Study on the marine ejector refrigeration-rotary desiccant air-conditioning system

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Abstract: A newly developed ejector refrigeration-rotary desiccant air-conditioning (ERRD A/C) system is proposed to recover ship waste heat as far as possible. Its configuration is built firstly, then its advantages are analyzed, after that, with the help of psychrometric chart, some important parameters such as power consumption, steam consumption and COP of ERRD A/C system are calculated theoretically under design conditions of a real marine A/C, and comparative analysis with conventional A/C is deployed. The results show that the power consumption of ERRD A/C system is only 32.87% of conventional A/C, which meant that ERRD A/C system has potential to make full use of ship waste heat to realize energy saving and environmental protection when using green refrigerant such as water.

1 Introduction

The carbon emissions of shipping industry accounted for about 3.3% of global carbon emissions in 2007, and the amount of emissions has been increasing year by year [5]. Therefore, the International Maritime Organization (IMO) has developed Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) and other related technologies and operation measures to reduce carbon emissions. Ship waste heat recovery, as one of the most important measures for energy conservation and emission reduction, has been widely concerned.

In modern ships, the thermal efficiency of ship diesel engine is about 50%, the remaining 50% is taken away by exhaust, cylinder cooling water and other ways. In order to strengthen the recovery and utilization of ship waste heat, in addition to the use of traditional exhaust boiler to produce high temperature steam for ship space heating, heavy oil heating, ballast water heating and other auxiliary heating; exhaust turbocharging and vacuum desalination are also adopted. The shipping industry is active in the research and application of new types of waste heat recovery and utilization technologies, especially those that can be driven by waste heat.

Marine A/C is one of the main electrical equipment on ship. Its power consumption accounts for about 20% of electricity consumption of the whole ship, therefore, is of great significance for energy saving and emission reduction. That’s the reason why the related marine refrigeration and A/C technology driven by waste heat has been widely concerned. In recent years, more and more attention has been paid to rotary desiccant [2, 8] and ejector refrigeration [3, 7] because both of them have simple structure, fewer moving parts and reliable work, besides, they can be driven by waste heat and adapted to the working conditions of the ship. Therefore, they have good application potential and many advantages when used on ships. In addition, both technologies can be combined together to form an ejector refrigeration-rotary desiccant air-conditioning (ERRD A/C) system, which has more advantages than single use. However, detailed and in-depth study on marine ERRD A/C system is still few.

In this paper, the configuration of a newly-developed ERRD A/C system and its advantages will be firstly described and analyzed. Then, power consumption, steam requirement and COP of ERRD A/C system will be calculated theoretically and compared with a real conventional marine A/C.

2 The Configuration of Marine ERRD A/C System and its Advantages

2.1 *Schematics of ERRD A/C system*

Marine ERRD A/C system, composed of an ejector refrigeration subsystem and a rotary desiccant A/C

