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Experimental and numerical evaluation of temperature variation by frictional heating at the interface between snow and ski

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Abstract
To evaluate the frictional heating effect during ski gliding by temperature measurement, a temperature measurement system was developed and evaluated numerically and experimentally. The portable temperature measurement system with high temperature resolution and accuracy consisted of thermistors and a portable logger with a 24-bit A–D convertor. The thermistors were inserted in a hole in the ski board with thermal conductive adhesive. By using numerical simulation, the difference between the interface temperature and the averaged temperature in the sensing region was evaluated. The temperature difference was proportional to the value of frictional heat generation, and the maximum difference in the experimental range in this study was 0.17 K. To test the developed system, a gliding experiment was conducted at Shinjo Cryospheric Environment Laboratory. Three thermistors were installed in the ski board, and a moving object was constructed on the ski. By pulling the moving object with a guide wire, the moving object was glided, and the interfacial temperature was recorded. In the case of a total weight of 54 kg, which was near the optimal weight, the thermistor installed near the heel position had a large increment of temperature. In addition, similar temperature increments were observed during the acceleration phase of the moving object. After the acceleration phase, the gradient of the temperature increment changed. It was inferred that the variation of gradient was affected by the variation of the force balance on the moving object. This suggests that the local contact condition and friction might be estimated through temperature measurement.

Keywords: Ski, Temperature measurement, Friction, Numerical simulation, Heat transfer

1. Introduction

To improve the gliding performance of skiing, understanding of the friction mechanism between snow and ski and appropriate control of the ski surface are required; however, due to the complexity of the interfacial phenomena between snow and ski, the friction phenomenon has not yet been modeled. Temperature is one of the measurable and essential physical quantities in the friction phenomenon between snow and ski. It is known that a suitable ski wax is selected based on the environmental temperature. Additionally, the absolute temperature at the interface between ski and snow is required to estimate the ice properties under the condition of friction. Maeno (2016) pointed out that the friction coefficient should vary depending on the snow density, grain size, temperature, and so on.

In previous works, Warren et al. (1989) and Colbeck (1994) reported the temperature variation during downhill skiing...
by thermocouple. They evaluated the dependency of temperature increase on snow temperature. They concluded that temperature measurement would be a powerful tool for evaluating waxes and slider design. In addition, Schindelwig et al. (2014) measured interfacial temperature using an infrared temperature sensor. They conducted their experiment in an experimental room under an artificial snow condition. They measured a temperature increase of 4.0 °C during sliding in 2 seconds. However, these sensors have difficulties in principle in measuring absolute temperature. A thermocouple measures the temperature difference between a hot and cold junction. Additionally, the thermoelectric voltage is normally very weak. An infrared thermometer, on the other hand, measures the intensity of infrared light emitted from the surface of an object. This radiation intensity depends strongly not only on temperature but also on the emissivity of material surface.

To measure the interface temperature accurately, a temperature measurement system with a highly accurate sensor and logging device is required. Additionally, to measure the temperature during skiing, the size and portability of the logging system should be designed appropriately. Some authors, e.g., Okabe et al. (2017), have developed a highly accurate temperature measurement system with a thermistor and applied it to the diagnosis of skin cancer (Okabe et al., 2018, Okabe et al., 2019). By applying this knowledge, we developed a temperature measurement system and demonstrated the differences of frictional heating associated with different ski waxes through the measurement of interfacial temperature (Okajima et al., 2017). However, our final goal is to understand the relationship between the friction phenomenon and interfacial temperature. Therefore, the objective of this work was to clarify the effects of velocity and total weight on interfacial temperature by experiment and the temperature field around the sensor by numerical simulation. In this experiment, ski wax was not applied and the heating by friction between snow and bare surface of ski board is discussed.

2. Temperature measurement system

2.1 System configuration

Figure 1 shows a schematic of the temperature measurement system. This system consisted of thermistors inserted in a ski board and a portable temperature logger. The thermistors (No.13 Fμ, SEMITEC Corporation) had a diameter of 0.5 mm and a length of 2 mm. The relationship between resistance and temperature is shown in Fig. 1. At temperatures less than 0 °C, the resistance increases drastically and reaches the order of 100 kΩ. As shown in Fig. 1, the thermistors were inserted vertically through a hole bored in the ski and fixed with thermal conductive adhesive.

