Research on energy-saving conventional submarine air-conditioning system based on heat and humidity load calculation

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Abstract. The built-in air-conditioning and ventilation system of modern conventional submarines still adopts duct ventilation, which has high working noise, high energy consumption, poor dehumidification effect, and is mainly inter-cooled. For the air quality, hot and humid environment and comfort requirements in the submarine cabin. This project proposes an energy-saving cold storage air-conditioning system suitable for submarines. It adopts the air control method of temperature and humidity independent processing, and combines solution dehumidification and cold storage technology to independently control the temperature and humidity of the cabin, so as to achieve the purpose of efficient dehumidification and energy saving. The system makes full use of the limited space inside the submarine, reduces the energy consumption of refrigeration, improves the underwater endurance and concealment, and provides a healthy and comfortable air environment for the crew of the submarine, which has important strategic value.

Key words: submarine; air conditioner; heat load calculation; cold storage and energy saving.

1. Introduction

1.1 Research background

Due to the particularity of the internal working environment of the submarine and the harshness of the changeable working conditions, the navies around the world have put forward strict requirements for the air quality of the submarine cabin. The cabin atmospheric environment control level is regarded as an important indicator to measure the overall performance of the submarine. The status is second only to the weapon equipment system.

The air conditioning and ventilation systems built into modern conventionally powered submarines still use ducted ventilation[1]. The working noise is high, the energy consumption is high, the dehumidification effect is poor, and the intercooling type is mainly used. Taking the submarine intercooling air-conditioning system as an example, the system generally only regulates the temperature and humidity of the air in a centralized manner, the temperature difference of the supply air is small, and the ambient humidity is high[2]. The ideal dehumidification effect cannot be achieved through this air-conditioning refrigeration system alone, and the relative humidity is kept above 60%, which easily affects the life and working stability of various precision electronic instruments and equipment [3]. And relevant data show that the power consumption of the air-conditioning device during the underwater navigation of the submarine is nearly 37% of the electricity consumption of the whole boat, which greatly affects the concealment, mobility and underwater endurance of conventional submarines. Therefore, it has certain strategic significance to enhance the dehumidification ability and energy-saving effect of the submarine air-conditioning system[4].

Based on the above-mentioned requirements for energy saving and efficient dehumidification of the air-conditioning system of the submarine, this project proposes a cold storage and energy-saving submarine air-conditioning system with high efficiency and dehumidification. The purpose is to enhance the ability of the submarine air-conditioning system to independently handle heat and humidity loads and the ability to store and release cold, and reduce the energy consumption of the air-conditioning system under the premise of ensuring the stability of the system[5]. Improve the comfort of cabin personnel, the stability of precision electronic instruments and equipment, and the underwater navigation endurance of submarines.

1.2 Research progress at home and abroad

Jiang et al. studied the purification technology of CO2 in submarine cabins, and summarized the process and advantages and disadvantages of physical purification, chemical absorption and biological purification from the device and principle[6]. Wang and others reviewed the air treatment technology of submarine cabins, and pointed out that the CO2 treatment, O2 regeneration, electrostatic precipitator and exhaust gas combustion technology of conventional submarines are combined with air-conditioning box, filter, fan, heat exchanger, dust collector and combustion chamber. submarine air conditioning system. Through research, Qin and others pointed out that each air conditioner in the conventional submarine air system operates day and night, producing about 200kg of condensed water a day. And water quality analysis shows that the condensed water of the air conditioner contains a lot of oil, less minerals, and bacteria exceeding the standard. It cannot be directly used as domestic water, so it is mostly discarded[7]. Xie et al. took the US "Sea Wolf" nuclear submarine as an example to study the air conditioning method, and pointed out that the system draws out the polluted gas from each cabin and sends it to the mechanical filter, electrostatic precipitator and activated carbon filter first. It is then sent to the CO2 removal system for processing[8].

