ALTERNATIVE METHODS TO PENETRATE ICE LAYERS

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Abstract

The goal of a newly started study at the Space Research Institute in Graz is the development of a tool that is able to explore the vertical structure of ice sheets. This study was started in the frame of an ESA contract. There are two targets of primary interest: the polar areas of Mars and Jupiter's satellite Europa. From diverse space missions like *Mars Global Surveyor* it became evident that the permanent ice caps of Mars contain key information for the understanding of the recent geological history of the planet (Kieffer et al., 2000). A detailed investigation of Martian ice layers is also important for the understanding of the water exchange between surface and atmosphere. Jupiter's moon Europa is of special interest for exobiology, because there are strong indications for the existence of a subsurface water ocean, which may contain primitive forms of extraterrestrial life or precursor forms of life.

A *Melting Probe* would be a good device to explore the internal structure of such ice layers. Unlike traditional technology as used in geo–technical research on earth, where drilling, coring, or hammering are the main mechanisms for downward motion of probes, a *Melting Probe* is a much less complex instrument. Contrary to their terrestrial analogues, *Melting Probes* for space applications have to be smaller, very robust and must have a much lower weight. Here a possible mechanical and thermal design for a *Melting Probe* prototype and first results obtained from laboratory measurements and mathematical simulations are reported.

1 Introduction

Diverse information about the evolution of a planet can be obtained by investigating its subsurface layers. For example, ice layers contain details about the climate history of a planet. In case of Earth, a lot of information concerning climate variations was retrieved

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from the analysis of data from drill cores. However, to get such drill cores is a complex and expensive procedure. Another problem using this method is that the core can be contaminated by a drilling fluid and by the metallic abrasions from the drill.

An alternative method to get information about deeper layers on icy bodies is to melt into the ice with a so-called *Melting Probe*. Unlike drilling, coring, or hammering melting probes are much less complex. Philberth (1962) was the first one who built a prototype of such a probe (see Figure 1). At the same time Shreve (1962) worked out a detailed theory describing the penetration behavior of cylindrically shaped melting probes in isothermal ice. Aamot (1967) continued the work of Philberth and also built and tested some prototypes.

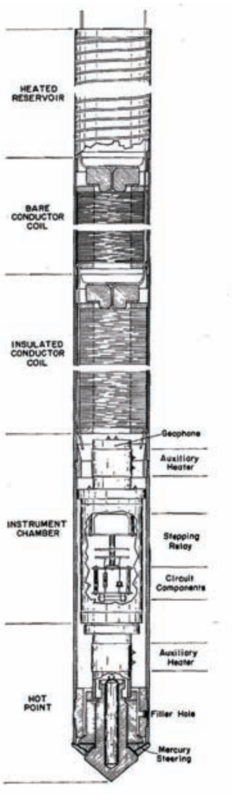

Figure 1: The Philberth Probe.

There have been discussions about the use of *Melting Probes* for getting access to planetary subsurface ice layers for several years (Paige, 1992; DiPippo et al., 1999). Also theoretical work was done (Kömle et al., 2002; Biele et al., 2002). For the investigation of extraterrestrial ices the melting probes have to be small, robust and of low weight, since their primary function is to carry sensors. The main requirement for the design is to find a special form for the tip (or "hot point", as named by Pilberth, see Figure 1), which allows on the one hand melting through ice layers contaminated with dust, and on the other hand ensures that the *Melting Probe* maintains its direction. *Melting Probes* should be inserted on extraterrestrial bodies with low gravity. The only driving force is their own weight. A form of the tip has to be found that makes it easy to place the center of gravity close to the front point of the tip so that forward motion is maintained. The cross–section of the *Melting Probe* has to be small to get a power consumption as low as possible. First tests with different tip shapes for small melting probes were done at the *Space Research Institute* Graz and the *DLR Planetary Environments Simulation Chamber* at Cologne. Some conclusions from these tests and results of theoretical models will be given in the following sections.

2 Tests with simple shaped Melting Probes

2.1 Spherically shaped Melting Probe

To get an idea about the energy consumption and the temperature inside a *Melting Probe* the most simple shape – a sphere – was used for the first experiments. The sphere was made of brass equipped with a heating foil built of copper tracks as heaters and Kapton as substrate and insulation material. The foil was mechanically fixed inside the *Melting Probe* (see Figure 2). The temperature was measured by two PT100 sensors.

