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Study on Operational Characteristics of a Hybrid Thermal wheel and Evaporative Cooling Air-conditioning System for Marine Ships

Liqing Liu[1], Yi Chen[1*], Huaxia Yan[1], Qiuhua Tao[1], Yiyan Fan[2]

1 College of Marine Equipment and Mechanical Engineering, Jimei University, Xiamen 361021, Fujian, China

2 Dongjing (Xiamen) Energy Co., Ltd
(*Corresponding Author: chenyi0511@jmu.edu.cn)

ABSTRACT

A hybrid air-conditioning (A/C) system has been proposed as an alternative energy-efficient solution for marine A/C application using waste-heat-driven dehumidification and a seawater-based evaporative cooler. This paper establishes a mathematical model of a hybrid thermal wheel and evaporative cooling A/C system, by taking the energy consumption characteristics, dehumidification capacity and cooling capacity as the evaluation indexes. The influence of the outdoor temperature and humidity, regeneration air temperature on the overall performance of the system is studied. It is found that the hybrid A/C system has excellent dehumidification and cooling capabilities at high inlet air temperature and humidity as well as high regeneration air temperature. The coefficient of performance (*COP*) of the hybrid system can reach 13.

Keywords: marine air-conditioning; evaporative cooling; thermal wheel; numerical model; energy-saving

NONMENCLATURE

Abbreviations	
A/C	Air-conditioning
COP	Coefficient of Performance
Symbols	
A	Duct cross-sectional area, m^2
A_1	Heat transfer area, m^2
c_p	Isobaric specific heat, J/(kg·K)
M	Mass flow, kg/s
K_y	Mass transfer coefficient, kg/(m^2·s)
h_v	Evaporation latent heat, J/kg
h	Air specific enthalpy, J/kg
Y	Humidity ratio, kg/kg
z	Axial direction, m
W	

	Water content of the desiccant
Q	material, kg/kg
f	Adsorption heat, J/kg
t	Specific mass, kg/m
T	Time, s
m_{ad}	Temperature, K
P	Process air flow, m^3/h
ω	Perimeter, m
Q_c	Coefficients in Eq.(1)
D	System cooling capacity, kW
	System dehumidification capacity,
W_f	kg/h
W_p	Fan energy consumption, kW
	Water pump energy consumption,
W_r	kW
ρ	Rotor energy consumption, kW
σ	Density, kg/m^3
α	Wettability
Subscripts	Heat transfer coefficient, W/(m^2·K)
i	
o	Input
p	Output
s	Primary air
a	Secondary air
ad	Dry air
reg	Adsorption
d	Regeneration
m	Desiccant
ew	Matrix material
w	Evaporation water
e	Wall
*	Environment
	Desiccant side

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1. INTRODUCTION

With the increasing need of global trade, maritime ship transportation occupies a nonnegligible proportion in the national economic system [1]. Currently, most ships use diesel engines as the main propulsion power unit, which consumes a large amount of fossil energy and also emits a large amount of exhaust gas and carbon dioxide [2]. The Initial International Maritime Organization Strategy on Reduction in Greenhouse Gas Emissions from Ships was developed as early as 2018 [3], and the shipping industry is facing higher emission reduction requirements. Therefore, there is a need to address intensive research on various energy saving and emission reduction technologies, including ship waste heat recovery and utilization technologies, in order to achieve the emission reduction visions and targets. Nowadays, on one hand, most of the power used to drive the A/C systems on board ships comes from diesel generators, where fossil energy is converted into high-grade electricity through combustion, but the conversion efficiency of electricity is low, and more than half of the fossil energy is turned into waste heat, which is carried away by the exhaust smoke and seawater cooling systems [4]. On the other hand, the internal thermal environment in a ship is closely related to the health of the crew and the normal operation of ship equipment. Therefore, marine A/C is essential. The thermal wheel dehumidification and evaporative cooling system, which is an A/C system that can make full use of the ship's waste heat and seawater cooling, can be used as an energy-saving solution for marine A/C, and is of great significance for the energy utilization and energy saving and emission reduction of marine vessels.