Cheng invented a closed-circuit water cycle semiconductor refrigeration and dehumidification air conditioning device, which can meet the dehumidification and heat dissipation requirements of certain relatively independent closed cabins of submarines and ships for precision instruments[9]. Among them, the drainage pipe of the water collecting tray diverts the condensed water to the water storage tank, which helps to form a circulating water utilization[10]. Liu g and others tested the air-conditioning system of hospital buildings and showed that the air-conditioning system with independent temperature and humidity treatment can save at least 25% energy than conventional air-conditioning. Peng and others discussed the submarine liquid dehumidification air conditioning system, and analyzed the necessity and feasibility of liquid dehumidification air conditioning applied to submarines[11]. M.Krause et al. constructed a static simulation model of dehumidification air conditioner based on rotary dehumidification, and studied the influence of the optimal outlet temperature of regeneration air in the heater, wheel speed, and discharge volume of regeneration air on COP. The driver provides guidance[12].

2. Calculation and classification of submarine working conditions

2.1 Conditions of conventional submarines

When a submarine is put into use in the sea area, there are generally four navigation states: surface navigation state, snorkel navigation state, semi-submersible navigation state, and underwater navigation state[13]. For conventional submarines, snorkel state and underwater navigation state are maintained most of the time. Some operating conditions of the power system of AIP submarine electric propulsion mode are shown in Table 1:

Table 1. Working conditions of the power system of AIP submarine electric propulsion mode

working condition	working power system	specific implementation
Surface and snorkel sailing	Diesel generator sets	Electricity is supplied to the propulsion motor and auxiliary machinery of the whole boat
Surface and snorkel sailing charging	Diesel generator sets	Part of the electrical energy is supplied to the propulsion motor; Distributed power for various electrical equipment; The rest are supplied to the battery pack for charging
underwater sailing	AIP system or battery pack	Part of the electrical energy is supplied to the propulsion motor, and part of the electrical energy is supplied to the electrical equipment

2.2 Cabin heat load

The mechanism by which the mechanical and electrical equipment, personnel and lighting heat sources inside the submarine are converted into heat loads is the same as that in the onshore buildings . In this calculation, four parts of lighting heat dissipation, human body heat dissipation, indoor process equipment heat dissipation, and pipeline heat dissipation are used to calculate the heat load of the cabin. The total sensible heat load of the living area excluding the canteen can be calculated according to the following formula:

$$Q = Q_l + Q_p + Q_s + Q_i + Q_a$$

Q - total sensible heat load, W; Q_l -- The heat dissipation load of lighting equipment, W; Q_p -- the load formed by the heat dissipation of the human body, W; Q_s -- the load formed by the heat dissipation of the equipment, W; Q_i - incoming heat around the cabin, W; Q_a - duct infiltration heat, W.

2.3 Load Qs formed by equipment heat dissipation

The cooling load at the calculation time formed by the heat dissipation of the thermal equipment and the hot surface can be calculated by the following formula:

$$Q_s = Q_{s1} \cdot C_{LQ1}$$

Q_s - cooling load due to heat dissipation from thermal equipment and hot surfaces, W; Q_{s1} -- Actual sensible heat dissipation of thermal equipment and hot surface, W; C_{LQ1} -- Cooling load coefficient of sensible heat dissipation of thermal equipment and hot surface, if the air-conditioning system is not running continuously, CLQ1=1.0 is preferable.

2.4 Load Q_{s1} formed by electric equipment

When the process equipment and its motor are both indoors:

$$Q_{s1} = 1000 n_1 \cdot n_2 \cdot n_3 (N / \eta)$$

N -- Installed power of motor equipment, kW; η -- motor efficiency, take 0.9; n1 -- Utilization coefficient, take 0.8; n2 -- motor load factor, take 0.5; n3 -- Coefficient of simultaneous use, take 0.5.

