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Development of a hot water drilling system for subglacial and englacial measurements

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(Received April 1, 2009; Revised manuscript accepted May 25, 2009)

Abstract

Hot water drilling is a technique suitable for drilling boreholes in a glacier, especially those meant for installing instruments. This method is considerably faster than a mechanical drilling. Moreover, the hot water drilling system is easy to operate and can be constructed by assembling simple devices. This paper reports on the development of a hot water drilling system for temperate ice 100–200 m thick. The system consists of water basin, high-pressure pump, heater, tripod, pulley, hose, drilling stem and nozzle. The total weight of the system, including a 250 m length of hose, is approximately 300 kg. The system generates a hot water jet at a temperature of 60–76℃ and a flow rate of 950–1000 l h^{-1} using straight jet nozzles of 1.6, 2.0 and 2.5 mm diameter. The drilling system was tested at Rhonegletscher, Switzerland during the summers of 2007 and 2008. Eight boreholes with a total depth of 925 m were drilled in 2007, and twenty-four boreholes with a total depth of 1118 m were drilled in 2008. The mean drilling rates achieved for each borehole were in the range of 27–70 m h^{-1}, depending on the drilling depth, the distance between the drilling site and the heater, and the elevation difference between the drilling site and the pump. During drilling at the glacier, the diesel and petrol consumption rates of the heater and pump respectively were 6.9 l h^{-1} and 1.8 l h^{-1}.

1. Introduction

Subglacial and englacial measurements can provide a wealth of information on glacier sliding (*e.g.* Fischer and Clarke, 1997; Engelhardt and Kamb, 1998), basal sediments (*e.g.* Fischer and Clarke, 1994; Tulaczyk *et al.,* 2001), subglacial hydraulic conditions (*e.g.* Engelhardt and Kamb, 1997; Iken and Truffer, 1997; Fudge *et al.,* 2008), ice temperature (*e.g.* Lüthi *et al.,* 2002) and internal deformations (*e.g.* Hooke *et al.,* 1992; Harper *et al.,* 2001). To drill a borehole for such measurements, it is preferable to employ a faster method than mechanical drilling, which is normally used for ice coring.

A hot water drilling system generally consists of water basin, high-pressure water pump, heater, hose and jet nozzle (Fig. 1). The nozzle, supported by tripod and pulley, emits a jet of water heated close to the boiling point at a glacier surface. As the drilling proceeds, the stem and hose are lowered into a borehole of about 100 mm in diameter created in the glacier ice. Hot water drilling has been used for a wide variety of measurements, both inside and underneath glaciers. The advantages of this method over mechanical drilling are as follows: (i) a much faster drilling rate of 50–100 m h^{-1}, (ii) the ability to drill both temperate and cold ice (*e.g.* Humphrey and Echelmeyer, 1990), (iii) simplicity of construction using commercially available devices, and (iv) ease of operation.

Hot water drilling systems have been developed by many researchers and employed at numerous mountain glaciers and ice sheets: South Cascade Glacier in the USA (Taylor, 1984; Fountain, 1994), Findelengletscher in Switzerland (Iken and Truffer, 1997), Storglaciären in Sweden (Hanson *et al.,* 1998), Jakobshavns Isbræ in Greenland (Iken *et al.,* 1993), Ice Stream B (Engelhardt *et al.,* 1990), Amery Ice Shelf (Craven *et al.,* 2004) and Dome C in Antarctica (Koci, 1984). No such system has ever been constructed in Japan.

We have developed a simple hot water drilling system for englacial and subglacial measurements, able to drill up to 200 m of temperate ice. This report describes the configuration of the system, test results, and its drilling performance at Rhonegletscher, Switzerland during the summers of 2007 and 2008.

