Model of thermal underwater gliders with PEMFC

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Abstract. In all kinds of underwater gliders, 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 is used to improve the performance of the thermal engine. This glider uses the heat from a Proton Exchange Membrane Fuel Cell (PEMFC) stack for the Phase Change Material (PCM) to drive the thermal engine for navigation while the PEMFC stack provides electricity for the sensors, control system and control actuators of the glider. The multi-functionality assures the underwater glider to navigate in all seas. Thus, this work presents a mathematical model and a thermodynamic model of the PEMFC-thermal glider on the basis of several assumptions. A Newtonian approach has been used to model the glider under the influence of water current.

1. Introduction
Widening the knowledge on Earth's oceans is not only scientifically relevant, but also crucial to human activities through its influence on climate, and as a supplier of natural resources, fishing, tourism and recreation. An efficient underwater platform needs to be developed as a tool for exploring the oceans resources and monitoring the oceans activities. Many researches and developments have been conducted since 1989 when the first “glider” concept was proposed by Henry Stommel [1]. The energy expended by these gliders is mostly used in buoyancy changes, and can reach as much as 80% [2] in electrically powered pumping procedures. It was developed as inexpensive remote sensing systems for oceanographic purposes and has recently also been considered for sovereignty upholding tasks [2].

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 [3]. The other is the “vapor lock” effect of the electrical buoyancy engine, which may fail to produce buoyancy change [4]. There are also other types of gliders using environmental energy like solar energy [5] or solar energy combined with a wave energy conversion mechanism [6]. The solar or wave powered devices must spend most of their time at sea surface which means that a glider 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 because none of the natural activities mentioned above exits underwater [7].

The conventional thermal underwater glider is propelled with the thermal engine that changes the buoyancy through the volume change of some type of materials (Phase Change Materials, PCM) present when changing from solid to liquid phase in heating and vice versa in cooling. 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 [3,8].
But the temperature difference between the surface and the deeps of sea must be greater than a certain value, which limits the navigation regions of the glider [3]. In addition, the thermal underwater glider has to float on sea surface until the thermal material heated by warm seawater. To improve the performance of the thermal engine, this paper proposes a PEMFC-thermal engine cogeneration power system for thermal underwater glider [9], as shown in Fig. 1.

Figure 1. Sketch-map of the PEMFC-thermal glider.

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 [9]. PEMFC converts chemical energy into electrical and thermal energy by consuming hydrogen-rich fuel and oxidant. 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. Mathematical model of PEMFC-thermal glider

2.1. Glider configuration

The configuration of the PEMFC-thermal glider and its components is critical because of the complexity of the design. In addition, effective configuration could further increase the glider's efficiency [10]. Fig. 2(a) shows the glider's configuration by Solidworks™. There are four important masses to the glider's configuration whose configuration will affect the glider's attitude. These masses can be divided into two types of mass: a fixed mass and a variable mass. Note $m_h$ as the hull mass, $m_p$ as the internal sliding mass, and $m_r$ as the internal roll mass, which are fixed masses. However, the internal sliding mass can change its position to control the pitch angle by a gravitational moment according to its distance. In addition, the internal rolling mass can change its position to control the roll angle by a gravitational moment according to its angle. On the other hand, the external bladder mass $m_{eb}$ is a variable mass with a fixed position. This mass is used to control the net buoyancy of the glider by alternately constricting and expanding the displaced volume. Therefore, the net buoyancy is defined as

$$m_0 = (m_h + m_p + m_r + m_{eb}) - m$$ (1)
Where \( m = \rho \Delta V \) is the mass of seawater displaced. The notation \( \rho \) represents the water density, which was set as \( 1 \times 10^3 \text{kg/m}^3 \), and \( \Delta V \) is the volume of the glider's body.

\[
\begin{align*}
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\end{align*}
\]

Figure 2. The configuration of the PEMFC-thermal glider.
1. Attitude adjustment module; 2. Body module; 3. PEMFC-Thermal engine module; 4. Control and navigation module; 5. Sensor and measurement module

In order to model the glider mathematically, we need to define the reference frames first. It is convenient to define two reference frames: the inertial frame and the body reference frame. Fig. 2(a) shows the glider and the reference frame. The inertial frame is considered to be a fixed frame, where the horizontal axes of X and Z are perpendicular to the gravity, and the Y axis is stretched in the negative direction of the gravity vector. On the other hand, the body reference frame, also known as a moving frame, coincides with the center of buoyancy (B), which is located at the geometric center of the glider’s hull. The x is the longitudinal axis, which lies in the direction from tail to the nose. The y is directed from bottom to top, which is also known as the normal axis, and the z is the transversal axis located on the star board side of the glider.

2.2. Equation of motion of the glider

The following assumptions are chosen when modeling the glider:

1. The glider is symmetrically through its longitudinal body coordinate planes.
2. The mass moment of inertia of the glider about the \( z \)-axis remains constant.
3. The glider is assumed to travel only in the vertical \( x-y \) plane in Fig. 2(b) with no yaw moment. As a result, hydrodynamic effects such as side force are neglected in the model.
4. The added mass of accelerating fluid during unsteady glider motion is assumed to be ignorable.