2.5 Incoming heat Q1 of non-air-conditioned cabin

Except for professional cabins equipped with independent air-conditioning equipment without heat exchange, the rest of the cabins are non-air-conditioned cabins with heat exchange.

$$Q_1 = \sum h \cdot A \cdot \Delta t$$

Q_1 -- Incoming heat from non-air-conditioned cabin, W; h -- heat transfer coefficient of bulkhead of non-air-conditioned compartment, to be taken as $0.9 W/m^2$, K; A — bulkhead area of non-air-conditioned compartment, to be taken as $10 m^2$; Δt-- The temperature difference between the non-air-conditioned cabin and the room, to be taken as 25℃.

2.6 Incoming heat Q_2 from upper and lower bulkheads

There are two forms of room wall insulation structure, one is the inner bulkhead insulation; the other is the outer bulkhead insulation. Consider the incoming heat Q_2 of the two battery compartments to the air-conditioning compartment.

$$Q_2 = \Sigma h \cdot A \cdot \Delta t \cdot$$

Q_2 -- (summer) incoming heat in the cabin, W; A -- heat transfer area of bulkhead, take 35m2; h - bulkhead heat transfer coefficient, to be taken as 0.9W/; Δt -- temperature difference of heat transfer bulkhead, taken as 25℃.

3. Heat and humidity load calculation enthalpy-humidity diagram

3.1 Underwater navigation (pure return air)

When the submarine sails underwater, oxygen mainly comes from Figure 1. Oxygen production by electrolysis of water; 2. Oxygen supply by oxygen candles and oxygen by super (super) oxide; One of the methods, and the third method is the new technological development direction in the field. The above three methods are mainly based on chemical reactions. It can be seen that the oxygen consumed by the crew when the submarine sails underwater without the introduction of fresh air comes from the supplement of chemical reactions. Figure 1 shows the submarine atmospheric environment control process and the schematic diagram of the air handling unit of the project system. Among them, 1-air valve, 2-air filter, 3-fan, 4-temperature and humidity processor, 5-air heater, 6-air purification system, 7-CO_2 filter, 8-O_2 regenerator, 9- Other equipment of air regeneration system in submarine atmospheric environment control system, 10-air purification and regeneration system of submarine atmospheric environment control system [14].

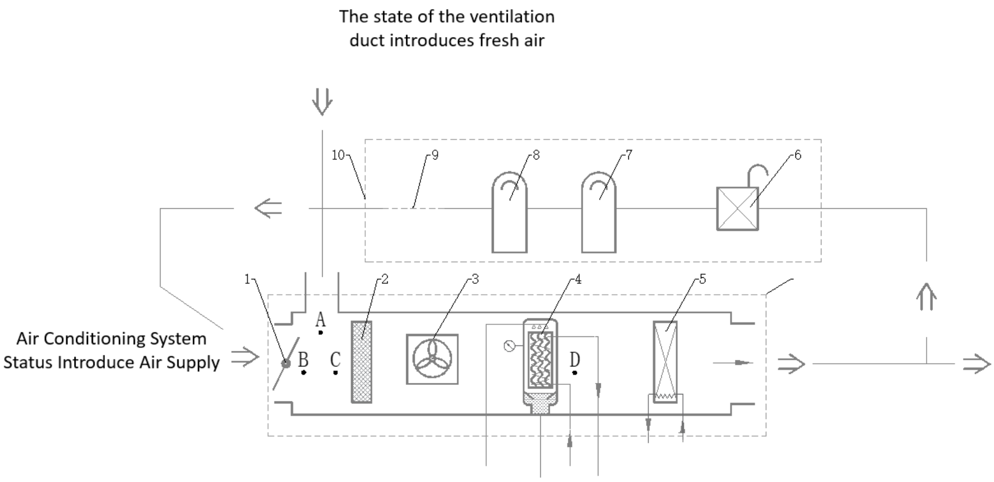

Figure 1. Atmospheric environment control system for underwater navigation

After passing through the indoor air state point B, make an isothermal-humidity ratio line and cross the isothermal line t=15°C with point D.

