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Harvesting of PEM fuel cell heat energy for a thermal engine in an underwater glider

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Abstract

The heat generated by a proton exchange membrane fuel cell (PEMFC) is generally removed from the cell by a cooling system. Combining heat energy and electricity in a PEMFC is highly desirable to achieve higher fuel efficiency. This paper describes the design of a new power system that combines the heat energy and electricity in a miniature PEMFC to improve the overall power efficiency in an underwater glider. The system makes use of the available heat energy for navigational power of the underwater glider while the electricity generated by the miniature PEMFC is used for the glider's sensors and control system. Experimental results show that the performance of the thermal engine can be obviously improved due to the high quality heat from the PEMFC compared with the ocean environmental thermal energy. Moreover, the overall fuel efficiency can be increased from 17 to 25% at different electric power levels by harvesting the PEMFC heat energy for an integrated fuel cell and thermal engine system in the underwater glider.

Keywords: Energy harvesting; Miniature PEMFC; Underwater glider; Thermal engine

1. Introduction

Proton exchange membrane fuel cells (PEMFC) produce heat in the process of generating electricity due to the irreversible electrochemical reactions and polarizations. This heat is usually 40–60% of the total chemical energy which is generally viewed as waste heat and expelled from the cell for the sake of safety and stability [1,2]. For high temperature fuel cells such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), or large-scale PEMFC and phosphoric acid fuel cells (PAFC), the heat energy can be recycled to improve the fuel efficiency by generating electricity or utilizing heat directly [3–7]. However, for a miniature PEMFC, the low temperature (about 60 °C) and the limited amount of heat make recycling of reaction heat difficult. A power system design that uses both the electricity of the miniature PEMFC and the heat energy would not only resolve the problem of thermal management, but also improve the fuel efficiency. This paper describes a power system for an underwater glider that makes use of reaction heat of the PEMFC as the inner heat source of the thermal engine so as to realize the integration of heat and electricity for the fuel cell, while the miniature PEMFC produces electricity for the sensors and control system of the glider. In this way, the thermal engine can convert the heat from the PEMFC into pressure energy, which is utilized to change the buoyancy of the glider in order to ascend form deep sea to surface. Laboratory experiments show that this new power system should be available for the needs of thermal and electrical loads in the glider and the heat-to-power (electricity) ratio of the PEMFC can be effectively altered under a variety of operating conditions beside the resistance heaters to satisfy the requirement of different navigational performance. Moreover, the overall power efficiency of the underwater glider can be greatly improved by the harvesting the PEMFC heat energy for the thermal engine application.

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2. Background

2.1. Fuel cell

A fuel cell is a device that directly converts chemical energy into electrical and thermal energy under isothermal conditions by consuming hydrogen-rich fuel and oxidant [8]. In the PEMFC, hydrogen flowing along a gas channel at the anode is mostly ionized into hydrogen ions under the action of a catalyst where electrochemical reactions take place. Hydrogen and oxygen are rigorously separated by a membrane through which hydrogen ions can easily pass while electrons travel around the external circuit from the anode to the cathode producing useful electrical energy. At the cathode, oxygen combines hydrogen ions and electrons into water with heat as a by-product. Electrochemical reactions for the anode and cathode are shown in Fig. 1 for a hydrogen–oxygen PEMFC.The total reaction is characterized as:

$$H_2 + O_2 \rightarrow H_2O\,(l) + \Delta H \tag{1}$$

where ΔH is the enthalpy change due to the electrochemical reaction of hydrogen and oxygen in a PEMFC. The total chemical energy that is released by the reaction is divided into electrical and thermal components. In practice, the total chemical energy is never completely utilized because of thermodynamic irreversibility including heat transfer, friction, mixing, chemical reaction and different polarizations [9]. Theoretically, the maximum PEMFC efficiency η_{max} can be determined as follows [10]:

$$\eta_{max} = \frac{\Delta G}{\Delta H} = 1 - \frac{T\,\Delta S}{\Delta H} \tag{2}$$

where ΔG is the Gibbs free energy change which describes the maximum energy including both electricity and heat, $T\,\Delta S$ is the irreversible entropy change due to thermodynamic irreversibility. Thermodynamic irreversibility results in lower voltage and lower fuel efficiency because the heat produced must be removed from the cell to prevent the membrane from dehydration and overheating. Therefore, thermal management is an important issue for PEMFC safety and stability. Waste heat should be properly managed with cooling channels in the stack, where the coolant cycles and carries waste heat to the heat exchanger continuously in order to maintain the isothermal condition for the PEMFC.

2.2. Underwater glider and thermal engine

As an underwater vehicle, an autonomous underwater glider can take a variety of sensors to perform long-duration measurements. The glider takes in and expels water to change its buoyancy to cycle vertically in the ocean and uses small wings in cooperation with the position adjustment of center of gravity to convert this vertical velocity into forward motion [11]. Underwater gliders can be divided into electric gliders and thermal gliders depending on the power sources they use [12,13]. Figs. 2a and 2b show the typical electric and thermal gliders respectively.

Electric gliders powered by electrical buoyancy engines have proven to be very reliable through many sea experiments. However, the battery capacity (lithium or alkaline batteries) limits the duration and range of navigation. Moreover, electric gliders with large operating depths usually adopt reciprocating pumps as buoyancy engines. The reciprocating pump is sensitive to "vapor lock" while it pressurizes the working fluid into the external bladder in order to increase the buoyancy of the glider. Sometimes the work fluid cannot be pressurized at all, because a pump cylinder filled with gas released from the work fluid has an insufficient compression ratio for the pump [11].

