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An energy conversion system based on deep-sea pressure

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Abstract

A novel seawater pressure energy conversion system that utilizes seawater pressure to generate electricity has been studied in this paper. The energy conversion system utilizes the pressure difference between the pressurized seawater and the empty pressure container to drive hydraulic motor and the coaxially coupled generator to generate electric power. The output electric energy is recorded by the data logger throughout the process. In the current study, technical analysis is performed with the emphasis on conversion efficiency between seawater pressure energy and output electric energy. The analysis is conducted at various pressure differences through the throttle valve so as to obtain maximum conversion efficiency. Research shows that the optimum pressure difference through the throttle valve and the maximum conversion efficiency can be theoretically calculated when the properties of the conversion system are given. Simulation results have demonstrated the influence of pressure difference on conversion efficiency. The test apparatus has been designed, built and tested in 2004. It successfully generated electric energy of approximately 0.85 kW h at the depth of 2400 m with empty pressure container's holding capacity of 200 L in the voyage "DY105-16" in South China Sea on June 12, 2004. The actual conversion efficiency from seawater pressure energy to electric energy reaches as high as 63.8% which is attractive for underwater equipments. The success of the experiment has tested the feasibility of utilizing seawater pressure energy and brings a new power supply way for long-term in-situ underwater equipments.
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Keywords: Seawater pressure energy; Electric power generation; Conversion efficiency

1. Introduction

There has been a growing interest for scientists and engineers all over the world to exploit the ocean since the ocean resources, such as mineral resources and energy resources are potentially remarkable. Large numbers of underwater equipments have been developed for the investigation and exploitation of the ocean. Remotely operated vehicles, autonomous underwater vehicles, long-term in-situ observatory stations are some typical underwater equipments which have been widely used in the ocean exploration nowadays. For most of these underwater equipments, high energy density electric power supply is of great importance as they are all electrically powered.

Currently there are two power supply ways in the underwater equipments. One is to use coaxial cable between the deck and the underwater equipments. Feng and Allen (2004) indicated that the existence of the cable had largely limited the working area and the mobility of the underwater equipments. The cost of such power supply way is also considerably high, as it needs the support of the vessel. Moreover, the transmission loss through the coaxial cable could be seriously heavy due to the long transmission distance.

The power supply way using cable is probably practical in the short-term and limited-area applications. For those who have a large working area such as AUVs, and those who work under the deep sea for more than several months such as long-term in-situ observatory stations, the most appropriate power supply way is to use battery. In a typical application, standard battery is installed inside a pressure resistant container and it works at normal pressure. Øistein Hasvold and Nils Størkersen (2001) pointed out that the

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Nomenclature

p_s	seawater pressure, MPa
p_m	inlet pressure of the hydraulic motor, MPa
Δp	pressure difference through the throttle valve, MPa
q_s	flow rate through the hydraulic motor, L/min
C_d	flow coefficient
A_{open}	restriction area of the throttle valve, m^2
ρ	density of the hydraulic oil, kg/m^3
ω	shaft rotary speed of the hydraulic motor, r/min
D_m	displacement of the hydraulic motor, mL/r
E_a	armature electromotive force of the generator, V
K_e	electromotive force coefficient, V/rpm
R_a	inherent resistance of the generator, Ω
R_{load}	load resistance, Ω
T_D	driving torque of the generator, N m
I_{load}	current through the load resistance, A
K_t	moment coefficient of the generator, N m/A
U_{load}	voltage on the load resistance, V
P_{out}	output electric power of the conversion system, W
P_{in}	input hydraulic power of the conversion system, W
η	conversion efficiency of the conversion system
Δp_{op}	optimum pressure difference through the throttle valve, MPa
η_{max}	maximum conversion efficiency of the conversion system

pressure resistant container could become even larger when the battery needed increased which would make the whole battery package much heaver and the energy per weight would decrease. Another competing battery in Nils Størkersen and Øistein Hasvold (2004) is the pressure compensated battery working at ambient pressure while electrically isolated from the seawater. Typically there is a flexible membrane between the electrolyte and the outside seawater to balance the inner and outer pressure. Although there is no need to use a pressure container to hold the battery, the use of membrane has added the risk of electrolyte leakage and reduced the reliability of the battery.

One common disadvantage of these batteries proposed in Øistein Hasvold et al. (2006) is the bad discharge performance in the cold seawater environment as most of them are electrochemical batteries. Moreover, it is inconvenient to recharge these batteries without recovering them to the deck. For those underwater equipments who work for a long period of time under the deep sea, such as long-term in-situ observatory stations, it is not practical to recover them from the seafloor to the deck for recharge as all the observational data could be discontinuous both in the time series and in the spatial series, which would influence the in-situ observation.

To make the long-term in-situ observatory stations work for a long period of time under the deep sea, the energy latent inside the pressurized seawater—seawater pressure energy can be harnessed to power these observatory stations. For the seawater with the volume of 2 m^3 at the depth of 6000 m, the pressure energy inside it can be calculated as the product of the pressure and the volume, which is 33.33 kW h. If all this pressure energy can be converted into electric energy, it could power a sensor with the power consumption of 20 W more than 60 days which is remarkably attractive.

Therefore in this paper a novel seawater pressure energy conversion system that utilizes seawater pressure to generate electricity has been studied. The energy conversion system utilizes the pressure difference between the pressurized seawater and the empty pressure container to drive hydraulic motor and the coaxially coupled generator to generate electric power. The electric energy generated by the energy conversion system is not only relative to the working depth of the system and the holding capacity of the empty pressure container, but also relative to the conversion efficiency between seawater pressure energy and electric energy.

