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Model and simulation of the energy retrieved by thermoelectric generators in an underwater glider

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ABSTRACT

The need of a more persistent human presence on sea is driving the development of increasingly more efficient Autonomous Underwater Vehicles. A particularly promising solution to power these vehicles is the retrieval of energy from the ocean temperature gradient. This paper investigates the use of thermoelectric generators (TEGs) for that purpose, by presenting a complete model of thermoelectric generators embedded in the hull of an underwater glider. The model includes not only the thermoelectric generators but also the heat transfer process and the behaviour of different heat storage materials. Several simulations are performed, for each storage material, to determine the adequate design parameters leading to sufficient energy generation for a thermal glider. It is shown that the use of Phase Change Materials (PCM) as an energy storage material is highly advantageous over the use of sea water or stainless steel. Furthermore, it is shown that this approach, although leading to a high number of TEGs and mass of PCM, is compatible with current existing glider dimensions.

1. Introduction

It is commonly accepted that ocean will play an increasingly important role in the world's near future economy, namely in what concerns energy resources [1]. Ocean monitoring is vital to enlarge human knowledge on Earth's oceans and its existing assets. Several examples can be found on the importance of ocean monitoring for food resources [2], oceanographic purposes [3–5], sovereignty upholding tasks [6], ecosystem studies [7] or energy resources [8]. As buoys or ship based campaigns do not provide sufficient spatial and temporal resolution, an increasing tendency towards the use of Autonomous Underwater Vehicles (AUV) is underway [9]. It is therefore of major importance the development of smart, small and inexpensive autonomous vehicles, which may potentially build up into a network allowing constant monitoring of the oceans. Only recently has technology evolved to the point at which it is possible to exploit autonomous paradigms to concurrently measure physical and biological variables throughout large oceanic regions. A convenient AUV must provide excellent survivability features and long endurance. Better survivability characteristics are often ensured by the use of underwater vehicles, which are less prone to storms, waves and wind. Regarding the increase of mission length, a tendency towards the use of renewable energies can be found in vehicles using solar harvesting [10], wave [11] and ocean temperature gradient harvesting [12–14]. Solar powered vehicles are limited on recharge periods due to available light and wave powered vehicles are heavily dependent on the existing wave profiles. Furthermore, both solutions require the vehicle to spend a considerable amount of time at surface level, therefore potentially compromising its survivability. On the contrary, the use of the ocean temperature gradient requires the vehicle to remain mostly underwater and additionally, as a temperature gradient exists in the majority of Earth Oceans [15], ocean thermal energy constitutes a predictable and reliable source of energy. In fact, the use of ocean temperature gradient may allow the enhancement of the autonomy of underwater gliders from ca. 1 to ca. 5 years in commercially available devices [15], as the energy consumed by these vehicles is predominantly directed to buoyancy changes (up to 80% [6] in electrically powered pumping).

In the context of autonomous vehicles, the thermal energy of the ocean is typically collected by converting the volumetric changes of certain materials (Phase Change Materials, PCM) when undergoing a phase change from solid to liquid and vice versa. The mechanical work performed is then transformed to hydraulic energy using a hydraulic circuit containing a storage device [13,14]. Typically, the material used to convert thermal into mechanical energy is paraffin [13,16,17]. There are, however, some difficulties with this retrieval procedure. For instance, the working pressures required for a more efficient thermodynamic cycle may be very high [12,13], and the need for an hydraulic system with moving parts to retrieve and store energy leads to a more complex and failure prone system.

In this work a different approach is followed, in which the use of thermoelectric generators (TEGs) for a direct conversion of thermal to electric energy is pursued. TEGs have been used in very different applications [18]. For instance, in [19,20–22], TEGs are used to harvest waste heat from combustion engines. In order to circumvent the problems posed by the highly

