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A NOVEL HYBRID AIR-CONDITIONING SYSTEM COMBINED WITH SEA SPRAY AEROSOL REMOVAL DRIVEN BY LOW-TEMPERATURE HEAT SOURCE

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ABSTRACT

The air of high humidity and high sea spray aerosol (SSA) on islands or coastal area always leads to the serious equipment corrosion and affects the living comfort of residents. Conventionally, the air-conditioning system can only provide the cooling dry air, and the SSA reduction process is always separated and consumes precious electricity power as well as expendable materials. To simplified the procedure and reduce the energy consumption, this paper proposed a novel hybrid air-conditioning system combined with sea spray aerosol removal. Based on the characteristics of liquid-desiccant dehumidification and phase transitions of the ternary solution system, the combined system can be driven by the waste heat source of 90 °C. The proposed system was simulated by the thermodynamic equilibrium model. The results showed that the humidity ratio of the supply air can reach 6.83 g/kg(dry air), with a temperature of 21.14°C. Compared with the conventional cooling dehumidification system utilizing vapor compression refrigeration driven by power, the power saving ratio (*PSR*) and the equivalent power generation efficiency (η_{eq}) of the proposed system can reach 92.16% and 8.74%, respectively. Besides, the crystallization experiment is conducted to verify the feasibility of the NaCl separation process. This study provides a new hybrid air-conditioning system to simultaneously remove moisture and sea spray aerosol by using low-temperature waste heat.

Keywords: Low-temperature heat utilization; Absorption refrigeration; Liquid desiccant dehumidification; Sea spray aerosol removal; Combination principle; System optimization

NONMENCLATURE

Abbreviations	
SSA	Sea Spray Aerosol
HVAC	Heating, Ventilation and Air Conditioning
Symbols	
a_w	water activity
COP	coefficient of performance
H	enthalpy
m	mass
$\dot{m}$	mass per unit time
Q	heat transfer rate
t	time, h
T	temperature
y	ionic strength fraction
η_{eq}	equivalent power-generation efficiency

1. INTRODUCTION

There are a large number of islands situating in the tropical marine area, with the feature of high temperature, high humidity and a certain amount of sea spray aerosol (SSA). Under high-wind conditions, breaking waves and whitecaps eject large numbers of droplets into the atmosphere which are the major source of SSA. Sea spray aerosol consists of particles with radius from 0.01 μm to millimeter range, and its main component is NaCl [1]. SSA together with moisture could aggravate the electrochemical corrosion of the metal parts [2]. A hybrid air-conditioning system which can achieve the function of cooling, dehumidification and

SSA removal becomes an active requirement for the numerous islands.

Due to high transportation costs, power and resources on islands are more precious. Meanwhile, most waste heat from power generation unit on the islands is still not fully utilized, such as heat source below 90°C [3, 4]. So, it's promising to explore new multifunctional air-conditioning system driven by waste heat with low energy level. At present, absorption refrigeration and liquid-desiccant dehumidification have shown the advantage of reducing the electric power consumption by utilizing low-temperature thermal energy [5, 6]. Current technologies of removing SSA requires precious electricity power and expendable materials, such as cyclone separator and high-efficiency particulate air filter [7]. However, there's no report about the single technology of dehumidification combined with SSA removal. Also, no relevant studies for SSA removal driven by thermal energy have been reported in the literature works.

In this paper, a hybrid air-conditioning system combined with SSA removal process driven by low-temperature heat source is proposed. By operating the proposed system, the corrosiveness of the indoor atmosphere could be reduced effectively, which is advantageous in saving energy and extending the service time of user equipment on the island.

2. SYSTEM DESCRIPTION

The mechanism of the combination of dehumidification and SSA removal process as well as the critical experimental verification are shown as follows.

2.1 Mechanism description

A typical liquid-desiccant dehumidification process in a cross flow dehumidifier is adopted in the system [8]. Through the direct contact between the air flow and the liquid desiccant, the SSA will be captured and absorbed by the surface of the liquid desiccant, which is similar to the process in a wet filter. In this absorption process, the moisture and SSA are both removed from the fresh air together.