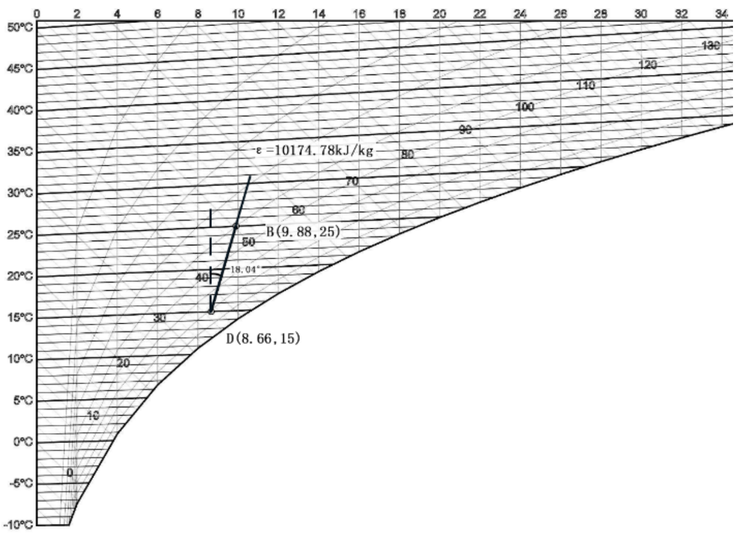

Figure 2. Enthalpy-humidity diagram of pure return air

3.2 Navigation on the water surface or snorkel (with fresh air)

3.2.1 Drawing of enthalpy-humidity diagram with fresh air

The submarine sails on the surface or in the snorkel state, and the atmospheric environment control system incorporates fresh air[15]. Point A represents the air outside the boat, point B represents the air inside the boat, point C represents the air mixed with the fresh air and return air, and point D is the air that has been dehumidified and cooled by the solution.

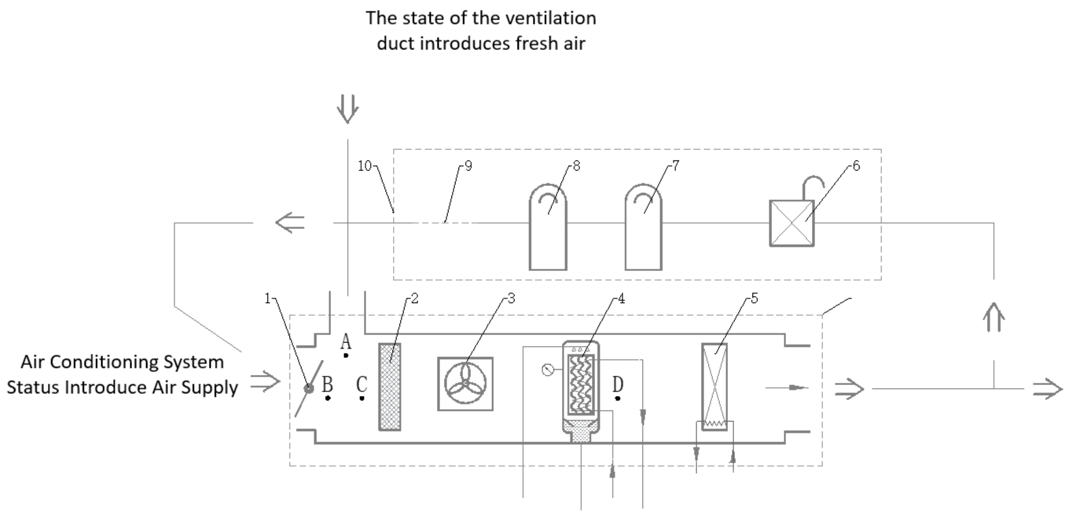

Figure 3. Atmospheric environment control system under the sailing state of the snorkel

3.2.2 The state of the mixing point C of the fresh air and the return air

Take the fresh air ratio as 0.5, then VA=VB. By mass conservation:

$$\rho_A V_A + \rho_B V_B = \rho_C (V_A + V_B)$$
$$\rho_A + \rho_B = 2\rho_C$$

By conservation of energy:

$$\rho_A V_A h_A + \rho_B V_B h_B = \rho_C V_C h_C$$
$$\rho_A h_A + \rho_B h_B = 2\rho_C h_C$$