2. A hot water drilling system

2.1 Configuration of the system

The drilling system is shown in Figure 2. Hot water is generated by a commercially available high-pressure hot water machine, the Kärcher HDS1000BE (Fig. 3a), which is commonly used for cleaning vehicles and buildings. The same device has been used by a research team for drilling mountain glaciers (Hubbard and Glasser, 2005). A petrol-driven water pump engine (Honda GX390) and diesel combustion heater are combined to achieve flow rates in the range of 450–900 l h^{-1}, pressures of 6–21 MPa, and temperatures of 30–140℃ when they are used with a cleaning nozzle which is specially designed to change the flow rate for a cleaning purpose. The total weight of the machine is 165 kg. A safety device is installed between the pump and the heater, which turns off the heater when the water pressure drops below an operating threshold. The pump draws water from a 3000 l basin with a diameter of 2 m and a weight of 28 kg (National Marine Plastic Inc. Type E) (Fig. 3b). On site, it can also draw water from natural streams. The drilling hoses, which individually are 50–100 m long and have an internal diameter of 8 mm, are connected with couplings to obtain enough length. During drilling, the hose is supported by a pulley hung on a tripod (Fig. 3c). The pulley is designed to measure the length of hose by counting rotations. The aluminum tripod has a length of 2.2 m and a weight of 10 kg, and can be disassembled for transportation. The drilling stem was constructed at the workshop of the Institute of Low Temperature Science, Hokkaido University. The nozzle (Katorigumi Seisakusho Inc. Type K-18) is mounted on the stem to produce a narrow and straight jet (Fig. 3d). Two 1.5 m long stainless steel pipes with internal and external diameters of 19.6 and 27.2 mm were connected with a brass coupling (Fig. 3e). Two pieces of pipe were used in order to have enough length and weight to drill a straight borehole. A conic spray nozzle (Type K-20) is used to enlarge the diameter of a borehole after drilling (Fig. 3f). The total weight of all equipment (hot water machine, water basin, tripod, pulley and drilling stem) is approximately 220 kg, plus 30 kg per 100 m of hose.

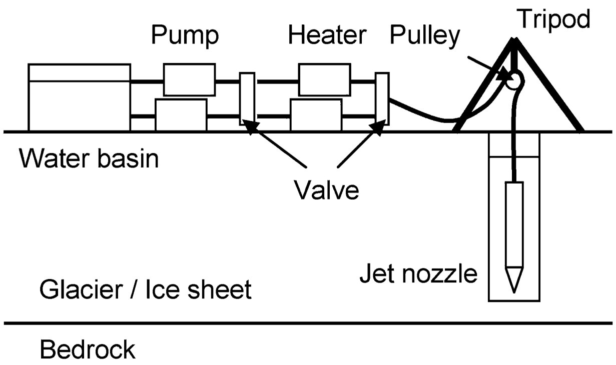

Fig. 1. Schematic of a hot water drilling system.

2.2 *Laboratory performance test*

To test the performance of the drilling system, its water temperature and flow rate were measured while directly connected to a tap in a laboratory. The test was conducted using hoses with lengths of 1, 50, 100 and 150 m, straight jet nozzles with diameters of 1.6, 2.0, 2.5 and 3.0 mm, and a conic spray nozzle with a diameter of 2.0 mm. The cleaning nozzle provided by the manufacturer was also used to change the flow rate only in the laboratory test. Because the water jet was very narrow, an accurate measurement of water temperature in the vicinity of the nozzle was difficult (Fig. 3e). The jet was trapped in a 10 l plastic