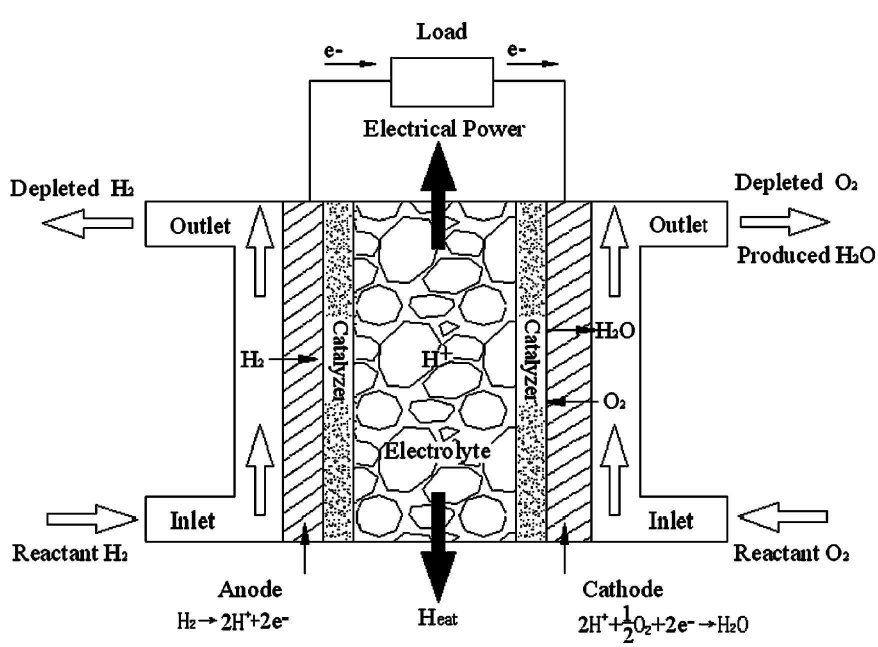

Fig. 1. Electrochemical reactions in a hydrogen–oxygen PEMFC.

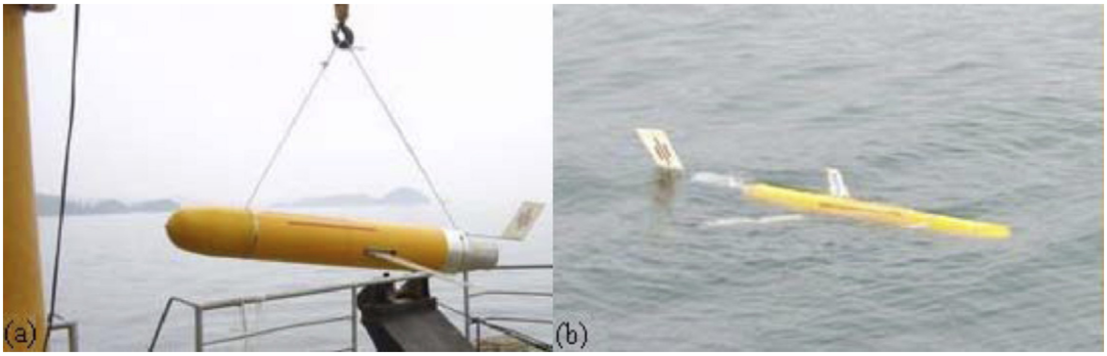

Fig. 2. The typical electric and thermal gliders: (a) an underwater glider powered by electricity; (b) an underwater glider powered by a thermal engine. Both have similar appearance except for the power source.

Considering the limitations of battery powered electric gliders, Webb Research Corporation was the first to design a thermal glider, SLOCUM, using propulsion energy harvested from the thermocline successfully. Different from electric gliders, thermal gliders use thermal engines as the buoyancy engine that utilizes ocean thermal energy to change the buoyancy of the gliders through contraction and expansion of the thermal material [14,15].

The principle of a thermal engine is described as follows [15]: while the glider descends into the cold deep seawater due to the working fluid transfer from the external bladder to the internal bladder, heat flows out of the thermal material inside the thermal engine and the thermal material contracts as it freezes while part of working fluid is inhaled into the thermal engine from the internal bladder. When the glider ascends to the sea surface with inflated external bladder, heat from the warm surface seawater flows into the thermal material. The thermal material expands as it melts while the inhaled working fluid is pressurized into the accumulator. In this way, the thermal engine converts thermal energy from the environment to pressure energy saved in the accumulator in order to release it to the external bladder as propulsion power when the glider ascends from the deep seawater next time. Thus, the thermal engine recovers the original state and prepares it for the next work circulation.

Instead of using batteries, the use of environmental energy for the thermal engine powered gliders extends the duration and the range of the navigation. However, gliders powered by thermal engines also have limitations. The most important one is that the temperature gradient of the ocean profile cannot be available in all areas of the sea [15]. A minimum temperature difference of 10 °C between surface and depth temperatures is generally needed for thermal gliders SLOCUM [15] to function effectively. Thus, navigational range of thermal gliders is restricted by ocean environment conditions.

