snow.

4. Discussion

As shown in Fig. 4 the pressure is concentrated mainly on two pressure areas of the ski, wherein about 80% of the pressure is acting on the rear pressure area. Since the friction force for a selected area is the product of friction coefficient, pressure and area, heat is generated mainly in these areas. The temperature increase from sensor 1 (ski tip) appears to be independent of the velocity and is always around 1°C. This is relatively high, because the pressure percentage from the ski tip to sensor 1 is only about 5%. The reason for this could be the initial dry friction, which has a higher friction coefficient and thereby enhances the heat generation. Another indicator for the dry friction is the independence of velocity. The temperature rise of the sensor 2 is composed of the temperature increase in the first pressure area and the temperature decrease during the unloaded area (Fig. 7). The highest temperature increase was measured at the end of the second pressure area with sensor 3. The fast temperature decrease between sensor 3 and sensor 4 was unexpected. It was about the same as the temperature increase between sensor 2 and sensor 3. This fast temperature decrease is even more surprising, since the distance between sensor 3 and sensor 4 is only 0.34 m, which leads to a time difference of only 0.034 s at a velocity of 10 m/s. For a more accurate determination of the temperature profile course along the ski length, more temperature sensors would be required. Also Colbeck et al. (1991) obtained similar results with downhill skis on hard snow.

In the present work the temperature profile under the ski base was investigated along the ski at different velocities. For a better understanding of the involved processes a model is studied to investigate the development of the temperature profile. The model is an inverse problem. The produced heat can be computed if the friction coefficient μ as a function of the temperature difference ΔT and the velocity of the skis are known. This heat leads to a temperature increase. Melting of snow and dissipation of heat into snow and ski lead to a temperature decrease, which is a function of time and ΔT. For the solution of the inverse problem one has to find functions which give the measured temperature profile. We tried to find a solution by trial and error. Preliminary results for the velocities 5 and 10 m/s are encouraging. However, the model should hold for all velocities. For small ΔT values μ was larger than 0.2, what could be a value for dry friction. The smallest value for μ was around 0.02 at a ΔT of 2°C. At higher ΔT the friction coefficient was increasing. This explains also the higher friction coefficient at higher velocities, because ΔT is due to the fast temperature increase at the pressure area clearly over 2°C. The input variables were slightly different for the old and new snow, especially the temperature decrease. However, additional measurements are required for an exact determination of the input variables.

5. Conclusion

In this work friction and temperature measurement under realistic circumstances of cross country ski was done. The reliability of the values was high. The temperature along the ski distance was strong different. With the measured data a model to simulate the heat course along the ski was created. At this model the friction coefficient is changing significantly along the ski length. Accordingly a different structure or wax along the ski length could reduce the whole friction.

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