In addition, we developed a portable temperature logger with a 24-bit analog–digital converter. This device was designed for temperature measurement with the thermistor for a field experiment. Hence, it was powered by batteries, and the data were stored in a microSD card. Before the experiment, the temperature measurement system was calibrated using a quartz thermometer as a standard thermometer. The sampling frequency, accuracy, and temperature resolution of the measurement system were 16 Hz, 50 mK, and less than 0.1 mK, respectively.

Fig. 1  Schematic of the portable and accurate temperature measurement system.
2.2 Thermal phenomena around the sensor

2.2.1 Numerical model

Because the thermistor has a heat capacity, there should be a difference between the true temperature at the interface and the measured temperature. To evaluate this difference, a three-dimensional simulation of the temperature variation of the gliding surface was conducted. Figure 2 shows the three-dimensional model for simulation of the thermal phenomena on the gliding surface and around the temperature sensor. It consists of a ski board and snow, and they are in contact. The governing equations in each region are as follows:

\[
\begin{align*}
\text{ski board: } & \quad \rho c_i \frac{\partial T}{\partial t} = \nabla \cdot (k_i \nabla T), \\
\text{snow region: } & \quad \rho_{\text{snow}} c_{\text{snow}} \frac{\partial T}{\partial t} + \rho_{\text{snow}} v_{\text{snow}} \frac{\partial T}{\partial z} = \nabla \cdot (k_{\text{snow}} \nabla T),
\end{align*}
\]

where \(\rho\), \(c\), \(T\), \(t\), \(k\), \(v\), and \(z\) are density [kg/m\(^3\)], specific heat [J/(kg·K)], temperature [°C], time [s], thermal conductivity [W/(m·K)], velocity [m/s], and position [m], respectively. Subscript \(i\) and \(\text{snow}\) represents the index of ski board, thermistor, and adhesive and snow, respectively. In the numerical simulation, instead of gliding the ski board on the snow, snow was moved from the tip to the end of the ski. Hence, the advective term was added in Eq. (2). At the interface between the ski board and the snow, the frictional heat generation \(Q\) was set as in Eq. (3):

\[
Q = \mu P v_{\text{snow}} = \frac{\mu mg v_{\text{snow}}}{A_{\text{ski}}},
\]

where \(Q\) is the frictional heat generation per unit surface [W/m\(^2\)], \(\mu\) is the coefficient of kinetic friction [-], \(P\) is the contact pressure [Pa], \(v_{\text{snow}}\) is the gliding velocity [m/s], \(m\) is the total weight [kg], \(g\) is the gravitational acceleration [m/s\(^2\)], and \(A_{\text{ski}}\) is the apparent contact area [m\(^2\)]. The ski board had a width of 10 mm and thickness of 5 mm. The snow region was 4 mm thick. To investigate the influence of sensor position, the sensor positions of 75, 315, and 1260 mm from the tip of the ski board were considered. These sensor positions correspond to the positions of thermistor in experimental system which is explained in Section 3.1. At the location of a sensor position, a thermistor with a diameter of 0.5 mm and length of 2 mm was installed in a hole with a diameter of 1 mm and the hole was filled with thermal conductive adhesive. Here, the thermistor was assumed to be a homogenous material, and the effects of the lead wire and coating were neglected. The boundary conditions of the ski region were the adiabatic condition, except for the gliding interface and symmetric plane. In the snow region, constant temperature and uniform velocity were assumed at the inlet and zero gradient was applied at the outlet. The remaining planes of the snow region were under the adiabatic condition. Additionally, the phase change between water and ice was not considered in this simulation.