The main energy consumption of the thermal wheel dehumidification A/C system comes from two sources: the desiccant regeneration of the thermal wheel and air cooling after dehumidification [5]. Since ships have abundant waste heat that can be used for desiccant regeneration, thus realizing the utilization of ship waste heat. Many scholars have conducted theoretical and experimental studies on the energy saving effect of thermal wheel dehumidification A/C on ships. Zheng et al. [6] analyzed a two-wheel two-stage rotary desiccant A/C system based on the operating parameters of a real ship,finding a 33.4% reduction in energy consumption compared to traditional marine A/C. Zhu and Chen [7] conducted orthogonal experiments to investigate the effects of various parameters of a marine rotary desiccant A/C system. The results show that the application of marine rotary desiccant A/C in high temperature and high humidity marine environments is advantageous. Zheng et al. [8] proposed a newly developed Ejector Refrigeration Rotating Desiccant A/C (ERRD A/C) system. Under the design conditions of a real marine A/C, demonstrated only 32.87% of the power consumption of conventional A/C.

A combination of a thermal wheel dehumidification and evaporative cooling system, where the thermal wheel is utilized to handle the latent loads while the low-energy evaporative cooling handles the sensible heat loads, will result in a further increase in the energy efficiency of the A/C system. However, current research on this system is focused on the building sector. Ge et al. [9] simulated and discussed the two-stage rotary desiccant cooling system performance with respect to different combinations of two regeneration temperatures. The results show that cooling power of the system increases with the increase of regeneration temperature. However, thermal coefficient of performance decreases. Comino [10] found the annual energy consumption of the desiccant wheel-indirect evaporative cooler system was lower than that of the direct expansion system through simulation studies in six climate zones, achieving significant energy savings up to 46.8%. Chaudhary [11] proposed an integrated solar assisted cooling system consisting of a solid desiccant system and a Maisotsenko cycle based evaporative cooling system. The experimental resulted average cooling capacity of the system is around 3.78 kW with average *COP* of 0.91 at solar fraction of about 70%.

As it can be seen from the above, most of the research on marine thermal wheel dehumidification A/C is based on the composite A/C system of rotor and vapor compression, i.e., the air is dehumidified by the thermal wheel and then needs to be cooled by the surface cooler with a low temperature refrigerant. Therefore, it still partially relies on traditional mechanical refrigeration. Hybrid A/C systems with thermal wheel dehumidification and evaporative cooling are currently concentrated in the field of building A/C, which utilizes fresh water as the cooling medium for evaporative cooling. The hybrid A/C system proposed in this paper uses seawater as the cooling medium for evaporative cooling and utilizes the waste heat from the ship for the regeneration of the thermal wheel desiccant, making full use of the natural refrigerant and the ship's waste heat to further improve the energy efficiency of the A/C system. This paper establishes a numerical model of the hybrid A/C system. By taking a certain type of ship as a case study, the air treatment process of the hybrid A/C system is analyzed. The influence of the air parameters and regeneration air temperature on the overall performance of the system is also analyzed.

2. METHODOLOGY

2.1 Working principle

As shown in Fig. 1, the hybrid A/C system consists of a thermal wheel and a seawater dew point indirect evaporative cooler connected in series, which can independently treat the temperature and humidity of the air. The air treatment process of the system is divided into the following two parts.

Processing air: fresh air from outside is mixed with return air from the ship's cabin (40% fresh air ratio), and enters the dehumidification area of the thermal wheel for dehumidification, and then the outlet air is cooled by a seawater intercooler, and then further cooled by a seawater dew-point indirect evaporative cooler, and finally sent into the ship's cabin.

Regeneration process: fresh air from outside is heated by the ship's waste heat and sent into the regeneration area of the thermal wheel to heat the desiccant of the thermal wheel, so that the moisture inside it evaporates and the dehumidification capacity is recoveried.