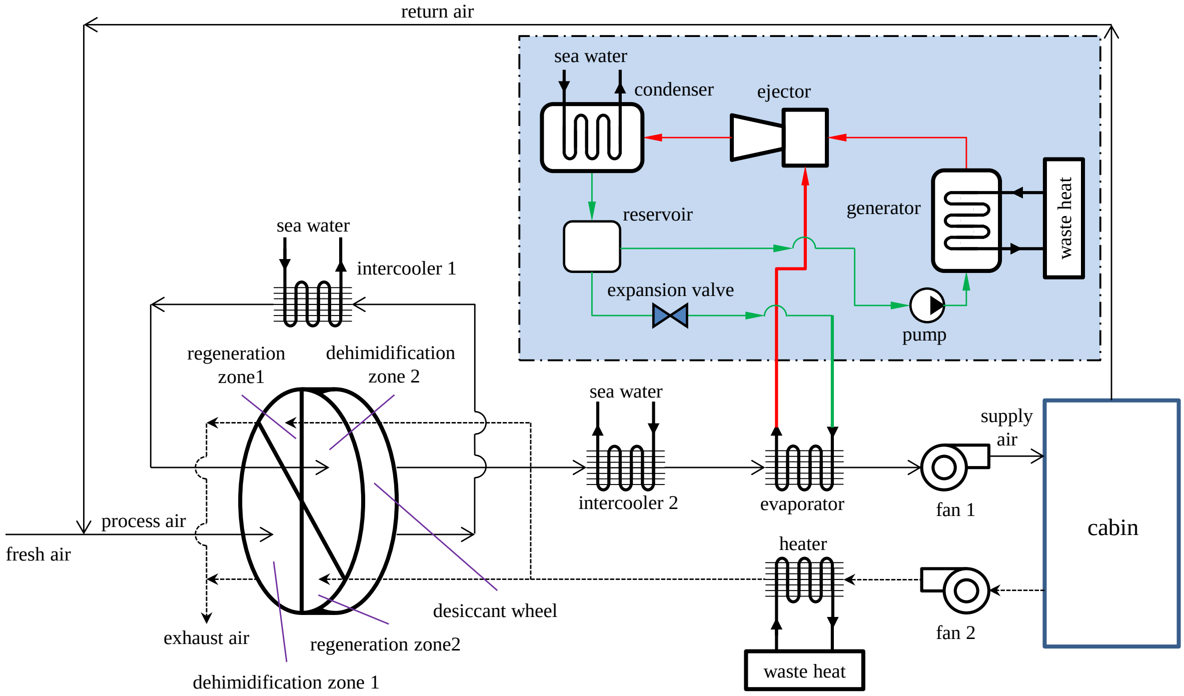

Figure 1. Schematics of ERRD A/C system

subsystem. In the ERRD A/C system, the sensible heat load is handled by ejector refrigeration subsystem, and the latent heat load is dealt with by rotary desiccant subsystem. Both subsystems are driven by waste heat, the schematics of ERRD A/C system is shown in figure 1.

The ejector refrigeration subsystem consists of generator, ejector, condenser, evaporator, expansion valve and circulating pump. The circulating pump, generator and ejector replace the function of compressor in the conventional vapor compression refrigeration cycle. The ejector is a key component of the ejector refrigeration subsystem, which consists of nozzle, suction chamber, mixing chamber and diffuser. The liquid refrigerant is heated to a high temperature and a high pressure state (named primary flow) by ship waste heat in the generator. Then primary flow passes through the nozzle with a reduced pressure and a greatly increased velocity, high velocity primary flow create a low pressure zone in suction chamber when flow through it. At the same time, due to absorbing heat from evaporator, the vaporized refrigerant is entrained into suction chamber (named secondary flow). Primary flow and secondary flow mix in mixing chamber where momentum exchange occurs, and then they flow through diffuser with a decreased velocity and an increased pressure. In the condenser, gaseous refrigerant is cooled to liquid, and liquid refrigerant is stored in reservoir. The circulating pump drives liquid refrigerant in the reservoir into the generator, and some refrigerant is injected into the evaporator through the expansion valve. The refrigerant of ejector refrigeration subsystem should be selected according to the grade of the waste heat. In this paper, water is selected as refrigerant.

The rotary desiccant A/C subsystem consists of one-rotor two-stage silica gel desiccant wheel, regeneration heater, intercoolers, evaporator and fans. Process air, which is mixed by fresh air and return air in a certain proportion, flows through dehumidification zone 1 where the vapor in the process air is adsorbed by silica gel and the latent heat is released, thus making the air temperature increase obviously. Then after the first dehumidification, high temperature process air is cooled by sea water in the intercooler 1 and flows through dehumidification zone 2 for a second dehumidification. It can be seen that the process air temperature increases again due to the released latent heat and then it is cooled again in intercooler 2. After two rounds of dehumidification and cooling, the process air always has a lower humidity. However, its temperature is still high and it needs a cold source with a low temperature for cooling. Therefore, it is sent to the evaporator of the ejector refrigeration subsystem for further cooling, and then to the cabins after reaching supply air requirements by fan 1. After the adsorption of vapor in the process air, dehumidification capacity of silica gel adsorbent in the desiccant wheel decreases, and it is regenerated by high temperature air in regeneration zone 1 and regeneration zone 2. The system uses low moisture content cabin exhaust air as regeneration air, which is heated to the regeneration temperature by ship waste heat such as high temperature diesel exhausts or high temperature steam, and the vapor adsorbed by silica gel is evaporated by regeneration air so as to recover the dehumidification capacity of silica gel.