![Fig. 2 Three-dimensional model for simulation of the thermal phenomena on the gliding surface and around the temperature sensor. The model consists of a ski board and snow in contact.](image-url)
The thermophysical properties shown in Table 1 were used in this calculation. Additionally, the initial and inlet temperatures of the snow were assumed to be −10 °C, and the velocity of the snow was 3 m/s. The coefficient of kinetic friction was assumed to be the constant value of 0.05. The total weight loaded on the ski was either 34 kg or 54 kg, which are the same values as in the experiment described later. Computational meshes were generated to resolve the thermal boundary layer on the gliding plane, and the minimum mesh size was 0.023 mm × 0.11 mm × 0.023 mm. The general-purpose finite element analysis software COMSOL Multiphysics ver. 5.3a was used for the calculation.

The interface temperature \( T_b \) was evaluated directly from the calculation result. The measured temperature by thermistor \( T_s \) was evaluated by averaging the temperature field in the thermistor region. The sensing region was assumed as 1 mm from the tip of the thermistor.

### Table 1  Thermophysical properties for the calculation.

|                  | Ski board* | Snow** | Thermistor*** | Adhesive*** |
|------------------|------------|--------|---------------|-------------|
| Density [kg/m³]  | 960        | 255    | 5000          | 1800        |
| Specific heat [J/(kg·K)] | 2300      | 2500   | 200           | 1800        |
| Thermal conductivity [W/(m·K)] | 0.50      | 0.145  | 10            | 4.22        |

*The ski board was assumed as polyethylene and its properties were referred from the handbook (Japan Society of Thermophysical Properties, 2008).

**The density was measured value in the experiment and the others were estimated with the density according to the handbook (Japan Society of Thermophysical Properties, 2008).

***The thermophysical properties of thermistor and adhesive were used typical values referred from catalog.

### 2.2.2 Calculation results and discussion

Figure 3(a) shows the time variation of temperature increase from the initial temperature, and Fig. 3(b) shows the temperature distribution around the thermistor in the case of a total weight of 54 kg. As shown in Fig. 3(a), the interfacial temperature increased 0.30 °C and 0.52 °C in 3 sec under the total weight of 34 kg and 54 kg, respectively. The maximum temperature difference between the interfacial and averaged temperature was 0.08 °C and 0.15 °C under the total weight of 34 kg and 54 kg, respectively. This difference was caused by the temperature distribution in the thermistor. When a temperature distribution existed in the thermistor, as shown in Fig. 3(b), the measured temperature \( T_s \) became lower value than the interfacial temperature \( T_b \).

Figure 4 shows the relationship between temperature difference and frictional heat generation. Temperature difference was defined as the difference between the temperature at the interface and the average temperature in the sensor region. The temperature at 3 sec from the beginning of gliding was used. As shown in Fig. 4(a), both the total weight and gliding velocity affected the temperature difference. Additionally, as shown in Fig. 4(b), the sensor position also affected the temperature difference. At the more distant sensor, the integral of frictional heat generation from the tip to the sensor becomes larger; hence, the temperature difference at the position farther from the tip became larger. As a general trend, the temperature difference increased proportionally with frictional heat generation.

The temperature distribution in the thermistor was determined by the ratio between the heat conduction in the thermistor and the surrounding material and the heat generation rate at the interface. Hence, it was presumed that the accuracy of the temperature measurement would be affected by the variation of the factors affecting the frictional heating, such as total weight, coefficient of kinetic friction, and gliding velocity. As a summary, in addition to the uncertainties of the thermistor and data logger, the measurement value in the experiment should include an uncertainty of less than 0.3 °C caused by the temperature distribution in the thermistor, and this uncertainty varies with the degree of frictional heating. However, this uncertainty is smaller than that of a typical thermocouple (±0.5 °C, in the case of T-type thermocouples of Class 1) (Japanese Industrial Standards Committee, 1995) or an infrared thermometer (±1–2 °C) (The Japan Society of Mechanical Engineers, 2009). Therefore, the system developed should be appropriate for measuring the interfacial temperature during skiing.
3. Gliding experiment

