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A novel application of the SAWD-Sabatier-SPE integrated system for CO_2 removal and O_2 regeneration in submarine cabins during prolonged voyages*

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Abstract: To improve the working and living environment of submarine crews, an integrated system of CO_2 removal and O_2 regeneration was designed to work under experimental conditions for 50 people in a submarine cabin during prolonged voyages. The integrated system comprises a solid amine water desorption (SAWD) unit for CO_2 collection and concentration, a Sabatier reactor for CO_2 reduction and a solid polymer electrolyte (SPE) unit for O_2 regeneration by electrolysis. The performances of the SAWD-Sabatier-SPE integrated system were investigated. The experimental results from the SAWD unit showed that the average CO_2 concentration in the CO_2 storage tank was more than 96% and the outlet CO_2 concentration was nearly zero in the first 45 min, and less than 1/10 of inlet CO_2 after 60 min when input CO_2 was 0.5% (1000 L). About 950 L of CO_2 was recovered with a recovery rate of 92%~97%. The output CO_2 concentration was less than 0.2%, which showed that the adsorption-desorption performance of this unit was excellent. In the CO_2 reduction unit we investigated mainly the start-up and reaction performance of the Sabatier reactor. The start-up time of the Sabatier reactor was 6, 8 and 10 min when the start-up temperature was 187.3, 179.5 and 168 °C, respectively. The product water was colorless, transparent, and had a pH of 6.9~7.5, and an electrical conductivity of 80 μs/cm. The sum of the concentration of metal ions (Ru^{3+}, Al^{3+}, Pb^{2+}) was 0.028% and that of nonmetal ions (Cl^-, SO_4^{2-}) was 0.05%. In the O_2 regeneration unit, the O_2 generation rate was 0.48 m^3/d and the quantity was 2400 L, sufficient to meet the submariners' basic oxygen demands. These results may be useful as a basis for establishing CO_2-level limits and O_2 regeneration systems in submarines or similar enclosed compartments during prolonged voyages.

Key words: CO_2 removal, O_2 regeneration, Solid amine water desorption (SAWD), Sabatier reactor, Solid polymer electrolyte (SPE), Submarine

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INTRODUCTION

A submarine cabin is a typical enclosed compartment isolated from the atmosphere during prolonged underwater voyages, and is similar in this respect to a spacecraft or space station (Millet *et al*., 1995; Shen and Zhou, 2000; Ross, 2006; Zhang, 2006). There are various pollutants in the atmosphere of a submarine cabin (Mouritz *et al*., 2001). Moreover, air pollution has become a more important issue since the use of nuclear power in submarines (Ross, 2006; Zhang, 2006).

The atmosphere in nature contains about 0.03% CO_2. When atmospheric CO_2 reaches 0.1%, people feel sick; at 1%, causes dizziness and dullness; at 2%, breathing and pulse rates increase, and people feel lethargic; at 3%, the function of the central nervous system begins to deteriorate; at 5%, people have only

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30 min respiratory subsistence (Shen and Zhou, 2000). In submarines, carbon in the form of CO_2 is produced as a result of the crew's breathing (a normal adult can exhale from 0.7~1.0 kg CO_2 per day) and the decomposition of materials (Chen *et al*., 2006). The average inhalation of O_2 by human metabolism is 0.83 kg per person per day (Chen *et al*., 2006). One of the most important tasks in a submarine cabin is to remove excess CO_2 immediately, and maintain CO_2 at a low level while providing O_2 for the crew (Shen and Zhou, 2000; Zhou *et al*., 2003; Russell and Klaus, 2007). The treatment and use of CO_2, within a reasonable integrated atmospheric circulation system, is a key issue for submarines at present. Therefore, the development of an efficient, low energy consuming and stable submarine cabin CO_2 removal and O_2 regeneration system is of great significance for improving a crew's working and living environment.

Although there have been some recent studies on CO_2 removal and O_2 regeneration, there have been few studies of relevance to submarine cabins. The design of a CO_2 removal and O_2 regeneration system for a submarine cabin includes three main parts: a CO_2 collection and concentration unit, a CO_2 reduction unit and an O_2 regeneration unit (Shen and Zhou, 2000). The advantages and disadvantages of existing technologies relating to each of the three components are shown in Table 1.