2.2 *The advantages of ERRD A/C system*

Compared with single steam ejector refrigeration or rotary desiccant technology, the combination of both has more advantages. Firstly, in a single rotary desiccant A/C system, the process air temperature is difficult to be adjusted to the supply temperature only with sea water cooling. Therefore, a cold source with lower temperature is needed such as a vapor compression refrigeration unit with less power, which still needs electricity. In ERRD A/C system, both subsystems are driven by ship waste heat, and abundant sea water can be used as one of the cold sources, therefore, the energy efficiency is enhanced. Secondly, the sensible heat load and latent heat load can be handled by ejector refrigeration subsystem and rotary desiccant subsystem respectively, so independent control of temperature and humidity is realized, and the comfort and health of ship cabin air is improved. Thirdly, steam is a green environmental protection working fluid. Lastly, since most even all latent heat load is turned into sensible heat load when the air passes through desiccant wheel, then is removed by intercooler after the desiccant wheel, the steam ejector refrigeration subsystem almost has no need to undertake dehumidification task. Compared with conventional A/C, the evaporation temperature can be increased, and the working condition and efficiency of steam ejector refrigeration subsystem can be improved. In ejector refrigeration A/C system, due to the requirement of dehumidification, according to the standard of ISO7547 [4], for the ship with unrestricted area of navigation, the indoor design parameters of A/C in summer are 27℃ and 50% RH, its dew point is 15.7℃. In consideration of 5℃temperature difference of heat transfer and medium transport respectively, the evaporation temperature is 5.7℃, its evaporation pressure is 0.916 kPa. In ERRD A/C system, in evaporator, there is almost no dehumidification requirement, thus, the evaporation temperature can be increased greatly e.g. 12℃, its evaporation pressure is 1.403 kPa. At the same back pressure, the pressure ratio decreases by 34.7%, which is helpful to improve the operation efficiency of steam ejector refrigeration subsystem. Lastly, through a reasonable design, such as suitable desiccant and refrigerant selection, it is possible that waste heat required in two subsystems has different energy levels. Consequently, the utilization efficiency of waste heat can be improved.

3 **Theoretical Calculations and Comparative Analysis**

3.1 *Design parameters of a real marine A/C*

In order to deploy the research on ERRD A/C system, design parameters of a real marine A/C system is introduced [6]. In summer, outdoor air temperature and relative humidity are 35℃and 85%; indoor air temperature and relative humidity are 26℃and 50%; supply air temperature and relative humidity are 16℃and 77.6%; sea water temperature is 32℃; total air volume is 20388m^3/h; fresh air ratio is 60%. The A/C system of the real ship adopts traditional mechanical compression refrigeration A/C system with primary return air, the operating efficiency (COP) of the refrigeration unit is 3.6, and the designed power consumption of supply air fan is 20kW.

3.2 *The air handling process and state points*

The air handling processes of conventional A/C system and ERRD A/C system are shown on psychrometric chart in figure 2. The points O, I, M

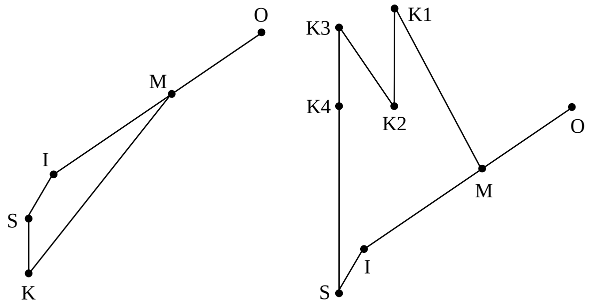

Figure 2. The air handling process of conventional A/C and ERRD A/C system on psychrometric chart

and S represent the state of fresh air, return air, mixed air and supply air respectively. For the conventional A/C system, the air handling process is expressed as M-K-S in figure 2(a), the process air mixed by fresh air and indoor air with fresh air ratio, then it was cooled and dehumidified by evaporator. In order to meet the requirements of air supply, the temperature should be reduced to the corresponding machine dew point (K, the relative humidity is 90%), and the temperature is always lower than supply air temperature, so the process air must be heated so as to increase its temperature. For ERRD A/C system, the air handling process is expressed as M-K1-K2-K3-K4-S in figure 2(b). M-K1 represents an isenthalpic dehumidification process corresponding to the first dehumidification in dehumidification zone 1; K1-K2 represents a dry-cooled process corresponding to the first cooling in intercooler 1; K2-K3 represents an isenthalpic dehumidification process corresponding to the second dehumidification in dehumidification zone 2; K3-K4 represents a dry-cooled process corresponding to the second cooling in intercooler 2; K4-S is also a dry-cooled process corresponding to the third cooling in evaporator of ejector refrigeration subsystem. In order to facilitate the subsequent calculation, parameters of partial state points are listed in table 1. It should be noted that the temperature of process air is cooled to 35℃ at state point K2 and K4 corresponding to first and second cooling using sea water, which means that small temperature difference design is adopted in consideration of no need for dehumidification as well as more effective second dehumidification.