In order to guarantee the stability of the dehumidification performance with the dissolution of NaCl, which is the main component of SSA, LiCl aqueous solution is adopted as the working medium in the proposed system. With NaCl getting into the LiCl solution, the vapor partial pressure of the solution, which represents the dehumidification driving force, will not change rapidly, if the concentration of NaCl could be controlled much lower than that of LiCl[9]. It can be easily guaranteed due to the phase transitions characteristics of the LiCl-NaCl-H_2O system, which is explained as follows.

In order to ensure the stability of the system operation, it is necessary to separate the water and NaCl from the system timely. A certain amount of water in the solution is volatilized and separated when the heated solution contacts air directly. The NaCl separation process is based on the phase transitions characteristics of the LiCl-NaCl-H_2O system. Previous research showed that in the eutectic point of a saturated LiCl-NaCl-H_2O system, the solid phases are NaCl and LiCl·$2H_2O$. Further, Fig. 1 gives the solutes composition of the ternary system corresponding to the eutectic point [10, 11]. When the LiCl concentration of the saturated system is lower than that corresponding to the eutectic point, the system composition moves towards the composition at the eutectic point by cooling. This makes the concentration of NaCl decreased, leading to the NaCl crystallized and separated from the system firstly. Therefore, a certain LiCl concentration of the solution could ensure the crystallization process of NaCl by cooling the saturated solution, which matches the concentration of the dehumidification process. Based on the above principles, a liquid-desiccant dehumidification system combined with SSA removal is proposed and the details description is shown as followed.

Based on the above principles, a hybrid air-conditioning system combined with SSA removal is proposed and the details description is shown as followed.

2.2 System description

Figure 2 shows the flow chart of the proposed system. It consists of an absorption refrigeration process, a dehumidification combined with SSA removal process, a water separation process, a NaCl separation process, and a water-solutes mass balance process. In absorption

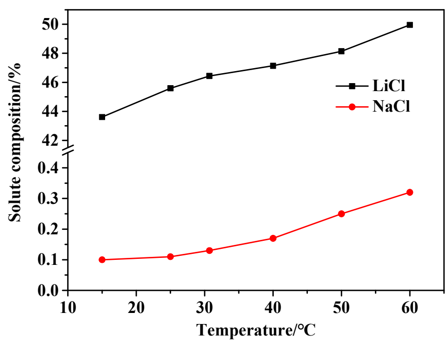

Fig. 1 The solutes composition of the ternary system corresponding to the eutectic point

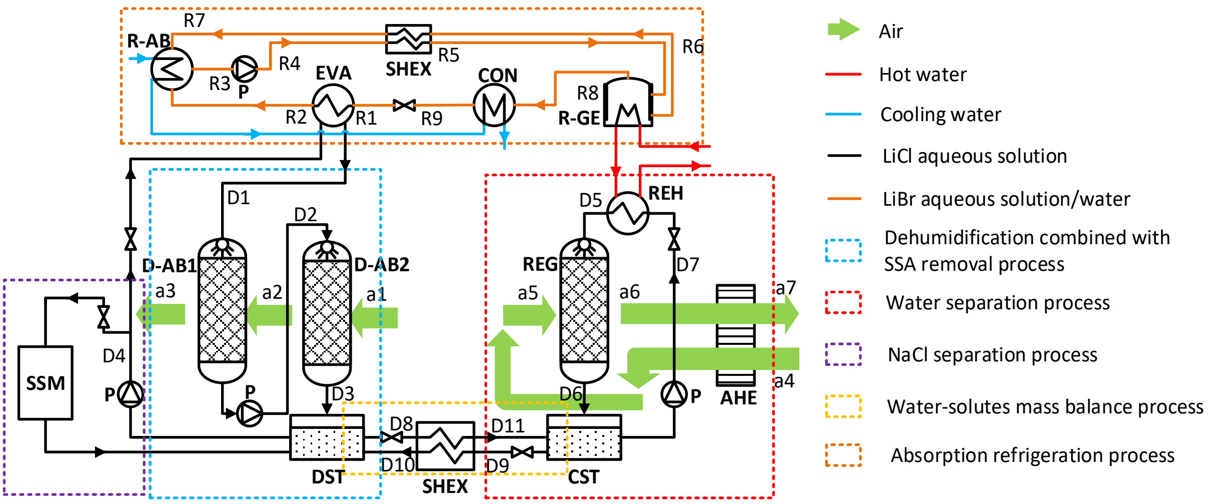

Fig. 2 Flow chart of the hybrid air-conditioning system combined with sea spray aerosol removal driven by low-temperature heat source