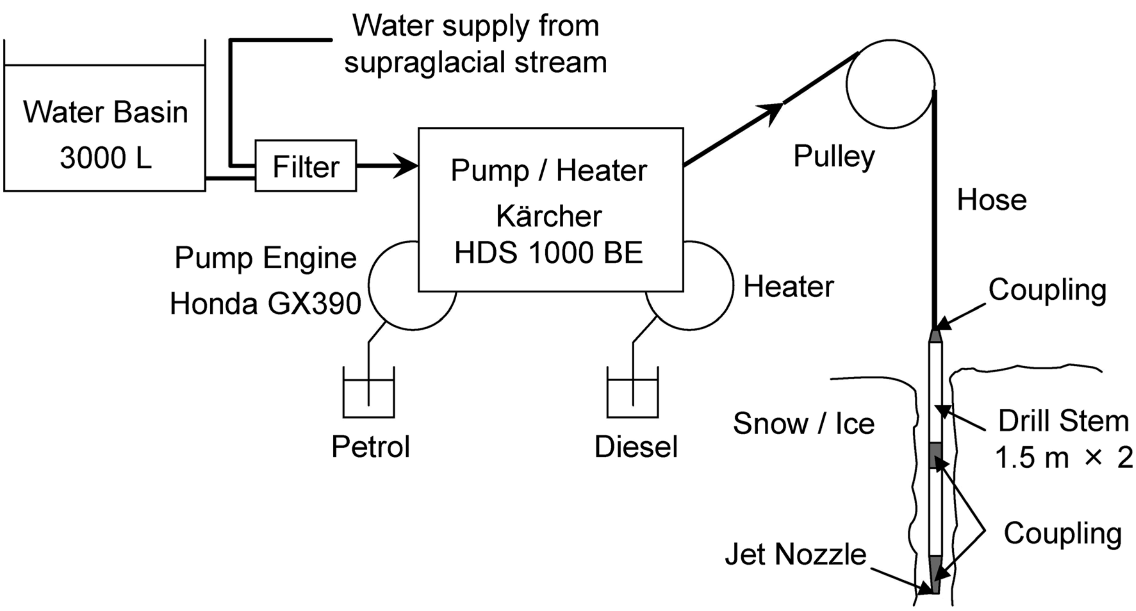

Fig. 2. Block diagram showing the configuration of the hot water drilling system constructed for this project.

Fig. 3. (a) The high-pressure hot water machine (Kärcher HDS1000BE), (b) the 3000 l water basin, (c) the tripod with its pulley, (d) a jet nozzle mounted at the tip of the drilling stem, (e) a water jet from a 3 m long drilling stem with a straight nozzle, and (f) a water jet from the conic spray nozzle.

bottle, and the water temperature in the bottle was measured every 15 seconds as it filled using a temperature logger (HIOKI 3633). During the water jet temperature measurement, the temperature setting of the heater was gradually raised from 50 to 135–150℃. The water flow rate was calculated from the time required to fill a box of 0.02 m^3. The consumption rates of petrol and diesel during the experiments were measured as well. The drilling performance of the system was tested by drilling ice blocks of 0.5×0.25×1 m^3 with the 50 m hose, the 2.0 mm straight jet nozzle, and water supplied from the basin.

2.3 Results

The 3.0 mm diameter straight nozzle was not suitable for the system because the pressure dropped below operating range and the heater was automatically shut down by the safety device. In laboratory tests the diesel consumption rate of the heater was 4.7 l h^{-1}, and the petrol consumption rate of the pump was 1.9 l h^{-1}.

Using the 2.0 mm straight nozzle, we measured the water temperature as a function of time for vari-