The center of gravity (G) of the glider is located slightly under the center of buoyancy (B). Fig. 2(b) shows these two important parameters defined as \( r_G = [x_G, y_G, z_G]^T \) and \( r_B = [x_B, y_B, z_B]^T \) correspondingly. The position of the glider relative to the inertial frame is defined as \( \vec{r} = [\epsilon, \rho] \), where \( \epsilon = [x, y, z]^T \) is its position, and \( \rho = [\varphi, \theta, \psi]^T \) is its vector of Euler angles. The velocity of the glider is denoted as \( \dot{V} = [\Sigma, \Omega] \), where \( \Sigma = [u, v, w]^T \) is its linear velocity, and \( \Omega = [p, q, r]^T \) is its angular velocity.

We can change the position of the glider from the inertial frame to the body frame in the following way. The body frame axes are first rotated by a yaw angle, \( \theta \) about \( y \), which yields a new body frame. This new frame is then rotated by a pitch angle, \( \psi \) about \( z \). At the end, the new body frame obtained from the second rotation is then rotated by a roll angle, \( \varphi \) about \( x \), which can be denoted as the following rotation matrix:

\[
C_B = \begin{bmatrix}
\cos \theta \cos \psi & \sin \theta & -\cos \theta \sin \psi \\
-sin \theta \cos \psi & \cos \theta & \sin \theta \sin \psi + \cos \psi \sin \theta \\
\sin \theta \cos \psi + \sin \psi & -\cos \theta \sin \psi & \cos \psi \sin \theta
\end{bmatrix}
\] (2)

At the initial state the glider is steady since its gravity equals to its buoyancy. In the body reference, they are defined respectively as


\[ \mathbf{F}_G = \mathbf{C}_B^E \begin{bmatrix} 0 \\ -G \\ 0 \end{bmatrix} = \mathbf{G} \begin{bmatrix} -\sin \theta \\ -\cos \theta \cos \varphi \\ \cos \theta \sin \varphi \end{bmatrix} \] (3)

\[ \mathbf{F}_B = \mathbf{C}_B^E \begin{bmatrix} 0 \\ B_{w0} \\ 0 \end{bmatrix} = B_{w0} \begin{bmatrix} -\sin \theta \\ -\cos \theta \varphi \\ \cos \theta \sin \varphi \end{bmatrix} \] (4)

In fact, the center of gravity (G) does not coincide with the center of buoyancy (B). Thus, there is a righting moment \( \mathbf{r}_G \) to keep the glider in balance. Because the body reference frame coincides with the center of buoyancy (B), the position in the body reference frame for the center of gravity (G) is \( \mathbf{r}_G = (0, -y_G, 0)^T \).

So, the moment of gravity to the body-frame origin is defined as

\[
\mathbf{r}_G \times \mathbf{F}_G = \mathbf{G} \begin{bmatrix} 0 \\ -y_G \\ 0 \end{bmatrix} \times \begin{bmatrix} -\sin \theta \\ -\cos \theta \cos \varphi \\ \cos \theta \sin \varphi \end{bmatrix} = -Gy_G \begin{bmatrix} \cos \theta \cos \varphi \\ 0 \\ \sin \theta \end{bmatrix}
\] (5)

Since the volume of external bladder is variable, the changeable buoyancy system creates additional buoyancy \( \Delta \mathbf{B} = \Delta \mathbf{BY} \) in the inertial frame.

Then, it is transformed to the body frame origin which defined as

\[
\Delta \mathbf{B} = \mathbf{C}_B^E \begin{bmatrix} 0 \\ \Delta \mathbf{B} \\ 0 \end{bmatrix} = \begin{bmatrix} \Delta B \sin \theta, \Delta B \cos \theta \cos \varphi, -\Delta B \cos \theta \sin \varphi \end{bmatrix}^T
\] (6)

In the body frame, the center of additional buoyancy is \( \mathbf{R}_{\Delta B} = [l_{\Delta B}, 0, 0]^T \).

Thus, the moment of additional buoyancy to the body-frame origin is denoted as

\[
\mathbf{M}_{\Delta B} = \mathbf{R}_{\Delta B} \times \Delta \mathbf{B} = \begin{bmatrix} 0, \frac{\Delta B \ell \sin \varphi}{2}, -\frac{\Delta B \ell \cos \theta \sin \varphi}{2} \end{bmatrix}^T
\] (7)

Then, the force and moment of the buoyancy system to the glider can be noted as

\[
(\Delta \mathbf{B}, \mathbf{M}_{\Delta B})^T = \begin{bmatrix} \Delta B \sin \theta, \Delta B \cos \theta \cos \varphi, -\Delta B \cos \theta \sin \varphi, 0, \ell \sin \varphi, -\ell \cos \theta \sin \varphi \end{bmatrix}^T
\] (8)

When the internal sliding mass move a distance, the whole mass isn’t changed, so the additional moment by \( m_p \) \( \mathbf{M}_p = \mathbf{R}_p \times \mathbf{G}_p \). In the body frame, the gravity of \( m_p \) is denoted as

\[
\mathbf{G}_p = \mathbf{C}_B^E \begin{bmatrix} 0 \\ -G_p \\ 0 \end{bmatrix} = \begin{bmatrix} G_p \sin \theta, -G_p \cos \theta \cos \varphi, -G_p \cos \theta \sin \varphi \end{bmatrix}^T
\] (9)

The position of \( m_p \) can be defined as \( \mathbf{R}_p = [l_p, 0, 0]^T \).