The typical application of the seawater pressure energy conversion system is to power the Bottom Station of the GEOSTAR system on the seafloor. GEOSTAR is a long-term single-frame, autonomous seafloor observatory station which can simultaneously monitor a broad spectrum of geophysical and environmental processes, including seismicity, geomagnetic field variations, water temperature, pressure, salinity, chemistry, currents and gas occurrence at the maximum depth of 4000 m for more than one year (Beranzoli et al., 1998, 2004; Berta et al., 1995). The GEOSTAR consists of three subsystems: the Bottom Station, which is the monitoring system; MODUS, the dedicated deployment/recovery vehicle; the Communication Systems. The Bottom Station is a four-leg marine frame hosting the monitoring system including electronics, hard disks for data storage, communication systems and scientific sensors. It uses batteries for power supply. The sensors are selected with low power consumption (Cenedese et al., 2004; Favali et al., 2004).

Although the electric energy generated by the energy conversion system is limited by the holding capacity of the empty pressure container, it can still be recharged with the help of ROV when the energy is exhausted. The recharge process is a reverse procedure of the electric power generation process. As the seawater pressure energy conversion system is only an energy converter between seawater pressure energy and electric energy, additional input energy from ROV is needed in the recharge process for pumping the hydraulic oil in the pressure container back into the elastic waterproof bladder so as to restore the system to the electric power generation status in the seawater environment. Although the input mechanical energy in the recharge process is higher than the seawater pressure energy as well as the generated electric energy as both the conversion efficiency in the electric power generation process and the recharge process are less than 100%, it is still more practical for the in-situ observation than recovering the observatory stations for recharge. It is therefore a suitable power supply way for long-term in-situ observatory stations.

In the current study, technical analysis of seawater pressure energy conversion system with the emphasis on conversion efficiency between seawater pressure energy and output electric energy is performed. The analysis is conducted at various pressure differences through the throttle valve so as to obtain maximum conversion efficiency. Simulation results have demonstrated the influence of pressure difference on conversion efficiency and the success of the experiment has also tested the feasibility of utilizing seawater pressure energy. Moreover, the study has also taken the theoretical limit of seawater pressure energy conversion system into consideration in order to compare the actual process with an ideal case.

2. Seawater pressure energy conversion system

2.1. System overview

To harness energy from the pressurized seawater, an energy conversion component which can convert pressure energy to mechanical movement is required. The hydraulic motor is the component that can realize this conversion. However, the working fluid in the hydraulic motor widely used in the industrial machinery is hydraulic oil. When the working fluid changes to seawater, most of the parts inside the hydraulic motor could be seriously corrupted by the seawater. Although the seawater hydraulic motor which is designed to use seawater as working fluid is developed, the performance is not satisfactory and the efficiency is under improvement as the viscosity of the seawater is much lower than the oil which would lead to serious leakage problems. It is one of the reasons why it is not widely applied to the deep-sea hydraulic systems.

Therefore, conventional hydraulic motor is adopted in the seawater pressure energy conversion system as the conversion efficiency is the one to be emphasized. To generate pressurized hydraulic oil, an elastic waterproof bladder is used not only for transforming the seawater pressure energy into oil pressure energy, but also for supplying a container for the hydraulic oil.

The hydraulic motor can only be driven under certain pressure difference. To create this pressure difference, there must be an empty pressure container so as to release the pressurized oil. To harness the pressure energy more efficiently, the hydraulic motor can not be fully accelerated, thus a throttle valve is used to regulate the flow rate through the hydraulic motor.

To evaluate the conversion efficiency, another component which can convert mechanical movement to electric power—electric generator is used as the electric power can be easily measured. The generator is coupled with the hydraulic motor coaxially. A resistive heater is used as the load of the generator. A data logger is installed to record the output voltage for every few seconds.

The structure of seawater pressure energy conversion system is shown in Fig. 1. The conversion system mainly consists of four parts: an elastic waterproof bladder full of hydraulic oil, an empty pressure container, a pressure container where the control valve, the hydraulic motor, the generator and the data logger are inside and a pressure container where the resistive heater is inside.

When the seawater pressure energy conversion system is deployed to the deep sea, the elastic waterproof bladder full of hydraulic oil is compressed to balance the outside seawater pressure. The pressure difference occurs. Under this pressure difference, the hydraulic motor is driven and the coupled generator generates electric power to the resistive heater. The output electric power is recorded by the data logger throughout the process.

2.2. Analytical model

Pressure difference through the throttle valve in the seawater pressure energy conversion system shown in Fig. 2, can be expressed as the difference between the seawater pressure p_s and the inlet pressure of the hydraulic motor p_m:

$$\Delta p = p_s - p_m. \tag{1}$$

Assuming the orifice of throttle valve as the thin edged restriction, the flow rate through the throttle valve and also the hydraulic motor q_s, can be formulated as (Lu Yongxiang and Hu Dahong, 1988)

$$q_s = C_d A_{open}\sqrt{\frac{2\Delta p}{\rho}}, \tag{2}$$

where C_d is flow coefficient, A_{open} is restriction area of the throttle valve and ρ is density of the hydraulic oil.

Ignoring the leakage of hydraulic motor and the compressibility of hydraulic oil, the shaft rotary speed of hydraulic motor ω is proportional to the flow rate through it (Lu Yongxiang, 2002):

$$\omega = \frac{q_s}{D_m}. \tag{3}$$

where D_m is the displacement of the hydraulic motor.