Figure 2: Spherical shaped Melting Probe *with commercial Kapton heating foil.*

The cable connected to the *Melting Probe* had a length which insures that the probe, if the melting is not interrupted, can reach the bottom of the sample used for the test. With this kind of probe, four tests were done: melting into ice and snow under atmospheric pressure and melting into ice and snow under vacuum conditions. The last two tests were performed in a cylindrical shaped vacuum chamber of 40 cm diameter and 80 cm height. This chamber can be cooled by LN_2 and reaches pressures down to 10^{-5} mbar. For the tests compact cylindrical blocks of ice with 20 cm diameter and 35 cm height were used.

After the onset of the heating the *Melting Probe* which was placed at the top of the sample started to sink with an average speed of $\sim$2.5 cm/h. During the experiment an interesting effect occurred: in spite of the surrounding vacuum a liquid phase was temporarily present. Water droplets which had formed at the contact surface between the *Probe* and the ice sputtered off the sample and there they built fine ice needles. Due to this effect the melting channel starts to close behind the *Probe*. At a penetration depth of approximately 10 cm the *Melting Probe* got stuck. Since it was further heated, the ice around it sublimed and due to this the *Probe* lost contact to the ice. Therefore the heat could not be transferred and the temperature inside the *Probe* reached values of > 473 K. Though the *Probe* got hot, the distance between the *Melting Probe* and the ice was less than 1 mm. For the ice tests done under atmospheric pressure less power was necessary to heat up the *Melting Probe* since the ice temperature was higher than in case of vacuum. At this test the *Probe* reached the bottom of the sample. After the test the ice block was cut. This showed that the melting channel was not straight along the vertical axis of the sample.

The experiment done under vacuum conditions using snow as sample material provided the following: due to the porous structure of the sample the *Probe* sank approximately half of its diameter into the sample before beginning of the heating phase. During the heating phase the melting channel remaind open. In this case the sublimated gas either escaped or recondensed in the pores of the snow. Different to the test done with ice no deviation from the vertical direction could be observed. For the test done under atmospheric pressure a similar behavior could be monitored. During this test a sudden effect occurred: though the penetration takes place via melting, no liquid water level was visible, not even after the end of the heating phase. It seems that the melted water was absorbed by the pores and re–freezed there.

These experiments showed that a sphere is not the best shape for a *Melting Probe* since it can not be guaranteed that the *Probe* melts in vertical direction. It also indicates that a way of storing the cable inside the *Probe* has to be found to ensure that in case of refreezing of the melting channel the *Probe* does not get stalled. For more details about these experiments see Kömle et al.(2005) and Treffer et al. (2006).

2.2 Cylindrically shaped Melting Probe with hemispherical tip

Next a test with a simple cylindrical *Melting Probe* with a hemispherical brass tip was done. Different from the spherical *Probe* a tether was wound inside the cylindrical part (Figure 3). The heating segment was also a commercial heating foil that was fixed mechanically between the tip and a brass disc. Those two parts were screwed on a pre–fabricated stainless steel tube. From the test with this probe, estimates about the penetration speed during the melt down and the power necessary for a *Melting Probe* with a diameter of 6 cm and a height of 22 cm should be obtained. The test was started with a value for the electrical power of 11.7 W. After 15 min the power was increased to 44.8 W and after another period of 15 min the power was set to its final level of 65 W. At the beginning of the experiment a faster penetration than at the end could be observed. This is due to the fact that the tip of the *Melting Probe* was pre–heated before it was released and that the cross–section of the *Probe*, due to its geometry, increases with time till it reaches the cross–section of the cylinder. A simple theory, which was at least confirmed for terrestrial conditions, says that the penetration speed is inverse proportional to the cross–section (Aamot, 1967; Kelty, 1995).

After a certain time a mechanical problem occurred: the launch pad started to incline, and with it the *Probe*. Therefore the *Probe* got stuck. But until this time the *Melting Probe* reached a penetration depth of ∼8.5 cm (see the black marking in Figure 3).