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Notation

A_{ESMH}	heat transfer area of the ESMH (transversal area of the ESMH) [m^2]
A_{finc}	compensated area of each heat transfer fin [m^2]
A_H	hull heat transfer area [m^2]
A_{TEG}	area of each TEG [m^2]
c_{pESMH}	specific heat at constant pressure of ESMH [kJ/(K kg)]
c_{pESM}	specific heat at constant pressure of the ESM [kJ/(K kg)]
c_{pfin}	specific heat at constant pressure of the fins [kJ/(K kg)]
c_{pH}	specific heat at constant pressure of the hull [kJ/(K kg)]
C_{ESM}	thermal capacitance of the energy storage material [kJ/(K)]
C_{ESMH}	thermal capacitance of the energy storage material housing [kJ/(K)]
C_{Hfin}	thermal capacitance of the hull and fins [kJ/(K)]
$\bar{c}_{H20}$	volumetric thermal capacitance of sea water [kJ/(K m^3)]
$\bar{c}_{SS}$	volumetric thermal capacitance of stainless steel [kJ/(K m^3)]
e_{ESMH}	energy storage material thickness [m]
e_H	hull heat transfer area thickness [m]
e_{fin}	heat transfer fins thickness [m]
e_{TEG}	TEG thickness [m]
E_T	total electrical energy generated by the n_{TEG} in a given period of time [J]
h_{H2Ofin}	heat transfer coefficient between sea water and fins $\left[\frac{\mathrm{W}}{\mathrm{m^2\,K}}\right]$
i	electrical current flowing through the TEG [A]
k_{ESMH}	hull thermal conductivity $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$
k_{fin}	heat transfer fins thermal conductivity $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$
k_H	hull thermal conductivity $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$
	TEG thermal conductivity $\left[\frac{\mathrm{W}}{\mathrm{m\,K}}\right]$
L_{fin}	heat transfer fins height [m]
m_{ESM}	energy storage material mass [kg]
m_{ESMH}	energy storage material housing mass [kg]
m_{fin}	heat transfer fin mass [kg]
m_H	hull heat transfer area mass [kg]
n_{fin}	number of heat transfer fins
n_{TEG}	number of TEG
q_A	heat transfer retrieved from the ocean [W]
Q_A	energy retrieved from the ocean in a given period of time [J]
q_F	heat transfer due to the Fourier effect [W]
q_J	heat transfer due to Joule effect [W]
q_{Pa},q_{Pe}	heat transfer due to Peltier effect on absorbing and emitting junction, respectively [W]
q_T	heat transfer due to Thomson effect [W]
r_l	electrical resistance of the load [Ω]
r_m	internal electrical resistance of the TEG [Ω]
R_{ESMH}	thermal resistance of the energy storage material housing [K/W]
R_{fin}	thermal resistance of each heat transfer fin [K/W]
R_H	thermal resistance of the hull heat transfer zone [K/W]
S	seebeck coefficient [V/K]
T	temperature [K]
T_a,T_e	temperature on absorbing and emitting junction, respectively [K]
T_{cold}, T_{hot}	ocean water lowest and highest temperature, respectively [K]
T_{ESM}	energy storage material temperature [K]
T_{H2O}	temperature of ocean water [K]
U_s	electromotive force generated in a TEG [V]
V_{ESM}	volume of energy storage material [m^3]
V_{ESMH}	volume of energy storage material housing [m^3]
V_H	volume of hull heat transfer zone [m^3]
x	distance across the TEG transversal area [m]
w_{fin}	heat transfer fin width [m]
z	glider depth [m]
δ	auxiliary parameter
ΔU	voltage generated by each TEG [V]
ΔU_T	total voltage generated by the n_{TEG} [V]
τ	Thomson coefficient [V/K]
η_{fin}	fin efficiency
η	efficiency of the energy conversion
ρ_{ESM}	mass per unit volume of the ESM [kg/m^3]
ρ_{ESMH}	mass per unit volume of the ESMH [kg/m^3]
ρ_H	hull mass per unit volume [kg/m^3]
ω	dive frequency [rad/s]
ESM	energy storage material
ESMH	energy storage material housing
H	Hull
PCM	phase change material

transient properties of the heat emitted by conventional combustion engines, in [23] TEGs are combined with phase change materials. It is also possible to find studies reporting the use of TEGs to retrieve waste heat from gas stoves (either residential or industrial) [24], and from industry processes like, for instance, in steelmaking [25]. An interesting study on ocean related energy retrieval using TEGs was presented by [26]. In that study, a thermoelectric cap that harvests the thermal energy from hydrothermal fluids using TEGs was developed. Field tests showed that the device was capable of sustainably delivering 0.2–0.5 W to power monitoring instruments.

However, in the context of underwater gliders and as far as the author's knowledge goes, only one study [15] has been published on the use of TEGs to retrieve energy from the ocean temperature gradient. Actually, it is possible to find several studies aimed at collecting energy from small temperature gradients in other contexts (see for example [27–30]), but studies involving gliders are more focused on its hydrodynamics [31,32] optimization of gliding paths and routing strategies, [33,34], gliding control [35], hybrid gliders [36,37] or on the enhancement of the thermal-hydraulic machine used in thermal gliders [12,14]. In [15] a model is developed comprising a set of TEGs in direct contact with sea water, on one face, and in direct contact with an energy storage material, on the other face. The glider was assumed to perform trajectories between 0 and 500 m deep with a linear temperature gradient between 25 °C and 5 °C. Stainless steel was chosen as the energy storage material, and it was found that 500 TEGs and a 200 kg stainless steel block would suffice to retrieve the energy typically required by a thermal glider. This energy, according to [15], is around 2 kJ per dive for 500 m dives, leading to a value around 4 kJ per each 1000 m diving cycle, as also mentioned in [38]. There are, however, other energy values mentioned in literature. For instance, in [12] and [39], an energy of 6 kJ per diving cycle is presented for similar dive cycle depth. In this work a conservative approach will be followed, by considering that for a convenient operation, the TEGs must retrieve 6 kJ per dive.

The authors believe that the TEG model developed in this work is more detailed and consistent than the one used in [15]. In [15] the thermal and electrical parts of the model are decoupled: the thermal part only considers Fourier conduction effects while the electrical part is calculated using measured data provided by the manufacturer, which implicitly includes other internal heat flow phenomena such as Peltier and Joule effects. This means that the TEG electrical power generation model in [15] includes all phenomena for a given TEG temperature difference, but the temperature difference itself is not accurately calculated as it depends on the heat transfer fluxes, which only account for the Fourier effect.

Furthermore, in [15] no heat transfer effects between sea water and