3.1 Experimental system

Figure 5 shows a schematic of the experimental system for measuring interfacial temperature during gliding of the ski board. The experiments were conducted in the large cold room at the Shinjo Cryospheric Environment Laboratory. The room temperature was \(-10 \, ^\circ\text{C}\). The length of the total gliding area was 14 m, however, actual gliding length was less than 14 m because of space for moving object itself and the measurement equipment. The actual gliding distance, which was varied in each experiment, was 8–10 m. The measurement system consisted of two skis, a frame, weights, and measurement devices. The two skis were installed parallel to the frame. The total weight was changed by adding weights. The base weight of the gliding object was 14 kg. The measurement system was dragged by a motor (BLM5400HP-AS, Orientalmotor). The gradient of time variation of the rotation speed was fixed at the fastest condition; therefore, the velocity profile until reaching the target velocity should be same. In addition, the velocity could be estimated roughly from the rotational speed of the motor. The actual velocity was estimated from the time variation of distance measured by a laser distance meter (LDM301S, 4Assist,Inc.).
In this experiment, MADSHUS Hypersonic Skate Ski was used, and no wax was applied on the gliding surface. The three thermistors were installed and labeled as TH1, TH2, and TH3 from the tip to the end of ski board. The ski board was bend originally and optimum weight for this board was 45–55 kg. Under applying 40 kg to the ski board on the flat place, the positions of TH2 and TH3 were completely contacted but there was a slight gap under the ski board.

![Fig. 5](image)

Schematic of the experimental system for measuring interfacial temperature during gliding on artificial snow.

3.2 Results and discussion

Figure 6 shows the time variation of measured temperature in the condition of target velocities and total weight of 0.5–3.0 m/s and 54 kg, respectively, are shown in the figure. The ski board had an initial temperature distribution caused by the non-uniform temperature of the snow surface and the history of the previous experiment. Additionally, the non-uniformity of pressure distribution on the ski surface also should be affected to the non-uniformity of initial temperature distribution, because of the cooling effect on the ski surface also should be affected by the contact condition. It was difficult to achieve a uniform temperature distribution before each experiment because of the low thermal conductivity of the ski board. The elapsed time of 0 sec indicates the starting time of gliding. After gliding began, the temperatures of positions TH2 and TH3 increased; however, the temperature of TH1 decreased in the early stage. At the tip of the ski, the snow had a cooling effect on the ski because the bare snow surface was cooled by the room temperature of −10 °C. From Figs. 6, by rough estimation, against the room temperature of of −10 °C, the ski board temperature was almost −8.5 °C initially and temperature increase measured by TH3 was almost 1 °C. To evaluate the frictional heating effect on the temperature increasing, the temperature variation from the initial temperature is used for following discussion.

Figure 7 shows an example of the measurement displacement and calculated gliding velocity in the case of set velocity and total weight of 3.0 m/s and 54 kg, respectively. Figure 7(a) shows the time variation of the displacement measured by the laser distance meter. At the early stage of gliding, the measured value of displacement was smooth; however, at the late stage, the data were slightly scattered due to the vibration of the gliding object. The gliding velocity was calculated from the derivative of the time variation of displacement, as shown in Fig. 7(b). Due to the scattered data at the late stage, the derivative fluctuated strongly. Additionally, compared with the target velocity of 3 m/s, a constant region of 3 m/s was not achieved in the actual velocity.
Time variation of temperature measured by thermistor during gliding. The total weight was fixed at 54 kg and gliding velocity was varied from 0.5 m/s to 3.0 m/s.

Fig. 6
Time variation of (a) displacement and (b) calculated gliding velocity under target velocity of 3.0 m/s and total weight of 54 kg.