Table 1. Parameters of partial state points of marine A/C system

State point	dry-bulb temperature (℃)	Relative humidity (%)	Humidity (g/kg(d.a))	Enthalpy (kJ/kg(d.a))
O	35.0	85.0	30.95	114.56
I	26.0	50.0	10.54	53.00
M	31.4	77.5	22.77	89.85
S	16.0	77.6	8.82	38.41
K	13.7	90.0	8.82	36.06
K4	35.0	25.1	8.82	57.82

3.3 *Parameter calculation of conventional A/C system*

The latent heat load and sensible heat load of conventional A/C system can be calculated based on the temperature and humidity difference between state point M and K in figure 2. The humidity content difference between M and K is 13.95 g/kg (d.a), assumed that the air density is 1.143kg/m^3, the vaporization heat of water is 2557.6kJ/kg, the designed air mass flow rate is about 23303.5kg/h (1.143kg/m^3×20388m^3/kg); the full heat load is about 348.2kW (23303.5kg/h×(89.85-36.06) kJ/kg(d.a)/3600); the latent heat is 231kW (23303.5kg/h×13.95g/kg(d.a)×2557.6kJ/kg/3600000); and the sensible heat is 117.2kW (348.2kW-231kW). In addition, the amount of heat required for increasing temperature from K to S is 15.2 kW (23303.5kg/h×(38.41-36.06)kJ/kg(d.a)/3600).

In the conventional A/C system, both latent heat load and sensible heat load are handled by evaporator, and the theoretical power consumption of refrigeration unit is about 96.7kW, which is approximately equal to full heat load divided by COP (348.2 kW/3.6) due to very small energy consumption of pump compared with compressor. In practice, it is acceptable that the power consumption of pump accounts for 5% of the total power consumption of the whole refrigeration unit, in this case, it is about 5kW. And the amount of heat taken away by sea water is about 445kW, which can be regard as compressor power consumption plus full heat load of A/C (348.2kW+96.7kW). In consideration of 5℃ temperature difference between condenser outlet and inlet, the specific heat of water is about 4.18kJ/kg/℃, then the required water flow rate can be obtained whose value is about 76650.72kg/h (445kW/5℃/4.18kJ/kg/℃). Therefore, the electric power demand and heating demand of conventional A/C system are about 121.7kW(96.7kW+20kW+5kW) and 15.2kW respectively.

3.4 *Parameter calculation of ERRD A/C system*

The full heat load of ERRD A/C system can be calculated based on the enthalpy difference between M and S, it is about 332.98kW (23303.5kg/h×(89.85-38.41)kJ/kg(d.a)/3600); and the latent load is the same as conventional A/C. However, due to using sea water for cooling, on the basis of enthalpy difference between K4 and S, the cooling load of evaporator in ejector refrigeration system is 125.6 kW(23303.5kg/h×(57.82-38.41) kJ/kg(d.a)/3600). In order to assess the performance of ERRD A/C system, some important parameters should be calculated such as steam consumption, power consumption and COP.

