A novel power system for thermal underwater gliders with PEMFC

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Abstract. Underwater gliders are effective buoyancy-driven vehicles for sea sampling tasks because they are inexpensive, reusable and achieve a high duration. In all kinds of them, the thermal underwater glider which is propelled by a thermal engine has better performance. But the properties of thermal material and ocean conditions limit the thermal glider’s behaviour. A cogeneration power system for the thermal underwater glider was developed in this work. A PEMFC-thermal engine cogeneration power system was used to improve the performance of the thermal engine. Experiments of the prototype indicate that the power system proposed can promote the flexibility and adaptability of the thermal glider. When the PEMFC operates at 400 mA cm⁻² current density, the heat from the PEMFC is able to make thermal material have a 12.64% volume change. Meanwhile the heat can provide up to 2.05 MPa pressure in the accumulator of the thermal engine, which assures the underwater glider to navigate in all seas.

1. Introduction
Multiple researches and developments have been conducted since 1989 when the first proposal for this concept was publicized by Henry Stommel, as a novel instrument of oceanography research that can traverse large areas with minimal use of energy [1]. Buoyancy is used as their primary means of propulsion. Wings on the glider produce a lift force that acts perpendicular to its glide path and allows the glider to convert buoyancy into horizontal translation.

There are typically two types of underwater gliders depending on the power sources for the buoyancy engines: electrical underwater glider and thermal underwater glider. The underwater gliders in service or test are Slocum [2][3, 9] (by Webb Research Corporation), Spray [4] (by Scripps Institution of Oceanography), Seaglider [5] (by Washington University) and Petrel [10] (by Tianjin University).

The electric underwater glider, though being effective for most sea sampling tasks, still possesses some limitations. One is the battery capacity that limits the navigation range and duration [6]. The other is the “vapor lock” effect of the electrical buoyancy engine, which may fail to produce buoyancy change [7].

The conventional thermal underwater glider, on the other hand, is propelled with the thermal engine that changes the buoyancy through the volume change of the working fluid (namely thermal material) in heating or cooling, as shown in Fig. 1 [2]. The thermal engine is powered by the thermal gradient of the ocean, which makes the thermal underwater glider have 3–4 times navigation capacity of a similar electric underwater glider [2, 6]. But the temperature difference between the surface and the deeps of sea must be greater than 10 °C, which limits the navigation regions of the glider [4]. In
addition, the thermal underwater glider has to float on sea surface for hours to wait for the thermal material heated by warm seawater.

Figure 1. Principle and work cycle of the thermal engine.
(a) The glider floats on the surface of sea. The Nitrogen in the accumulator keeps compressed. The working fluid is in liquid state; (b) The 3-way valve is switched on between the external bladder and the internal bladder. Then the external bladder is vented to the internal bladder. The glider will descend. When the glider descends below the thermocline, the working fluid will be cooled to solid and shrink to inhale the transfer fluid into the energy exchanger; (c) The glider has descended to the set depth. The 3-way valve is switched on between the external bladder and the accumulator, and the transfer fluid in the accumulator is compelled into the external bladder via the compressed Nitrogen. The glider will ascend; (d) When the glider ascends above the thermocline, the working fluid will be heated and expand to compel the transfer fluid into the accumulator. The Nitrogen is then compressed. Meanwhile the external bladder keeps filled and expanded.

To improve the performance of the thermal engine, the authors have proposed a PEMFC-thermal engine cogeneration power system for thermal underwater glider [8]. The PEMFC-thermal engine uses the heat from a PEMFC stack to drive the thermal engine for navigation while the PEMFC stack provides electricity for the sensors, control system and control actuators of the glider.

2. Power demands of thermal underwater glider
The power consumption analysis of thermal underwater glider is carried out by taking Petrel [10] as a reference.

The typical net buoyancy change of Petrel is 10 N (-5 N net buoyancy for descent, and +5 N net buoyancy for ascent) [10], equivalent to a volume change of about 1000mL. Taking hexadecane as the thermal material, the thermal engine will need 10 L of hexadecane and about 1155 kJ of latent heat and additional sensible heat of 1358 KJ for heating or cooling the thermal material to produce the designated buoyancy change according to the properties of hexadecane (Table 1). For thermal underwater glider with the cogeneration power systems, the thermal energy for heating the thermal
material is provided by the PEMFC instead of the thermal gradient between the surface and deeps of sea.

| Density  | Velocity | Specific latent heat of fusion | Specific heat capacity | Rate of volume change of solid-liquid phase transformation |
|----------|----------|-------------------------------|------------------------|----------------------------------------------------------|
| (g cm⁻³) | (ms⁻¹)   | (kJ kg⁻¹)                     | [kJ (kg K)⁻¹]          | (%)                                                      |
| 0.77     | 16-18    | about 150                     | about 1.89             | about 10                                                 |

3. The cogeneration power system
The control actuators generally are of large power load and operate shortly, which produces intermittent high peak electrical loads to the PEMFC. Therefore, the PEMFC of the PEMFC-thermal engine has to be designed and operate to meet the peak electrical power loads. This will result in excessive capacity and fuel consumption of the PEMFC. An auxiliary energy storage system will complement such drawbacks of the PEMFC-thermal engine power system, as in the hybrid power system of electric vehicles, where the auxiliary energy storage system charges during low power demands and discharges during high power demands.