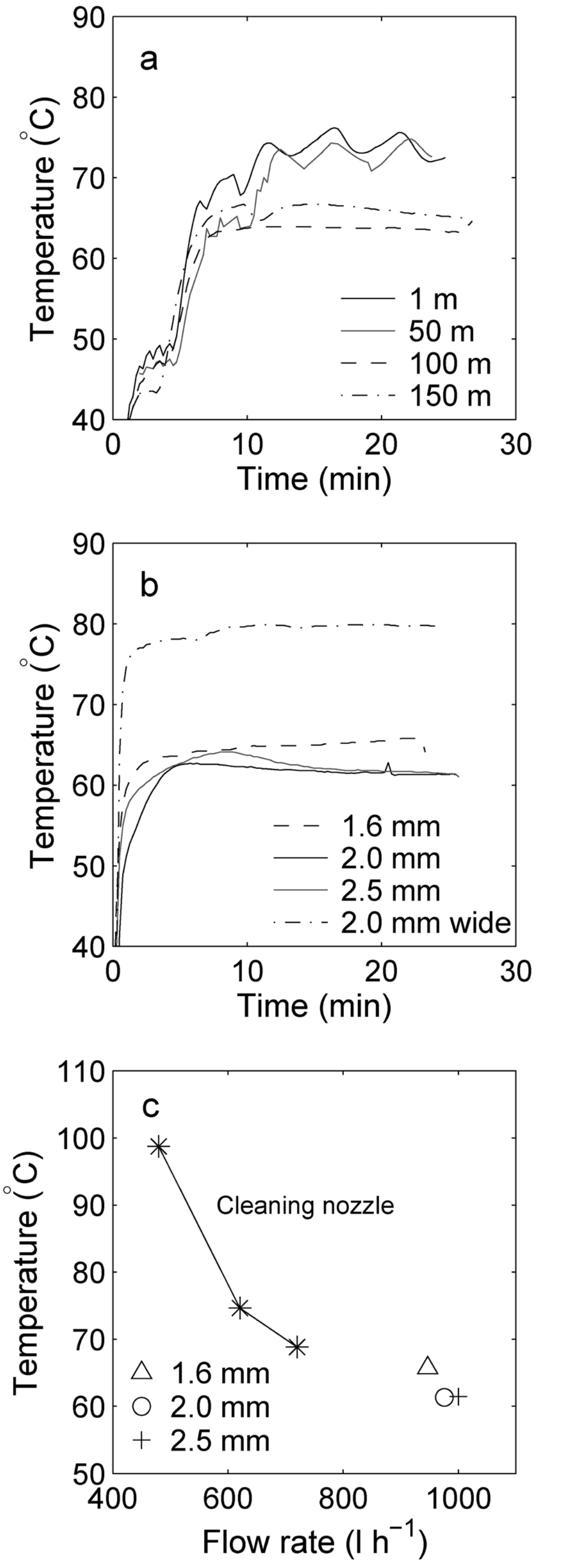

Fig. 4. Water jet temperature vs. time with (a) various hose lengths and (b) various jet nozzle diameters. (c) Flow rates and water jet temperatures obtained with the three jet nozzles and the cleaning nozzle.

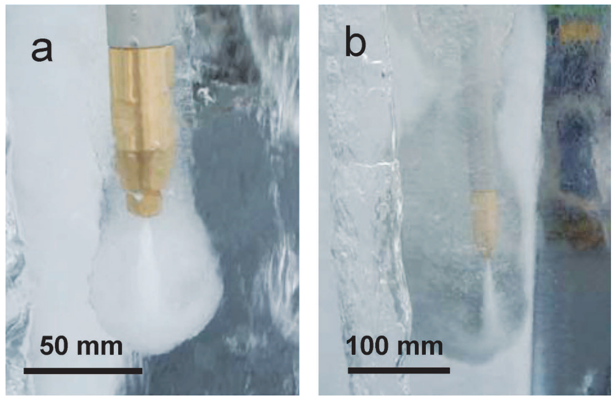

Fig. 5. Drilling nozzle and water jet in the ice block used for the test. The nozzle was lowered quickly in (a), while it was lowered slowly to enlarge the borehole diameter in (b).

Table 1. Time required drilling through 1 m thick ice blocks and drilling speed. Water temperature was 7.4℃ in the case of no heating.

Heater setting ℃	Time sec	Speed m h^{-1}
no heating	124	29
30	53	68
50	43	84
70	27	133
90	39	92
110	28	129
135	31	116
150	31	116

ous hose lengths (Fig. 4a). The maximum temperatures reached ranged from 64–76℃. The temperature is generally higher for shorter hoses, although the maximum temperature at 150 m length hose exceeds that at 100 m. As the water pressure from a tap is expected to be unstable, the flow rate may have fluctuated in these experiments and influenced the water temperature. When we fixed the hose length at 50 m, the maximum temperature for 1.6–2.5 mm nozzles ranged from 60–65℃ (Fig. 4b). The temperature reached 80℃ for the conic spray nozzle, as its flow rate was much lower. These results indicate that the temperature of the water jet is higher than 60℃ and it is slightly influenced by hose length and nozzle diameter. The jet temperature is saturated when the heater setting is above 70℃ because the heater is designed for a flow rate lower than our use.

The relationship between flow rate and temperature was investigated using a 50 m long hose by and the cleaning nozzle (Fig. 4c). The temperature is very close to the boiling point when the system is operated at 450 l h^{-1}, and decreases as the flow rate increases. For the jet nozzles with diameters of 1.6–2.5 mm, the temperature is about 60℃ and the flow rates are 950–1000 l h^{-1}. This rate is the upper limit of the pump capacity. With the 3000 l water basin, drilling can continue for 3 hours at this rate.

Testing the system on an ice block confirmed that the drilling process is very fast. It took about 30 seconds to drill through a 1 m thick ice block, excavating a hole of 50 mm diameter (Fig. 5a). A wider hole can be drilled by lowering the nozzle more slowly (Fig. 5b). The times required to drill through 1 m of ice were measured at various temperature settings of the heater (Table 1). As expected from the abovementioned results (Fig. 4a, b), the drilling speed is nearly constant when the heater setting temperature is higher than 70℃. Drilling is even possible with cold water (7.4℃).