3.4.1 *Steam consumption*

The waste heat used in ERRD A/C system is steam from exhaust-gas boiler equipped on ship, its pressure is 0.7MP and the corresponding saturated temperature, saturated steam enthalpy and saturated condensation enthalpy are 164.96℃, 2762.9kJ/kg and 693.63kJ/kg respectively. In rotary desiccant subsystem, the steam is used to heat regeneration air so as to regenerate the dehumidification capacity of silica gel, and the selected regeneration temperature is 120℃. Regeneration air flow rate is another important factor for recovering the dehumidification capacity of silica gel. Literature proposed that 30% of total air volume is a proper value, however, in this paper, 25% for each dehumidification zone is adopted. Firstly, due to two-stage dehumidification, each stage undertakes less dehumidification task. Secondly, the fresh air ratio adopted is 60%, and return air is 40% of total air volume. In consideration of leakage, total regeneration air volume is no more than 60%. Therefore, regeneration air flow rate selected is 11651.75kg/h, which is 50% of total air volume. The heat required for increasing regeneration air temperature is on the basis of enthalpy difference between regeneration state and indoor air state, their enthalpy are 149.35kJ/kg(d.a) and 53kJ/kg(d.a), and the value is about 311.85kW (11651.75kg/h×(149.34-53) kJ/kg(d.a)/3600). Therefore, the required steam can be simply calculated by the required heat for silica gel desiccant regeneration and the difference between saturated steam enthalpy and saturated condensation enthalpy, and the value is 542.54kg/h (311.85kW×3600/(2762.9-693.63)kJ/kg).

In the ejector refrigeration subsystem, the steam is used as primary flow. The steam consumption can be calculated by the entrainment ratio which is defined as the ratio of mass flow rate of secondary flow to that of primary flow, because the mass flow rate of secondary flow can be calculated by the cooling load of evaporator (125.6kW). On the basis of cooling load of evaporator and the vaporization heat of water, the corresponding secondary flow rate is 176.79kg/h (125.6kW×3600/2557.6kJ/kg). However, the entrainment ratio of ejector is impacted by many factors such as steam state, evaporation temperature and condensation temperature, in this study, they are 0.7MPa, 12℃and 40℃respectively. Under these similar working conditions, the performance of the ejector refrigeration system from literature is adopted, according to the research of Alexis & Rogdakis [1], an entrainment ratio 0.45 is available. Thus, the mass flow rate of primary flow is 392.87kg/h (176.79kg/h/0.45).

To sum up, total steam consumption is about 935.41kg/h.

3.4.2 *Power consumption*
The main power consumption devices in ERRD A/C system are fans and pumps. For fans, the power consumption of supply air fan is 20kW, and the power consumption of regeneration air fan (fan 2) is related to regeneration air flow rate, which is 50% of total air volume in this paper, its power consumption can be simply regarded as half of the supply air fan, and the value is 10kW. For pumps, in ejector refrigeration subsystem, two pumps are used to transport sea water for condenser and fresh water for generator. The mass flow rate of generator water pump is equal to the primary flow of ejector, and the value is 392.87kg/h. The mass flow rate of condenser pump can be calculated by the heat taken away by sea water, which can be regard as cooling load of evaporator plus the enthalpy difference of primary fluid between ejector inlet (saturated steam, 0.7MPa) and condenser outlet (saturated water, 40℃), the calculated result is 408.83kW (125.6 kW+392.87×(2762.90-167.53)kJ/kg/3600). Under the same conditions as in the conventional A/C, the corresponding mass flow rate is about 70420.50kg/h (408.83kW×3600/5℃/4.18kJ/kg/℃). In rotary desiccant A/C subsystem, two pumps are used to transport sea water for intercooler 1 and intercooler 2 where the heat taken away by sea water is 207.38kW based on the difference between full heat load and cooling load of evaporator (332.98kW-125.6kW), and the corresponding mass flow rate is about 35720.90kg/h (207.38kW×3600/5℃/4.18kJ/kg/℃). Therefore, the total mass flow of water for pumps in ERRD A/C system is about 106534.27kg/h (392.87kg/h+70420.50kg/h+35720.90kg/h), which is about 139% of the conventional A/C. However, in consideration of more pumps and higher lift generator pump, the power consumption of pumps in ERRD A/C system selected is 10kW, double of conventional A/C. To sum up, the total power consumption is about 40kW, which is 32.87% of the conventional A/C.

3.4.3 *COP*
The COP of ERRD A/C system is defined as the ratio full heat load to power consumption, and the value is about 8.32.

4 **Conclusions**
Compared with the conventional marine A/C, the combined use of ejector refrigeration and rotary desiccant technology for marine A/C can make full use of ship waste heat and abundant sea water so as to realize independent temperature and humidity control, and achieve 67.13% power saving. However, the steam consumption of ERRD A/C system reaches up to 935.41kg/h, which may affect normal use of steam on ships, and the related influence need to be further studied.

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