Figure 3: Picture of the Melting Probe *after the test. The black line marks the penetration depth reached during the melt down.*

This simple test showed that a fixed launch pad is necessary. The launch pad has to assure that the *Melting Probe* does not change its direction until it has penetrated the sample over its whole length. Also it could be seen that a power of at least 60 W at the tip is necessary to get an adequate penetration speed.

3 Melting Probe design for flight model needs

3.1 Mechanical design

Based on the information about melting probes used for terrestrial applications and the results obtained from the tests done at IWF Graz a first simple prototype for a *Melting Probe* with functionality close to the expected needs for a flight model was designed. Its body is cylindrical and the tip ogive–shaped, both parts contain several heater elements and sensors. In general the design is separated into five parts: the ogive–shaped tip, the envelope, the inner compartments for payload, the electronics, and the tether. The latter two are placed into separate boxes (see Figure 4).

Similar to the *Probe* with a hemispherical tip, the power for the heater elements was supplied through a tether which is stored in the rear part. The power is controlled by a separate module operating from outside. For communication also the tether is used,

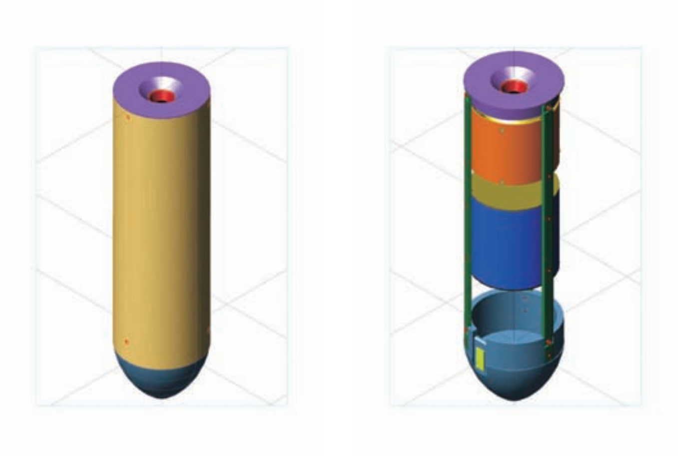

Figure 4: Left panel: Outer view of the Melting Probe. Right panel: Melting Probe with the envelope removed. In the middle the electronics box and in the rear part the cable magazine is positioned.

since in case of an application on a planet or moon the quality of wireless communication would heavily depend on the potentially unknown structure and condition of the material to be explored.

Since the center of gravity of the *Melting Probe* has to be as low as possible, the shape of the tip was chosen to be ogive. Due to this, the tip contains more volume than a cone–shaped one and still has a sharper front point than a spherical one. The tip used is made of brass, with a total height of 65 mm. The inside of the tip is milled out to a depth of 30 mm and a diameter of 54 mm. This was done to have space for a possible payload and to place heaters inside. At one side of the tip a slot is foreseen as outlet for cables and mounting point for external sensors and magnetic markers (see the green area in Figure 4).

Due to cost limitations and the usage of commercial electronic components, the envelope of the *Melting Probe* was made of a pre-fabricated stainless steel tube with an outer diameter of 63.5 mm. At the inner walls of the envelope three heaters are fixed, each consisting of a parallel circuit of three commercial heating foils. On the upper side, the envelope is capped by a steel lid with a conical opening for the tether. The internal compartments are mounted independent of the envelope on three braces evenly spaced at an arc distance of 120°.

The mechanically most complicated part of the *Melting Probe* is the cable magazine. It should – for optimized conditions – contain a tether sufficient for some hundreds of meters. As a self-supporting compartment, the cable magazine can be removed and handled independently. For the first tests done a simple but well tested method for coiling the tether was chosen: a 3 m long tether was stored in “∞”–shaped coils inside the cable magazine. This ensures that the tether can be paid out without complications.

Another independent compartment of the *Melting Probe*is the electronics box. It has an outer diameter of 57 mm and a total height of 62 mm. It is mounted in the center and has an interface to the cable magazine, the heater circuits and, in case of a flight instrument, the payload. It includes the interface electronics, the part which represents the function of the surface module and provides the connection to the power supply and a standard PC. The payload compartment is limited by the volume between the electronics box and the cavity inside of the tip.