Conservation by humidity:

$$\rho_A V_A d_A + \rho_B V_B d_B = \rho_C V_C d_C$$
$$\rho_A d_A + \rho_B d_B = 2\rho_C d_C$$

Solutions have to:

$$\rho_C = 1.1653\text{kg/m}^3$$
$$h_C = 67.22\text{kJ/kg}$$
$$d_C = 15.70\text{g/kg}$$

Since some equipment such as oxygen generators do not work when in the state of the snorkel or on the water surface, the latent heat load and sensible heat load in the cabin are taken as 0.95 times that of the underwater sailing, so the heat-moisture ratio and the pure return air state at this time are same below[16].

After passing through the indoor air state point B, make an isothermal-humidity ratio line and cross the isothermal line t=15℃ with point D.

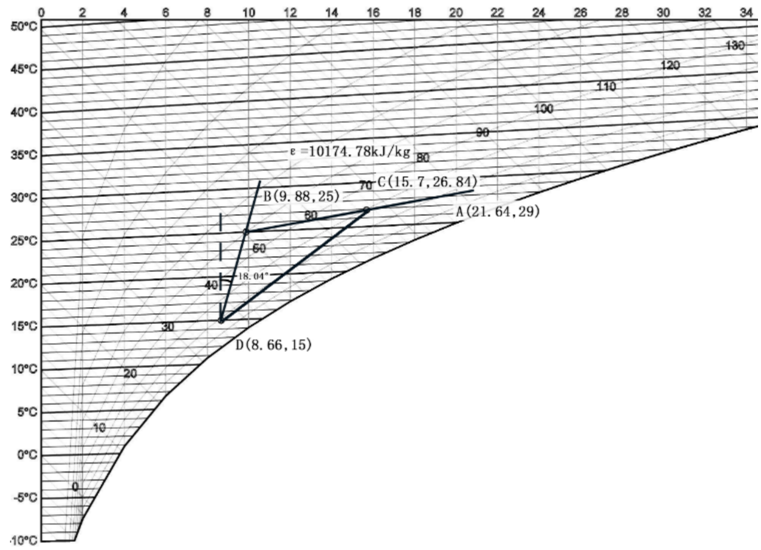

Figure 4. Enthalpy-humidity diagram with fresh air

4. Feasibility analysis and implementation plan of refrigeration unit of cold storage system

4.1 System operation parameter scheme

4.1.1 Solution dehumidification

The solution dehumidification system mainly includes temperature and humidity processor, solution regenerator, solution pump, concentration meter, electromagnetic three-way valve, concentrated solution tank [17]. Based on the strict requirements on the hygroscopic performance and stability of the dehumidifier in the high humidity environment inside the submarine, the dehumidifier of the solution dehumidification module is planned to use a mixed solution of calcium chloride and zinc chloride with a substance ratio of 1:1. The relevant papers show that , The mixed solution of calcium chloride and zinc chloride has the ability to wash the air, and can properly remove impurities, aerosols, etc., and further clean the air [18].