3. A new PEMFC-thermal engine

As a power conversion device, the PEMFC has been used in various underwater vehicles such as AUV DeepC and AUV Urashima. This is due primarily to its high conversion efficiency, high power density, low operating temperature, fast start-up and responsiveness to load changes [16–19]. The underwater application of PEMFCs achieves miniaturization of power system and long endurance time compared with other batteries [17]. However, the thermal energy from PEMFC is viewed as the waste heat and removed from the cells, which causes the low fuel efficiency in underwater vehicles.

Although the thermal engine is a good choice for utilizing ocean thermal energy to power the underwater glider, it is unstable and subjected to the environmental conditions at sea. Hence, the desirability of integrating a PEMFC with a thermal engine exists, which will be called PEMFC-thermal engine (PTE), in the remainder of the paper. A PTE combines heat and electricity of a fuel cell in the underwater glider by making use of available thermal energy from the PEMFC to heat the thermal engine in order to improve the performance of the thermal engine and the overall fuel efficiency, resulting in a more efficient and stable power source for the underwater glider. The overall performance of the system depends both on the performances of the individual subsystems and the coupling interaction between the two. The principle of the PTE power system is shown in Fig. 3 and is described as follows.

a. The control system of the glider opens the three-way valve and transfers working fluid from the external bladder to the work cavity I under sea pressure (Fig. 3a). The glider begins to descend from the warm seawater due to the negative buoyancy. The PEMFC is cooled by circulation of fluid through an external heat exchanger at this time.
b. The thermal engine is cooled naturally by dumping this heat to the glider's environment as it descends toward deep-sea cold water (Fig. 3b). The thermal material in the thermal engine freezes and contracts gradually. Working fluid transfers from work cavity I to the thermal engine. Pressure in work cavity I is reduced to a partial vacuum again. Cooling of the PEMFC is continued by circulation of fluid through the external heat exchanger.
c. Once the glider reaches the design depth (Fig. 3c), the three-way valve opens allowing pressurized working fluid in work cavity II to move to the external bladder. The glider ascends owing to the buoyancy changing from negative to positive. But PEMFC remains inactive.
d. PEMFC heats the thermal engine through the inner circulation shown in Fig. 3d. The thermal material begins to melt and expand at the time the two-way valve opens. As working fluid flows into work cavity II, thermal energy is changed