The generator coupled with the hydraulic motor coaxially then generates the armature electromotive force E_a at the above shaft rotary speed:

$$E_a = K_e\omega = \frac{K_e}{D_m}q_s, \tag{4}$$

where K_e is electromotive force coefficient.

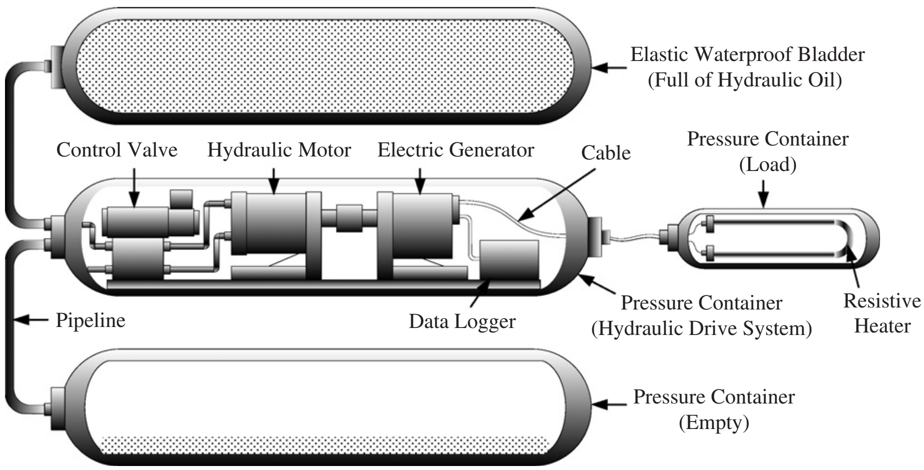

Fig. 1. Structure of seawater pressure energy conversion system.

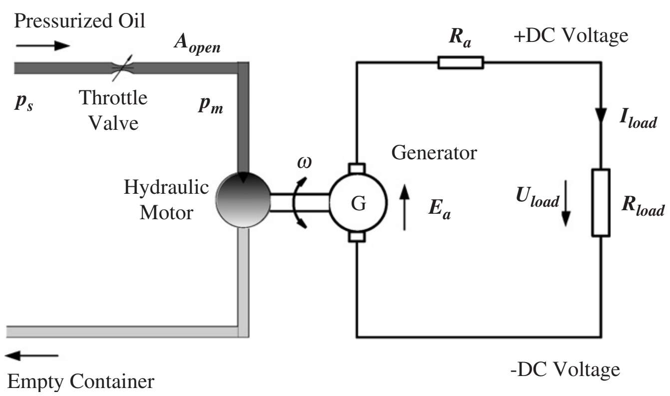

Fig. 2. Schematic diagram of the seawater pressure energy conversion system.

Ignoring the mechanical friction losses of both the hydraulic motor and the generator, the driving torque needed for the generator T_{D} is determined by the load current of the generator I_{load} and this driving torque can be generated under the pressure P_{m} at the inlet port of hydraulic motor with the displacement of D_{m} (Wu Genmao et al., 1993; Luo Hanxiu et al., 1994):

$$T_{\mathrm{D}} = p_{\mathrm{m}} D_{\mathrm{m}}, \tag{5}$$

$$I_{\mathrm{load}} = \frac{T_{\mathrm{D}}}{K_{\mathrm{t}}} = \frac{D_{\mathrm{m}}}{K_{\mathrm{t}}} p_{\mathrm{m}}, \tag{6}$$

where K_{t} is moment coefficient of the generator.

Considering the existence of generator's inherent resistance R_{a}, the output voltage of the generator U_{load} can be formulated as:

$$U_{\mathrm{load}} = E_{\mathrm{a}} - I_{\mathrm{load}} R_{\mathrm{a}} = \frac{K_{\mathrm{e}}}{D_{\mathrm{m}}} q_{\mathrm{s}} - \frac{D_{\mathrm{m}} R_{\mathrm{a}}}{K_{\mathrm{t}}} p_{\mathrm{m}}. \tag{7}$$

The output electric power P_{out} can be expressed as the product of the output voltage and the load current with respect to inlet pressure of hydraulic motor p_{m}, flow rate through hydraulic motor q_{s} and other parameters:

$$P_{\mathrm{out}} = I_{\mathrm{load}} U_{\mathrm{load}} = \frac{K_{\mathrm{e}}}{K_{\mathrm{t}}} p_{\mathrm{m}} q_{\mathrm{s}} - \frac{D_{\mathrm{m}}^2 R_{\mathrm{a}}}{K_{\mathrm{t}}^2} p_{\mathrm{m}}^2. \tag{8}$$

Similarly, the input hydraulic power P_{in} can be defined as the product of seawater pressure and flow rate through hydraulic motor:

$$P_{\mathrm{in}} = p_{\mathrm{s}} q_{\mathrm{s}}. \tag{9}$$

Therefore, the conversion efficiency of seawater pressure energy conversion system η can be formulated with respect to two variables: inlet pressure of hydraulic motor p_{m}, flow rate through hydraulic motor q_{s}, and other parameters such as seawater pressure, displacement of hydraulic motor, generator's inherent resistance, electromotive force coefficient, moment coefficient which are regarded as fixed constant:

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{K_{\mathrm{e}}}{K_{\mathrm{t}} p_{\mathrm{s}}} p_{\mathrm{m}} - \frac{D_{\mathrm{m}}^2 R_{\mathrm{a}}}{K_{\mathrm{t}}^2 p_{\mathrm{s}} q_{\mathrm{s}}} p_{\mathrm{m}}^2. \tag{10}$$

The maximum conversion efficiency can be easily calculated when the conversion efficiency is expressed with respect to only one variable. Substituting p_{m} with Eq. (11) and q_{s} with Eq. (2) into Eq. (10):

$$p_{\mathrm{m}} = p_{\mathrm{s}} - \Delta p. \tag{11}$$

The conversion efficiency is thus formulated with respect to only one variable Δp—pressure difference through the throttle valve:

$$\eta = \frac{K_{\mathrm{e}}}{K_{\mathrm{t}} p_{\mathrm{s}}} (p_{\mathrm{s}} - \Delta p) - \frac{D_{\mathrm{m}}^2 R_{\mathrm{a}} \sqrt{\rho/2}}{K_{\mathrm{t}}^2 p_{\mathrm{s}} C_{\mathrm{d}} A_{\mathrm{open}}} \frac{(p_{\mathrm{s}} - \Delta p)^2}{\sqrt{\Delta p}}. \tag{12}$$

The maximum conversion efficiency can be achieved at the condition of having an optimum pressure difference, which is determined by differentiating the above equation with respect to Δp:

$$\frac{d\eta}{d(\Delta p)} = -\frac{K_e}{K_t p_s} - \frac{D_m^2 R_a \sqrt{\rho/2}}{K_t^2 p_s C_d A_{open}} \times \frac{-2(p_s - \Delta p)\sqrt{\Delta p} - (p_s - \Delta p)^2 \left(1/2\sqrt{\Delta p}\right)}{\Delta p} = 0. \quad (13)$$

Substituting the square root of Δp with χ and coefficients with k_1, k_2 to simplify the equation:

$$x = \sqrt{\Delta p}, \quad (14)$$

$$k_1 = \frac{K_e}{K_t p_s}, \quad (15)$$

$$k_2 = \frac{D_m^2 R_a \sqrt{\rho/2}}{K_t^2 p_s C_d A_{open}}. \quad (16)$$

The simplified equation is a polynomial equation with the order of four in which the multinomial coefficients are parameterized:

$$3k_2 x^4 + 2k_1 x^3 - 2p_s k_2 x^2 - k_2 p_s^2 = 0. \quad (17)$$

There should have been four roots of the equation in which the positive real root χ_{preal} is practically reliable, thus the optimum pressure difference Δp_{op} can be expressed as the square of χ_{preal} according to Eq. (14):

$$\Delta p_{op} = x_{preal}^2. \quad (18)$$

Accordingly, the maximum conversion efficiency η_{max} based on the optimum pressure difference can be represented in the following form:

$$\eta_{max} = \frac{K_e}{K_t p_s}(p_s - \Delta p_{op}) - \frac{D_m^2 R_a \sqrt{\rho/2}}{K_t^2 p_s C_d A_{open}} \frac{(p_s - \Delta p_{op})^2}{\sqrt{\Delta p_{op}}}. \quad (19)$$

Once the throttle valve, the hydraulic motor and the generator have been chosen and the working depth is definitely known, the parameters such as seawater pressure, displacement of hydraulic motor, generator's inherent resistance, electromotive force coefficient, moment coefficient and restriction area of the throttle valve can be calculated easily. Thus the optimum pressure difference through the throttle valve and the maximum conversion efficiency based on it can be theoretically calculated which is instructive for the design of the test apparatus.

3. Simulation results

The simulation of the seawater pressure energy conversion system is to proof the validity of theoretical analysis and also to give an instruction for the design of test apparatus. All the properties used in the simulation are taken from the test apparatus as well as the working conditions. The simulation is performed using Matlab and Simulink. The properties of the conversion system are listed in Table 1.

Table 1
Properties of the conversion system

Property	Value
Seawater pressure, p_s	24 MPa
Restriction area of the throttle valve, A_{open}	1.32E−6 m^2
Flow coefficient, C_d	0.62
Displacement of the hydraulic motor, D_m	2.5 mL/r
Density of the hydraulic oil, ρ	870 kg/m^3
Inherent resistance of generator, R_a	11.2 Ω
Moment coefficient of the generator, K_t	1.72 N m/A
Electromotive force coefficient, K_e	1.72 V/rpm

According to the previous analysis, the optimum pressure difference through the throttle valve and the maximum conversion efficiency based on it can be theoretically calculated. The coefficients k_1, k_2 in Eq. (17) can be calculated easily from above properties:

$$k_1 = 4.167E - 8, \quad (20)$$

$$k_2 = 6.37E - 13. \quad (21)$$

Substituting the value of k_1, k_2 into Eq. (17) and the polynomial equation can be simplified as follows:

$$1.911E - 12x^4 + 8.334E - 8x^3 - 3.058E - 5x^2 - 366.9 = 0. \quad (22)$$

The four roots of the equation are listed below:

$$\chi_1 = -43977,\ \chi_2 = 1744,\ \chi_3 = -689 + 1424i,\ \chi_4 = -689 - 1424i, \quad (23)$$

where the positive real root is practically reliable:

$$x_{preal} = 1744. \quad (24)$$

Thus the optimum pressure difference through the throttle valve Δp_{op} and the maximum conversion efficiency η_{max} can be calculated below:

$$\Delta p_{op} = 3.04E + 6\,\text{Pa} = 3.04\,\text{MPa}, \quad (25)$$

$$\eta_{max} \approx 71.3\%. \quad (26)$$

Fig. 3 presents both seawater pressure and flow rate through hydraulic motor of the conversion system at various pressure differences through the throttle valve. The seawater pressure, which is also the inlet pressure of the throttle valve, maintains at a constant value of 24 MPa due to the huge seawater pressure energy. The flow rate through hydraulic motor varies from 2.35 to 5.26 L/min as the pressure difference varies from 1 to 5 MPa. The flow rate increases exponentially as respect to pressure difference through the throttle valve with the exponential of 0.5 according to Eq. (2).