Table 1 CO_2 removal and O_2 regeneration technologies

No.	Technology	Advantage	Disadvantage	References
CO_2 collection and concentration				
1	MEA absorbent	Low cost	Higher CO_2 concentration at 0.5%~1.0%	(Shen and Zhou, 2000)
2	2, 4 zeolite absorbent	5A zeolite adsorbent can adsorb CO_2 selectively	Needs drying equipment; larger size, weight, and energy consumption	(Diaz *et al*., 2008; Zhang *et al*., 2008)
3	Membrane technology	Equipment is simple	Some technologies are not mature	(Keshavarz *et al*., 2008)
4	Amine-polyol methods	Effect is better than MEA	CO_2 concentration is still higher	(Shen and Zhou, 2000)
5	SAWD	Better physical properties; non-toxic, lower volume and energy consumption; CO_2 concentration was lower than 0.2%	Limited adsorbent's life	(Shen, and Zhou, 2000; Zhang *et al*., 2008; Gray *et al*., 2008)
CO_2 reduction				
1	Bosch response system	System can recover materials fully	Catalyst replaced frequently; recycling materials are polluting; the system size and weight are larger	(Otsuji *et al*., 1987; Shen and Zhou, 2000; Keshavarz *et al*., 2008)
2	Sabatier response system	One-way conversion rate is as high as 99%; system is simple and reliable; catalysts could be used long-term	Response is insufficient	(Otsuji *et al*., 1987; Shen and Zhou, 2000; Keshavarz *et al*., 2008)
O_2 regeneration				
1	FAE technology	Electrolyte limited to the porous electrode material, greatly reducing corrosion	A large water supply needed due to a large loss of electrolytes in fixed materials	(Shen and Zhou, 2000)
2	SFWT technology	Relatively low power consumption; without water, gas separation; lower volume and weight	Intolerance of high pressure; limited life	(Shen and Zhou, 2000)
3	SPE technology	High-pressure-resistant; excellent ion conduction capability, no corrosion; ensures system security; facilitates water/gas separation issues	As with moisture separator and other devices, increases the volume and weight of the system	(Shen and Zhou, 2000; Zhao, 2001; Rasten *et al*., 2003; Zhou *et al*., 2004)
4	FAE technology	A wide range of current density; easy to control the density of alkaline batteries; facilitates exclusion of formatted gas from the region	Corrosion and mobility of alkaline adds great insecurity to the system	(Shen and Zhou, 2000)

MEA: mono-ethanolamine; SAWD: solid amine water desorption; FAE: fixed alkaline electrolyzer; SFWT: static fixed water-supply electrolytic; SPE: solid polymer electrolyte

Some studies have compared the advantages and disadvantages of CO_2 removal and O_2 regeneration techniques from the perspective of their safety, the volume and weight of the installation, the life cycle of the materials, the conversion rate of the applicable reaction and their economic cost (Meng and Shang, 1994; Kunugi *et al*., 1998; Li *et al*., 1999; Zhao, 2001; Choi *et al*., 2004; Liu and Hou, 2004; Zhou *et al*., 2004; Zhang *et al*., 2007; Zhao *et al*., 2007). In this study, we focused on three components: SAWD CO_2 collection and concentration, Sabatier CO_2 reduction and SPE O_2 regeneration.

Solid amine water desorption (SAWD)-Sabatier-solid polymer electrolyte (SPE) membrane integrated systems have seldom been applied to the treatment of CO_2 and O_2 regeneration, therefore, an investigation of the suitability of using this type of system for this application is justified. Thus, an integrated system of CO_2 removal and O_2 regeneration comprising an SAWD unit for CO_2 collection and concentration, a Sabatier reactor for CO_2 reduction and an SPE unit for O_2 regeneration using electrolysis technology, was developed for a 50-person experimental situation in a submarine cabin during a prolonged voyage. In the SAWD CO_2 collection and concentration unit, the operating performance of adsorption and desorption was evaluated using adsorption curves of resin after each cycle of desorption. In the CO_2 reduction unit, the start-up and the reaction performance of the Sabatier reactor was investigated. In the O_2 regeneration unit, the effects of temperature and current density on electrolysis voltage were investigated over long periods of operation.

