Journal of Power Sources 221 (2013) 272–283

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Modeling a hybrid Rankine-cycle/fuel-cell underwater propulsion system based on aluminum–water combustion

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HIGHLIGHTS

► Underwater propulsion using aluminum–water combustion for high energy density.
► Included SOFC for eliminating H_2 venting, improved efficiency, depth independence.
► Developed scaling methods to link thermodynamics to system energy density.
► 2.5- to 7-fold range improvement over batteries with aluminum combustor system.
► 3- to 4-fold improvement over batteries (and no H_2 venting) when SOFC is added.

ARTICLE INFO

Article history:
Received 13 June 2012
Received in revised form
26 July 2012
Accepted 30 July 2012
Available online 11 August 2012

Keywords:
Modeling
Fuel cell
Solid oxide
Aluminum
Underwater
UUV

ABSTRACT

This work investigates the integration of solid oxide fuel cells with a novel underwater propulsion system based on the exothermic reaction of aluminum with seawater. The purpose of the fuel cell is to increase the overall thermodynamic efficiency of the system and consume waste hydrogen produced by the aluminum–water reaction. The system is modeled using a NASA-developed framework, Numerical Propulsion System Simulation, by assembling thermodynamic models of components. The base aluminum–water system can increase range/endurance by factors of 2.5–7 over equivalent battery powered systems. Incorporating the fuel cell may not be beneficial when venting hydrogen overboard is permissible. However, when venting hydrogen is not permissible – which would be the situation for most naval underwater missions – the fuel cell is essential for consuming waste hydrogen and the combined combustor/fuel cell system provides a 3–4 fold increase in range/endurance compared to batteries. Methodologies for predicting how component volumes scale with power are developed to enable prediction of power and energy density. The energy density of the system is most sensitive to the efficiencies of the turbine and H_2 compressor. The ability to develop a compact and efficient isothermal hydrogen compressor is also critical to maximizing performance.

1. Introduction

The United States Navy has a growing need for advanced Unmanned Undersea Vehicles (UUVs) that can complete critical missions while keeping sailors out of harm's way. Several key naval missions including intelligence, surveillance, and reconnaissance have been identified as best performed by UUVs [1]. Underwater power and energy systems that maximize vehicle range and endurance while minimizing detectability are critical to the success of all of these missions.

1.1. Range and endurance

The range and endurance of a UUV cruising at constant speed (v_C) is given by [2]:

$$\text{Range} = \frac{\eta_p \cdot ED_V \cdot V_{sys}}{\left(\dot{W}_{PL}/_{v_C}\right) + \left(\frac{1}{2}\rho_{seawater} v_C^2\right) \cdot (C_D A_{cross})} \tag{1}$$

$$\text{Endurance} = \Delta t = \frac{\eta_p \cdot ED_V \cdot V_{sys}}{\dot{W}_{PL} + \left(\frac{1}{2}\rho_{seawater} v_C^3\right) \cdot (C_D A_{cross})} \tag{2}$$

In these expressions, $\dot{W}_{PL}$ is the payload power, C_D is the vehicle drag coefficient, A_{cross} is the vehicle cross-section area, η_p is the

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http://dx.doi.org/10.1016/j.jpowsour.2012.07.085

propulsive efficiency, V_{sys} is the total volume of the power and energy system, and ED_V is the 'effective' energy density of the power and energy system. The 'effective' energy density is the total recoverable energy available in the system divided by the total system volume (conversion system plus fuel). It is given by:

$$ED_V = \eta_t \cdot \Delta H_{V,reac} \cdot \frac{V_{reac}}{V_{sys}} \quad (3)$$

where η_t is the thermodynamic efficiency of the power and energy system, $\Delta H_{V,reac}$ is the volumetric energy density of the fuel and V_{reac}/V_{sys} is the fraction of total system volume allocated for fuel storage. This work is concerned with evaluating the aluminum combustor/SOFC system as a 'drop in' replacement for existing power and energy systems. Therefore, V_{sys} and η_p are fixed and ED_V becomes the performance parameter of primary interest in this study. Eq. (3) shows that realizing the benefits of high energy density propellants requires devising compact and efficient energy conversion systems where the energy density of the propellant is not 'consumed' by the size and inefficiency of the conversion system.

