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A thermoelectric cap for seafloor hydrothermal vents

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ABSTRACT

Long-term in situ monitoring is crucial to seafloor scientific investigations. One of the challenges of operating sensors in seabed is the lifespan of the sensors. Such sensors are commonly powered by batteries when other alternatives, such as tidal or solar energy, are unavailable. However, the batteries have a limited lifespan and must be recharged or replaced periodically, which is costly and impractical. A thermoelectric cap, which harvests the thermal energy of hydrothermal fluids through a conduction pipe and converts the heat to electrical energy by using thermoelectric generators, was developed to avoid these inconveniences. The thermoelectric cap was combined with a power and temperature measurement system that enables the thermoelectric cap to power a light-emitting diode lamp, an electronic load (60 Ω), and 16 thermocouples continuously. The thermoelectric cap was field tested at a shallow hydrothermal vent site near Kueishantao islet, which is located offshore of northeastern Taiwan. By using the thermal gradient between hydrothermal fluids and seawater, the thermoelectric cap obtained a sustained power of 0.2–0.5 W during the field test. The thermoelectric cap successfully powered the 16 thermocouples and recorded the temperature of the hydrothermal fluids during the entire field test. Our results show that the thermal energy of hydrothermal fluids can be an alternative renewable power source for oceanographic research.

1. Introduction

Long-term deep-sea observation has been the focus of significant interest over the past decade. Seafloor devices powered by batteries usually run out of power easily over time, and retrieving these deployed devices to replace the depleted batteries takes considerable effort. Recently, the reduction in size and power consumption of consumer electronics has opened up many new opportunities for low-power seafloor observation stations. An effective power source is still a key factor for better endurance of the seafloor observation station. Therefore, the development of seafloor observation systems revolves around the ability to capture ambient energy surrounding the device and convert it into usable electric power.

Deep-sea hydrothermal vents often discharge fluids with velocities up to meters per second and temperatures up to approximately 400 °C [1]. The heat flux of a hydrothermal vent is estimated to reach 10 MW. Considerable attention has been focused on the exploration of the thermal energy of hydrothermal fluids in recent years [2]. Researchers of the IMPULSA project of Mexico investigated the thermal energy of hydrothermal fluids for the purpose of utilizing renewable energy sources to desalinize seawater [3]. Several investigators have attempted to demonstrate the possibility of using the thermal energy of hydrothermal fluids as the power source for sea exploration. The US company CREAK plans to develop a turbo-Rankine power system for deep-sea hydrothermal vents, which could enable remote sea sensors, underwater vehicles, deep-sea drilling and mining, and scientific applications [4]. Maritime Applied Physics Corporation demonstrated on its official website that its new hydrothermoelectric energy harvesting system successfully generates electric power [5]. However, to date, scant literature is available on the utilization of the thermal energy of hydrothermal fluids.

The thermal gradient between hydrothermal fluids and seawater could reach 400 °C. The straightforward operation of thermoelectric conversion makes it a feasible method to utilize the thermal gradient between hydrothermal fluids and seawater. Thermoelectric devices convert thermal energy directly into electricity by solid-state technology based on the Seebeck effect. Given their simple, small-scale, environment-friendly, and solid-state energy conversion mechanism, thermoelectric generators (TEGs) have been applied in many areas, such as aerospace [6], automobile [7–10], building [11], and remote sensing [12].

Many studies have shown thermoelectrics to be a potential power source for a variety of sensors in scientific and industrial

