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Model of a thermal driven volumetric pump for energy harvesting in an underwater glider

J. Falcão Carneiro*, F. Gomes de Almeida

INEGI, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465, Porto, Portugal

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A B S T R A C T

Underwater gliders are one of the most promising approaches to achieve an increase of human presence in the oceans. Among existing solutions, thermal driven gliders present long range and endurance capabilities, offering the possibility of remaining years beneath water collecting and transmitting data to shore. A key component in thermal gliders lies in the process used to collect ocean's thermal energy. In this paper a new quasi-static model of a thermal driven volumetric pump, for use in underwater gliders, is presented. The study also encompasses an analysis of the influence different hydraulic system parameters have on the thermodynamic cycle efficiency. Finally, the paper proposes a simple dynamic model of a heat exchanger that uses commercially available materials for the Phase Change Material (PCM) container. Simulation results validate the models developed.

1. Introduction

In order to widen the knowledge on Earth's oceans and its underlying resources, a more persistent human presence on and under water is required. However, common techniques based on ships or buoys are currently expensive and do not allow the acquisition of data with an adequate spatial and temporal resolution. It is therefore vital to develop compact, smart and low cost devices that allow the creation of constantly monitoring networks. This scenario has led, in recent years, to an exponential increase in the number of studies involving Autonomous Underwater Vehicles (AUV) [1]. Furthermore, this trend has pushed AUV technology to evolve from concept demonstrators to commercially available products [1].

One particularly well suited type of AUV for collecting ocean data is the underwater glider. This AUV type uses buoyancy changes as propeller mean, therefore leading to very low energy consumptions. Furthermore, given its natural sawtooth trajectory profile, it allows collecting data along the water column, a fact of major importance regarding biological data acquisition [2].

Gliders were originally proposed and developed as inexpensive remote sensing systems for oceanographic purposes and have recently also been considered for sovereignty upholding tasks [3]. Data gathered by these vehicles can be used in data assimilation procedures and to calibrate circulation models, e.g. Refs. [4,5]. The energy expended by these vehicles is mostly used in buoyancy changes, and can reach as much as 80% [3] in electrically powered pumping procedures. Presently there are several proposals to tackle the problem, some aim to use the waste heat from internal systems [6], while others aim to completely remove the need for significant pre-installed energy and are based on the conversion of environmental energy, like the use of the ocean thermal gradient (OTG) [7]. There are also other types of vehicles using environmental energy like solar energy [8] or solar energy combined with a wave energy conversion mechanism [9]. The use of solar [8] or wave powered [9] devices in this context suffers a major drawback, as these devices must spend most of their time at sea surface. This means that a vehicle, in the absence of survival maneuvering capability, which has been the case for most, will be subject to storms, strong waves and winds which may lead to decreased operational life. On the contrary, collecting energy from the sea temperature differences provides a safer travelling environment since none of the above mentioned natural activity is present underwater. Within the context of autonomous vehicles, the ocean's thermal energy is typically collected by converting the volumetric expansion, or contraction, that some type of materials (Phase Change Materials, PCM) present when changing from solid to liquid phase and vice

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* Corresponding author.
E-mail address: jpbrfc@fe.up.pt (J. Falcão Carneiro).