DESIGN OF THE CO_2 REMOVAL AND O_2 REGENERATION SYSTEM

CO_2 collection and concentration unit

In this study, SAWD technology was used to collect and concentrate the CO_2 in a submarine cabin. Solid amine is the resin formed by chloromethylation polystyrene and grafted diethylenetriamine or triethylenetetramine. In the 1990s, Chinese scientists began to study solid amine synthesis and its CO_2 absorption. Two types of solid amine were developed (Zhou *et al*., 2004; Zhao *et al*., 2007): MP solid amine was developed by Nankai University and a naval institution, and JD solid amine was developed by Jilin University, China and was commissioned by the Institution 718 (Ai *et al*., 2000). The general physical and chemical properties of the two solid amines are shown in Table 2.

In this study, JD solid amine resin was chosen to adsorb and desorb CO_2 because of its lighter bulk density and greater water uptake and swelling ratio (Table 2). JD solid amine also has better thermal stability. After several days in air at 180 °C there is no decomposition and when steamed continuously for 70 d at 100 °C, its performance is unchanged and there is no oxidative decomposition or secondary pollution (Ai *et al*., 2000).

CO_2 reduction unit

The CO_2 methanation reaction was first proposed by the French chemist Paul SABATIER, therefore, CO_2 reduction is also called the Sabatier reaction. The Sabatier reduction reaction is a reversible exothermic reaction. In the presence of a catalyst and at a certain temperature, a mixture of CO_2 and H_2 reduces to H_2O and CH_4 (methane). Its principles are as follows:

$$CO_2+4H_2\rightarrow CH_4+2H_2O+\text{Heat.} \quad (1)$$

In applying the Sabatier CO_2 methanation reduction reaction process, the design of the Sabatier reactor is critical (Araki *et al*., 2007). The reactor in this experiment used a triple tube structure. The outer layer had an inlet pipe with a countercurrent inlet form; the middle layer was a cooling pipe used to cool gas; and the inner layer was the reaction pipe. The Sabatier

Table 2 Physical and chemical properties of solid amines

Type	Color	Bulk density (g/cm^3)	Particle size (mm)	Specific surface area (m^2/g)	Water uptake with a swelling ratio (%)	Characteristics
MP	Orange yellow	0.90	0.3~1.5	75	20	Flexibility and mechanical strength
JD	Off-white	0.47	0.8~1.2	28	24~30	Flexibility and better mechanical strength

reactor was composed of a two-terminal flanged stainless steel cylinder. The reactor connected with the import and export flanged joints through a high-temperature heat insulation gasket. There was an electric heater, sensors measuring and controlling temperature and catalyst in the cylinder. A basic structural schematic is shown in Fig.1.

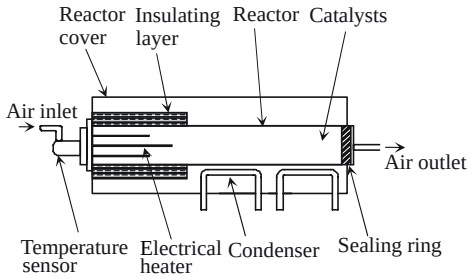

Fig.1 Schematic diagram of Sabatier device

Two single-ended heaters placed symmetrically were used for starting the reactor. One of the four thermocouples was used for controlling the reactor starting temperature, and the other three measured the reaction temperature of the reactor at points along its length. Ruthenium on Al_2O_3, comprising 20% ruthenium, was used as the catalyst in this study.

SPE electrolysis O_2 regenerator

Normally, one person needs to breathe 0.83 kg O_2 and exhale 1 kg CO_2 per day (Chen *et al*., 2006). In enclosed submarine cabins, the supplementation of O_2 is related directly to the life and safety of workers. As a result, the O_2 regenerator is one of the most critical devices of Environmental Control and Life Support System (ECLSS) (Zhou *et al*., 2003). For large- and medium-size submarines during prolonged voyages, the supply of O_2 depends mainly on electrolysis (Tanaka *et al*., 2003; 2005). After purification treatment, the water collected in the CO_2 reduction unit is supplied to the anode of the electrolyzer. The water is decomposed into oxygen (O_2), hydrogen ions (H^+) and electrons (e) in the presence of a current. H^+ acts in its hydrated form ($H^+ \cdot xH_2O$) and moves through the membrane to the cathode, while the electrons (e) pass through an external circuit. There the electrons combine with H^+ evolved hydrogen (H_2). At the same time, some of the water is taken to the cathode:

$$\text{Anode reaction} \quad 2H_2O \rightarrow 4H^+ + 4e + O_2, \tag{2}$$

$$\text{Cathode reaction} \quad 4H^+ + 4e \rightarrow 2H_2. \tag{3}$$

Nafion membrane is the material typically used for such applications (Millet *et al*., 1995). Nafion membranes have a acidity similar to that of a 20% (w/w) sulfuric acid solution (Millet *et al*., 1995). For this reason, acid resistant noble metal catalysts (such as platinum and iridium) or their oxides must be used as electrocatalysts (Millet *et al*., 1995). The main disadvantage of this technology is its expense. The cost of the electrodes plus the cost of the solid electrolyte seriously limits the development of SPE water electrolyzers in the industry (Millet *et al*., 1995). However, when cost considerations are less important (such cases do exist) SPE technology should be carefully considered (Zhou *et al*., 2003; Tang *et al*., 2006). For example, consider O_2 generation in submarine craft where security and reliability are particularly crucial (Millet *et al*., 1995).

Matching scheme of CO_2 removal and O_2 regeneration

A schematic diagram of the CO_2 removal and O_2 regeneration system is shown in Fig.2. Exhaled CO_2 is collected and concentrated by the SAWD system; the concentrated CO_2 is sent to the Sabatier reactor and reduced to H_2O and CH_4; H_2O is sent to the SPE by the electrolyzer; CH_4 is used for electricity production, space heating, water heating and process heating; The O_2 of the electrolyze is sent to the submarine cabin by fans for respiration; H_2 is sent back to the CO_2 reduction system. Cycling as above, the CO_2 removal and O_2 regeneration circuit of the submarine cabin is completed.

The process of SAWD CO_2 removal includes three cycle stages: absorption, desorption and cooling. The cabin's air with CO_2 is driven into the solid amine beds (reactionary pot) using an air blower, and the CO_2 is absorbed by the solid amine, then clean air is returned to the cabin after cooling by the cooling apparatus. CO_2 absorbed by the solid amine is desorbed by heating using steam from the steam generator, and transferred into the condenser with the steam. The steam passes into the cold water tank after condensation, and is pumped back to the steam generator to be used as reused water. After cooling and demisting, flow sensors detect the flow of CO_2, and then the CO_2 is compressed by the compressor and stored in the storage tank. This CO_2 acts as the reaction product in the Sabatier CO_2 reduction response.

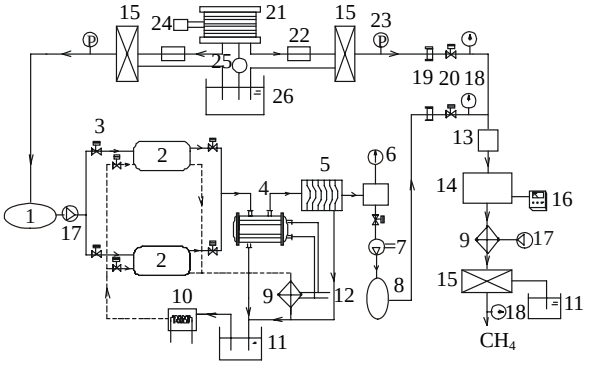

Fig.2 Schematic diagram of CO_2 removal and O_2 regeneration system

1: cabin; 2: canister; 3: regulating valve; 4: condenser; 5: mist eliminator; 6: flow sensor; 7: CO_2 compressor; 8: CO_2 tank; 9: cooler; 10: steam generator; 11: cold water basin; 12: cooling water; 13: gas-mix device; 14: Sabatier reactor; 15: moisture separator; 16: multi-point temperature recorder; 17: fan; 18: flowmeter; 19: filter; 20: pressure reducing valve; 21: battery pack; 22: heat exchanger; 23: pressure gauge; 24: power; 25: pump; 26: circulating water tank

The SPE electrolysis O_2 generating system is composed mainly of main devices like power, batteries, separators, heat exchangers and a circulation pump. Firstly, purified water and separated water goes to the electrolyzer, and some of the water is electrolyzed into H_2 and O_2. The remainder is exported from the electrolyzer through the anode outflow with O_2 after absorbing heat produced by the electrolysis process. After cooling by heat exchangers and separation by a moisture separator, the O_2 re-enters the cabin and H_2 goes into the CO_2 reduction system for use as a reducing agent.

