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Generation of electricity from deep-sea hydrothermal vents with a thermoelectric converter

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HIGHLIGHTS

- We developed a thermoelectric converter (TEC) to harvest hydrothermal energy.
- The TEC was deployed at the Dragon Flag Field along the Southwest Indian Ridge.
- The TEC obtained a sustained power of 2.6–3.9 W during the field test.
- The TEC can make the thermal energy of hydrothermal fluids a viable power source.

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ABSTRACT

The high temperatures of sea-floor hydrothermal vents make them good targets for the exploitation of thermal energy. Taking advantage of this prospect, this study developed a thermoelectric converter that harvests thermal energy from hydrothermal fluids through a heat pipe and converts heat to electrical energy with thermoelectric generators. A power management system that enables the thermoelectric converter to continuously power a data logger and a light-emitting diode lamp was also proposed. The thermoelectric converter was field tested at a deep-sea hydrothermal vent with a depth of 2765 m at the Dragon Flag Field along the Southwest Indian Ridge. With the use of the thermal gradient between hydrothermal fluids and seawater, the thermoelectric converter obtained a sustained power of 2.6–3.9 W during the field test. Our results demonstrate that the thermal energy of hydrothermal fluids can be an alternative renewable power source for seabed observation equipment that requires watt-level power.

1. Introduction

Public interest in long-term deep-sea observation has increased in recent years. Providing enormous fluxes of heat and mass to oceans, deep-sea hydrothermal vents are among the most spectacular features on the seafloor along mid-ocean ridges. The long-term in situ monitoring of hydrothermal vents can provide data for modeling the heat flux and plumes from hydrothermal discharges. One challenge in the long-term observation of hydrothermal plumes is prolonging the service life of sensors, which is limited by their power source. Traditionally, seafloor observatories are powered by either batteries or power cables. In submarine observation, replacing batteries is relatively costly. In many cases, the deployment of power cables on the seafloor is expensive and impractical. Therefore, the development of renewable power sources as a replacement for traditional power sources for submarine observation is imperative. These alternative power sources should require minimal maintenance and produce power for long periods with the use of local resources around hydrothermal vents.

Potential candidates for such power source include piezoelectric energy, seawater batteries, and hydroelectricity [1–3]. Each of these candidates has its disadvantages, particularly for submarine sensors with high power requirements. Piezoelectric energy generators have limited power generation capacity, whereas seawater batteries have limited service life, which is dependent on the size of sacrificial anodes. In seawater around hydrothermal vents, seawater batteries produce very low power because of the limited oxygen content in the cathodes. Hydroelectric power sources depend on water flow, which is not always available on the seafloor. Moreover, currently available small-scale hydroelectric generators are larger than submarine sensor systems [4]. Benthic microbial fuel cells (BMFCs) present great promise as an alternative renewable power source for submarine

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observation. BMFCs can operate for long periods using only local resources on the seabed, and they do not require regular maintenance or replacement. Recently, BMFCs have been developed for power production in remote environments, such as in rural areas and deep-sea hydrothermal vents [5,6]. However, the power densities of BMFCs for electricity generation are modest in the order of μW–mW m^{-3} [7]. Some researchers have explored the chemical energy of seafloor hydrothermal fluids as alternative power sources for deep-sea observation. Yamamoto et al. powered three light-emitting diodes (LEDs) using an environmental fuel cell with a generated power of 21 mW [8]. Environmental fuel cells utilize the oxidation–reduction potential between hydrothermal fluids and ambient seawater to generate electricity [9]; however, such fuel cells have the same limitation as BMFCs.

Hydrothermal fluids contain large amounts of thermal energy, which could power the exploitation and observation of seabed resources. The heat fluxes of a hydrothermal vent could reach 10 MW [10]. In recent years, the focus on the exploration of the thermal energy of hydrothermal fluids has obviously increased [11]. For example, the investigators of the IMPULSA project of Mexico proposed the utilization of the thermal energy of hydrothermal fluids as renewable energy sources for seawater desalination [12]. Some researchers have extensively explored power generation using deep-sea hydrothermal energy. The US company CREAK developed a turbo-Rankine power system, which harvests deep-sea hydrothermal energy [13]. The turbo-Rankine power system was designed to provide energy on the seabed for scientific instruments and ocean observatories. The Maritime Applied Physics Corporation reported that its new hydrothermoelectric energy harvesting system successfully produces electric power [14]. However, to date, the available literature on the thermal energy conversion of seafloor hydrothermal fluids is limited.