3. Drilling on Rhonegletscher

3.1 Study site

Rhonegletscher is located in the Swiss Alps at the source of the Rhone River. This temperate valley glacier is 7.85 km long, with an area of 15.9 km^2. Its terminus is 2200 m a.s.l. (Huss *et al.,* 2008). The glacier length has decreased by approximately 1150 m from 1880 to 2003 (Zahno, 2004). A proglacial lake formed in 2005 because the terminus position retreated behind a bump of the bedrock (Sugiyama *et al.,* 2008). The formation of this lake is expected to accelerate the glacier's retreat by initiating an ice calving process. The influence of the lake water on the subglacial water pressure reaches further upglacier if the lake will more enlarge in the near future, which is likely to increase the glacier's flow speed. To investigate the impact of lake formation on the glacier, both subglacial and englacial borehole measurements are crucial in addition to surface observations. In particular, boreholes are required for accurate measurements of ice thickness, subglacial water pressure, basal flow speed, internal ice deformation, and subglacial sediment properties. As part of ongoing research on the response of Rhonegletscher to lake formation, we carried out hot water drilling at the terminal part of the glacier in 2007 and 2008.

3.2 Borehole drilling

From 13 to 29 July 2007, eight boreholes (BH1-BH8) were drilled to the glacier bed at positions 300–800 m from the terminus (Fig. 6). The pump and heater were always located near BH1, while the hose was extended to each drilling site. Before drilling, the required length of hose was piled up and insulated with cotton cloth. The hose would melt a groove into the ice during operation, increasing its contact with the ice surface. To minimize heat loss, the hose was often taken out of this groove. We normally pumped water into the hot water machine directly from a supraglacial stream. The basin was used only when the amount of running water was not sufficient. At times the heater would automatically shut down due to the accumulation of black sediment from the glacier in a filter installed at the water intake (Fig. 2). The drilling was carried out using either the 2.0 or 2.5 mm jet nozzle. For some boreholes, the 2.0 mm conic spray nozzle was also used to enlarge the borehole. The maximum borehole depth was determined by the length of the hose used for drilling, and the current depth was recorded every 5–15 minutes to measure the drilling speed. During the drilling, operator kept the nozzle slightly above the borehole bottom to drill a straight borehole. Drilling continued until the nozzle reached the glacier bed, a moment which could be recognized by the change in hose tension. The reported borehole depths may be underestimated by 1–2 m because the hose stretched during drilling. The fuel consumption rates of petrol and diesel were also calculated.

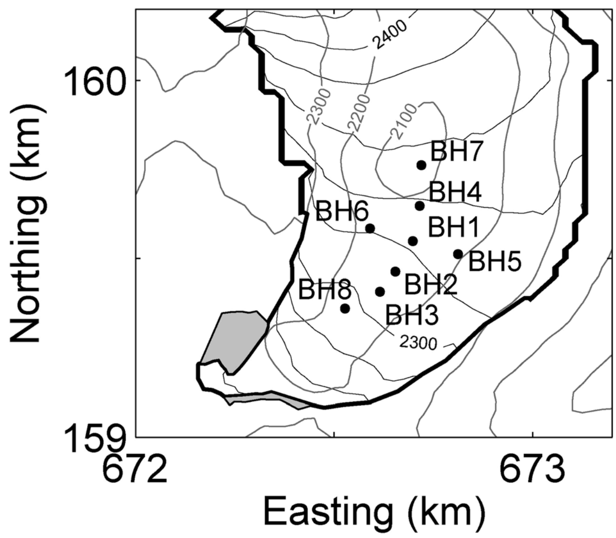

Fig. 6. Map of the study site in Rhonegletscher with the borehole locations from 2007 marked (●). The black contours indicate surface elevation at 20 m intervals. The gray contours are bedrock elevations estimated by Zahno (2004) at 100 m intervals. The shaded regions indicate marginal lakes. The official Swiss coordinate system is used in this map.

The drilling was repeated in 2008 in the lower reaches of the 2007 drilling sites. During these experiments, the heater and pump were located at BH8 (Fig. 6) while the hose was extended downglacier very close to the calving front. We drilled twenty-four boreholes with depths ranging from 18–99 m. In the following section, we compare total drilling depths to those measured in 2007, and refer to the fuel consumption rates to calculate a mean value.

3.3 Results and Discussion

The depths of BH1-BH8 range from 87–138 m (Table 2). The diameters of these boreholes were 100–150 mm near the surface, but are expected to be narrower at depth (Fig. 7). The total drilling depths in

Table 2. Depth and mean drilling rate of the boreholes in 2007. Horizontal distance and elevation difference between the drilling sites and the hot water machine are also indicated.