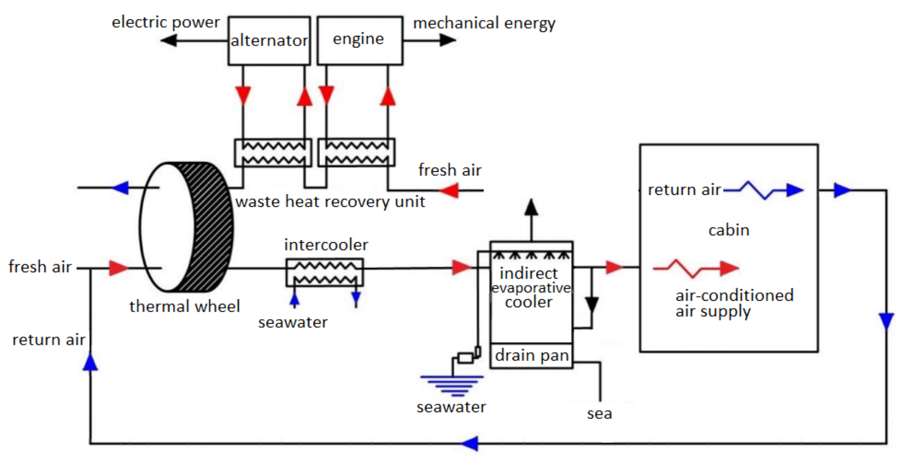

Fig. 1. Schematic diagram of hybrid thermal wheel and evaporative cooling air-conditioning system for marine ships

2.2 Modeling

The one-dimensional thermal wheel model established with reference to the literature [12] uses a honeycomb silica gel thermal wheel. The angle between the dehumidification zone and the regeneration zone is 3:1, the radius of the thermal wheel is 200 mm, the thickness is 200 mm, the rotational speed is 7 r/h, the treated air flow rate is 1.474 m/s, and the regeneration air flow rate is 3.095 m/s. Inside the differential cell dz, the governing equations are established based on the conservation of mass and energy, as shown in equation (1).

$$\begin{cases} \frac{\partial Y}{\partial t}+V\frac{\partial Y}{\partial z}+\omega_1\frac{\partial W}{\partial t}=0 \\ \frac{\partial W}{\partial t}+\omega_2\left(Y_{\mathrm{w}}-Y\right)=0 \\ \frac{\partial T}{\partial t}+V\frac{\partial T}{\partial z}+\omega_3\frac{\partial T^*}{\partial t}=\omega_4\left(Y-Y_{\mathrm{w}}\right) \\ \frac{\partial T^*}{\partial t}+\omega_5\left(T^*-T\right)+\omega_6\left(Y_{\mathrm{w}}-Y\right)+\omega_7\left(Y_{\mathrm{w}}-Y\right)\left(T-T^*\right)=0 \end{cases} \tag{1}$$

where,

$$\omega_1=\frac{f_{\mathrm{d}}}{2A\rho_{\mathrm{a}}};\quad \omega_2=\frac{2K_yP}{f_{\mathrm{d}}};\quad \omega_3=\frac{f_{\mathrm{d}}\left(c_{pd}+Wc_{pl}\right)+f_{\mathrm{m}}c_{pm}}{2A\rho_{\mathrm{a}}\left(c_{pa}+Yc_{pv}\right)};$$

$$\omega_4=\frac{K_yPQ}{A\rho_{\mathrm{a}}\left(c_{pa}+Yc_{pv}\right)};\quad \omega_5=\frac{2\alpha P}{f_{\mathrm{d}}\left(c_{pd}+Wc_{pl}\right)+f_{\mathrm{m}}c_{pm}};$$

$$\omega_6=\frac{2K_yPQ}{f_{\mathrm{d}}\left(c_{pd}+Wc_{pl}\right)+f_{\mathrm{m}}c_{pm}};\quad \omega_7=\frac{2K_yPc_{pv}}{f_{\mathrm{d}}\left(c_{pd}+Wc_{pl}\right)+f_{\mathrm{m}}c_{pm}}$$

The governing equations were solved by Gauss-Jordan elimination method, and the simulation results were verified by comparison with the experimental data in the reference [12]. The results show that under the same conditions, the difference in the outlet temperature of the treated air is 2.08% and the difference in the moisture content is 1.28%. Therefore, the simulation results of the heat and mass transfer model of the thermal wheel are reliable.