refrigeration process, the LiBr solution is used as the working fluid. The process includes a generator, condenser, absorber, heat exchanger, pump, throttling valve and evaporator. The cooling energy generated by the lower-temperature heat is used to cool the LiCl solution in the evaporator (EVA). In the dehumidification with SSA removal process, the dilute solution pressurized by the solution pump (P) is firstly cooled for improving the dehumidification capacity. Then the cooled solution passes through two dehumidification absorbers (D-AB) and absorbs water and SSA in direct contact with the outdoor air (a1). After that, the solution will flow back into the dilute solution tank (DST). Outdoor air (a1) continuously flows through D-AB2 and D-AB2 in order to match the dehumidification capacity of the solution. In the water separation process, the pressurized concentrated solution exchanges heat with the waste heat source in a regeneration heater (REH) to rise the vapor partial pressure. Then the heated solution is volatilized in the contact process with the air flow (a5) and flows back into the concentrated solution tank (CST), which makes the a4 temperature rises by heat transfer. Through an air heat exchanger, the sensible heat of heated air is recovered to reduce the heat loss of the system. In the NaCl separation process, part of the solution (D4) flows into the sodium chloride separation module (SSM) periodically. The NaCl is crystallized and separated under a low-temperature condition with a chiller. This process operates intermittently to keep the solution stationary, which promotes NaCl crystal growth. In the water-solutes mass balance process, the circulation flow between the CST and DST makes the water absorbed in the absorber transfer into the regenerator.

Figure 3 gives the flow chart of a conventional cooling dehumidification system utilizing vapor compression refrigeration driven by power, selected as the reference system. The refrigerant is R134a in the system. In order to obtain a low humidity ratio, the temperature of the air after dehumidification in the cooling dehumidifier need to reach the dew point temperature corresponding to the humidity ratio, which is much lower than the comfortable air supply temperature. Therefore, an air heat exchanger is utilized to recover the sensible heat of a1 to rise the temperature of a3.

3. SYSTEM SIMULATIONS

3.1 Mathematic models

A stable thermodynamic model is established based on the energy balance theory. The thermal effect of the SSA removal process in the absorber is negligible, because the mass of the vaper absorbed is thousands of times that of SSA. The NaCl separation process is not included in the model, for the state of intermittent operation, which will be analyzed section 4.2.

Based on the mechanism description, the thermophysical properties of the ternary solution are extremely close to that of the LiCl solution, which can be

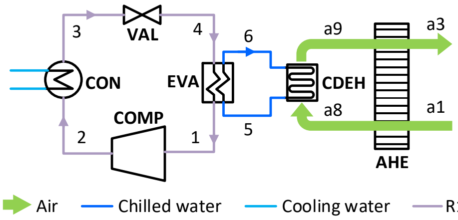

Fig. 3 The flow chart of a conventional vapor compression air-conditioning system driven by electricity

calculated with the numerical equation proposed by Pátek [12]. A cross-flow heat and mass transfer model reported in [13] is utilized to simulate the processes in the ABS and the REG, and the key parameter NTU_m is correlated with the corresponding experimental performance, which is set to 1.2. The design conditions of the system are shown in Table 1. All the parameters of flows could be obtained through the mass balance and energy balance of the air and solution.

3.2 Evaluation indices

Coefficient of performance (*COP*) is a common criterion to evaluate the system driven by heat source, which is defined as Eq. (2).

$$COP = \frac{Q_R}{E_D} = \frac{H_{a1} - H_{a3}}{E_D} \quad (2)$$

where Q_R is the enthalpy difference between outdoor air (a1) and supply air (a3), and E_H is the total energy input.

The power saving ratio (PSR) is used to evaluate the power-saving ability of the proposed system. The definition is as Eq. (3).

$$PSR = \frac{W_{ref} - W_{prop}}{W_{ref}} \quad (3)$$

Where W_{prop} is the power consumption of the proposed system and W_{ref} is that of the reference system.

