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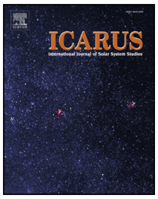

Melting probe technology for subsurface exploration of extraterrestrial ice – Critical refreezing length and the role of gravity

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ABSTRACT

The 'Ocean Worlds' of our Solar System are covered with ice, hence the water is not directly accessible. Using melting probe technology is one of the promising technological approaches to reach those scientifically interesting water reservoirs. Melting probes basically consist of a heated melting head on top of an elongated body that contains the scientific payload. The traditional engineering approach to design such melting probes starts from a global energy balance around the melting head and quantifies the power necessary to sustain a specific melting velocity while preventing the probe from refreezing and stalling in the channel. Though this approach is sufficient to design simple melting probes for terrestrial applications, it is too simplistic to study the probe's performance for environmental conditions found on some of the Ocean Worlds, e.g. a lower value of the gravitational acceleration. This will be important, however, when designing exploration technologies for extraterrestrial purposes.

We tackle the problem by explicitly modeling the physical processes in the thin melt film between the probe and the underlying ice. Our model allows to study melting regimes on bodies of different gravitational acceleration, and we explicitly compare melting regimes on Europa, Enceladus and Mars. In addition to that, our model allows us to quantify the heat losses due to convective transport around the melting probe. We discuss to which extent these heat losses can be utilized to avoid the necessity of a side wall heating system to prevent the probe from stalling, and introduce the notion of the 'Critical Refreezing Length'. Our results allow to draw important conclusions towards the design of melting probe technology for future missions to icy bodies in our Solar System.

1. Introduction

The presence of subglacial liquid water on the icy moons of our Solar System (Lunine, 2017) implies the possibility of habitable environmental conditions. Especially the cryovolcanically active Saturnian moon Enceladus seems to be a promising candidate (Lunine et al., 2015) and there is some hope in the scientific community that an exploration mission to Enceladus might unravel the existence of extraterrestrial life. Next generation mission concepts focus on orbiting and sample-returning of plume material (Lunine et al., 2015; Sherwood, 2016). Should these further strengthen any evidence for life, then the natural next step is to sample and analyze the subglacial ocean directly (Konstantinidis et al., 2015; Sherwood, 2016). In order to access the extraterrestrial subglacial water reservoirs, a thick ice layer must be penetrated.

A very promising technological approach for this task is to use a thermal melting probe (Konstantinidis et al., 2015). Melting probes enforce ice penetration by heating, such that the ice in the vicinity of the probe melts and the probe eventually sinks down. Because the necessary power roughly scales with the cross-sectional area of the melting channel, a melting probe typically looks like an elongated cylinder with a heated melting head. In comparison to other ice penetration technologies, e.g. hot water or mechanical ice drilling, the advantage of a melting probe for space exploration purposes is its smaller, lighter, and mechanically less complex design. Melting probes are not a novel technology as they have already been applied successfully for terrestrial research since the 1960s (Kasser, 1960; Philberth, 1962). In recent years, however, more advanced melting probe designs have been proposed and tested (Zimmerman et al., 2001; Stone et al., 2014; Kowalski et al., 2016; Winebrenner et al., 2016; Kömle et al., 2018).

A very common and relevant engineering approach to design melting probes also dates back to the 1960s and considers a straightforward energy balance (Aamot, 1967): Knowing the electrical power P generated in a melting probe's head as well as its conversion efficiency

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Nomenclature

A	cross-sectional area
c_p	heat capacity
F	exerted force
F^*	buoyancy corrected exerted force
g	gravitational acceleration
h_m	latent heat of melting
h_m^*	reduced latent heat of melting
J_0, Y_0	Bessel functions of first and second kind
k	thermal conductivity
L	length of the melting probe
L^*	critical refreezing length
m	mass
n, d	fit constants
P	power
p	pressure
p_0	pressure at the probe's back
$\dot{Q}$	heat flow rate
$\dot{Q}_{\min}$	minimum heat flow rate
$\dot{q}$	heat flux
R	radius of the melting head
T	temperature
T_m	melting temperature
W	melting velocity
(r, z)	coordinates, see figure 1
(u, w)	velocity components in the melt film
Ste	Stefan number
Re	Reynolds number
$\alpha = k/(\rho\, c_p)$	thermal diffusivity
Γ	boundary
γ	efficiency related to convective losses (equation (29))
δ	melt film thickness
ϵ	melting probe efficiency
η	power conversion efficiency
μ	dynamic viscosity of the water
ρ	density

Indices

L	liquid phase (ρ_L, $c_{p,\,L}$, k_L, α_L)
S	solid phase (ρ_S, $c_{p,\,S}$, k_S, α_S, T_S)
C	at the phase interface (Γ_C, $\dot{Q}_C$)
H	at the melting head (Γ_H, $\dot{Q}_H$)
E	at the outflow boundary (Γ_E, $\dot{Q}_E$)