The numerical model of the seawater dew-point indirect evaporative cooler is based on the conservation of mass and energy in the dry and wet channels, and its governing equations are shown in equation (2). The length of the primary air channel is 1.2 m and the primary air flow rate is 1.92 m/s. The numerical model is programmed by MATLAB and solved by using the finite difference method. To validate the accuracy of the model, the simulation results are compared with the experimental results in the literature [13]. The maximum relative error of the outlet temperature is 6.37% and the average relative error is 1.46%. Therefore, the established dew point indirect evaporative cooler model is reliable.

$$\begin{cases} \alpha_{\mathrm{p}}(T_{\mathrm{p}}-T_{\mathrm{w}})\mathrm{d}A_1 = c_{pa}M_{\mathrm{p}}\mathrm{d}T_{\mathrm{p}} \\ \alpha_{\mathrm{s}}(T_{\mathrm{w}}-T_{\mathrm{s}})\mathrm{d}A_1 = c_{pa}M_{\mathrm{s}}\mathrm{d}T_{\mathrm{s}} \\ K_{ys}(Y_{T,\mathrm{w}}-Y_{\mathrm{s}})\mathrm{d}(\sigma A_1) = M_{\mathrm{s}}\mathrm{d}Y_{\mathrm{s}} \\ \mathrm{d}M_{\mathrm{w}} = M_{\mathrm{s}}\mathrm{d}Y_{\mathrm{s}} \\ M_{\mathrm{s}}\mathrm{d}h_{\mathrm{s}} - c_{pa}M_{\mathrm{p}}\mathrm{d}T_{\mathrm{p}} = c_{pw}T_{\mathrm{ew}}\mathrm{d}_{M,\mathrm{w}} \end{cases} \tag{2}$$

2.3 Performance index

For the performance index of the hybrid A/C system, the system cooling capacity (Q_{c}), the system dehumidification capacity (D), and the system coefficient of performance (COP) are used, expressed as equation (3), (4) and (5):

$$Q_{\mathrm{c}}=c_{pa}m_{\mathrm{ad}}\rho_{\mathrm{a}}\left(T_{\mathrm{p,i}}-T_{\mathrm{p,o}}\right)+m_{\mathrm{ad}}\rho_{\mathrm{a}}h_{\mathrm{v}}\left(Y_{\mathrm{ad}}-Y_{\mathrm{ad,o}}\right)/3600 \tag{3}$$

$$D=m_{\mathrm{ad}}\rho_{\mathrm{a}}\left(Y_{\mathrm{ad}}-Y_{\mathrm{ad,o}}\right) \tag{4}$$

$$COP=Q_{\mathrm{c}}/\left(W_{\mathrm{f}}+W_{\mathrm{p}}+W\right) \tag{5}$$

2.4 Parameter setting

The influence of three parameters on the hybrid A/C system, including outdoor temperature and humidity, and regeneration air temperature is studied. The value range of outdoor temperature and humidity is selected according to the working conditions in the marine environment. The value range of each parameter is shown in Table 1.

Table 1 Summary of the parameters' range

Research parameters	T_{e} (°C)	RH_{e} (%)	T_{reg} (°C)
T_{e} (°C)	24-40	70	140
RH_{e} (%)	35	30-90	140
T_{reg} (°C)	35	70	100-145

3. HYBRID A/C SYSTEM CONSTRUCTION

3.1 Cabin load calculation

Setting temperature of the ship's cabin is 26 °C and the relative humidity is 40%. In the hybrid A/C system, 40% fresh air from outdoor is mixed with 60% of the return air from the ship's cabin. Based on a ship information, the cabin sensible and latent heat load is calculated. Using a cabin room in the ship as an example, the room's sensible heat load (including fresh air) is calculated to be 0.83 kW, and the latent heat load (including fresh air) is calculated to be 1.09 kW, and the air supply flow rate is 180 m^3/h.

3.2 Example of an air treatment process

Outdoor air temperature: 35 °C, 70%; Thermal wheel: regeneration air temperature is 140 °C, relative humidity is 0.82%.

Based on numerical simulation, when the indoor air supply flow rate is 180 m^3/h, the hybrid A/C system provides the indoor sensible heat cooling capacity of 1.56 kW and the latent heat cooling capacity of 1.9692 kW, which meets the demand of the ship's room A/C load.