ANALYTICAL METHODS

This study simulated the confined space environment of submarine cabins for the experimental condition of a 50-person loading. The input CO_2 was 0.5% (v/v) and the input quantity was 1000 L. The gas sent into system was CO_2 from gas cylinders and air mixed together using a fan.

The SPE membrane used by the electrolytic oxygen system was Nafion 117, a total fluorine sulfonic acid film about 0.2 mm thick. It has the same high-intensity physical characteristics as polytetrafluoroethylene (PTFE) films containing acid groups. They have excellent ion-conduction capability after water saturation. Because water is the only liquid in the system and is non-corrosive, the safety of the system is guaranteed. The concentrations of CO_2, H_2 and CH_4 on the imports and exports of the reactor were analyzed using gas chromatography (GC) (GC5890H, Nanjing Kejie Analysis Instruments Co., Ltd., China). The GC was equipped with an injector (220 °C), a hydrogen flame ionization detector (220 °C) and a 2 m×5 mm (length×inner diameter) stainless-steel column packed with a supporter of GDX-103 (60~80 meshes). The operation of the stainless-steel column was amenable to a temperature programming process from 100~200 °C, sampled per 5 min. An automatic sampling valve was used for injection. Computer programs were used to control the operation of the device and parameters were monitored using LONTEK marine products. Flow meters (LWQ, Anhui Zhongyuan Instrument Co., Ltd., China) were used to measure the gas flow. A multi-point temperature logger (XMD, Wuxi Zhonggang Instrument Co., Ltd., China) was used to detect the internal and external temperatures of the reactor and other relevant parts of the system. Electrical conductivity was measured using a DDS-11A (Shanghai Tianpu Instrument Co., Ltd., China) digital-conductivity meter. The concentrations of metal ions (Ru^{3+}, Al^{3+}, Pb^{2+}) and nonmetal ions (Cl^-, SO_4^{2-}) were measured with an automatic potentiometric titrimeter (ZD-2A, Shanghai Tianpu Instrument Co., Ltd., China).

RESULTS AND DISCUSSION

Performance of the CO_2 collection and concentration unit

The CO_2 adsorption-desorption performances of the JD solid amine collection and concentration unit were analysed using adsorption curves of desorption resins per cycle (Fig.3). The main indexes were the input CO_2 concentration, the uptake CO_2 concentration, the concentrated CO_2 concentration, and the CO_2 removal rate and air flow (Table 3). The outlet CO_2 concentration (Fig.3) was nearly zero in the first 45 min and was less 1/10 of the inlet CO_2 concentration after 60 min per cycle. The occurrence of a minimum in CO_2 adsorption between 60~80 min results from the physical and chemical characteristics of solid

amine. After the desorption reaction, bicarbonate ions cannot be completely desorbed from $(R_1R_2NH_2)HCO_3$. Through experimental detection, after desorbed solid amine resins are heated for 60 min, almost no remaining bicarbonate ions are desorbed from $(R_1R_2NH_2)HCO_3$. After heated for 20 min, bicarbonate ions are almost separated from solid amine reins. The input CO_2 quantity was 1000 L, the uptake CO_2 quantity was 950 L, the concentrated CO_2 concentration was 92%~97% and the CO_2 concentration after collection was 0.2% (Table 3), which showed that the adsorption-desorption performance of this unit was excellent, and that the quantity of output CO_2 could be controlled effectively.

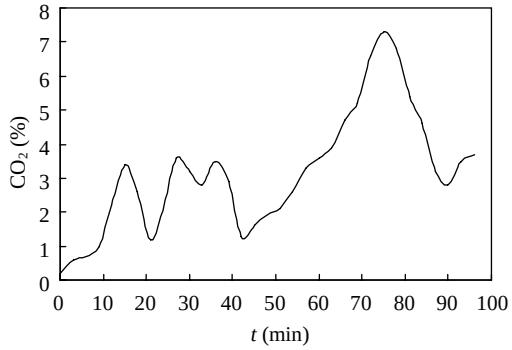

Fig.3 Adsorption curves of desorption resins per cycle

Table 3 Performance of CO_2 collection and concentration unit by JD solid amine

Parameter	Value
Air flow (m^3/h)	360~480
Solid amine dry weight (kg)	100
CO_2 input (L)	1000
CO_2 uptake (L)	950
CO_2 removal rate (L/min)	20
Concentrated CO_2 concentration (%)	92~97
CO_2 concentration after collection (%)	0.2
Solid amine life (d)	≥90
Situation to cabin pollution	No pollution