To further evaluate the level of waste heat utilization, the equivalent power-generation efficiency (η_{eq}) is adopted, which is expressed as Eq. (4)

$$\eta_{eq} = \frac{W_{ref} - W_{prop}}{Q_H} \quad (4)$$

Although the NaCl separation process will consume extra energy, the time interval of every two processes can be long enough to neglect energy consumption. The minimum operating time interval is adopted to evaluate the energy consumption influence of the NaCl separation process, which is defined as Eq.(5).

$$t_{min} = \frac{m_{c,NaCl}}{\dot{m}_{a,NaCl}} \quad (5)$$

Where t_{min} is the minimum operating time interval, $m_{c,NaCl}$ is the mass of NaCl crystal separated in each NaCl separation process, and $\dot{m}_{a,NaCl}$ is the NaCl mass absorbed in the absorber per unit time.

Table 1
Main parameter specifications for system simulations.

Items	Value
Dry-bulb temperature, °C	30
Fresh air humidity ratio, g/kg	21.57
Air flow rate, m^3/h	3000
Mass concentration of weak LiCl aqueous solution, %	35
Mass concentration of weak LiBr aqueous solution, %	45.85
Cooling water temperature, °C	27
Heat source water temperature, °C	90
Solution-water minimum temperature approach, °C	5
Efficiency of the solution-solution heat exchanger	0.75
LiCl aqueous solution flow rate, L/s	1.5
mass of solution processed in each NaCl separation process, kg	200

4. RESULTS AND DISCUSSION

4.1 Case study of the proposed system

The main parameters of the system are summarized in Table 2. It shows that the proposed system is driven by the waste heat source of 90°C, partial moisture and SSA in the fresh air (3000 m^3/h) is removed during the absorption process. The humidity ratio of the supply air (a3) can reach 6.83 g/kg(dry air), with a comfortable temperature of 21.14 °C.

Table 3 presents the thermodynamic performance of the proposed system compared with the reference system. The *COP* of the proposed system is 0.41. The reference system can provide the same supply air by utilizing 10.21 kW electric power, with a *COP* of 4.29, which is much higher than the proposed system because of the high energy level of electricity.

However, the power saving ratio (*PSR*) reaching 92.16% because only 0.8 kW power is needed to drive the proposed system. It means the proposed system has a strong power-saving ability. On the other hand, the proposed system also needs 107.65 kW of additional heat input at 90°C compared with the reference system. The equivalent power-generation efficiency (η_{eq}) is 8.74%, which is higher than the thermal efficiency (2.3%) of an ORC (Organic Rankine Cycle) system with R245fa as a working fluid driven by heat source at 90°C[14]. Through the system simulation, the proposed system shows the advantages of saving power and low-temperature heat source utilizing ability.

4.2 Influence of NaCl separation process

The NaCl separation process is considered to be periodical for providing a better crystal growth environment. The effect of crystallization temperature on the minimum operating time interval (t_{min}) is discussed under the following operating conditions. The solute of SSA in fresh air is around 5 mg/m^3, and the SSA removal efficiency of the absorber is set as 70%. Fig 4

Table 2
Stream state parameters in the proposed system

State	t/°C	ξ/%	d/(g/kg(da))	m/(kg/s)	State	t/°C	ξ/%	P/kPa	m/(kg/min)
D1	18.00	32.00	-	1.794	R1	15.00	0.00	1.7	1.18
D2	20.76	31.93	-	1.798	R2	15.00	0.00	1.7	1.18
D3	26.42	31.76	-	1.808	R3	37.00	49.90	1.7	7.31
D4	26.85	32.00	-	1.794	R4	37.00	49.90	8.2	7.31
D5	69.65	38.00	-	1.820	R5	67.22	49.90	8.2	7.31
D6	59.48	38.29	-	1.806	R6	85.00	59.54	8.2	6.13
D7	58.94	38.00	-	1.820	R7	42.00	59.54	8.2	6.13
D8	26.85	32.00	-	0.088	R8	85.00	0.00	8.2	1.18
D9	58.94	38.00		0.074	R9	42.00	0.00	8.2	1.18
D10	34.86	38.00		0.074	H1	90.00	0.00	101.3	59.10
D11	45.85	32.00		0.088	H2	76.88	0.00	101.3	59.10
a1	30.00	-	21.57	0.957	H3	63.94	0.00	101.3	59.10
a2	25.43	-	11.10	0.947					
a3	21.14	-	6.83	0.943					
a4	30.00	-	21.57	0.957					
a5	43.10	-	21.57	0.957					
a6	58.10	-	36.31	0.971					
a7	45.00	-	36.31	0.971					

Table 3
Thermodynamic performance comparison of two system.