3.2 Thermal design

The *Melting Probe* is heated by standard Kapton insolated heating foils. This type of foils was chosen since Kapton is a thin half–transparent material, which is designed for applications with limited areas and for the use under vacuum conditions. Furthermore, the foils have an aluminium layer and an adhesive acrylic film at one side to ease the fixing on curved surfaces. Aluminium layers help to distribute the thermal energy between the heating conductors and improve the adhesion of glues. With its minimum-bending radius of 0.8 mm it can be used inside cylindrically shaped bodies with narrow inner radii. For the first prototype foils which are deliverable from stock were used (*www.minco.com*).

Though the properties of the heating foils are specified over a wide temperature range, a facility to limit the operation temperature was included in the electronic design. This was necessary to ensure that no electrical parts inside the electronics box or the payload will be overheated during operation.

The total heating equipment is separated into 5 circuits. Three of these are placed at the inner walls of the envelope, each consisting of three foils electrically connected in parallel. The fourth consists of two foils located at the inner wall of the milled out area of the tip electrically connected in series and the fifth heating circuit is a ring–shaped foil placed at the inner bottom of the tip. This type of foil was chosen to make the mounting of an additional weight or payload possible if necessary. The movement of the *Probe* is forced by gravitation only. But the upright position of the *Melting Probe* can be controlled by the heating elements since each of them can be activated independently. Figure 5 shows a drawing of the position and the electrical connection (|| stands for parallel connected and + for serial connection) of the foils inside the probe.

Each heating circuit is equipped with a temperature sensor of type PT100. These sensors monitor the thermal state of the heater foils as housekeeping sensors for the controller element. Additionally, they serve as reference points for thermal models. In a passive mode of the *Probe* they may also be used as scientific sensors for measuring the temperature of the environment.

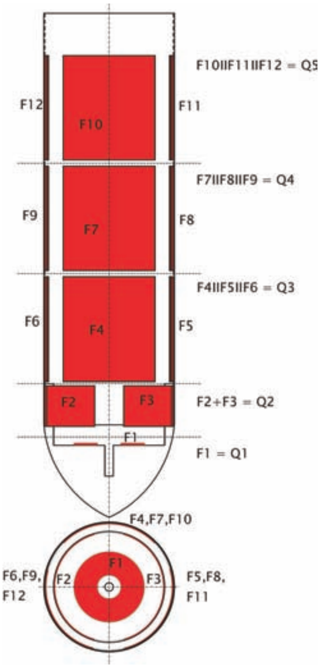

Figure 5: Position of the foils inside the melting probe. The single foils are marked F1 up to F12 and the heaters formed by the foils are named Q1 up to Q5.

4 Melting Probe test at the DLR Institute of Space Simulation, Cologne

Since the space of the vacuum chamber at IWF Graz is limited, only small penetration depths can be reached. Therefore a test at the *DLR Planetary Environments Simulation Chamber* at Cologne was done. This chamber consists of a double hulled container which thermally insulates the inner simulation vessel. Inside the inner volume planetary atmospheres and vacuum environments can be established. The inner container is made of three segments: the top cap, the wall and the bottom. They can be cooled independently from room temperature down to 77 K. The inner diameter of the chamber is 140 cm and the inner height is 180 cm.

The goal of the test was to obtain information about the performance of the *Melting Probe*, i.e. the penetration speed, the behavior of the tether when it is uncoiled and the temperature development during the heating phase under vacuum conditions. The test was performed with a mean pressure of 0.3 mbar. The sample used was prepared in a cold chamber, had a total height of 120 cm and a diameter of ∼37 cm.

First simulations done with Aamot's model (Aamot, 1967) with the parameters:

- *Melting Probe*radius = 0.03175 m
- *Melting Probe*length = 0.246 m
- Total heating power = 80 W
- Temperature of the ice = 243 K

predicted a total heating time for the experiment of 2 days 14 hours and 24 minutes. The previous experiments with the spherical *Probe* showed that the actual measured values of the penetration speed reached only about 20%−50% of the predicted value (Treffer, 2004). To keep the duration time of the experiment within a period of 4 days, the temperature value of the ice sample was controlled to be 258 K though this is not the mean temperature on Mars or Europa. Limiting factors which forced this decision were the available time when the chamber could be used and the available amount of LN_2.