1.2. Stealth

Since many Navy missions require stealth, a propulsion system's detectability can be at least as important as its range and endurance. Many factors contribute to a vehicle's ability to avoid detection. These include its acoustic, magnetic, electric, and pressure signatures [1], its external reflective properties (radar cross-section), and any physical/chemical trails left behind in the water through which it travels. Noise generation (acoustic signature) is unavoidable in conventional propeller-driven undersea vehicles although it can be reduced through careful hydrodynamic design and the use of sound absorbing materials. Any detectable trail left by the vehicle would also be a significant problem. A primary concern is buoyant waste products vented or dumped from the vehicle that could rise to the surface leaving an easily visible and traceable path. Another concern is invisible but chemically detectable traces left in the water like elevated Al_2O_3 or H_2 concentrations.

1.3. UUV power/energy options

At present, the US Navy primarily utilizes two forms of underwater propulsion. The first is Otto fuel driven heat engines used by torpedoes like the Mk48. Otto fuel is a relatively stable liquid monopropellant which rapidly decomposes into hot gaseous products when ignited [3]. It is very effective for the torpedo's high power, short endurance mission but is not well suited for UUVs whose missions require much less propulsive power (because they travel at much lower speeds), much more electrical power for guidance, sensors, etc., must start and stop frequently, and have a need for 'stealth'. As a result, the current fleet of UUVs is battery-powered [1]. This means its range and endurance are relatively limited because the energy densities of state-of-the-art batteries are relatively low. Batteries also have long turn-around times associated with replacement and/or recharging after every mission. However, despite a battery's low ΔH_V, its conversion efficiency is very high (>95% if discharged at an adequately low rate) and the volume of the conversion system is negligible compared to the volume of the energy storage material. These factors combined with a battery's simplicity, silence, and ability to turn on and off instantly make it very attractive in underwater systems.

There have been attempts over the years to construct systems that could supplant batteries. These efforts have investigated various types of fuel cells (including solid-oxide [4], direct borohydride [5], etc.) as well as strategies for storing energy dense reactants like hydrocarbon fuels [4], oxygen-dense compounds [6], and cryogenic liquid O_2 [7]. The lower portion of Table 1 shows energy densities of 'conventional' fuel and oxidizer systems as well as Otto fuel [3] and batteries [5,8,9]. Air is excluded as an oxidizer because it is not available in the underwater environment. H_2 and O_2 are assumed to be stored in their liquid states. The data show that the overwhelming energy density advantage enjoyed by liquid hydrocarbons in air-breathing systems disappears entirely when oxidizer must be included in the propellant mass/volume.

A promising alternative to battery-based energy storage that has been investigated since the early 1960s is metals that react exothermically with seawater [3]. Such systems offer advantages similar to those enjoyed by air-breathing engines where the oxidizer is harvested from the vehicle's surroundings and does not need to be stored on board. Many metals have been investigated over the years including aluminum [10] and lithium [11]. The top portion of Table 1 summarizes the energy content of various metal fuel/oxidizer systems. Other high energy density propellant combinations like boron-water and beryllium-water are excluded from the list for reasons of cost and/or toxicity [12]. Unlike aircraft where lift-induced drag makes vehicle weight a key restriction, underwater vehicles are primarily influenced by skin drag and form drag (both heavily dependent on the vehicle's physical dimensions) [13]. Therefore, energy content on a 'per volume' basis is the primary consideration for the underwater environment. The lithium–water reaction rates highly on a 'per mass' basis, but the low density of lithium results in poor 'per volume' performance. Similarly, combinations with hydrogen fuel have high 'per mass' energy content but are not ideally suited for underwater use because of hydrogen's extremely low density (even in liquid form).

Table 1 shows that the aluminum–water reaction (Eq. (4)) provides the largest heat release per unit volume and therefore is most suitable for underwater applications.

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2; \quad \Delta H = -409\ \mathrm{kJ/mol_{AL}} \quad (4)$$

The energy content of this reaction relative to batteries suggests that improvements in range/endurance of an order of magnitude or more are thermodynamically possible provided suitably compact and efficient energy conversion systems can be devised.

Table 1
Energy content of various undersea reactant combinations.

Fuel	Oxidizer	Specific energy (W h kg^{-1})	Energy density, ΔH_V (W h L^{-1})
Al	H_2O	4212	11,374
Zr	H_2O	1611	10,503
Al	$LiClO_4$	3523	8898
Mg	H_2O	3609	6273
Li	H_2O	7969	4256
H_2	O_2	3728	1535
H_2	H_2O_2	2280	1551
C_XH_Y	O_2	2730–2790	2300–2800
C_XH_Y	H_2O_2	1840–1870	2100–2500
$NaBH_4$	O_2	3470	3869
$NaBH_4$	H_2O_2	2377	3224
CH_3OH	O_2	2214	2147
Otto fuel [3]		705	895
Li-ion batteries [5,8]		90–130	180–315
Alkaline batteries [9]		110–200	150–270
Pb-acid batteries [9]		70–120	30–60