In order to study the influence on the conversion efficiency caused by the pressure difference, the current simulation is conducted at a pressure difference ranging from 1 to 5 MPa. This pressure difference range is practically reasonable as the flow rate through hydraulic motor at $\Delta p = 5$ MPa is more than twice as the flow rate at

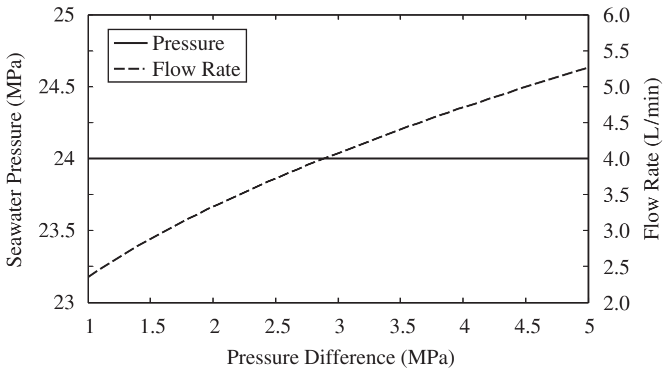

Fig. 3. Seawater pressure and flow rate through hydraulic motor at various pressure differences.

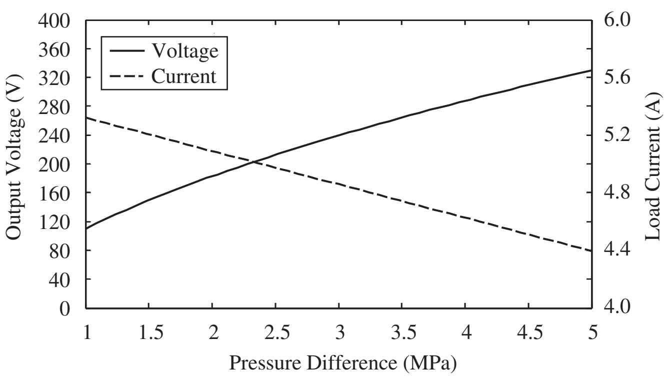

Fig. 4. Output voltage and load current at various pressure differences.

$\Delta p = 1$ MPa, which means both the hydraulic motor and the generator should have a wide range of rotary speed. In the current study, the rotary speed ranges from 942 to 2106 r/min, which is feasible for both the hydraulic motor and the generator.

The output voltage of the generator and the load current at various pressure differences are represented in Fig. 4. The output voltage varies from as low as 110 V at $\Delta p = 1$ MPa to as high as 330 V at $\Delta p = 5$ MPa. On the other hand, the load current varies from 5.32 A at $\Delta p = 1$ MPa to 4.4 A at $\Delta p = 5$ MPa. The flow rate through the throttle valve as well as the hydraulic motor increases due to the increase of the pressure difference. Thus the rotary speed of the generator steps up and the armature electromotive force rises. It should be noted that the increase of the pressure difference is performed by reducing the load current. According to Eq. (6), the driving torque of the generator is lightened as the load current drops, which will lead to the decrease of the inlet pressure of the hydraulic motor and thus the pressure difference through the throttle valve increases. The increase of the output voltage attributes to both the rise of armature electromotive force and the drop of load current.

The input power of the conversion system is hydraulic power which is defined as the product of seawater pressure and flow rate. In the current analysis, the seawater pressure maintains constant and the flow rate increases exponentially as respect to pressure difference with the exponential of 0.5. As shown in Fig. 5, the input hydraulic power varies from 942 to 2106 W as the pressure difference varies from 1 to 5 MPa. On the other hand, the output power of the conversion system is electric power, which is the product of output voltage and load current. Although the output voltage increases and the load current decreases as the pressure difference varies from 1 to 5 MPa, the total output electric power conversion system generated still grows from 585 to 1451 W as shown in Fig. 5.

Fig. 6 shows the conversion efficiency of seawater pressure energy conversion system at various pressure differences. It is obvious that the maximum conversion efficiency does exist when the pressure difference varies from 1 to 5 MPa. The maximum conversion efficiency reaches as high as 71.3% at the pressure difference of 3 MPa, which conforms to the previous analysis precisely. Thus 3 MPa is the optimum pressure difference. The conversion efficiency increases from 62.2% to 71.3% as the pressure difference varies from 1 to 3 MPa while decreases after 3 MPa.

The properties of the conversion system at the optimum pressure difference of 3 MPa are listed in Table 2.