Borehole	Borehole depth m	Drilling rate $m\ h^{-1}$	Distance m	Elevation m
BH1	138	50	0	0
BH2	120	70	95	-10
BH3	119	49	163	-17
BH4	124	32	103	15
BH5	99	66	121	4
BH6	87	40	113	-2
BH7	135	27	216	35
BH8	103	40	254	-29

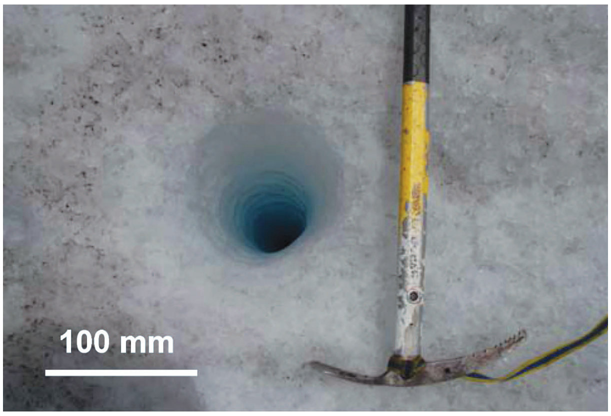

Fig. 7. The appearance of a borehole at the surface.

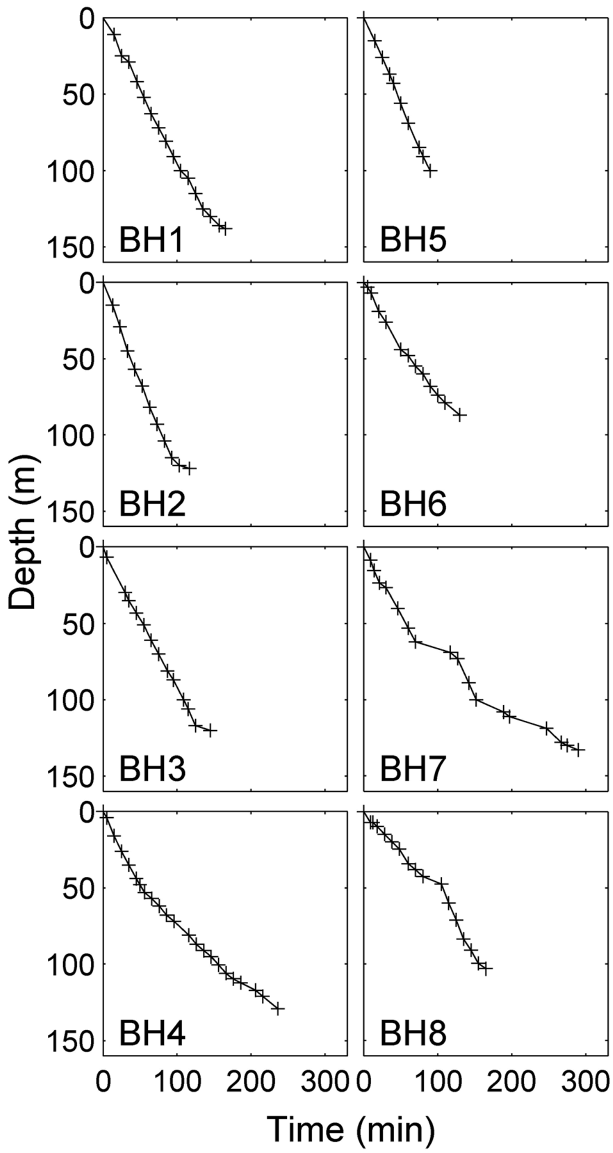

Fig. 8. Drilling depth as a function of drilling time for the boreholes from 2007.

2007 and 2008 were 925 m and 1118 m respectively. Figure 8 plots borehole depth vs. drilling time for BH1-BH8. The mean drilling rates ranged from 27–70 $m\ h^{-1}$. Hubbard and Glasser (2005) used the same hot water machine at an altitude of 2800 m a.s.l in Haut Glacier d'Arolla, Switzerland. The pump drew water from a 4000 l basin which was filled by melting snow. They obtained drilling rates of 120 $m\ h^{-1}$ near the ice surface and 30 $m\ h^{-1}$ at depths greater than 120 m. They reported the water temperature as 80℃. In order to detect the bedrock from a change in hose tension, the drilling rate was deliberately decreased during the last 10–20 minutes. This effect can be observed in the plots for BH1, BH2, BH3, BH6 and BH8. In BH4, BH6 and BH7, the drilling rate decreased when water drained from the borehole. Drilling in an empty borehole is more difficult. This was because the loss of buoyancy force makes the operation of the hose hanging in the borehole more difficult. Other factors may have influenced the drilling rate in some cases, such as the experience of the operator and interruptions due to refueling or filter cleaning.