For the test all heaters inside the *Melting Probe* were active and first set to a temperature of 303 K. After a pre-heating time of 1 h the *Probe* was launched. The temperature for each of the heaters fixed in the envelope was reduced to a value of 283 K after 18 h and 40 min. At this time it could be visually detected that the *Melting Probe* was slowing down and that a crater was starting to form around it. After a duration time of 47 h and 27 min the test had to be stopped because the LN_2 reservoir was exhausted and the temperature inside the chamber started to rise. During the active heating time the *Probe* was able to penetrate the ice to a depth of approximately 15 cm. It slowed down from a speed of ∼15 mm/h at the beginning to ∼3 mm/h at the end of the test. After the end of the experiment the sample was removed from the chamber and cut in halves for a closer examination of the produced crater. Figure 6 shows an image of the *Melting Probe* and the ice sample after it was taken out of the chamber.

Figure 6: Images of the Probe*and the ice sample obtained from the test at the DLR.*

This result indicates that with the prototype used, the heat effectively necessary to melt the ice cannot be sufficiently transported through the tip. Heating energy was lost via the sides of the *Melting Probe*and therefore instead of a forward motion a crater surrounding the *Probe* formed with time. It has to be expected that if more LN_2 would have been available and the test could be continued over a longer period the *Probe* would have further slowed down and got stuck at last.

5 Melting Probe tests at the Space Simulation Chamber Graz

5.1 Modifications of the Melting Probe

The experiment at DLR showed that a way has to be found to increase the heating power at the tip. This was tried by adding a third heating element (H1, see Figure 7). To avoid complicated changes in the electronic part of the *Melting Probe* the heating segment Q4 was disconnected. This was possible since at this part of the *Probe* the heat dissipated by the electronics box is adequate to heat the wall of the *Probe* close to it. Thus, there are still five heating circuits inside the *Melting Probe* that can be used separately or as an assembly. The additional heater is a custom–made device consisting of a cylindrical aluminium core with a diameter of 10 mm and a height of 14 mm. Along the vertical axis a hole with a diameter of 2.5 mm was drilled to enable the placement of a PT100 inside the tip. At the outer edge of the core a PT100 sensor was fixed in a notch of the heater to ensure the temperature control. This aluminium core was lagged with a Kapton foil were a heater wire that was positioned in a sinuous line was fixed.

For placing H1 inside the tip a hole was drilled out. To fill the free space between the hole and the outer diameter of H1 an aluminium tape was wrapped around the heater. Additionally to enhance the contact between H1 and the tip, H1 was coated with a silicone heat transfer compound.

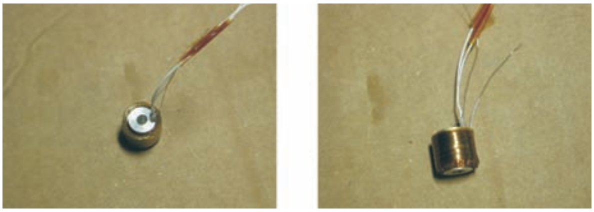

Figure 7: Images of the custom–made heater.

Also four additional internal standard PT100 temperature sensors (further named IPT1 to IPT4) were placed inside the tip to get a better control of the temperature and the temperature gradient.

With the modified *Melting Probe* some fundamental experiments were done in the vacuum chamber at IWF Graz:

Experiment 1:
The *Melting Probe*was operating under atmospheric conditions, with all heaters active, and set to the same temperature of 313 K.

Experiment 2:
The test was done under vacuum conditions, with all heaters active and set to a temperature of 313 K.

Experiment 3:
The test was done under vacuum conditions, with only the ring shaped foil at the bottom of the tip active and the temperature set to 313 K.

Experiment 4:
The test was done under vacuum conditions, only H1 was active, the temperature was set to 313 K.

Experiment 5:
The test was done under vacuum conditions, the vacuum chamber was cooled by LN_2. The *Melting Probe* was set up on a cylindrical ice sample with 27 cm diameter and 35 cm height. All heaters were activated, the heaters inside the tip were set to a temperature of 293 K and the temperature of the heaters fixed at the inner wall of the envelope were set to 278 K.