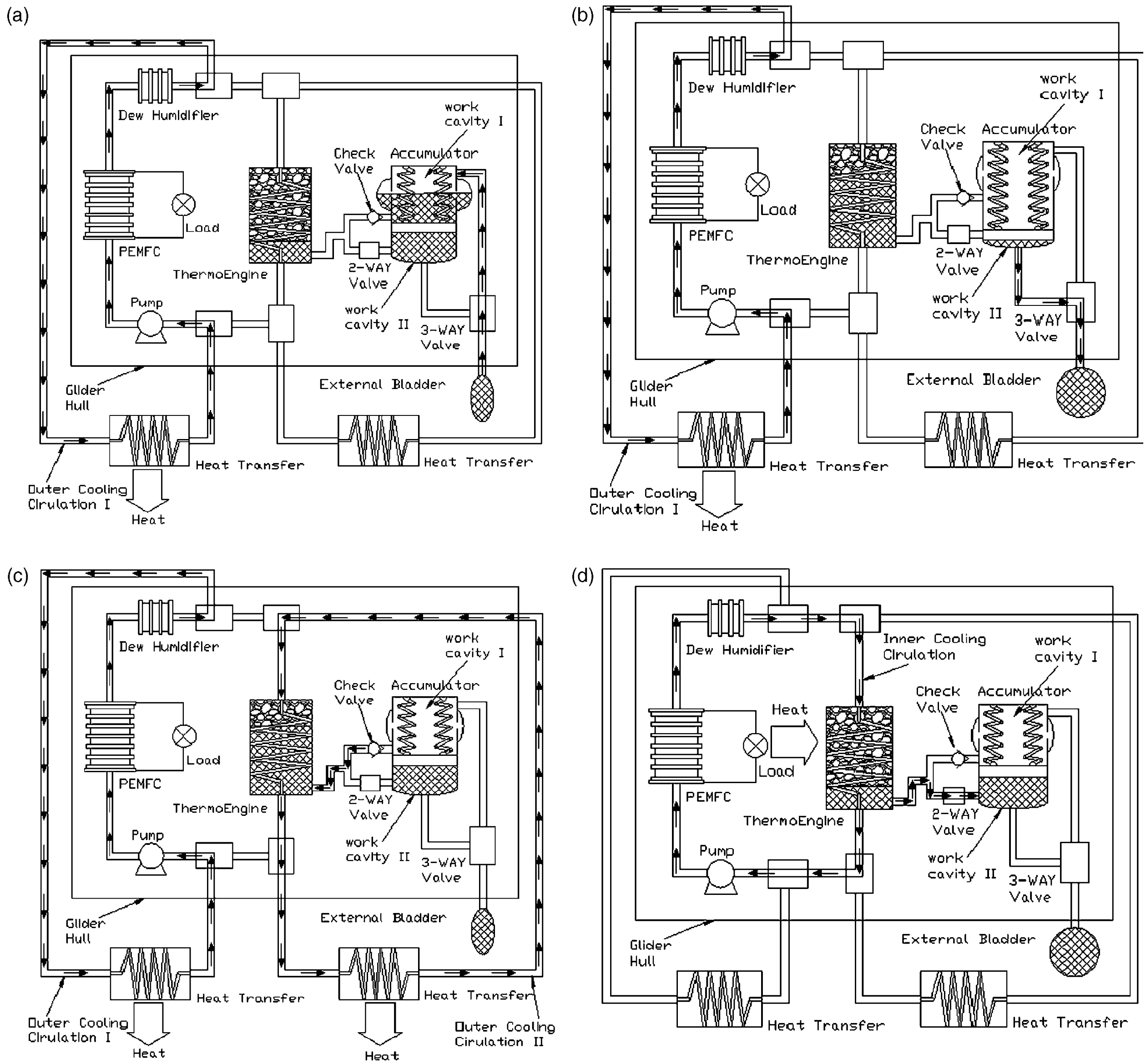

Fig. 3. The work cycle of the PTE power system. (a) The glider begins to descend from sea surface; (b) descend to deep cold seawater with heat flow from the thermal engine to the environment; (c) the glider begins to ascend from deep sea; (d) ascend to sea surface with heat flow from PEMFC to the thermal engine.

into pressure energy that is saved in work cavity II. Eventually, the pressure in the work cavity II is a little more than the maximum pressure produced by deep seawater. The two-way valve closes after work cavity II gets to the programmed pressure. PEMFC then switches the cooling circulation from inner to out. The integrated system completes the work cycle and gets back to the original state.

4. Experiments for PTE power system

4.1. Setup

An experimental system as shown in Fig. 4 is designed to demonstrate the feasibility of the PTE power system. A PEMFC stack having a voltage rating of 12 V and a power rating of 100 W is used. The effective area of the Nafion112 membrane is 32 cm^2. Ten pieces of cooling panel are installed for the stack. The reaction gas is humidified by a dew humidifier out of the PEMFC stack. Electrical load is made up of 30 bulbs in a parallel electrical circuit. Each bulb can be turned on or off by its own switch. Cooling water is circulated counter to the reaction gas stream by a pump. Thus, heat produced by the PEMFC is transferred by the heat exchanger to the thermal engine. There is 400 ml of thermal material that has contracted to the minimum volume in the thermal engine. Heat flows into the thermal material through the heat exchanger, at the same time the thermal material begins to melt and expand during the process of phase transformation, and this overcomes an environmental pressure of about 0.4 MPa.

4.2. Analysis of heat-to-power ratio

Because the PEMFC acts as the only source of heat and electricity in the power system, the proper heat-to-power ratio (useful thermal to electrical energy) is very important to ensure

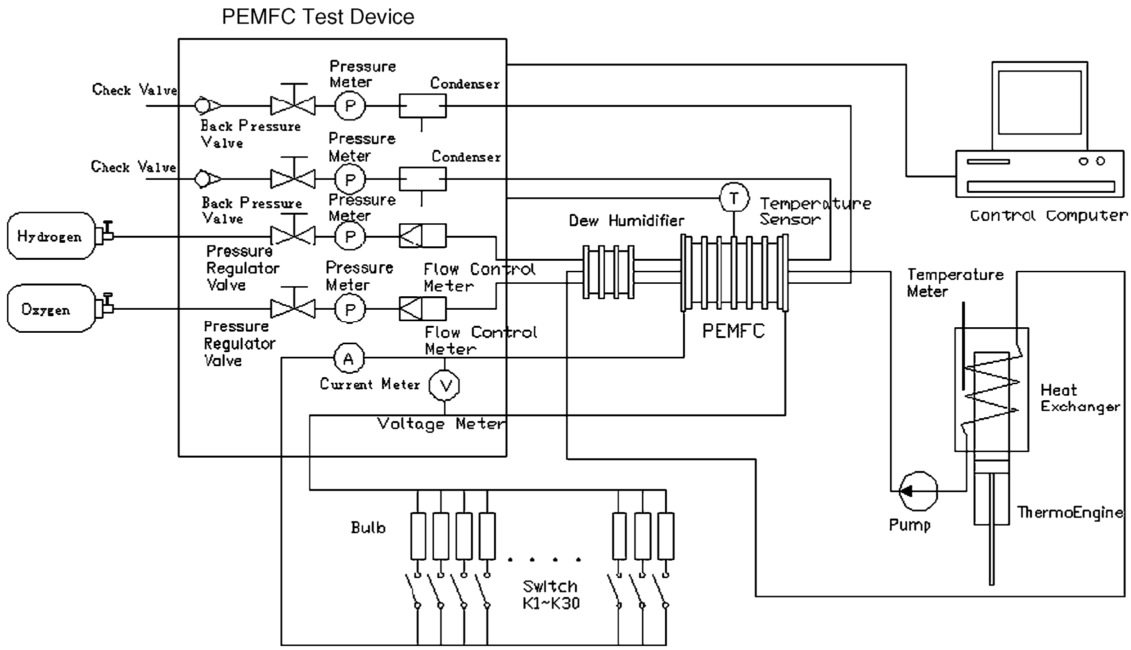

Fig. 4. The experiment scheme of the PTE power system.

the match of thermal and electrical loads in the glider and affect the overall power efficiency.