4.1.2 Schematic diagram of cold storage technology

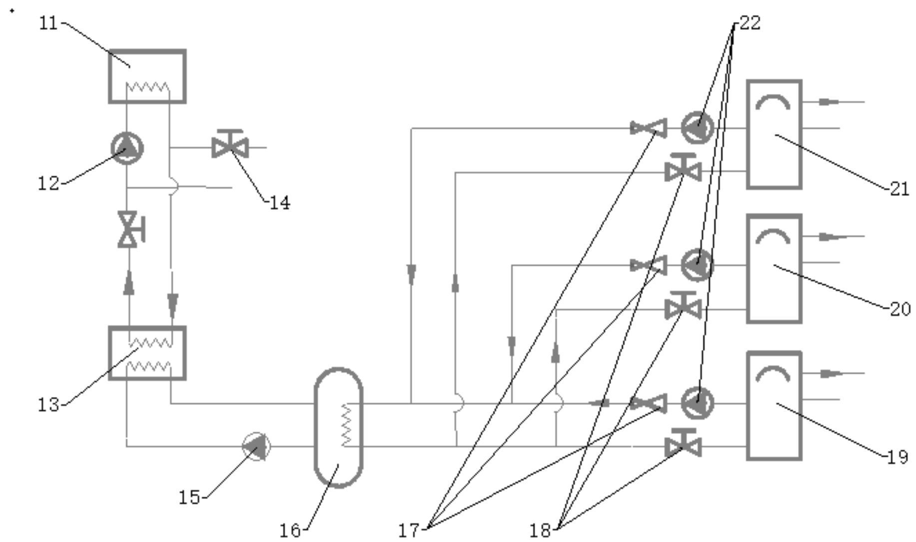

Figure 5. Schematic diagram of cold storage technology

The cold storage system mainly includes an ice storage pump, a throttle valve, an ice storage tank, and an ice melting pump. Generally, conventional submarines have three air-conditioning zones, and each air-conditioning zone is equipped with an indirect cooling centralized circulation air-conditioning system. When the submarine is sailing in the snorkel state, the idle refrigeration unit stores the cold storage system. When the submarine is in the underwater navigation state, the cold energy stored in the cold storage system can be used to replace the refrigeration unit in a certain area as the surface cooler of the air handling unit in that area. For cooling, the refrigeration unit in this area can be turned off, so as to reduce the energy consumption and noise of underwater navigation, and the other two areas are still cooled by their respective refrigeration units for the air handling unit.

4.1.3 Treatment of evaporated water vapor

The water vapor evaporated from the concentrated solution of the desiccant through the seawater heat exchange system needs to be condensed. The project team proposed two schemes for water vapor condensation. One is to use the cooling seawater of the seawater cooling system as the water vapor cooling water, and the other is to use the refrigerant water of the air conditioning system as the cooling water for the water vapor. However, using the second scheme will increase the heat load of the system. . Option 1 is temporarily adopted in this system to collect and utilize the condensed water vapor. The feasibility of option 2 will be analyzed and compared in subsequent studies. The water vapor generated in the dehumidification system is of high quality after being collected by condensation. It can be connected to the fresh water treatment system, and then sent to the fresh water tank for storage, or as a supplementary distilled water for the electrolyte of the submarine battery, so as to be further recycled.

4.2 Feasibility analysis under the condition of fresh air

4.2.1 Feasibility analysis of refrigeration unit under fresh air condition

The principle of applying regenerative air-conditioning technology to conventional submarines is that when the submarine is charging and sailing on the water (or snorkel), the surplus power of the diesel generator set is used to start the regenerative air conditioner for cooling.Residual power = generator available power - battery charging power - auxiliary engine power - propulsion motor power

Table 2. Residual power of submarine snorkel at each stage

Remaining power of submarine snorkel at each stage						
stage	I	II	III	IV	V	VI
residual power	276	276	184	92	690	92

The submarine refrigeration unit adopts three 4FVT reciprocating refrigeration compressors. The power required for the cold storage of the three units is about: compressor power consumption + glycol pump power consumption = 49.5kW

From this calculation, it can be seen that the diesel generator set still has a surplus power supply device for cooling after meeting the energy required for battery charging and the power consumption of auxiliary machines. If the charging at sea is used, the auxiliary power is reduced, so the remaining power is more. Therefore, in the state of fresh air, the refrigeration unit can meet the demand.

5. Conclusion

This project calculates the heat and humidity load related to the submarine to determine the cooling capacity of the air conditioner. The parameters of the two core systems of temperature and humidity independent processing and cold storage and their corresponding system components such as dehumidifier, air cooler, ice storage tank and surface cooler are designed. And select the appropriate dehumidifier and refrigerant. Two cooling schemes for water vapor are designed and compared after calculation and analysis, and the better cooling scheme is selected. Relying on physical data to analyze and process the dehumidification capacity and energy-saving effect of the system, reasonably evaluate the advantages and disadvantages of the system and further optimize the design scheme.