It should be stressed that although the above results are based on theoretical analysis and computational

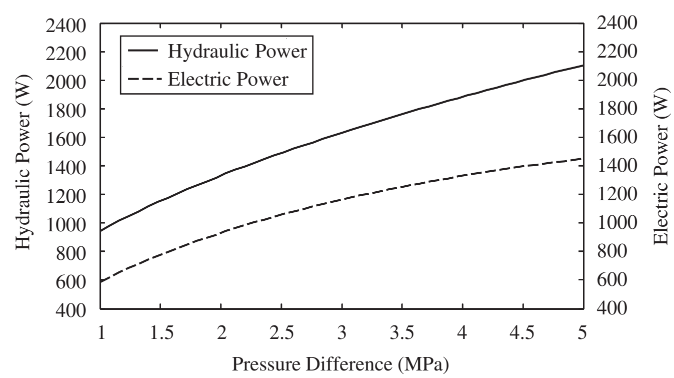

Fig. 5. Input hydraulic power and output electric power at various pressure differences.

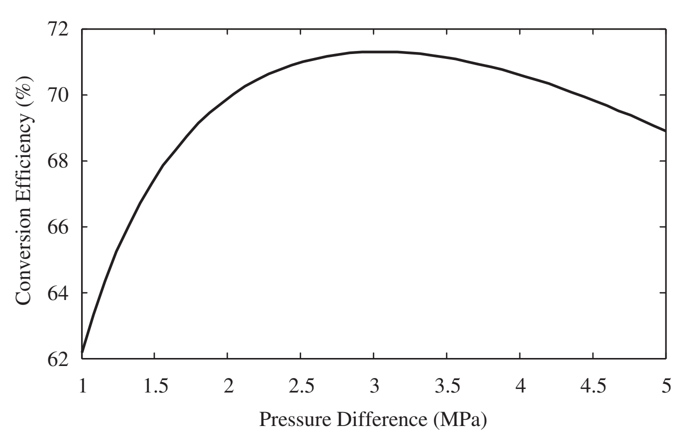

Fig. 6. Conversion efficiency of seawater pressure energy conversion system at various pressure differences.

Table 2
Properties of the conversion system at the optimum pressure difference of 3 MPa

Property	Value
Seawater pressure, p_s	24 MPa
Flow rate through the hydraulic motor, q_s	4.1 L/min
Shaft rotary speed of the hydraulic motor, ω	1631 r/min
Voltage on the load resistance, U_{load}	239.4 V
Current through the load resistance, I_{load}	4.86 A
Load resistance, R_{load}	49.3 Ω
Input hydraulic power, P_{in}	1631 W
Output electric power, P_{out}	1163 W
Maximum conversion efficiency, η_{max}	71.3%

simulation, the significance of instruction on the design of test apparatus can not be neglected.

4. Experimental results

The test apparatus of seawater pressure energy conversion system was built in March 2004. The whole test apparatus is shown in Fig. 7, where the elastic waterproof bladder and three pressure containers are furnished firmly on a square frame. Fig. 8 shows the internal structure of the pressure container, where the throttle valve, hydraulic motor, generator and the data logger are assembled inside with high space utilization factor.

The main properties of the test apparatus are shown in Table 3. A hydraulic motor with the displacement of 2.5 mL/r is coupled with a generator with the rated power of 1.1 kW and rated output voltage of 220 V. The flow rate through hydraulic motor is controlled by a throttle valve with the maximum flow rate of 6 L/min. A resistive heater with the resistance of 42 Ω is installed separately inside a small pressure container as the load of the system.

Before the test apparatus was deployed to the deep sea, it had been tested for many times for assessing the reliability such as pressure resistance, waterproofness, electrical insulation, etc. and also been calibrated repeatedly for evaluating the output electric power in the workshop. The output electric power can be obtained by measuring the output voltage of the generator, which is normally a little higher than 200 V. However, the sampling voltage range of the date logger is from −1.5 to +1.5 V. To measure the actual output voltage, a potentiometer is used to transform the actual output voltage to the sampling voltage range of the data logger. By sampling the output voltage of the potentiometer, the actual output voltage can be obtained. The calibration needs to be done in order to obtain the proper transformation coefficient between the sampled voltage and the actual output voltage. A series of actual output voltages measured by the voltmeter and the corresponding sampled voltages measured by the data logger have been included in the calibration which are shown in Table 4. The average transformation coefficient is 0.1750 V/mV, which means that a sampled voltage of 1 mV represents the actual output voltage of 0.1750 V. This average transformation coefficient has been used to evaluate the actual output voltage in the experimental results.

The experiment of the test apparatus in the deep sea has been carried out in the voyage "DY105-16" in South China Sea with the longitude of E116°33.83′ and the latitude of

Fig. 7. Photograph of the whole test apparatus in the workshop.

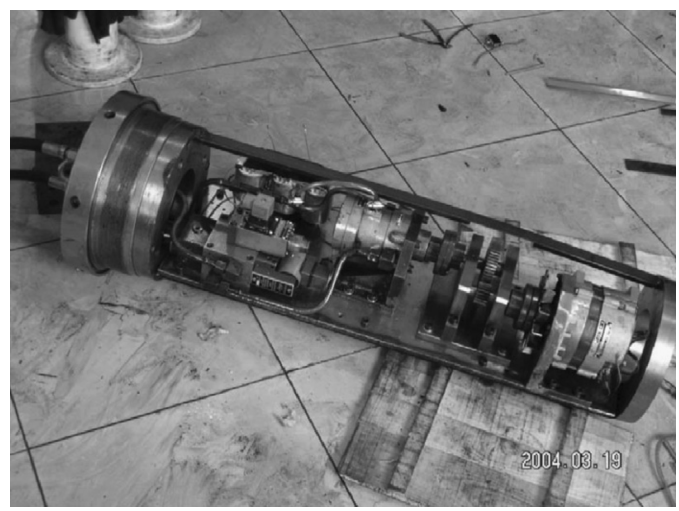

Fig. 8. Photograph of the internal structure of the pressure container.