Figure 8 shows time developments of the temperature variation from the initial temperature and the gliding velocity under the condition of a total weight of 54 kg. To remove the effect of initial temperature distribution, the temperature variation from the initial temperature was calculated. The absolute temperature shown in Fig. 6 shows the actual range of temperature variation and non-uniformity of temperature on the snow surface. On the other hand, the temperature variations shown in Fig. 8 should be related to the frictional heating effect. Therefore, the calculated temperature variations are used in following discussion. As shown in Fig. 8, except for (d), target velocity of 3.0 m/s, the constant velocity condition was achieved during gliding. Because the gliding distance was limited to less than 14 m and it took
almost 2 sec for acceleration and deceleration phase, the constant velocity was not achieved in the case of target velocity of 3.0 m/s. In all conditions, the temperature variations at TH1 were very small compared with those of TH2 and TH3. In the case of TH2, large temperature fluctuations were observed. As an example, in Fig. 8(c), one fluctuation was observed in the temperature response from 2 sec to 4 sec. When the ski board separates from the snow surface during gliding, the surface temperature of the ski increases greatly due to reduction of the cooling effect by snow. Afterward, when the ski surface contacts again, the surface temperature decreases by the cooling effect. Therefore, this fluctuation indicates the contact condition between the ski board and snow. On the other hand, target velocity of 0.5 m/s, smooth variations of temperature increment were observed at TH3. The position of TH3 was the heel position. Therefore, stable contact between ski board and snow could be achieved.

As shown by the gliding velocity line in Fig. 8, an acceleration phase, constant velocity phase, and deceleration phase occurred. During the acceleration phase, a similar temperature increment at TH3 was observed, as shown in Fig. 8. Figure 9 shows a comparison of the temperature variation at TH3 for the velocities of 0.5–3.0 m/s. As shown in Fig. 9, similar temperature trends were confirmed for all conditions at the acceleration stage in Fig. 8. However, After the acceleration stage, the gradient of the temperature increment changed. The largest gradient was observed in the condition of 3.0 m/s. On the other hand, the gradients in the cases of 0.5 m/s and 1.0 m/s were almost the same. Maeno (2016) showed that the friction coefficient of dry snow increased when the gliding velocity was smaller than 1 m/s. Hence, it is speculated that the frictional heat generations of 0.5 m/s and 1.0 m/s were similar because the condition of 0.5 m/s had a higher friction coefficient. In addition, temperature variations from the initial temperature were almost the same during the acceleration phase, although the absolute temperatures in these conditions were different, which implies that the developed temperature measurement system has good repeatability. As mentioned in section 3.1, the velocity profile in the acceleration phase becomes similar because the gradient of rotation speed variation with time was fixed.
Figure 10 describes the effect of the total weight on the temperature increase. In these experiments, the velocity measurement was not succeeded; hence, only temperature variation was plotted. As shown in Fig. 10(a), unlike in the case shown in Fig. 8, the sensor of TH3 did not sense the temperature variation. This means that the position around TH3 did not contact the snow surface or that pressure was not applied. Additionally, in Fig. 10(b), the temperature increment of TH3 stopped and the sensor of TH2 detected a large temperature increment. These results were caused by applying unsuitable weight, which would make the gliding object unstable. Therefore, the case shown in Fig. 10 implies that the effect of dynamic motion, namely vibration of the moving object or variation of the tension force by the guide wire, affected temperature measurement.

4. Conclusions

In this study, with the aim of evaluating the friction heating phenomenon by temperature measurement at the gliding surface, a portable temperature measurement system with high resolution and accuracy was developed and evaluated. The difference between the true interface temperature and the measured temperature was evaluated by numerical simulation. Additionally, the effects of total weight and gliding velocity on temperature variation were assessed by gliding experiment. The following results were obtained.
• By numerical simulation, the difference between the true interface temperature and the averaged temperature in the sensing region was calculated. The measurement value in an experiment should contain an uncertainty of around 0.27 °C caused by the temperature distribution in the thermistor, and this uncertainty varies with the degree of frictional heating. However, this uncertainty is smaller than that of a typical thermocouple (±0.5 °C) or infrared thermometer (±1–2 °C).

• An acceleration phase, constant velocity phase, and deceleration phase existed in the time variation of gliding velocity. During the acceleration phase, similar temperature increments at TH3 were confirmed with the total weight of 54 kg irrespective of the target velocity. This result implies that the developed temperature measurement system has good repeatability.

• When the total weight was changed from the optimum value, the effect on dynamic motion, i.e., vibration of the moving object or variation of the pulling force by the guide wire, affected temperature measurement. This result implies that the temperature measurement on the ski surface could be used for detection of the contact condition at the snow surface. Moreover, the temperature measurement has possibilities for applying an estimation of the local frictional force.

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