Comprehensive utilization system of waste heat of hydrogen fuel cell powered ship

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Abstract: At present, about 50% of the energy of hydrogen fuel cells is converted into heat energy loss, and the comprehensive energy utilization technology is still immature. For the transport ship powered by proton exchange membrane hydrogen fuel cell, a set of comprehensive waste heat utilization system was designed through theoretical calculation and simulation analysis. A set of self-adaptive controllers with PLC (Programmable Logic Controller) as the core and fuzzy PID (Process Identification) control law based on the collected operating parameters and environmental parameters of each module was developed to control the input energy of each module. Based on the fuel cell-powered green ship technology, this system realizes the cogeneration of low-grade heat sources of hydrogen fuel cells, which greatly improves energy utilization efficiency. The results can promote the application of fuel cells in ships.

1. Introduction

Research shows that fossil energy-powered transport vessels emit 15% and 13% of total human pollution sources each year. As world trade volume increases year by year, pollution emissions from shipping also continue to rise. Promoting the application of clean energy on ships is the future development trend.

Fuel cells can directly convert chemical energy into electrical energy. It is not limited by the Carnot cycle and has a high energy conversion rate. Its reactants contain almost no nitrogen and sulfur oxides. It is a clean and efficient new energy power device. At the same time, it has the advantages of noise-free, modular and continuous work. Compared with other types of fuel cells, proton exchange membrane hydrogen fuel cells have more advantages in terms of energy density, applicability and economy, and are the first choice for current fuel cell power boats. The Energy Technology Revolution and Innovation Action Plan (2016-2030) clarifies the goals and routes of hydrogen energy and fuel cell technology innovation. With the support of national policies for the hydrogen energy industry and the maturity of fuel cell technology, the overall cost is declining. Hydrogen fuel cell powered ships are the most promising green ship solutions to reduce ship emissions in the future [1].

It is reported that the United States will build the first hydrogen-oxygen fuel cell ship to be delivered and put into operation in September 2019; the French Sogestran Group is advancing a new hydrogen fuel cell ship sailing on the Rhone River, which Delivered in 2021; Japan regards fuel cells as a major part of its new energy strategy; and the discipline of "Power Electronics and Power Transmission" at Shanghai Maritime University in China has established a "Fuel Cell Power Propulsion" laboratory dedicated to fuel cell ships. At present, the fuel cell ship is in the research and
development stage, and no related report considering the comprehensive utilization of energy of the fuel cell system has been seen \(^2\).

![World's First Commercially Operated Fuel Cell Ship](image)

Figure 1. World's First Commercially Operated Fuel Cell Ship

Among the three main ways of using solar energy, solar thermal utilization is the most widely used and the most diverse. The combination with the building can provide the building with the required energy consumption for domestic hot water, heating, ventilation, and cooling, effectively reducing consumption of conventional energy in buildings, low carbonization of buildings, and even "zero energy consumption", provide people with good home living space. The research content of this project is a new type of solar heating system based on oil-water staged heat collection mode applied in buildings.

2. Design of comprehensive utilization system of waste heat from hydrogen fuel cell power ship

2.1. Temperature control module

The secondary lithium bromide absorption refrigeration can make full use of hot water at 70-80 °C as the driving heat source. After testing, the unit can operate normally when the heat source is 66 °C. The \(\xi\) (thermal coefficient) of the refrigeration unit is about 0.3 to 0.4, and a large flow of hot water is required as a heat source during operation. It is very suitable for integrated application with a fuel cell system. At the same time, the normal operation of the unit requires a large amount of cooling water. Compared with land, it has more advantages in ship applications. In the high-pressure stage cycle, the dilute solution from the high-pressure absorber is heated and concentrated in the high-pressure generator, and the generated water vapor condenses in the condenser. The concentrated solution enters the high-pressure absorber through the high-pressure heat exchanger and absorbs the low-pressure generator. Water vapor, the dilute solution after absorbing water vapor is boosted by the solution pump, and then re-enters the high-pressure generator through the high-pressure heat exchanger to complete the high-pressure cycle. The dilute solution from the low-pressure absorber is heated and concentrated in the low-pressure generator. Water vapor is absorbed by the high-pressure absorber. The concentrated solution enters the low-pressure absorber through the low-pressure heat exchanger and absorbs the water vapor from the evaporator. The dilute solution is boosted by the solution pump and re-enters the low-pressure generator through the low-pressure heat exchanger \(^3\).

The heating module uses plumbing and heating air devices, uses the cooling water of the fuel cell as a heat source, and introduces heat exchangers in the plumbing and heating air devices through hot water pipes to heat the air sent by the fans to generate warm air. The air duct, the air door, and the air pipe connected to the casing are sent out.

The RTD temperature sensor monitors the cabin temperature in real time, the signal is input to the RTD module of the PLC, and the cabin temperature is controlled by the energy management device.