Additionally to the internal temperature sensors four temperature sensors were mounted on the outside of the tip: One close to the front point (EPT1) and three more PT100 sensors equally separated every 10 mm (EPT2, EPT3 and EPT4). Due to the curvature of the tip it was not possible to get good thermal contact between the tip and the sensors. In case of the internal sensors the thermal contact could be enhanced with the help of a two components glue (IPT3 and IPT4) and a silicone heat transfer compound (IPT1 and IPT2). The first and the last experiment will now be discussed in more detail and results obtained from simulations will be shown.

5.2 Thermal Model

The model approach is designed to specify the general thermal requirements for the melting probe. It includes following single parts: the steel envelope with its top cap, the brass tip, each single heater and the glue or heat transfer compound layer between the heater and the part of the *Probe* were it is fixed, the internal sensors IPT1 and IPT2 and, in case of experiment 1, the electronics box. The model is based on the classical equation of heat transfer and a two dimensional axially symmetric approach was chosen for the calculations:

$$\rho c \frac{\partial T(r,z,t)}{\partial t} - \nabla \cdot (\lambda \nabla T) = Q \tag{1}$$

where ρ stands for density, c for the heat capacity and λ for the thermal conductivity of the different materials. The temperature is specified by T and Q denotes the interior heat source given by P/V, the electrical power divided by the volume of the heating element. The model is separated into subdomains. Each subdomain is defined by ρ, c and λ. For the calculations the subdomains describing the heaters are deactivated and the heat source is defined via the boundary conditions. This means that the temperature values measured during the experiment were approximated by exponential functions and these functions were used as boundary conditions for the diverse subdomains. The same was done for the calculation of the influence of the electronics box.

5.2.1 Simulation results for Experiment 1

As mentioned above, the subdomains describing the heaters and the electronics box were deactivated and the influence of these parts was approximated by exponential functions. With this first approach and the single parameters for the glue and heat transfer compound layers given by the manufacturer, the measured heat slope could not be reproduced, the simulated one was much steeper than the measured one. During the simulations it was shown that the width of the glue and heat transfer compound layers and the single values for λ, ρ and c have a strong influence on the results of the simulations. The width of the single glue layers could not be measured, these values had to be adapted to give the best results for the calculations. All glue layers were taken to be 50 μm thick, the same width as the acrylic layers of the heating foils as defined by the manufacturer. The simulations also showed that the measured values for the internal sensors could only be reproduced with a mean deviation of about or less than 3 K if the calculations were done with a temperature dependent λ for the two components glue, the heat transfer compound and the acrylic glue layer. The values used for the calculations are listed in Table 1.

material	ρ [kgm^{-3}]	c [Jkg^{-1} K^{-1}]	λ [WK^{-1} m^{-1}]
air	1.29	1010	0.026
acryl	1012	1440	5.609767/(1+T)
glue	1200	1890	7.53101/(1+T)
heat transfer compound	2100	1400	7.56386/(1+T)

Table 1: Parameters used for the simulation of experiment 1.

As initial conditions for the different subdomains the averages of the measured temperature values at the beginning of the heating phase were taken. The surroundings of the *Melting Probe*was simulated by a cylinder with a diameter and a height of 1 m filled with air. As boundary condition for this sub-domain the temperature was set to a fixed value of 295.15 K. Since the thermal sensors IPT1 and IPT3 have a certain length, the simulated values are an average over three model points: one at the top of the subdomain simulating the sensor, one in the middle and one at the bottom.

Figure 8 shows a comparison between the simulated and the measured temperatures for IPT1. The figure shows that in the first part of the slope and at a simulation time between 1 and 2 h the simulated and the measured values are in good agreement. At the end of the heating phase the temperature differences between the calculated and measured values increases. An ad–hoc explanation of the continuing increase of the gap could be an additional parasitic heat flux via the sensor cabling, originating from the electronics box that is not included in the simulation.

A similar behavior can be seen for IPT2 and IPT3. The results for IPT2 show a greater gap than for IPT1 and IPT3. The measured and simulated values for the external temperature sensors display an analog curve progression than the values for the internal sensors. In case of the external sensors the simulated values are approximately 5 K higher than the measured ones. This may be due to the poor thermal contact between the sensors and the tip.

