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Powering sea-ice instrumentation via the Seebeck Effect☆

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ABSTRACT

This paper details the design of a novel thermoelectric energy harvesting device, capable of powering sea-ice instrumentation during the polar winter, when other sources of energy are either unavailable or unreliable. The current device employs no moving parts and exploits the Seebeck Effect and the temperature differential across the sea–ice interface to convert a flow of heat into electrical energy. Fundamental limitations are discussed and thermodynamic modelling is employed to ensure a reasonable device output. Test results from a prototype reveal typical voltage and power outputs in the region of 3 V and 200 mW, respectively, given an applied temperature differential of 30 °C.

1. Introduction

Between 1979 and 2007 the summer sea ice extent in the Arctic has halved, from over 8 million km^2 to just over 4 million km^2 (Stroeve et al., 2007). Moreover, data from submarines suggest that its thickness has reduced by some 40% (Wadhams and Davis, 2000). As to the future, there is unanimous agreement between all the climate prediction models used in the latest report of the Intergovernmental Panel on Climate Change (IPCC) that these reductions will continue, and that the Arctic could be ice free by the end of this century (Pachauri and Reisinger, 2007). The properties of sea ice are constantly evolving, driven by changes in local environmental conditions such as air temperature, snow depth, ocean temperature and so on. This complex dynamical behaviour is yet to be fully understood, a fact that is reflected by the widely differing predictions of existing models. In order to refine these models, substantial experimental data is required, hence the need for inexpensive instruments that can operate reliably over extended periods of time. The critical problem, addressed in this work, is how to power such instruments during the polar winter, when there is no solar energy to call upon. Traditional solutions, such as those displayed in Fig. 1, employ wind generators and/or lead-acid batteries, both of which are unreliable in the extreme conditions encountered.

The approach adopted in this work employs thermoelectric generators: compact solid-state devices that exploit the Seebeck Effect (e.g. Stevens (1999); Snyder (2009)). Such generators, converting a flow of heat between hot and cold reservoirs into electricity without the use of moving parts, have been widely used in the space industry (e.g., Gylfe and Wimmer (1966)), but have to date found little or no use in polar regions. The main drawback is that the efficiency of such generators is low when the temperature difference between the ‘hot’ reservoir (the sea beneath the ice in the current study) and the cold reservoir (the air above the sea ice) is only a few tens of degrees. However, given the compact size of the generators and the low power requirements of most modern polar instruments, a Seebeck Effect generator of modest size ought to be capable of delivering useful amounts of power during the winter months, when it is typically most needed. Such an approach has been considered as a power source in Antarctic plateau regions, but the poor thermal conductivity of snow dictated the use of an impractically large heat-collector (Rose, 2002). However, a different situation exists for instrument packages and buoys deployed upon sea-ice, where the excellent thermal conductivity of sea-water allows for much smaller heat-collectors. Transporting heat efficiently across the sea-ice divide represents a significant challenge, which in the present case is overcome though the use of a heat-pipe. Like thermoelectric generators, heat-pipes employ no mechanical moving parts and thus offer the potential of high reliability. However, given the non-standard nature of the current application, careful attention must be paid to the heat-pipe design to ensure correct operation.

The design of the Seebeck Effect generator is shown in Fig. 2. The device consists of three main parts: a condenser, an evaporator and an intermediate section, and is designed to slide through a hole in the sea-ice. The function of the evaporator section is to absorb and

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Fig. 1. A SAMS ice mass balance station in the Arctic Ocean. The solar and wind generators, together with the large battery box, could be replaced by the proposed Seebeck generator.

transfer heat from the surrounding sea-water to a central heat-pipe. The heat-pipe, extending the full length of the device, transports the acquired heat up to the condenser section, where it is released to the ambient environment through an array of thermoelectric generators and heat-sinks, creating electricity in the process. The intermediate section plays no role, other than protecting and insulating the heat-pipe from the surrounding sea-ice.

The rest of the paper is organised as follows. Section 2 discusses the functional requirements of the Seebeck Effect generator. The design of each section of the generator is then explained in Section 3, where the relevant thermodynamic laws and concepts are presented. Section 4 presents results from cold-chamber tests, and conclusions and suggestions for future work are discussed in Section 5.

2. Design specifications

The primary functional requirements of the Seebeck Effect generator are listed as follows:

- Deployable through a 6 in. hole in sea-ice.
- Mass not in excess of 70 kg.
- Possess a length between 2 m and 2.5 m.
- Rugged construction.
- Provide a power output of several hundred milliwatts at a potential difference of several volts, into a matched load impedance, assuming sea-water and air temperatures of 0 °C and −30 °C, respectively.
- Design for worst-case conditions i.e., still air above the sea-ice and still water below the sea-ice.

The first two requirements basically ensure the device is practically deployable by two people working on sea-ice. Six inches is a standard drill diameter and holes of this size can easily be drilled to depths of several metres through sea-ice, by a two-man team. The third requirement ensures the device is of sufficient length to penetrate most first year sea-ice and yet be of a manageable size in terms of manhandling and transportation. Assuming the sea-ice remains intact, then the device is required to function for a period in excess of one year. As such, rugged construction is required to ensure the device withstands all reasonable forces and is resistant to corrosion.

Given the low power requirements of most polar instruments, an output power of several hundred milliwatts should be sufficient to trickle-charge a battery, whilst an output of several volts enables the end-user the option of selecting from a wide range of regulators to match the generator to particular requirements. The actual power