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Energy and exergy performance analysis of a marine rotary desiccant air-conditioning system based on orthogonal experiment

Jun Zhu [a], Wu Chen [a, b, *]

[a] School of Marine Engineering, Jimei University, Xiamen 361021, China
[b] Fujian Provincial Key Laboratory of Naval Architecture and Ocean Engineering, Xiamen 361021, China

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ABSTRACT

A novel marine rotary desiccant A/C (air-conditioning) system was developed and studied to improve energy utilization efficiency of ship A/C. The orthogonal experiment was first carried out to investigate the influence of various parameters of the marine rotary desiccant A/C system. During the orthogonal experiment the analysis of variance was used to exclude interference from the secondary influencing factor on system performance. The significant influencing factors of system were studied in great detail using the first and second laws of thermodynamics to find optimal setting parameters for best system performance. It is suggested from the analysis results that as regeneration temperature increases, the COP_{th} (thermal coefficient of performance) and exergy efficiency of system (η_e) decreases by 46.9% and 38.8% respectively. They decrease in proportion to the increase of the temperature. η_e reaches its maximum value of about 23.5% when the inlet humidity ratio of process air is 22 g/kg. Besides, the exergy loss of system concentrates on the regeneration air heater, the desiccant wheel and the regeneration air leaving the desiccant wheel, which account for 68.4%–81% of the total exergy loss. It can be concluded that applying the marine rotary desiccant A/C in high-temperature and high-humidity marine environment is advantageous.

1. Introduction

With the gradual depletion of energy and environment deterioration, energy conservation has become the focus worldwide. Based on pertinent statistics, the energy consumption of world seaborne trade accounts for about 3% of the world's total energy consumption, and its pollution accounted for 3%–7% [1]. Among them, the ship A/C is one of the principal equipment of electricity consumption and accounts for 20% of the total electricity consumption for ships [2]. Therefore, it is of great significance to improve the energy consumption efficiency of A/C technologies for ships.

The rotary desiccant A/C technology is a kind of green A/C technology, which has been applied widely in the field of industrial and civic buildings to control air humidity. So far, the hybrid A/C system has been studied extensively by integrating the desiccant wheel with the solar collector [3–5], the vapor compression refrigeration unit [6–8], and the evaporative cooling unit [9–11]. So far, most of the existing works have been focusing on applying it to ground buildings, while its application on ships is rare. In fact, large latent heat load of marine A/C and abundant residual heat on ship are very suitable for the rotary desiccant A/C. The abundant residual heat can be reclaimed to work as the driving heat source to heat the regeneration air of rotary desiccant A/C system on ships. The thermal efficiency of the modern marine diesel engine is only about 50% and the residual heat of exhaust gas is about 30% [12]. The easily available seawater cooling source can be utilized to cool the high-temperature process air leaving the desiccant wheel. Lei and Liu [13] pointed out that the residual heat of ship exhaust gas could be used to heat the regeneration air for marine rotary desiccant A/C for energy savings. Digiovanni et al. [14] proposed to use the desiccant wheel to pre-process the fresh air of ship A/C. Chen and Yang [15] constructed four schemes of marine rotary desiccant A/C based on characteristics of ship A/C, and carried out technical feasibility study on each solution. Zheng et al. [16] analyzed the energy consumption of a marine two-stage rotary desiccant A/C. Yang [17] built an experiment platform of the marine rotary desiccant A/C, and investigated the operating performance of the system.

To the best of our knowledge, there is very few in-depth study on the marine rotary desiccant A/C. Therefore the purpose of this

* Corresponding author. School of Marine Engineering, Jimei University, Xiamen 361021, China. Tel.: +86 592 6181551; fax: +86 592 6180332.
E-mail address: chenwu73@163.com (W. Chen).

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paper is to experimentally analyze the performance of the marine rotary desiccant A/C by means of adequate evaluation indices including moisture removal (D_W), COP_{th} (thermal coefficient of performance), power COP_e (coefficient of performance), exergy efficiency of system (η_e) and exergy loss rate (σ). It is expected to find the system's weakness from the viewpoint of energy utilization and performance optimization of the system.

2. The marine rotary desiccant A/C system

The conventional ship A/C system, which is of vapor compression type, has to lower the supply air temperature below its dew point to accomplish dehumidification. In some installations an auxiliary heater might be required to reheat the supply air temperature, which further lowers the system's COP (coefficient of performance). While in the rotary desiccant A/C system, the rotary desiccant wheel is used to adsorb moisture of the process air or to handle the latent load of the system. The sensible load of process air is handled by the system's cooling devices such as seawater-air heat exchangers. In the marine rotary desiccant A/C system, the ship's residual heat is used to heat the regeneration air, which is sent to the desiccant wheel to regenerate its dehumidification capacity. As a result, the marine rotary desiccant A/C can make full use of the ships' residual heat and abundant seawater source, achieving the independent control of the air temperature and humidity, and great energy saving as well. Compared with the conventional ship A/C system, it was found that a new kind of marine rotary desiccant A/C can save up to 33.4% of energy consumption [15].