4. Prototype and experiments of the cogeneration power system

4.1. A subsection Configuration of the prototype
To validate the concept of the cogeneration power system, we constructed a functional prototype of the system. Commercial PEMFC stack of 12 V rated voltage and 100 W rated power. The effective area of the Nafion112 membrane of the PEMFC is 32 cm². The flow rate of the pump of the cooling circulations of the PEMFC is set to 5 L min⁻¹. The pressure of the reaction gases (H₂ and O₂) is set to 0.3 MPa. The reaction gases are humidified to 100% by a dew humidifier through water in the cooling circulations of the PEMFC. The PEMFC is cooled through the ‘internal’ cooling circulation to heat the thermal material or through the ‘external’ cooling circulation to transfer the heat to environment (Fig. 2).

![Diagram](http://example.com/fig2.png)

(a) Heat transfer circulation during ‘descending’ (‘external’ cooling circulation of PEMFC and cooling circulation of the thermal engine).

(b) Heat transfer circulation during ‘ascending’ (‘internal’ cooling circulation of PEMFC as heating circulation of the thermal engine).

Figure 2. Heat transfer circulations of the prototype.

4.2. Performance of the Prototype
Fig. 3 shows the temperature change of the PEMFC system, which demonstrates that the electrical current density has dominant influence on the temperature of the PEMFC. The temperature at the
outlet of the cooling circulation of the PEMFC is 36 °C, 46 °C and 58 °C at a current density of 200 mA cm⁻², 300 mA cm⁻² and 400 mA cm⁻², separately. Considering the melting point 16–18 °C of the thermal material, the cogeneration power system is thus able to provide effective and stable heat for the thermal engine.

![Temperature change of the cooling water at the outlet of the cooling circulation on the PEMFC stack under different current density.](image)

5. Conclusions
In this work, a cogeneration power system is developed to ensure the applicability of the thermal underwater glider to all seas. The PEMFC in the cogeneration power system significantly makes the power system compact, efficient, and adaptable to the fluctuating electrical power demand of the glider.

Experiments of the prototype indicate that the heat from the PEMFC is able to produce 12.64% volume change of the thermal material and 2.05 MPa pressure in the accumulator of the thermal engine when the PEMFC operates at 400 mA cm⁻² current density, which assures the underwater glider to navigate in all seas.

Further works will be the optimal design of the cogeneration power system and development of the newly powered underwater glider.

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References
[1] Stommel, H. (1989). The slocum mission. Oceanography, 2(1), 22-25.
[2] Webb, D. C., Simonetti, P. J., & Jones, C. P. (2001). SLOCUM: An underwater glider propelled by environmental energy. IEEE Journal of oceanic engineering, 26(4), 447-452.
[3] Jenkins, S. A., Humphreys, D. E., Sherman, J., Osse, J., Jones, C., & Leonard, N., et al. (2003). Underwater glider system study. Scripps Institution of Oceanography.
[4] Sherman, J., Davis, R. E., Owens, W. B., & Valdes, J. (2001). The autonomous underwater glider" Spray". IEEE Journal of Oceanic Engineering, 26(4), 437-446.
[5] Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., ... & Chiodi, A.
M. (2001). Seaglider: A long-range autonomous underwater vehicle for oceanographic research. IEEE Journal of oceanic Engineering, 26(4), 424-436.

[6] Davis, R. E., Eriksen, C. C., & Jones, C. P. (2002). Autonomous Buoyancy-Driven Underwater Gliders. The Technology and Applications of Autonomous Underwater Vehicles, chapter 3.

[7] Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., & Perry, M. J. (2004). Underwater gliders for ocean research. Marine Technology Society Journal, 38(2), 73-84.

[8] Wang, S., Xie, C., Wang, Y., Zhang, L., Jie, W., & Hu, S. J. (2007). Harvesting of PEM fuel cell heat energy for a thermal engine in an underwater glider. Journal of power sources, 169(2), 338-346.

[9] Jones, C., Allsup, B., & Webb, D. Slocum glider expanding the capabilities.

[10] Jianguo, W., Minge, Z., & Xiujun, S. (2011). Hydrodynamic characteristics of the main parts of a hybrid-driven underwater glider PETREL. In Autonomous Underwater Vehicles. InTech.