The experimental results showed that the CO_2 collection and concentration unit was relatively successful and the system could be controlled effectively and operate continuously. CO_2 removal in a submarine cabin using the weak alkaline JD solid amine resin is based on some chemical reactions. Amines and water form hydrated amine, and then form bicarbonate with CO_2. By heating amine with steam, the bicarbonate decomposes and releases CO_2. The equation is

$$R_1NHR_2+CO_2+H_2O\rightarrow(R_1R_2NH_2)HCO_3. \quad (4)$$

Performance of the CO_2 reduction unit

In the CO_2 reduction unit, we mainly investigated the start-up and reaction performance of the Sabatier reactor. The performance indexes included:

(1) Start-up time and start-up temperature: we started the experiments at different temperatures and recorded the times from stopping heating to arriving at a reaction balance. Table 4 shows the relationship between start-up time and temperature when the mole ratio of CO_2 and H_2 was 1:4. The start-up time of the Sabatier reactor was 6, 8 and 10 min when the start-up temperature was 187.3, 179.5 and 168 °C, respectively. The higher the start-up temperature, the shorter the start-up time.

Table 4 Start-up temperature and time of the Sabatier reactor

Parameter	Experiment		
	1	2	3
Start-up temperature (°C)	187.3	179.5	168.4
Balance temperature (°C)	452.3	449.7	450.8
Start-up time (min)	6	8	10

(2) Reaction conversion: we calculated the reaction conversion of the poverty component under different conditions. Reaction rate and conversion were the main evaluation indexes of Sabatier reactor performance. Table 5 shows the effects of H_2/CO_2 on reaction conversion. When H_2/CO_2 was more than 4.0, CO_2 conversion rates were calculated; when less than 4.0, H_2 conversion rates were calculated. After achieving inlet air balance, temperatures were different everywhere in the Sabatier reactor. The reaction rate was high because of high temperature. A high temperature could improve the activated energy. However, a lower temperature would improve the balance conversion, and reduce the production of by-products. A moderate temperature could ensure not only a high reaction rate but also a high reaction conversion. Three pieces of data were recorded by a multi-point temperature recorder. The maximum equilibrium temperature in the front of the Sabatier reactor was 456.3 °C; the equilibrium temperature in the middle was 268.4 °C; and the minimum equilibrium temperature in the back was 203.5 °C.

Table 5 Effects of the molar ratio of H_2/CO_2 on conversion efficiency

No.	Inlet air			Outlet air			Conversion rate (%)	
	H_2 concentration (%)	CO_2 concentration (%)	Mole ratio H_2/CO_2	CH_4 concentration (%)	H_2 concentration (%)	CO_2 concentration (%)	H_2	CO_2
1	85	18	4.72	43.6	16.4	0.9		98.6
2	82	20	4.10	83.9	8.5	2.1		97.3
3	78	23	3.39	68.6	15.6	16.6	94.9	
4	72	26	2.77	52.7	11.2	31.7	95.4	
5	68	33	2.06	32.6	5.1	58.6	97.8	

(3) Product water quality: the pH, impurity concentration and electrical conductivity of the product water were measured. The product water was colorless and transparent, and had a pH of 6.9~7.5, and an electrical conductivity of 80 μs/cm. The sum of the concentration of metal ions (Ru^{3+}, Al^{3+}, Pb^{2+}) was 0.028% and that of nonmetal ions (Cl^-, SO_4^{2-}) was 0.05%. Water quality was relatively pure and could be used for electrolysis after further treatment and decreasing the electric conductivity.

Performance of the SPE electrolysis O_2 regenerator unit

The core component of electrolytic O_2 regeneration was the electrolytic battery. The structural design of the battery affected its electrochemical performance. The experiment tested mainly the effect of temperature on the electrolysis current density and voltage. The relationship between electrolysis voltage and electrolysis water temperature under different temperature conditions is shown in Fig.4. The higher the water temperature, the lower the electrolysis voltage. The reason was that the changes in enthalpy were less than Gibbs free energy when water was electrolyzed. The higher temperature was better for electrolysis. It was easy to stabilize the electrolysis tank temperature by regulating the supply of water. The electrolytic performances were all stable at various temperatures. This showed that the electrolytic cell structure ensured uniform distribution of electrolysis water and smooth excretion of air products.