Then, the additional moment by the internal sliding mass is

\[
\mathbf{M}_p = \mathbf{R}_p \times \mathbf{G}_p = G_p \begin{bmatrix} 0, \ell \sin \varphi, -\ell \cos \theta \sin \varphi \end{bmatrix}^T
\] (10)

Similarly, when the internal rolling mass rotates at an angle of \( \delta \), it can create an additional moment

\[
\mathbf{M}_r = \begin{bmatrix} G_r \ell \sin \delta, 0, 0 \end{bmatrix}^T
\] (11)

Thus, the pitching and rolling moment of the attitude adjustment system to the glider is noted as

\[
\left( \begin{array}{c}
\mathbf{F}_a \\
\mathbf{M}_a
\end{array} \right) = \left( \begin{array}{c}
\mathbf{0} \\
\mathbf{M}_p
\end{array} \right) + \left( \begin{array}{c}
\mathbf{0} \\
\mathbf{M}_r
\end{array} \right) = \left( \begin{array}{c}
0 \\
0 \\
0 \\
0 \\
\Delta l_p \cos \theta \sin \varphi \\
\Delta l_p \cos \theta \cos \varphi \\
0 \\
0 \\
G_r \ell \sin \delta \\
0 \\
0 \\
0 \\
\Delta l_p \cos \theta \sin \varphi \\
\Delta l_p \cos \theta \cos \varphi
\end{array} \right) = \left( \begin{array}{c}
0 \\
0 \\
0 \\
\Delta l_p \cos \theta \sin \varphi \\
\Delta l_p \cos \theta \cos \varphi
\end{array} \right)
\] (12)
3. Thermodynamic model of the PEMFC-thermal glider

3.1. Overall view of the system
The heat transfer circulation in this work is depicted in Fig. 3. It includes an energy exchanger that contains the PCM, which can absorb the heat from PEMFC and release the heat to the cold seawater. Two heat exchangers are within two wings separately in contact with the Ocean. The heat exchanger is typically implemented using several long tubes [8]. The PCM volumetric expansion or contraction can pressurize or depressurize the oil of the hydraulic circuit that includes an accumulator to store retrieved energy. A bladder type accumulator has been considered for energy storage, containing gas, for instance nitrogen (N₂).

(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 3. Heat transfer circulation of the PEMFC-thermal glider.

3.2. Equation of energy of the glider
Fig. 4 shows the thermodynamic model of the PEMFC-thermal glider.

![Thermodynamic model diagram](image)

Figure 4. The thermodynamic model of the PEMFC-thermal glider.
According to the mass conservation equation and the first law of thermodynamics, mass and energy of input and output of the heat transfer circulation must follow \( \sum M_{in} = \sum M_{out} \) and \( \sum E_{in} = \sum E_{out} \) respectively. Then the mass equation and the energy equation of the PEMFC-thermal glider are defined as bellow

\[
\begin{align*}
    m_{H_2,in} - m_{H_2,out} - m_{H_2,consume} &= 0 \\
    m_{O_2,in} - m_{O_2,out} - m_{O_2,consume} &= 0 \\
    m_{H_2,consume} + m_{O_2,consume} - m_{H_2O,product} &= 0 \\
    m_{\text{humidifying}-H_2O,in} - m_{\text{humidifying}-H_2O,out} &= 0 \\
    m_{\text{cooling}-H_2O,in} - m_{\text{cooling}-H_2O,out} &= 0 \\
    m'_{\text{cooling}-H_2O,in} - m'_{\text{cooling}-H_2O,out} &= 0 \\
    m_{\text{cooling}-H_2O,out} - m_{\text{cooling}-H_2O,in} &= 0 \\
    (\sum H_{in} - \sum H_{out}) - W_{\text{electricity}} - Q &= 0 \\
    Q &= Q_{\text{cooling}} + Q_{\text{evaporation}} + Q_{\text{radiation}} \\
    W_{\text{electricity}} &= (Q'_{PCM} + Q'_{\text{phase change}}) \cdot \eta_{TE-recover}
\end{align*}
\] (13)

\[
\begin{align*}
    Q_{\text{cooling}} &= Q' = Q_{PCM} + Q'_{\text{phase change}} + Q'_{\text{radiation}} \\
    W_{\text{electricity}} &= (Q'_{PCM} + Q'_{\text{phase change}}) \cdot \eta_{TE-recover}
\end{align*}
\] (14)

4. 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 and efficient. A mathematical model and a thermodynamic model of the PEMFC-thermal glider are proposed on the basis of several assumptions.

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

Acknowledgments

The work reported here is sponsored by the Science and Technology Program of Weihai, China under grant No. 2016GGX008-3. The authors gratefully acknowledge the supports.

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