Projects	Items	Proposed system	Reference system
Energy output	Cooling energy output, kw	43.80	43.80
Energy input	Total heat input, kw	107.65	-
	Total power input, kw	0.80	10.21
Evaluation indices	*COP*	0.41	4.29
	PSR,%	92.16%	-
	η_{eq},%	8.74%	-

shows the mass of NaCl crystal and minimum operation cycle under different crystallization temperature. With the decrease of the crystallization temperature, the mass of NaCl crystal and t_{min} gradually improve. At a temperature of 7 °C, the Mass of NaCl crystal is 0.63 kg and time interval of every two processes can reach 25 hours. Compared with the other continuous processes in the system, the energy consumption of this process is very small and can be neglected. After the separation process, the heat input of the proposed system would also be stable by controlling the flow rate of the solution back to DST.

To further verify the feasibility of the NaCl separation process, the key process of the system, the experiment of cooling and crystallization of LiCl-NaCl-H_2O ternary saturated solution is carried out. The mass concentration of LiCl is 30%, with an initial temperature of 30°C, and the crystallization temperature is set to be 10°C. Fig. 5 shows the NaCl crystal separated from the solution. The results show that NaCl can be crystallized from the saturated solution through cooling process. However, a large number of primary crystal nuclei are formed in the solution when the degree of supersaturation reaches a certain level. Due to the mass of NaCl crystal is constant under the same crystallization temperature, the final size of the crystal particle drops with the number of the crystal nuclei rising, which means it is more difficult to separate the crystal from the solution. Adding some NaCl crystal particles before cooling process as the crystal nucleus could solve this problem.

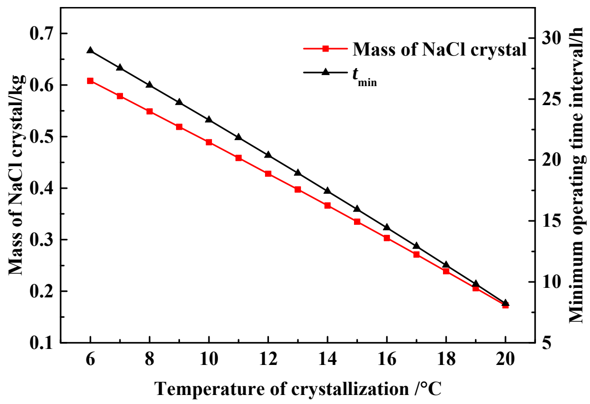

Fig 4 Effect of crystallization temperature on the NaCl separation

Fig 5 NaCl crystal separated from the solution

5. CONCLUSIONS

In this paper, a novel hybrid air-conditioning system combined with sea spray aerosol removal driven by low-temperature heat source is proposed. Based on the characteristics of liquid-desiccant dehumidification and phase transitions of the ternary solution system, the combined system can be driven by the waste heat source of 90 °C.

The proposed system was simulated by the thermodynamic equilibrium model and the optimization of the design parameter are presented. The results showed that the humidity ratio of the supply air can reach 6.83 g/kg(dry air), with the temperature of 21.14°C. The power saving ratio (*PSR*) reach 92.16% compared with the conventional vapor compression air-conditioning system, and the equivalent power generation efficiency (8.74%) is 6.44 percentage point higher than that of an ORC driven by the same heat source. The proposed system presents the advantages of saving power and low-temperature heat source utilizing ability. The feasibility of the NaCl separation process is verified with the experiment.

The proposed system provides a suitable environment for residents and equipment, which helps to reduce the corrosiveness of the indoor atmosphere effectively and has obvious advantages of extending the service lifetime of the user equipment. It makes full use of the waste heat with low energy level and shows a good performance on resources saving on islands, which has favorable prospects for application.

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