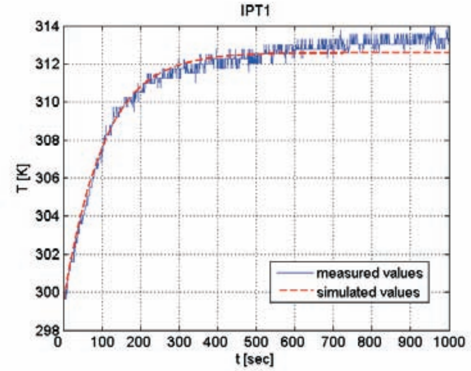

Figure 8: Comparison between the measured and simulated data for IPT1.

5.2.2 Simulation results for Experiment 5

Experiment 5 was done under vacuum conditions. The *Melting Probe* was was positioned above a cylindrical ice sample with 27 cm diameter and 35 cm height. The chamber was cooled by LN_2. As described above in this case all heaters were active. Before this test was started, the *Probe* was stored in a freezer to get lower initial temperatures and to minimize the cavity in the sample prior to the start of the heating that arises due to the difference between the temperature of the tip and of the ice. During the heating phase a chamber pressure of approximately 1.3 mbar was maintained. The *Melting Probe* was heated for about 1h 50min. During this time no distinct forward motion due to melting or sublimation could be observed. This could be due to the fact that the *Probe* initially was in contact with the ice only via the tiny additional thermal sensor mounted on the front point of the tip. Again, for the simulation the subdomains describing the heaters were deactivated and the single heat sources were simulated by exponential functions obtained from the measured temperature values. The calculations were done with the same values for λ, c and ρ for the metals and glues as for Experiment 1. Since the test was done under vacuum conditions, one sub-domain had to be changed. The cylinder filled with air was removed from the model geometry and an ice cylinder was added. For the model geometry it was assumed that the tip reaches 3 mm into the ice when the heating of the *Probe*starts. Phase change of the ice was also considered in the model. The parameters necessary for the calculation with ice are: $\rho = 917$ [kgm^{-3}], $c = T + 90$ [Jkg^{-1}K^{-1}] (Klinger, 1981) and $\lambda = 567/T$ [Wm^{-1}K^{-1}] (Klinger, 1980).

The curve progressions measured and simulated were similar to the ones obtained for experiment 1, for both the internal and the external temperature sensors. In case of atmospheric conditions maximum temperatures of about 314 K were reached, under vacuum conditions in a cooled environment the maximum values were about 290 K. Figure 9 shows a comparison between the measured and the simulated values for IPT1. In this case the mean deviation between the measured and calculated values is for all internal sensors less than 1 K.

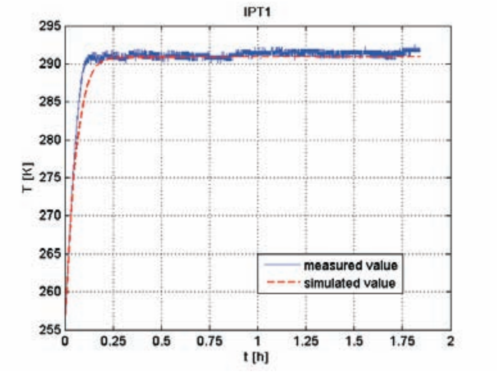

Figure 9: Results for the simulation and measurement for IPT1 for experiment 5.

Like for Experiment 1 the simulated values for the external sensors overestimate the measured ones. Except for EPT1 the mean deviation obtained is about 2.5 K. Due to its poor thermal contact no analyzable values could be obtained from EPT1. As for the test done under atmospheric conditions a nearly isothermal temperature profile in the tip was obtained. Also under these conditions, the heat necessary to melt the *Probe* into the ice could not be transferred to the front point of the tip.

6 Conclusions

All these simple tests, regardless if they where done under vacuum conditions or at atmospheric pressure, showed that a new way of transporting the energy necessary to heat the front point of the tip has to be found. Otherwise no suitable forward motion in ice will be obtained. Also a practicable way of storing the tether is necessary. At the Space Research Institute in Graz new studies were heaters are fixed at the outside of the *Melting Probe* and were other heater materials were used are currently in progress.

Acknowledgments

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