For an actual glider with the PTE power system, the overall power of the PEMFC can be used for the propulsion and electric devices in a drive cycle. The propulsion power of the glider is generated by the volume change of the thermal material in the thermal engine. Hence, the thermal power of PEMFC depends mainly on the total volume of the thermal material which is set by navigational parameters including speed and depth in the design process of the glider. Generally, a glider with faster speed and larger depth needs larger volume change of the thermal material to satisfy the buoyancy requirement. The basic electric devices of a glider include mainly sensors, microprocessor controllers, motors, and communication devices. Normally, the electrical power of PEMFC is related to the number of devices and the complexity of the control system in the glider.

As an example, consider a typical glider with the PTE system which works with the speed of 0.25 m/s and a depth of 1000 m [14]. Given that the rate of volume change of the thermal material is 10%, 500 ml buoyancy produced by 5 l thermal material is needed for the glider to keep the normal navigation. Theoretically, the heat flux of the thermal material is a function of temperature change and latent heat of phase transformation. The thermal power of the typical glider can be calculated which was 47 W [20]. Additionally, for the typical glider with the basic sensor such as conductivity temperature depth (CTD) and control units, the electrical power needed is approximately 42 W. Therefore, the typical ratio of thermal and electrical loads is 47/42 = 1.1.

A volume range of the thermal material from 3 to 7 l and a thermal power from 28 to 66 W is required to accommodate buoyancy requirements taken from design parameters for electric gliders for different oceanographic tasks [14]. Also, considering the glider with basic sensors and control units, the typical ratio of thermal and electrical loads is from 0.7 to 1.6 for the glider with the PTE system under different navigational requirements. Generally, a miniature PEMFC is able to keep the heat-to-power ratio from about 0.5 to 2.8 [2,6], which covers the range of the thermal and electrical loads required by the glider with the PTE system.

Generally speaking, the useful thermal energy in a PEMFC increases with an increase of electrical energy. Theoretically, the amount of heat can be calculated because it is a function of the output of electrical energy. The heat-to-power ratio is shown in Fig. 5. As the current density increases, the heat-to-power ratio of the PEMFC shifts upward continuously as the polarization curve declines [21].

In practice, the heat-to-power ratio of a PEMFC is not constant. It can be increased directly by use of resistance heaters to convert electricity to heat. Moreover, it can also be changed indirectly by altering the operating conditions such as temperature, pressure, and relative humidity. Operating conditions have a remarkable influence on the performance of a PEMFC. Thus, changing the operating conditions is an effective way to alter the shape and position of the polarization curve in order to meet the different requirements of the heat-to-power ratio [22–24], Fig. 6a–c show the polarization curves and the heat-to-power ratios under different operating conditions.

It has been seen in Fig. 6a that temperature plays a major role in a PEMFC s polarization curve [25]. Take a current density of 250 mA cm^{-2} for example. As the temperature rises from 20 to 60 °C, the stack voltage is improved from 12.6 to 13.7 V at 250 mA cm^{-2}, while the heat-to-power ratio declines from 0.95 to 0.79. But the relationship between voltage and temperature is non-linear according to the experimental data. The influence of temperature begins to weaken above 40 °C, whereas the rate of change in voltage (an increase) declines from 2.5 mV per degree at 20 °C to 1.2 mV per degree above 40 °C as the temperature

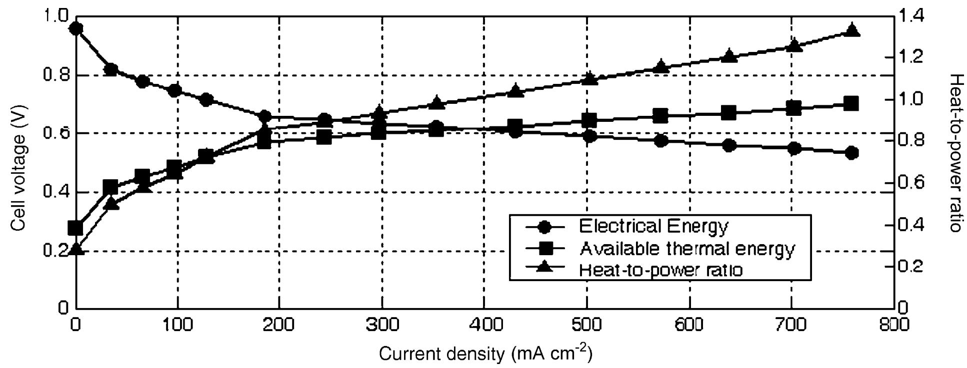

Fig. 5. The heat-to-power ratio of a single cell at 60 °C, 0.3 MPa and RH = 50%.

rises per 1 °C. The performance of a PEMFC has only a marginal improvement for a current density greater than 460 mA cm^{-2} at the temperature of 60 °C. The improvement is even less at temperatures higher than 60 °C.

Fig. 6b shows that a higher power density can be achieved by increasing the pressure. The increase of pressure improves the partial pressure of reactants and the rate of mass diffusion from diffusion layer to catalyst layer. However, the improvement of the performance of a PEMFC by pressure is insignificant at pressures greater than 0.2 MPa, and the adjustment for the heat-to-power ratio is also small. Taking the life of the membrane into consideration, one concludes that the maximum pressure should be limited to 0.4 MPa.