References

[1] Fang Xiaomin, Song Yichao, Naval Military Representative Office in Guilin, et al. Status and development trend of AIP system technology of foreign conventional submarines [J]. Ship Power Technology, 2015, 35(01): 40-4.

[2] Peng Guangming, China Ship Research and Design Center, Wuhan. Analysis of Oxygen Supply Measures in Submarine Airtight Chambers [J]. Ship and Marine Engineering, 2005, 05): 69-72

[3] Guo Fengtao, Liu Zhongquan, Wang Jinzhong, Chen, et al. Allowable concentrations of air components in the cabin of conventionally powered submarines [J]. PLA Journal of Preventive Medicine, 1994, 04): 255-8

[4] Peng Guangming. Research on atmospheric environment control system of AIP submarine cabin [J]. Chinese Ship Research, 2006, 02): 62-5.

[5] Miao Zhixin, Lian Zhiwei, Zhang Xiaojing, et al. Investigation and actual measurement of residential wet environment in Shanghai in winter [J]. Refrigeration and Air Conditioning (Sichuan), 2017, 31(01): 28-33

[6] Geng Shibin, Guo Hailin, School of Engineering, PLA University of Science and Technology, et al. Humidity load calculation of dehumidification equipment in underground buildings; proceedings of the National HVACR 2000 Academic Annual Conference F,2000 [C].

[7] Zhong Xuexue, Shu Mingjun, Second Artillery Engineering University. Calculation of internal heat and humidity load in underground engineering [J]. Clean and Air Conditioning Technology, 2013, 02): 64-7

[8] He Guohui, Zhong Minjun, Gao Xiang. Transfer function method for calculating the heat load of submarine air-conditioning [J]. Journal of Naval Engineering University, 2002, 03): 45-8+58.

[9] Ma Yunyi. Theory and Technology of Modern Submarine Design [M]. Harbin: Harbin Engineering University Press, 2012.

[10] Lei Yi. Research on design optimization of conventional submarine lighting system [J]. Ship Power Technology, 2017, 37(05): 30-2.

[11] Ma Zuiliang, Yao Yang. Civil Building Air Conditioning Design 3rd Edition [M]. Beijing: Chemical Industry Press, 2015.

[12] Zhang Xing, Chen Ning. Thermal design optimization of high-power submarine power equipment based on FLoEFD [J]. Mechanical Engineering and Automation, 2018, 2): 81-3.

[13] Diao Sufang. Thoughts on the selection of design parameters of HVAC system for offshore oil platforms [J]. Petroleum and Chemical Equipment, 2020, 23(06): 8-10.

[14] Zhong Minjun, Chen Jinzeng, Wu Gang. Energy consumption analysis and energy saving research of a certain type of submarine air conditioner [M]. Proceedings of the 2006 National Conference on Ship Mechanical and Electrical Maintenance Technology. Wuhan. 2006: 391-6.

[15] Li Fucai. Drawing method of heat-moisture ratio line in commonly used enthalpy diagram [J]. HV&AC, 2015, 45(5): 56-8.

[16] Min Yong, Yang Lijuan, Teng Liang. In the design of primary return air conditioning system Analysis of several common problems [J]. HVAC HV&AC, 2009, 39(5): 130-4.

[17] Wu Zanxia, Wu Gang, Zeng Qianghong, et al. Numerical Simulation of Cool Storage Materials Applied to Submarine Air Conditioning [J]. Fluid Machinery, 2008, 36(5): 75-8,34.

[18] Wu Gang, Zeng Qianghong, Chen Jinzeng, et al. Research on using cold storage air conditioner to improve submarine underwater endurance [J]. Ship and Ocean Engineering, 2006, 35(6): 67-9.