2.2. Vacuum boiling desalination module

The cooling water of the fuel cell passes the flow distribution device along the pipeline and enters the water generator as a heating medium. The degree of vacuum in the water generator reaches the corresponding temperature so that the drawn outboard water boils at this temperature and then
condenses, and is stored in The daily fresh water tank is used as the daily production and domestic water for ships. When the fuel cell cooling water is insufficient or needs to be replaced, the produced fresh water enters the equipment’s circulating water tank and is used for fuel cell cooling after temperature and flow adjustment.

If it is parked, the modules will not work, and the fuel cell cooling water will directly enter the self-circulating water tank. After temperature and pressure adjustment, it will re-enter the fuel cell [4].

3. Energy management device
The energy management device uses ABB AC500 series PLC as the core and adopts fuzzy PID control algorithm to realize the comprehensive utilization of waste heat through cooling, heating and desalination devices of cooling water generated by hydrogen fuel cells. The operation output of the fuzzy PID control law controls the working water distribution, realizes the automatic switching of the mode, and accurately controls the room temperature, efficient lightening, monitoring and alarm functions. The PID control and fuzzy control are combined, and the three parameters of the PID control are adjusted by the fuzzy PID controller, which improves the control effect. The combination of PLC and man-machine interface can give full play to PLC’s powerful working efficiency and performance, as well as the advantages of intuitive and easy monitoring of HMI technology, thereby improving the overall human-computer interaction and control performance of the system [4].

Figure 2. Touch screen man-machine interface

The functions implemented by the system include: data collection and display functions, fault alarm and protection functions, work mode switching, energy distribution, data storage, and report output.

1) Data acquisition and display function: It can monitor and display the system working status in real time, which is convenient for personnel operation and management.

2) Fault alarm and protection function: When the system parameters are abnormal, the control system will immediately protect and alarm.

3) Working mode switching: The system controls the starting and stopping of each working pump and the opening and closing of valves through the touch-screen buttons on the upper display.

4) Energy distribution: The system adjusts the flow rate delivered to each module according to the monitoring data, thereby adjusting the working status of each module.

5) Data storage and report output: It is convenient for the staff to query and analyze historical data, provide parameter guidance for the optimization and improvement of the system, and establish a database to store and manage the historical data of the system.

4. Project innovation
(1) For hydrogen fuel cell powered ships, a comprehensive waste heat utilization system for cooling, heating and desalination modules driven by fuel cell cooling water is proposed to realize combined heat and power and improve energy efficiency;

(2) With PLC as the core and fuzzy PID control algorithm, the working water distribution is controlled according to the operating parameters of the fuel cell and each module, environment and
cabin real-time temperature, so as to realize automatic switching of the system working mode, accurately control the cabin temperature, and efficiently control Lightning and monitoring alarm functions [5].

5. Fuel cell cooling water

Fuel cell with power $P_{st} = 110$ kW, chemical input $Q = 328$ kJ per second of fuel input, removing the energy used for power generation and the chemical energy contained in hydrogen that is not participating in the reaction, and the remaining energy is converted into thermal energy. Part of the heat energy is taken out by the two-stage exhaust gas with $Q = 42$ kJ, which is exchanged with the cooling water in the heat exchanger. The efficiency of the heat exchanger is 50%. 2% of the remaining heat energy is used for humidification of the waste heat, 3% is lost due to heat radiation and convective heat transfer, and the rest of the heat energy is taken away by the cooling water and enters the waste heat utilization system.

The inlet temperature $T_{st.in}$ of the hydrogen fuel cell cooling water produced by Guangdong Guohong Hydrogen Energy is 66°C, the outlet temperature is $T_{st} = 76$°C, the inlet and outlet temperature difference is 10°C, and the mass flow is 2.97 kg/s.

After consulting the design standards for marine air-conditioning, combined with the power of the refrigeration and heating equipment designed by this system, ANSYS was used to carry out a simulation analysis of the cabin temperature distribution to reasonably set the cabin air supply temperature and air supply volume in winter and summer.

After the heating mode is turned on in winter, it can be seen from the horizontal plane distribution diagram and slice diagram of the temperature field that the cabin temperature range is 24-26°C. According to the calculation results, the average temperature in the cabin is 24.9°C. This shows that the predetermined heating effect can be achieved by the heating module.

After the cooling mode is turned on in summer, it can be seen from the horizontal plane distribution diagram and slice diagram of the temperature field that the temperature range of the room is 26 to 29°C. According to the calculation results, the average temperature in the cabin is 27.4°C. This shows that the refrigeration module can meet the air conditioning requirements of the cabin.

6. Conclusion

With the maturity of hydrogen fuel cells, hydrogen production and hydrogen storage technologies, and their cost reduction, it is bound to stimulate the rapid development of hydrogen fuel cell power boats. The comprehensive utilization system of the waste heat of the hydrogen fuel cell-powered ship designed by the project aims to further improve the comprehensive utilization of energy, and has certain foresight. This work has the characteristics of reasonable structure, high degree of automation, low power consumption, and easy management. It can reduce the cost of hydrogen fuel cell powered ships while achieving further energy saving and emission reduction, and will definitely promote the application and promotion of fuel cell powered ships.

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