Conclusions can be drawn by comparing the linear portions of the polarization curves in Fig. 6c. The results show that the inner resistances of the PEMFC with the relative humidity of RH = 20%, 50% are obviously more than the state that is completely humidified. The two polarization curves of RH = 20%, 50% deviate their own linear parts and the heat-to-power ratios begin to boom over the current density of 560 and 650 mA cm^{-2} separately, but the deviation of the curves and the boom of the heat-to-power ratios do not happen in the case of complete humidity (RH = 100%). It can be explained that this phenomenon is caused by concentration polarization, that is to say, when the membrane is humidified insufficiently and the stack works at the state of large current, the limit of proton diffusion on the anode will take place due to lack of water [26].

4.3. Results

Unlike the thermal engine of the thermal glider whose performance is obviously influenced by the season and the sea surface temperature distribution, the PTE will provide an underwater glider with the inner heat energy being generated from the PEMFC stack rather than the heat energy from surface seawater. The heat produced by the PEMFC is absorbed by a proper thermal material inside the thermal engine. The thermal material will transfer the heat energy into pressure energy saved into the accumulator through heat expansion by itself. When the glider needs buoyancy to ascend, the accumulator will release pressure energy to expand the external bladder caused by the contraction of the thermal material.

Hexadecane can be used as the thermal material for the glider operating in a deep-sea environment. The thermodynamics properties of hexadecane, density of 0.77 g cm^{-3}, melting point of 18 °C, latent heat about 150 kJ kg^{-1}, indicate the temperature difference that guarantees it to work through successive cycles is 10 °C and the rate of volume change is approximately 10%. Fig. 7a and b indicate the phase transformation processes of fluid-to-solid at low temperature and solid-to-fluid at high temperature, respectively, with contraction and expansion of 400 ml of hexadecane. Fig. 8 shows the statistics of heat power and the rates of volume change, while 400 ml hexadecane is heated to different high temperatures (relative to low temperature) from the minimal volume at the temperature of 5 °C. Fig. 8 shows that the higher temperature accelerates the speed of phase transformation and enhances the expansion volume.

Instead of ocean environment, the high quality and stable heat from the PEMFC should achieve a higher performance of the thermal engine. The experimental system as shown in Fig. 4 verifies this assumption through the combination of the PEMFC and the thermal engine. The temperature changes of the PEMFC stack and expansion rates of hexadecane are determined at electric power settings of approximately 50, 100 and 150 W to measure the influence of different electrical loads upon the remaining heat of the PEMFC. The change rates of temperature and the operating temperature at which the stack reaches heat equilibrium (the heat produced and expelled in PEMFC counteracts each other in unit time) are heightened as power output of the stack increases, as shown in Fig. 9a. According to energy equations [27], when a PEMFC is at the state of heat equilibrium, theoretical heat from the electrochemical reaction in the PEMFC is consumed primarily by the coolant stream, by exhaust gas at the cathode and anode, by product water, by convection and by radiation of the stack to the environment. The product heat in unit time increases as electrical loads increase. Thus, the former heat equilibrium will be broken. PEMFC will absorb the additional heat itself, following the operating temperature rises. Most of heat in the fuel cell system is transferred by cooling water and the increase of the water temperature lags a little behind the increase of the stack temperature. The temperature of exhaust gas at the cathode is very low because of the heat of vaporization of the water produced there. A large proportion of the total heat energy is heat loss from the surface of the stack [28]. The pro-