The stability of a battery for prolonged operation was investigated by conducting experiments on battery structure performance. The cell stack temperature was 37 ºC and the total current was 42 A. Fig.5 shows the change in the curve of electrolytic current and voltage with time during the whole trial period. The voltage data were obtained from the electrolytic power output, and the voltage drop was 1.22 V. The voltage from power was 16.2 V, and the voltage sent directly into the cell stack was 15.0 V. During 34 days, the electrolysis voltage remained steady, showing that the electrochemical cell had stable performance. From the 6th to the 10th day, the electrolytic current was artificially increased to 48 A, which was used to make up for the consumption of the hydrogen storage tank. After stabilizing to the first set cabin oxygen concentration on the 12th day, the current then changed back to 42 A. There was no significant change in voltage in the process of a slight increase in current. The battery polarization curve eventually levelled off (Fig.5). Changes in current were introduced by small voltage changes. However, a battery-heat up might cause the battery temperature to rise slightly, and the electrolysis voltage to reduce. Therefore, the overall electrolysis voltage was not obviously influenced by electrolytic.

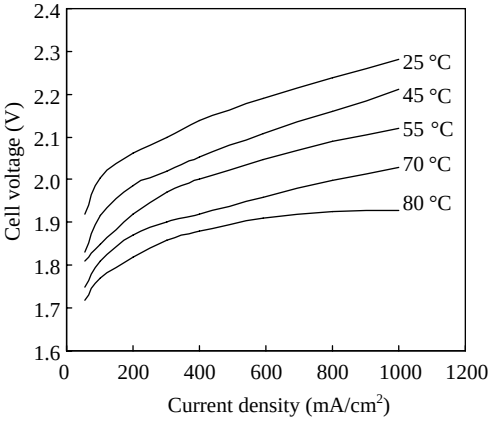

Fig.4 Relationship between current density and voltage at different temperatures

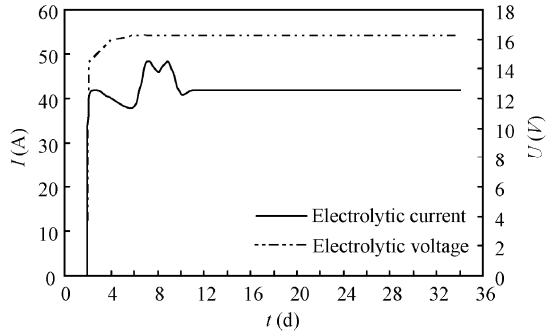

Fig.5 Relationship between electrolytic current, electrolytic voltage and time

Performance of the matching CO_2 removal and O_2 regeneration system

The matching CO_2 removal and O_2 regeneration system was designed to work under 50-person experimental conditions. CO_2 from the SAWD collection and concentration unit and H_2 from the SPE electrolysis unit were sent to the Sabatier CO_2 reduction system. To enhance the security of the system, the recovery of CO_2 concentration was more than 90%. The CO_2 concentration in the experiment was set around 96%. The experimental results of the matching CO_2 removal and O_2 regeneration system are shown in Table 6.

The experimental results showed that solid amine regenerative CO_2 controllable technology, Sabatier CO_2 reduction technology and SPE O_2 regeneration by electrolysis technology could achieve CO_2 emissions and a certain amount of O_2 regeneration. The capacity of O_2 disposal could meet demands. The input CO_2 concentration was 0.5%, while the average CO_2 concentration was more than 96%. The output CO_2 concentration in the submarine cabin was lower than 0.2%. O_2 production can meet the crew's basic oxygen demands.

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Table 6 Experimental results of the matching CO_2 removal and O_2 regeneration system

Cycle	CO_2 input (L)	CO_2 uptake (L)	Average concentration (%)	Collection capacity (L)	CO_2 reduction amount (L)	O_2 production (L)
1	1000	950	95.3	620	–	–
2	1000	960	96.0	650	630	2400
3	1000	960	96.7	650	630	2400
4	1000	960	96.2	650	630	2400
5	1000	960	96.4	650	630	2400

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