In the previous studies [15,18], the performance of various types of rotary desiccant A/C system with different scheme or configuration was compared, and it was found that the dehumidification capacity of single-stage system with one desiccant wheel was much lower than that of two-stage system under the same operation condition. Ge et al. [18] pointed out that when compared with the two-rotor two-stage rotary desiccant A/C system where two-stage dehumidification process was realized by two desiccant wheels, the optimized one-rotor two-stage system can reduce the size of system significantly without reduction in system performance. Therefore, considering the high humidity load of ship A/C and the small installation space available on ship, the newly-developed marine rotary desiccant A/C system was of one-rotor two-stage type. The novel marine rotary desiccant A/C system consists of a rotary desiccant wheel and some auxiliary cooling devices, including seawater-air heat exchangers, an auxiliary refrigeration unit and its direct-expansion air cooler (evaporator).

2.1. Working principle

Fig. 1 depicts the schematics and the typical psychrometric chart of a marine one-rotor two-stage rotary desiccant A/C system. The working of a marine rotary desiccant A/C comprises two processes, namely the air-handling process and the regeneration process of the desiccant wheel.

The air-handling process: The process air (state 2 in the psychrometric chart), which consists of the ambient air (state 1) and the cabin return air (state 8) in a required ratio (the ratio of fresh air, $\geq$ 50%), is dehumidified in the first stage dehumidification zone (I) of the desiccant wheel. The process air temperature is then raised to the temperature indicated by state 3 due to adsorption of heat effect from the desiccant wheel. Next, the process air flows into the first stage seawater heat exchanger (HE1) to be cooled. The temperature of the process air decreases to the one indicated by state 4. After being cooled by the HE1 the process air flows through the second stage dehumidification zone (III) of the desiccant wheel where the process air is dehumidified again and its temperature goes up to the one indicated by state 5. After leaving the desiccant wheel the process air is cooled again by the second stage seawater heat exchanger (HE2) and its temperature decreases again to that indicated by state 6. After being cooled by the HE2, the process air enters into the evaporator to be handled to meet the requirement of supply air (state 7) and then supplied to the cabin by a fan (Fan1).

The regeneration process of the desiccant wheel: The cabin return air (state 8) works as the regeneration air and is heated to the regeneration temperature (state 9) by the regeneration air heater which reclaims the residual heat of ship. The high-temperature regeneration air is divided into two streams and sent to the first regeneration zone (II) and the second regeneration zone (IV) respectively to remove the moisture of sorbent and recover the wheel's dehumidifying capacity. After leaving the wheel, the two streams of high-humidity regeneration air is mixed and exhausted outside the ship.

2.2. Test rig

The test rig of the marine rotary desiccant A/C, shown in Fig. 2, is composed of a solid rotary desiccant wheel, two seawater heat exchangers (HE1 and HE2), an auxiliary refrigeration unit, a regeneration air heater, a constant temperature and humidity air-conditioner (CTH) which is used to simulate ambient air with the various air states required by experiments and a thermostatic water device which is used to provide seawater with various temperatures. The conventional ship A/C system handles both the sensible and latent loads with the main electrical vapor compression refrigeration unit. In contrast, the novel marine rotary desiccant A/C system handles the system's latent load using the rotary desiccant wheel, and the system's sensible load using the seawater heat exchanger and the auxiliary refrigeration unit independently.

2.2.1. Desiccant wheel

The rotary desiccant wheel is the core component of the marine rotary desiccant A/C system, which is used to remove the moisture of air. Since the humidity ratio of ocean air is very high and cabin space of air-conditioner room is limited, only one honeycombed desiccant wheel is used by the marine rotary desiccant A/C system to achieve two-stage dehumidification process. The diameter and thickness of the desiccant wheel are 450 mm and 200 mm respectively. The air channels of desiccant wheel are divided into four parts, namely the first stage dehumidification zone (I), the second stage dehumidification zone (III), the first regeneration zone (II), and the second regeneration zone (IV). The angle of each dehumidification zone is 135°, and that of each regeneration zone is 45°. In addition, an electric motor with rated power of 0.1 kW is used to control precisely the rotation speed of desiccant wheel using an inverter.

2.2.2. Constant temperature and humidity air-conditioner

In order to simulate the states of ocean air under different conditions, we equip in the test rig a constant temperature and humidity air-conditioner, as shown in Fig. 3a. The air-conditioner has rated power of 4.5 kW, which can be used to accurately control the temperature and humidity of the preprocess air before entering the desiccant wheel. The temperature of the controlled air ranges from 20 °C to 40 °C and the relative humidity of the controlled air ranges from 50% to 95% respectively. The control accuracies of air temperature and air relative humidity are ±0.5 °C and ±2% respectively.