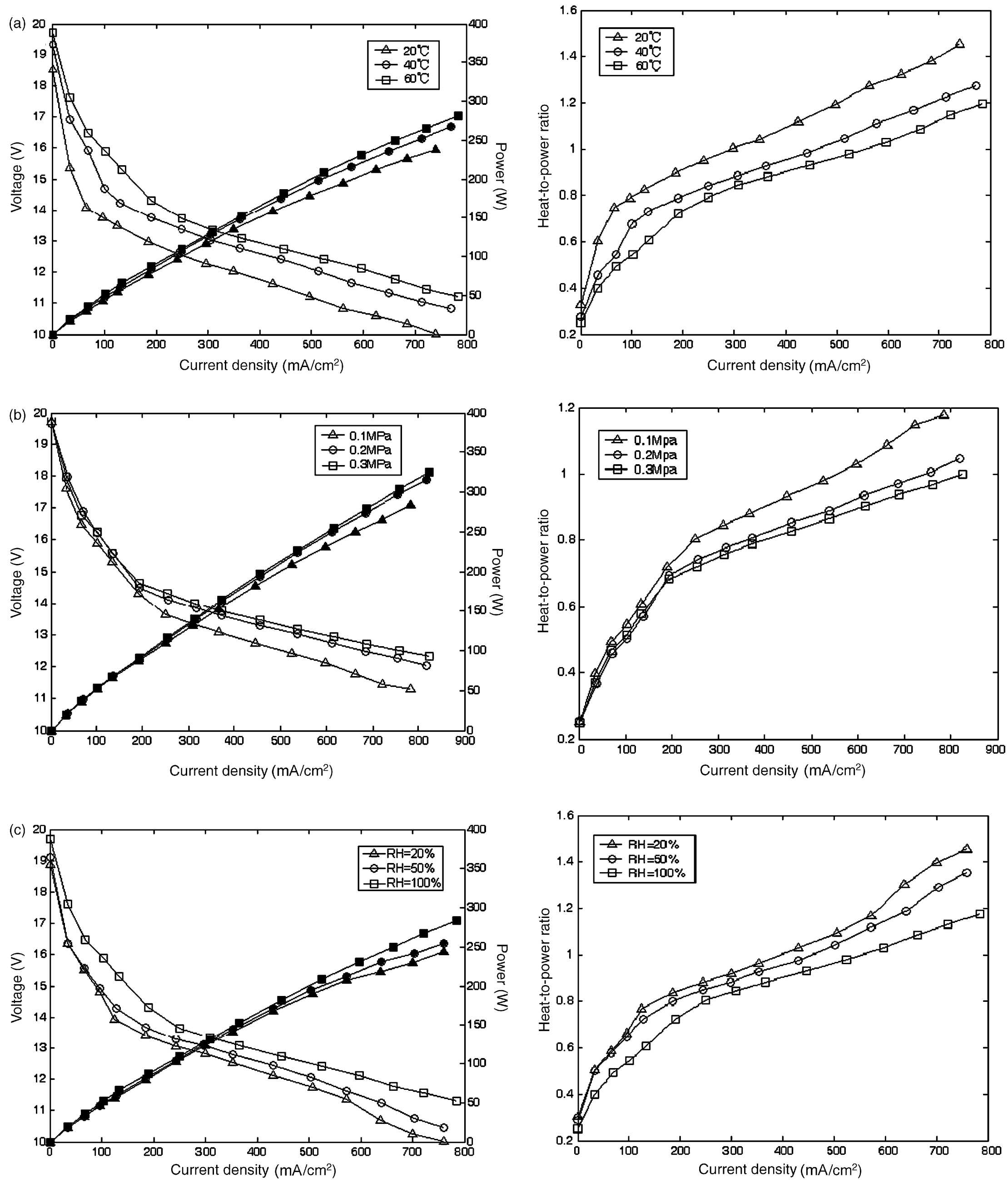

Fig. 6. The polarizations and the heat-to-power ratio of the stack: (a) at different temperatures, 0.1 MPa and RH = 100%; (b) at different pressures, 60 °C and RH = 100%; (c) at different relative humidities, 60 °C and 0.1 MPa.

portion increases as the operating temperature rises. Therefore, the measure of heat conservation is very important to the PTE system.

Different expansion curves in the PTE system and natural water environment are shown in Fig. 9b, which illustrates the fact that the thermodynamics performance of the thermal engine is remarkably improved as power output of the PEMFC increases. The maximum expansion rate of hexadecane increases to 13.61%, which is much more than the rate of 9.34% in the natural water environment. The time of phase transformation is also shortened from 55 min to about 30 min; thereby the average heat power is improved to approximately 61.1 W from 18.2 W.

Although the performance of the thermal engine is improved by the increase of heat power, excessive heightening of the heat power is not beneficial to the whole system. There are three reasons: first, a PEMFC is primarily a device for generating electricity. If it is used only to convert chemical energy into heat energy, its economics will drop during its lifetime which depends on the time used producing electricity [29,30]. Second, the cooling capacity of the system has been established after the setup of the PTE system. If power output of the PEMFC is excessive, it will accelerate the coolant stream in order to keep the operating stability of PEMFC. Thus, it will add extra energy consumption for the PTE system [31]. Finally, as viewed from the point of energy utilization, heat energy differs from electricity and can-

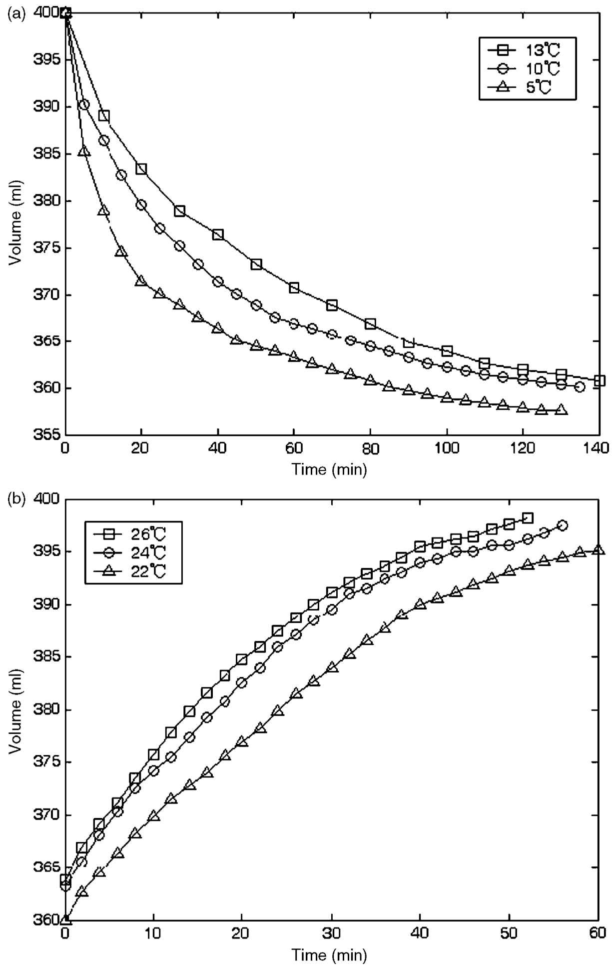

Fig. 7. (a) The contraction curves of hexadecane at different low temperatures; (b) the expansion curves of hexadecane at different high temperatures.