Table 3
Properties of the test apparatus

Property	Value
Displacement of hydraulic motor	2.5 mL/r
Maximum flow rate of throttle valve	6 L/min
Rated rotary speed of hydraulic motor	1450 r/min
Rated power of generator	1.1 kW
Rated output voltage of generator	220 V
Rated current of generator	5 A
Resistance of resistive heater	42 Ω

Table 4
Calibration for the output voltage measurement in the workshop

Measured output voltage By the voltmeter (V)	Sampled voltage By the data logger (mV)	Transformation Coefficient (V/mV)
148.27	846	0.1753
156.43	894	0.1750
163.52	935	0.1749
171.47	979	0.1751
180.64	1032	0.1750
187.78	1075	0.1747
196.46	1121	0.1753
204.85	1173	0.1746
212.31	1215	0.1747
221.14	1264	0.1750
227.97	1301	0.1752
236.19	1351	0.1748
	Average:	0.1750

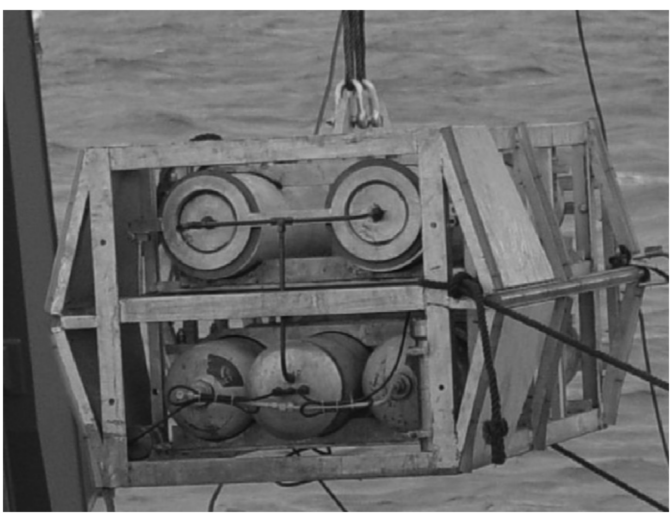

Fig. 9. Photograph of the test apparatus being deployed on deck.

N18°49.79′ with the help of Research Vessel "DY 1" on June 12, 2004. Fig. 9 shows the photograph of the test apparatus being deployed on deck.

Fig. 10 shows the cable length variation when the apparatus was tested. The apparatus was deployed to the sea at the depth of 2400 m while the cable is approximately 2800 m long due to the slope angle of the cable. The apparatus worked nearly for 1 h at this depth. It spent almost 1 h for both the deployment and the recovery. The whole experiment lasted for more than 3 h.

The output voltage and the output electric power of seawater pressure energy conversion system are shown in Fig. 11 and Fig. 12, respectively. The conversion system generated the electric power of approximately 1180 W at the output voltage of about 215 V continuously for 48 min. The output voltage and the output electric power at the last stage appear obviously low and unstable due to the exhaustion of the pressurized oil in the elastic waterproof bladder.

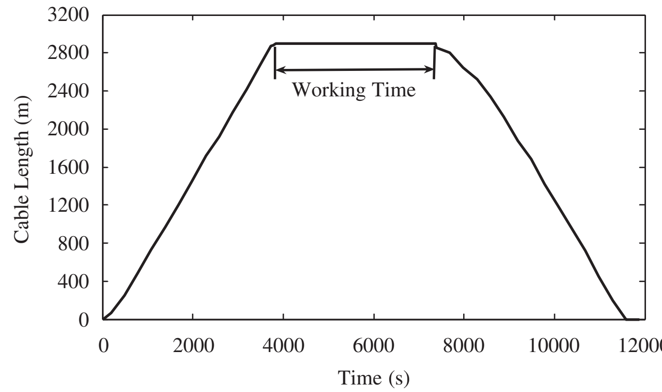

Fig. 10. Working depth of seawater pressure energy conversion system.

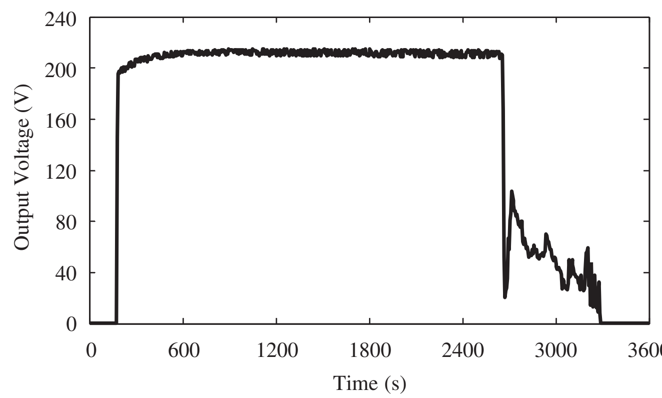

Fig. 11. Output voltage of seawater pressure energy conversion system.