The air treatment process for this condition is shown in Fig. 2, where state point 1 represents the outdoor air and state point 2 represents the indoor air, which are mixed to obtain point 3 (the inlet air of the system). Then, the air at point 3 is dehumidified by the thermal wheel after isenthalpic dehumidification and arrives at point 4. The air is then further sent to the seawater intercooler for sensible cooling and arrives at point 5, and then goes through the process of sensible cooling in the indirect evaporative cooler at the dew point to reach state point 6. Finally, the dry-bulb temperature of the supply air at point 6 was 11.69 °C and the humidity content was 2.14 g/kg. Therefore, the hybrid A/C system could provide a compliant supply air state to remove the indoor load.

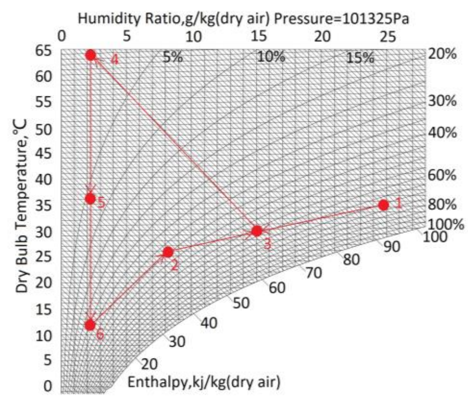

Fig. 2. Psychrometric chart of air treatment process

4. RESULTS AND ANALYSIS

4.1 Influence of outdoor air temperature

Fig. 3 shows that when the outdoor air temperature increases, the dehumidification capacity of the system gradually increases and tends to stabilize, and the cooling capacity of the system first grows and then decreases. As the outdoor air temperature increases, the humidity content of the treated air gradually increases, resulting in an increase in the difference in water vapor partial pressure between the treated air and the thermal wheel desiccant, enhancing the dehumidification capacity of the thermal wheel. The dry and wet bulb temperature difference of the air entering the dew point indirect evaporative cooler increases with the dehumidification capacity, increasing the system cooling capacity. However, when the dehumidifying capacity of the thermal wheel reaches its maximum when the outdoor temperature reaches 34 °C, the humidity content of the processed air continues to increase, but the dehumidifying capacity remains unchanged, resulting in a decrease in the dry and wet bulb temperature difference of the air entering the indirect evaporative cooler at the dew point and a reduction in the cooling effect, and therefore a decrease in the cooling capacity of the system.

The trend of the *COP* of the system is shown in Fig. 4. Since the flow rate of the air treated by the system and the thermal wheel speed remain unchanged, the motor energy consumption of the fan, the pump and the rotor remains the same, but the decrease in the cooling capacity leads to a decrease in the *COP*.

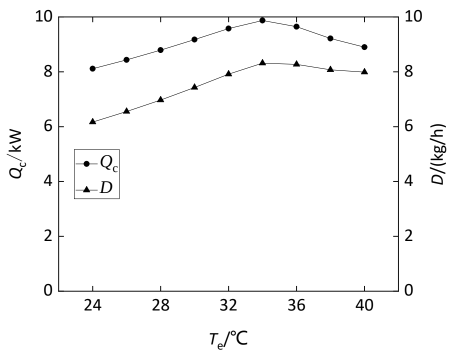

Fig. 3. Influence of outdoor air temperature on system cooling and dehumidification capacity

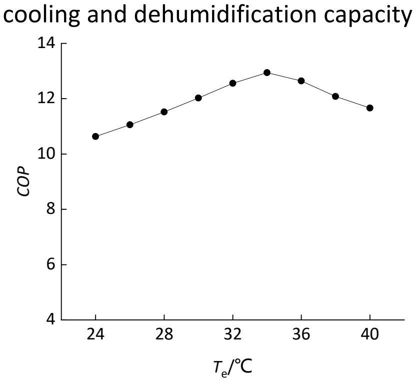

Fig. 4. Influence of outdoor air temperature on *COP*

4.2 Influence of outdoor air relative humidity

As the relative humidity of the outdoor air increases, the humidity content of the treated air entering the thermal wheel gradually increases. As shown in Fig. 5, the dehumidification capacity of the system increases and then stabilizes, and the cooling capacity of the hybrid A/C system shows a trend of increasing and then decreesing. At a relative humidity of 70%, the dehumidification capacity of the thermal wheel reaches its maximum, and the increase in relative humidity leads to a decrease in the dry and wet bulb temperature difference of the primary air entering the indirect evaporative cooler at the dew point, which reduces the cooling effect of the system. In Fig. 6, the electrical energy consumption of the system remains constant due to the constant flow rate of treated air, and the *COP* varies with the cooling capacity of the system.