Two other relatively important factors are the distance and elevation difference between the hot water machine and the drilling site. Table 2 shows that BH1 and BH2, located closest to the machine (0 and 95m), had relatively high drilling rates (50 and 70 m h^{-1}). BH7 and BH8, situated farther from the machine (216 and 254 m), had rather small drilling rates (27 and 40 m h^{-1}). This relationship is expected because the temperature of the water decreases with distance from the heater. BH4 and BH7, situated at elevations 15 and 35 m higher than the machine, also had smaller drilling rates (32 and 27 m h^{-1}). This effect is probably due to the fact that the flow rate decreases when the pump sends water to higher elevation. During drilling at BH7, the machine often turned itself off because the water pressure dropped below the threshold.

The mean petrol consumption rate was 1.8 l h^{-1} in both 2007 and 2008, which corresponds approximately to the result of our laboratory tests (1.9 l h^{-1}). However, there is a significant difference between the mean diesel consumption rates on the glacier (6.9 l h^{-1}) and in the laboratory (4.7 l h^{-1}). The former rate is also 1.7 times greater than that obtained at Haut Glacier d'Arolla (Hubbard and Glasser, 2005), even though our petrol consumption rate agrees with that experiment within 90%. It is not clear why drilling at Rhonegletscher consumed more diesel than drilling at Haut Glacier d'Arolla, although both pumps drew cold water from supraglacial stream or melted snow and the drillings conducted at a high altitude. If we take the mean drilling rate observed in BH1-BH8 (47 m h^{-1}) and the consumption rates measured at Rhonegletscher as benchmarks, our system is able to drill 100 m of ice in a little more than two hours with 14.7 l of diesel and 3.9 l of petrol.

After drilling, the boreholes were used to measure subglacial water pressure, vertical strain, and borehole inclination. Samples of the subglacial sediment were also collected. The closure rate of a borehole is controlled by the water level, but most of the boreholes remained open to the bedrock for at least several months (Sugiyama *et al.,* 2008).

4. Conclusion

A hot water drilling system was constructed capable of drilling up to 200 m through temperate ice. The system generates a hot water jet with a temperature of 60–76℃ and a flow rate of 950–1000 m h^{-1} using 1.6–2.5 mm diameter nozzles. The temperature is mostly controlled by the flow rate, and slightly dependent on the hose length and nozzle diameter. In laboratory tests, one meter of an ice block could be penetrated in 30 seconds.

The system was used at Rhonegletscher, Switzerland in the summers of 2007 and 2008. Eight boreholes with a total depth of 925 m were drilled in 2007, and twenty-four boreholes with a total depth of 1118 m were drilled in 2008. The mean drilling rates ranged from 27–70 m h^{-1}. The drilling rate decreased with the borehole's distance from the heater, owing to a reduction in the water temperature. The drilling rate was also dependent on relative elevation, as the water flows more slowly to elevations higher than the pump. The system consumed 6.9 l h^{-1} of diesel for the heater and 1.8 l h^{-1} of petrol for the pump.

Acknowledgments

We would like to thank K. Chubachi of the Institute of Low Temperature Science at Hokkaido University for designing and constructing the drilling stem. K. Nakamura of Nakamura Service Inc., K. Hirayama of Kärcher Japan Inc. and S. Asai of Martech Inc. provided useful information on the high-pressure hot water machine. We would like to thank D. Nishimura and T. Yoshizawa of Hokkaido University for their help in the field. H. Blatter of IAC-ETH Zurich constructed the tripod and helped with the drilling on the glacier. M. Funk, A. Bauder, T. Wyder and members of VAW-ETH Zurich provided materials for the field campaign and helped with transportation to the glacier. T. Sato of Hokkaido University helped in the laboratory experiments. We would like to thank R. Naruse for his helpful review comments and Scientific Editor N. Naito for handling the paper.

This research was funded by the Japanese Ministry of Education, Science, Sports and Culture through a Grant-in-Aid for Young Scientists (Start-up), 18840002, 2006–2007 and a Grant-in-Aid for Scientific Research C (Capital), 20540418, 2008–2010. It was also supported by an internal funding program of the Institute of Low Temperature Science at Hokkaido University, and by the Inoue Scientific Field Study Foundation.

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