η allows to infer the heat flow rate at the melting head's surface $\dot{Q} = \eta P$. The corresponding heat flux is given by $\dot{q} = \dot{Q}/A$, in which A stands for the cross-sectional area of the melting head. The minimum heat flow rate $\dot{Q}_{\min}$ required to operate the melting probe at a target melting velocity W is then given by the sum of the heat flow rate necessary to increase the temperature of the ice in front of the probe and the heat flow rate that is eventually needed to melt the ice:

$$\dot{Q}_{\min} = WA\rho_S[h_m + c_{p,S}(T_m - T_S)] \tag{1}$$

Here, ρ_S is the ice density, h_m is the latent heat of melting, $c_{p,S}$ is the heat capacity of the ice, T_S is the ice temperature and T_m is the melting temperature of ice. Note, that from Eq. (1) it is evident that the melting velocity scales inversely with the cross-sectional area of the melting probe. In order to accommodate some scientific payload it is hence beneficial to increase the probe's length L rather than its radius R and often a probe design is characterized by $R < < L$. Such an elongated geometry, however, poses another problem, namely the risk of stalling due to refreezing (Treffer et al., 2006). Various concepts have been proposed to avoid stalling during melting, e.g. by overheating the melting head beyond the minimally required power $\dot{Q}_{\min}$ given by Eq. (1) as proposed in Aamot (1967), or by implementing a side wall heating system, such as realized in Kowalski et al. (2016).

The amount of heat required to avoid stalling, in the following referred to as the lateral heat requirement $\dot{Q}_L$, has been estimated in Aamot (1967) based on quantifying heat conduction in an infinite region bounded internally by a circular cylinder (Jaeger, 1956). It is given by

$$\dot{Q}_L = \frac{8k_S T_S}{\pi}\int_0^L\int_0^\infty \frac{\exp\left(-\frac{\alpha_S b^2 z}{W}\right)}{b(J_0^2(Rb)Y_0^2(Rb))}dbdz, \tag{2}$$

in which b is the integration argument of the Bessel functions J_0 and Y_0, and z is the spatial coordinate along the longitudinal axis of the melting probe. R and L are the radius and the length of the cylindrical melting probe and $\alpha_S = k_S/(\rho_S\, c_{p,S})$ is the thermal diffusivity of the ice, in which k_S denotes its thermal conductivity.

Summing up the minimum heat flow rate to open the channel $\dot{Q}_{\min}$ and the lateral heat requirement $\dot{Q}_L$ provides a good approximation for the overall power necessary to sustain a specific melting velocity while preventing the probe from refreezing and stalling in the channel. This 'simple' approach has been used to design thermal melting probe robots both for terrestrial field tests, e.g. in Antarctica and Greenland (Aamot, 1968; Kowalski et al., 2016), and for conceptual studies to prepare extraterrestrial exploration missions (Zimmerman et al., 2001; Konstantinidis et al., 2015).

The main technological issues for the latter have been summarized in Ulamec et al. (2007). In that article, the authors find that a major challenge for the design of melting probe technology for extraterrestrial purposes is the very low ice temperatures at the target bodies, which result in a very low efficiency of the melting process. Power efficiency is hence of major concern, especially when facing restrictive power constraints during space missions. The melting probe efficiency can be defined as $\epsilon = \dot{Q}_{\min}/(\dot{Q}_{\min} + \sum_i \dot{Q}_{loss,i})$, in which $\sum_i \dot{Q}_{loss,i}$ denotes the sum of all losses. One potential loss is for example given by convective losses within the micro-scale melt film between the melting probe and the ice. The efficiency associated with these losses can either be studied experimentally (Kömle et al., 2018) or through advanced modeling techniques (Schüller and Kowalski, 2017) that go beyond the engineering design approach covered by Eq. (1).

Another great challenge is associated with initiating a melting mission in a low pressure regime that is below the triple point of water ($<$ 6.1 mbar). Then, the ice sublimates if heated. This complicates the initial penetration phase of a melting probe, which is operated on bodies like Enceladus or Europa (Kömle et al., 2018). After the probe has reached a certain depth, however, the melting channel is believed to refreeze and consequently the channel will sustain a pressure above the triple point, such that the probe operates in a pure melting regime (Treffer et al., 2006). The initial low pressure regime can be further shortened by using a top cap as proposed in Horne (2017). Although a reliable and robust technological solution for the initial low pressure phase of any such mission is unarguably key to success, still the larger part of the melting transit through hundreds of meters of ice will take place in a pressure regime above the triple point. Consequently, the vast amount of energy is spent in a regime that is characterized by melting rather than sublimation. This motivates to further study efficiency and dynamics of melting probe technology in a pressure regime above the triple point, while neglecting low pressure effects for the time being.

One aspect, which has not been investigated so far even for conditions above the triple point, is the effect of gravity on the melting process. The value of the gravitational acceleration is for example much smaller on Enceladus than it is on Europa, or even on Earth. A melting