not be completely transformed into available work. Therefore, energy destruction will increase with the addition of heat energy in the system, thus debasing the quality of the energy in reality [32,33]. Furthermore, the higher the operating temperature of the PEMFC, the more will be the heat loss in the system. Eventually, this loss leads to lower fuel efficiency (the summation of electricity and available heat) as shown in Fig. 10. Fig. 10 illustrates the statistics of each part of energy stream at electric power of approximately 50, 100 and 150 W. Observe that as the

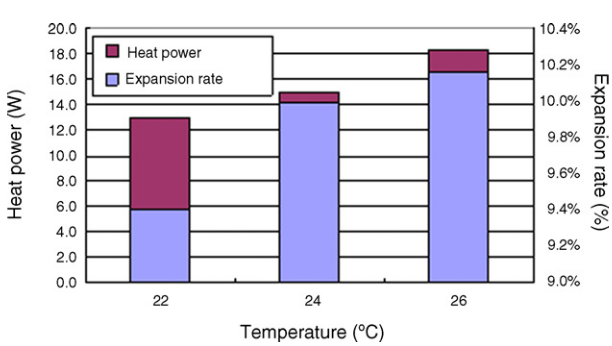

Fig. 8. The statistics of heat power and the rates of volume change at different temperatures.

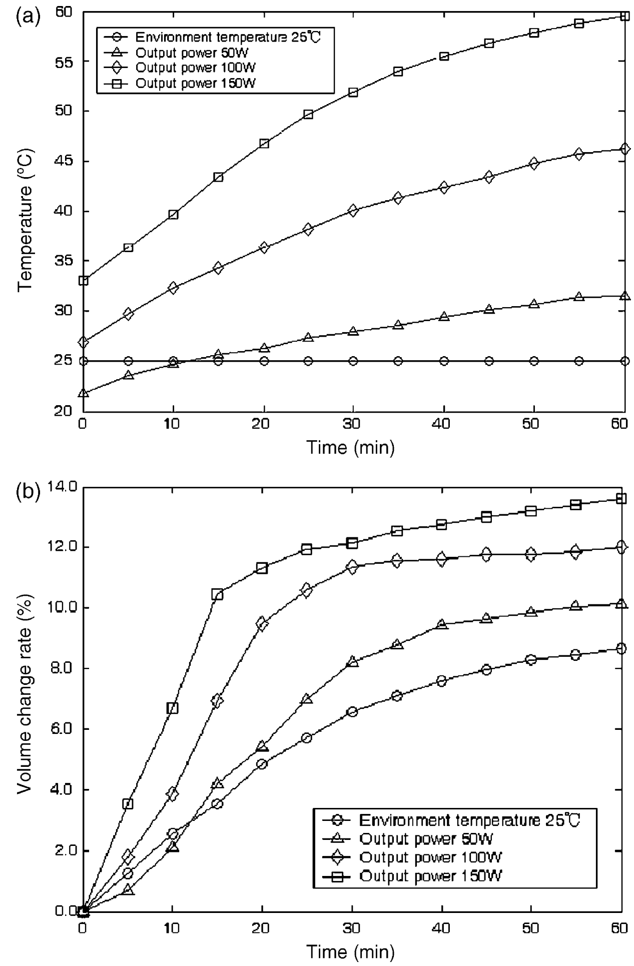

Fig. 9. (a) The temperature curves of the PEMFC stack; (b) the expansion curves of hexadecane.

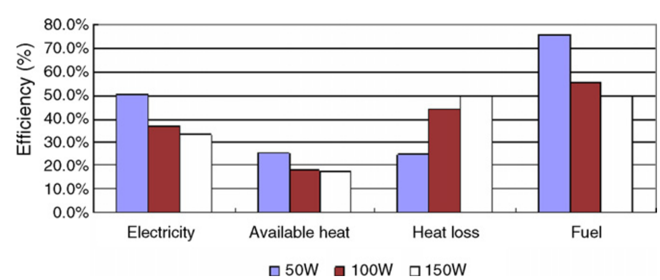

Fig. 10. The energy stream distribution of the PTE system. The fuel efficiency is the summation of electricity and available heat.

electric power increases, heat loss increases from 24.7 to 49.9% and fuel efficiency decreases from 75.3 to 50.1%. Thus, it is advisable for the economical operation to make PEMFC work at the state of low power density.

5. Conclusions

In a PEMFC, as much as 40–60% of the total chemical energy produces heat in the process of generating electricity. Recycling of this heat energy is difficult for a miniature PEMFC in order to improve the fuel efficiency. A new power system, integrated PEMFC-thermal engine (PTE), was designed to use the heat energy directly as part of the power system for underwater gliders. The system harvests the reaction heat of a PEMFC as the inner heat source to power the thermal engine while the miniature PEMFC produces electricity for the control system and sensors of the glider. The experimental results indicate that the PTE power system can meet the power need of the underwater glider. The fundamental advantage of the PTE system is that it changes the heat produced by the PEMFC into mechanical energy through a thermal material and improves the performance of the thermal engine due to the higher quality heat compared with the ocean environmental thermal energy. The PTE system not only resolves the problem of expelling heat from the PEMFC in underwater environment, but also improves the overall power efficiency of the PEMFC. The heat-to-power ratio of the PEMFC can also be effectively adjusted by using electric resistance heaters, or changing the operating temperature and humidity conditions to deal with the requirement of navigational performance for the glider. Furthermore, a conclusion can be drawn from the analysis of the fuel efficiency that the low power density operation of PEMFC is an advisable choice for the economical use of the fuel.

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