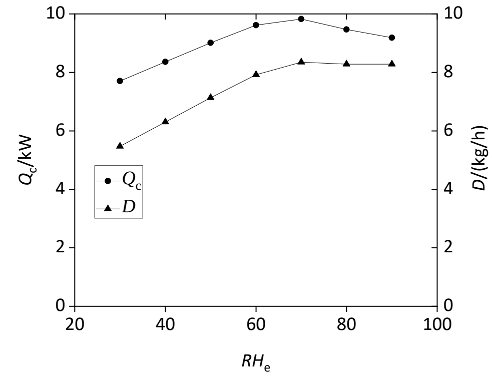

Fig. 5. Influence of outdoor air relative humidity on system cooling capacity and dehumidification capacity

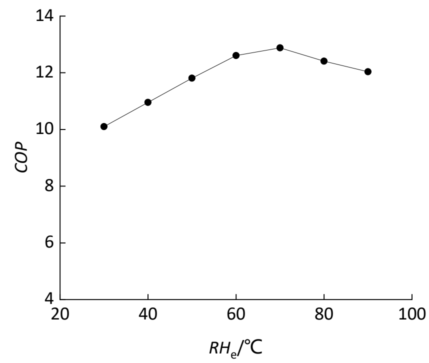

Fig. 6. Influence of outdoor air relative humidity on *COP*

4.3 Influence of regeneration air temperature

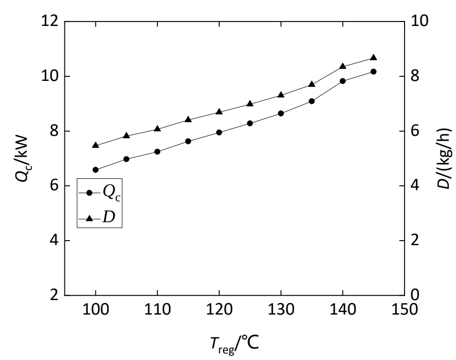

Fig. 7. Influence of regeneration temperature on system cooling and dehumidification capacity

As shown in Fig. 7, the regeneration temperature increases from 100 °C to 145 °C, the desorption capacity of the regeneration side of the thermal wheel is gradually enhanced, the dehumidification capacity of the system is strengthened. With the increase of dehumidification capacity, the temperature difference between the wet-bulb temperature and dry-bulb temperature entering evaporative cooler gradually increased, thus the cooling capacity of the system has been increased. Fig. 8 shows that as the regeneration temperature increases, the *COP* of the hybrid A/C system also increases gradually. Since the regeneration air is heated by the ship's waste heat and the treated air flow rate remains unchanged, the *COP* of the system increases with the increase in cooling capacity.

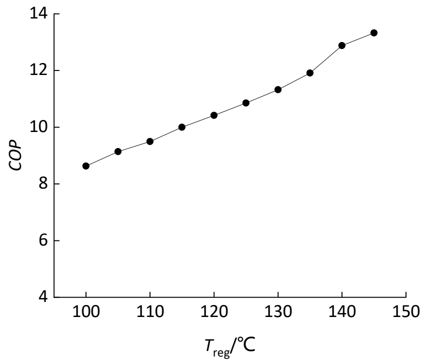

Fig. 8. Influence of regeneration temperature on *COP*

5. CONCLUSIONMS

This paper establishes a numerical model of a hybrid A/C system consists of a thermal wheel and seawater-based indirect evaporative cooler. The air treatment process and the influence of the air parameters and regeneration temperature are analyzed. Main conclusions are summarized as follows.

1) According to the requirements of cabin cooling load in summer, the cooling and dehumidification capacity of the hybrid air-conditioning system can meet the demand. The supply air temperature and relative humidity can reach 11.69 °C and 25%.

2) In the high-temperature and high-humidity marine environment, the hybrid air-conditioning system shows excellent cooling and dehumidifying capability with a coefficient of performance ranging from 9 to 13. As a result, the hybrid air-conditioning system provides a reliable and energy-saving air-conditioning solution for ships.

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