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Nomenclature

ρ	density of the hydrothermal fluids (kg m^{-3})
v_{in}	venting velocity of the hydrothermal fluids (m s^{-1})
d_{in}	diameter of the hydrothermal vent (m)
C_p	specific heat capacity of the hydrothermal fluids (J kg^{-1} K^{-1})
Nu	Nusselt number of the forced convection heat transfer
K_f	thermal conductivity of hydrothermal fluids (W m^{-1} K^{-1})
l_{cc}	characteristic length of the conduction pipe (m)
A_{cc}	area of the inner surface of the conduction pipe (m^2)
A_o	total surface area of the base and the fins of the heat dissipation shell (m^2)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
ZT	figure of merit of the TEGs
t_{hy}	temperature of the hydrothermal fluids (°C)
t_1	average temperature of hydrothermal fluids inside the conduction pipe (°C)
t_{cc}	temperature of the inner surface of the conduction pipe (°C)
t_{dso}	temperature of the outer surface of the heat dissipation shell (°C)
t_{sw}	temperature of seawater (°C)
t_h	temperature of the hot sides of the TEGs (°C)
t_c	temperature of the cold sides of the TEGs (°C)
ΔT_{cb}	temperature difference of the hot and cold sides of the conduction block (°C)
ΔT_{TEG}	temperature difference of the hot and cold sides of the TEG (°C)
Q	heat transfer rate of the testing system (W)
Q_{hy}	thermal energy of the hydrothermal fluids (W)
q_{fc}	heat input rate from the hydrothermal fluids to the thermoelectric cap (W)
q_{nc}	heat transfer rate of the natural convection heat transfer (W)
q_{TC}	heat transfer rate of the thermoelectric cap (W)
q_{TEG}	generated power of the thermoelectric cap (W)
q_{waste}	wasting energy of the hydrothermal fluids (W)
R_{cc}	thermal resistance of the conduction pipe (°C W^{-1})
R_{TEG}	thermal resistance of the TEGs (°C W^{-1})
R_{cp}	thermal resistance of the conduction pieces (°C W^{-1})
R_{ds}	thermal resistance of the heat dissipation shells (°C W^{-1})
R_{tg}	thermal resistance of the thermal grease coating (°C W^{-1})
R_{cb}	thermal resistance of the conduction block (°C W^{-1})
R_{in}	internal resistance of the TEG (Ω)
R_{load}	resistance of the load (Ω)
ΣR_{TC}	thermal resistance of the thermoelectric cap (°C W^{-1})
V_{op}	open-circuit voltage of the TEG (V)
V_G	output voltage of the TEG (V)
α_{pn}	Seebeck coefficient of the TEG (V °C^{-1})
η_f	fin effectiveness of the radial fins
η_{TEG}	efficiency of the TEGs

applications. Knight presented a thermoelectric device that utilizes the thermal gradient between air and water to power remote sensors [13]. Carstens monitored the fuel consumed during dry cask storage utilizing TEGs by using radio frequency modules [14]. Li proposed a power management system for TEGs to drive wireless sensors on a spindle unit [15]. Other studies that highlight the ongoing efforts in this topical area can be found in [16–23]. However, thermoelectric devices have never been used on seafloor hydrothermal vents as power source for ocean observation sensors.

The challenges posed by the extreme environment of hydrothermal vent systems must be addressed to fill the existing gap in the application of TEGs on seafloor hydrothermal vents. The high pressure and temperature, corrosive nature of saline and acidic hydrothermal fluids, and extreme rugged vent topography are the chief obstacles. Thermal energy also dissipates to seawater immediately after the hydrothermal fluids are ejected from the chimney, which makes it difficult to be captured. Meanwhile, the deposition of sulfide minerals on the instrument may affect the performance of the TEGs over time.

In this study, we build a thermoelectric cap to validate the possibility of using the thermal energy of seafloor hydrothermal fluids as energy source for ocean observation. The thermoelectric cap harvests seafloor hydrothermal energy through a conduction pipe and converts the heat into electrical energy by using TEGs. The thermoelectric cap is suitable for a variety of hydrothermal vents and can be conveniently deployed in harsh conditions because of the novel application of the conduction pipe. A power and temperature measurement system (PTMS), which enables the thermoelectric cap to power a light-emitting diode (LED) lamp, an electronic load (60 Ω), and 16 thermocouples continuously, was also developed. During its operation, the PTMS automatically monitors the output current and voltage of the thermoelectric cap and the temperature data of 16 thermocouples. We have successfully deployed the thermoelectric cap at a hydrothermal vent and evaluated its power generation ability. The thermoelectric cap successfully powered the 16 thermocouples, and the PTMS recorded the temperatures of the hydrothermal fluids during the entire field test.

2. Power targets for the thermoelectric cap

Long-term in situ monitoring is crucial to scientific and industrial investigations. One of the challenges of operating sensors in remote locations is the lifespan of the sensors. To address this challenge, sensors are developed to consume less power, thus extending endurance in remote locations. Table 1 presents examples of sensors with low power requirements that are mostly used in

Table 1
Power requirements of several typical oceanographic sensors.

Instrument	Parameter measured	Manufacturer	Power requirement/mW
Shield thermocouple	Temperature	Omega, Inc.	1–50
CT	Conductivity, temperature	TRDI, Inc.	50
CTD	Conductivity, temperature, and depth	Valeport, Inc.	250
Chlorophyll-*a* fluorometer	Fluorescence	Seapoint Sensor, Inc.	216
Turbidity meter	Turbidity	Seapoint Sensor, Inc.	42
pH sensor	pH	Seabird, Inc.	240
Dissolved oxygen meter	Oxygen	Seabird, Inc.	60