Deep-sea hydrothermal vents often discharge fluids with velocities of up to several meters per second and temperatures of up to approximately 400 °C [10]. The thermal gradient between hydrothermal fluids and seawater can reach 400 °C. The straightforward operation of thermoelectric conversion and its other advantages make it a feasible technology for utilizing the thermal gradient between hydrothermal fluids and seawater. Thermoelectric devices directly convert thermal energy into electricity with the use of solid-state technology based on the Seebeck effect. Given their simplicity, small scale, environment-friendly features, and solid-state energy conversion mechanism, thermoelectric generators (TEGs) have been applied in many areas, such as in aerospace, automotive engineering, and construction [15–18]. The typical heat resources of TEGs include biomass [19,20], solar energy [21,22], geothermal energy [23], and waste heat [24,25]. However, thermoelectric devices have never utilized the thermal energy of hydrothermal fluids as a heat resource.

To fill the existing gap in the application of TEGs to seafloor hydrothermal vents, we should first address the formidable challenges posed by the extreme environments of hydrothermal vent systems. In addition to high pressure and temperature, the corrosive nature of saline and acidic hydrothermal fluids and the extremely rugged vent topography are significant obstacles. The chimney-like structures of deep-sea hydrothermal vents are typically several meters high and have small orifices with diameters of several centimeters. Therefore, the deployment of large-sized equipment on these steep chimneys is usually impractical. Moreover, the thermal energy of hydrothermal fluids is difficult to capture because thermal energy dissipates in seawater immediately after hydrothermal fluids are ejected from the vents. Furthermore, the deposition of sulfide minerals onto the instruments may affect their performances over time.

In this paper, we propose a thermoelectric converter to explore the possibility of using the thermal energy of seafloor hydrothermal fluids as an energy source for deep-sea observation. The proposed thermoelectric converter harvests seafloor hydrothermal energy through a heat pipe and converts the heat into electrical energy with TEGs. Owing to the novel application of the heat pipe, the thermoelectric converter is suitable for a variety of hydrothermal vents and can be conveniently deployed under harsh conditions. For the effective separation of the hydrothermal fluids and seawater, the sulfide minerals from hydrothermal fluids will not be deposited on the heat pipe. Moreover, the thermoelectric converter can still convert thermal energy into electrical energy even if its surface is covered with sulfide minerals.

A power management system (PMS) that enables the thermoelectric converter to continuously power an LED lamp and a data logger is also developed. The data logger automatically monitors the output current and voltage of the thermoelectric converter during operation. The thermoelectric converter is successfully deployed at a deep-sea hydrothermal vent, and its power generation is evaluated accordingly.

2. Materials and methods

2.1. Thermoelectric converter

The proposed thermoelectric converter is designed according to the features of deep-sea hydrothermal vents and hydrothermal fluids. Although the central temperature of hydrothermal fluids could reach 400 °C, their thermal energy is difficult to be captured. Given that thermal energy dissipates in seawater immediately after hydrothermal fluids are ejected from vents, harvesting thermal energy directly from inside the orifice of hydrothermal vents is considered the best method. Meanwhile, the thermoelectric converter should be cooled down by seawater. As a result, a considerable distance exists between the heat source and the heat sink of the thermoelectric converter. Nonetheless, the high effective thermal conductivity of the heat pipe of the thermoelectric converter enables efficient heat transfer over such distance.

As shown in Fig. 1, the thermoelectric converter is composed of a heat pipe, four TEGs, four conduction blocks, a thermally insulated chamber, a heat dissipation shell, a protective shield, and an end cap. Owing to its high strength and corrosion resistance, titanium alloy (6Al4V) is used as the main material for the heat pipe, thermally insulated chamber, heat dissipation shell, and end cap. The conduction blocks are made of aluminum (6061), which ensures good heat conduction. Hydrothermal vents usually have internal diameters in the order of 1 cm. For easy deployment in various hydrothermal vents, the thermoelectric converter features a straight heat pipe with a diameter of 10 mm. This small heat pipe can be easily inserted into a hydrothermal vent to harvest thermal energy. Then, the thermal energy is transferred from the heat pipe to the TEGs, which can directly convert heat into electrical energy. Through conduction heat transfer, the thermal energy is transferred from the cold side surfaces of the TEGs to the conduction blocks and then to the heat dissipation shell. Finally, the thermoelectric converter is cooled down by the heat transfer between the heat dissipation shell and seawater. The protective shield is used to isolate the dissipation shell from high-temperature hydrothermal fluids and consequently reduces the temperatures of the cold side surfaces of the TEGs. Designed for use in deep seas, the thermoelectric converter, which weighs approximately 0.4 kg in seawater, can withstand high pressure conditions of up to 45 MPa.

2.1.1. Thermoelectric generator

A TEG consists of a series of thermocouples made up of dissimilar semiconductors. When a temperature difference exists