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Notation

$(\circ)_{SL}$	variable at solidus line
$(\circ)_{LL}$	variable at liquidus line
c_{HE}	specific heat of the heat exchanger
c_{PCM}	represents the specific heat capacity of the PCM
C_{HE}	thermal capacity of the heat exchanger
C_{PCM}	thermal capacity of the PCM
$\overline{C}_{\mathrm{PCM\_}\mathbf{S}_{i,j}}$	average value of the PCM heat capacity when travelling from S_i to S_j
c_p	specific heat at constant pressure
$c_{p\_PCM,s}$	PCM specific heat at constant pressure for solid phase
$c_{p\_PCM,l}$	PCM specific heat at constant pressure for liquid phase
c_v	specific heat at constant volume
$c_{v\_PCM,s}$	PCM specific heat at constant volume for solid phase
$c_{v\_PCM,l}$	PCM specific heat at constant volume for liquid phase
CV_i	check valve i
E_{HE}	Young modulus of the heat exchanger material
K	thermal conductivity of the PCM
k_i	auxiliary variable thermal conductivity of the PCM at either solidus or liquidus lines
k_L	thermal conductivity of the PCM in the liquid phase
k_S	thermal conductivity of the PCM in the solid phase
k_{LL}	thermal conductivity of the PCM at liquidus line
k_{SL}	thermal conductivity of the PCM at solidus line
H	enthalpy of the PCM
h	specific enthalpy of the PCM
h_I	auxiliary variable: enthalpy at either solidus or liquidus lines
h_{LL}	enthalpy at liquidus line
h_{SL}	enthalpy at solidus line
L_{HE}	length of the heat exchanger tubes
M_{HE}	mass of the heat exchanger
M_{PCM}	mass of the PCM
p_{N2}^{i}	N_2 pressure at state i
p_{N2}^{max}	thermodynamic cycle maximum pressure of the PCM
$p_{oil-PCM}$	pressure at $V_{oil-PCM}$
$p_{oil-\mathrm{N2}}$	pressure at $V_{oil-\mathrm{N2}}$
p_{PCM}	PCM pressure
p_{PCM}^{max}	maximum PCM pressure
PP	auxiliary variable defining the phase of the PCM before the transition phase
p_{t}	tank pressure
Q_f	PCM the heat of fusion at atmospheric pressure
Q_{PCM_in}	heat retrieved from the surrounding water by the heat exchanger
$Q_{\mathrm{PCM\_}\mathbf{S}i,j}$	heat exchanged by the PCM with the environment when travelling from S_i to S_j
$r_{\mathrm{ext\_HE}}$	external radius of the heat exchanger cylinder
$r_{\mathrm{inter\_HE}}$	intermediate radius of the heat exchanger cylinder
$r_{\mathrm{int\_HE}}$	internal radius of the heat exchanger cylinder
$r_{\mathrm{ext\_PCM}}$	external radius of the PCM cylinder
$r_{\mathrm{inter\_PCM}}$	intermediate radius of the PCM cylinder
$r_{\mathrm{int\_PCM}}$	internal radius of the PCM cylinder
$R_{\mathrm{H20\_HE}}$	heat transfer convective resistance between water and heat exchanger
R_{HE}	total heat transfer conductive resistance of the HE
$R_{\mathrm{HE\_EXT}}$	heat transfer conductive resistance between water and T_{HE}
$R_{\mathrm{HE\_INT}}$	heat transfer convective resistance between T_{HE} and the outer layer of the PCM
R_{PCM}	total heat transfer conductive resistance of the PCM
R_{cond}	conductive heat transfer resistance
R_{conv}	convective heat transfer resistance
$\mathbf{S}$	set of possible states the PCM experiences
S	state of the PCM
S_i	state i of the PCM
S_i^*	notable state i of the PCM
$(S)^{-1}$	previous state of the PCM on the state trajectory evolution
$\mathbf{S_{i,j}}$	set of states the PCM undergoes when travelling from S_i to S_j
S_{inter}	generic intermediate state of the PCM between S_i and S_j
v_{PCM}	PCM specific volume of the PCM
V_{N2}^{0}	volume of the accumulator
V_{N2}^{min}	volume of gas at the accumulator when $p_{N2} = p_{N2}^{max}$
$V_{oil-PCM}$	volume of oil between the PCM, CV_1 and CV_2
$V_{oil-PCM}^{i}$	$V_{oil-PCM}$ at state i
$V_{oil-\mathrm{N2}}$	volume of oil between CV_1 and the accumulator bladder
V_{PCM}	volume of the PCM
V_{f}	fixed volume comprising $V_{oil-PCM}$ and V_{PCM}
t	thickness of the heat exchanger tube
t_{MTS}	minimum thickness of the heat exchanger tube according to the MTS criteria
t_{CBC}	minimum thickness of the heat exchanger tube according to the CBC criteria
T_{c}	lower ocean temperature
$T_{\mathrm{F,L}}$	temperature at which the PCM melting process ends.
$T_{\mathrm{F,S}}$	the temperature at which the PCM melting process starts
$T_{\mathrm{F,M}}$	temperature at which the middle stage of the PCM melting process is reached
T_{h}	ocean temperature on surface
T_{HE}	heat exchanger temperature at an intermediate radius
T_I	auxiliary variable: temperature at either solidus or liquidus lines
T_{LL}	temperature of the PCM at liquidus line
T_{LL}^{i}	temperature of the PCM at liquidus line when the PCM is at state i
T_{PCM}	PCM temperature (at a radius corresponding to half the total volume of the PCM cylinder)
T_{PCM}^{i}	PCM temperature at state i
T_{SL}	temperature of the PCM at solidus line
T_{SL}^{i}	temperature of the PCM at solidus line when the PCM is at state i
U	internal energy of the PCM
u	specific internal energy of the PCM
v_v	vertical velocity of the glider
z	ocean water depth
W_{N2}	work performed during the cycle over the gas accumulator
α	thermal volumetric expansion coefficient of the PCM
β_{e_oil}	effective isothermal bulk modulus of oil
Δk	absolute difference between the thermal conductivity of the PCM at solidus and liquidus lines
ΔT_t	absolute difference between T_{SL} and T_{LL}
θ	convective heat transfer coefficient between sea water and heat exchanger
κ	compressibility coefficient of the PCM
ϕ	external diameter of the heat exchanger tubes
η	efficiency of the cycle
η_{max}	maximum cycle efficiency
$\eta_{\mathrm{max\_c}}$	maximum efficiency of the thermal driven volumetric pump (Carnot corollary)