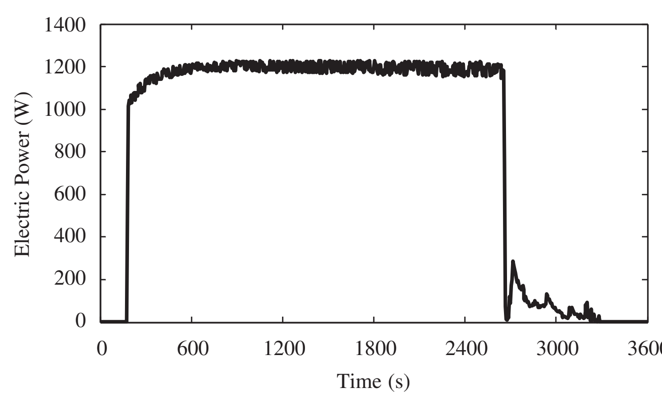

Fig. 12. Output electric power of seawater pressure energy conversion system.

The total electric energy of seawater pressure energy conversion system can be obtained by integrating the output electric power with respect to time. Fig. 13 represents the variation of total electric energy generated as the time increases. The total electric energy harnessed from the pressurized seawater reaches as high as 0.85 kW h.

The ideal conversion efficiency can be calculated with input hydraulic power and output electric power. However, the actual conversion efficiency in the test apparatus is

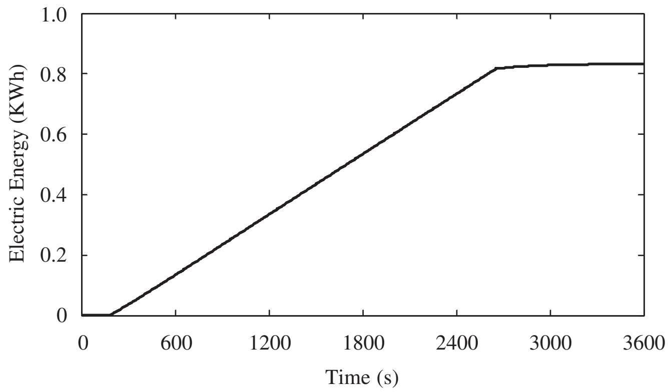

Fig. 13. Electric energy harnessed from pressurized seawater.

Table 5
Experimental results of seawater pressure energy conversion system

Property	Value
Working depth	2400 m
Holding capacity of empty pressure container	200 L
Continuous working time	48 min
Output voltage	215 V
Output electric power	1180 W
Input hydraulic energy	4.80E + 6 J
Output electric energy	3.06E + 6 J
Conversion efficiency	63.8%

measured with input hydraulic energy and output electric energy as both hydraulic power input and electric power output occur at the same time. The input hydraulic energy is defined as the product of pressure (24 MPa) and the volume of pressurized oil (200 L), which results to be 4.80E + 6 J. The output electric energy is 0.85 kW h, which is equivalent to 3.06E + 6 J. Therefore, the actual conversion efficiency of the test apparatus is 63.8%. The experimental results of seawater pressure conversion system are shown in Table 5.

The actual output voltage is slightly lower than the ideal output voltage as the resistance of resistive heater in the test apparatus is lower than the ideal load resistance, which could increase the load current. Thus the voltage drop on generator's inherent resistance rises and the output voltage falls. The actual conversion efficiency is also a little lower than the ideal conversion efficiency. The discrepancy between the numerical and experimental efficiency mainly results from the assumption of neglecting the leakage and the mechanical friction of the hydraulic motor. The mechanical friction is neglected in the theoretical analysis as the driving torque obtained by the hydraulic motor under the high pressure of 24 MPa is largely greater than the friction torque. Moreover, the leakage of the hydraulic motor is also ignored as the volumetric efficiency of the hydraulic motor adopted in the test apparatus can reach 95% or higher. The electric energy supplied by the test apparatus is relatively low due to the limitation of the empty pressure container's holding capacity. In general, the experimental results have been in accordance with the theoretical analysis acceptably.

5. Conclusions

A novel seawater pressure energy conversion system that utilizes seawater pressure to generate electricity has been designed, built and tested. The energy conversion system utilizes the pressure difference between the pressurized seawater and the empty pressure container to drive hydraulic motor and the coaxially coupled generator to generate electric energy. The output electric energy is recorded by the data logger throughout the process.

The conversion efficiency of the seawater pressure energy conversion system is mainly influenced by the pressure difference through the throttle valve. In the current study, technical analysis is performed at various pressure differences through the throttle valve so as to obtain maximum conversion efficiency. The optimum pressure difference through the throttle valve and the maximum conversion efficiency can be theoretically calculated when the properties of the conversion system are given. Simulation results have demonstrated the influence of pressure difference on the conversion efficiency.

The experiment of the energy conversion system has been carried out in South China Sea on June 12, 2004. It successfully generated approximately 0.85 kW h electric energy at the depth of 2400 m. The actual conversion efficiency of 63.8% is a little lower than the ideal conversion efficiency. The discrepancy between the numerical and experimental efficiency could be better explained as the leakage and the mechanical friction of the hydraulic motor are ignored in the theoretical analysis. In general, the experimental results have been in accordance with the theoretical analysis acceptably.

The typical application of the seawater pressure energy conversion system is to provide electric power for long-term in-situ observatory stations. Although the electric energy generated by the energy conversion system is limited by the holding capacity of the empty pressure container, it can still be recharged with the help of ROV when the energy is exhausted. The recharge process is a reverse procedure of the electric power generation process. Additional input energy from ROV is needed in the recharge process for pumping the hydraulic oil in the pressure container back into the elastic waterproof bladder so as to restore the system to the electric power generation status in the seawater environment. Although the input mechanical energy in the recharge process is higher than the seawater pressure energy as well as the generated electric energy, it is still more practical for the in-situ observation than recovering the observatory stations for recharge. It is therefore a suitable power supply way for long-term in-situ observatory stations.

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