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An experimental investigation of salt-water separation in the vacuum flashing assisted with heat pipes and solid adsorption

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HIGHLIGHTS

- Desalination is studied with using heat pipe and adsorbent beds.
- Adsorbent beds can decrease evaporator pressure by 0.4–1 kPa.
- An increase in the superheating temperature can be achieved.
- It provides a new way to utilize lower grade heat source.

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ABSTRACT

A novel single stage vacuum evaporator, as a salt-water separator, is developed to fully use ultra-low grade heat source as low as 50 °C. The novel design incorporates several technologies, including heat pipes (HPs), spray flashing and solid adsorption. Its performance is evaluated by separating water from NaCl solution with 3%concentration. The results of the experiment study show that HPs transfer heat to the droplets rapidly to assist a second evaporation and maintain the superheat degree for the salt-water separation process after the flash evaporation. It is also found that, when the adsorbent beds are applied, the evaporation pressure decreases by 0.4–1 kPa compared to the early experiment results, which results in an increase of the superheat degree. The introduction of solid adsorption in the salt-water separator provides a new way to utilize ultra-low grade heat source, although it brings a mixed success to the whole device while the separation ratio is slightly lower than expected due to the fact that there are both improved and impaired effects of heat transfer during the whole adsorption process. The lower cooling water temperature of the adsorption process, leads to better desorption effect, which improves the overall performance of the salt-water separator.

1. Introduction

Separating salts from seawater can be realized via evaporation and concentration, cooling crystallization, reverse osmosis technologies, etc. These technologies have been applied in many areas including desalination, liquid desiccant, and sewage disposal [1–4]. However, due to the existing technology constrains, the driving heat source temperature for these technologies normally exceeds 100 °C, i.e. the water boiling temperature. Double-effect lithium bromide absorption air conditioning, for example, needs driving heat source temperature over 130 °C. Ultra-low grade heat in the temperature range of 50–100 °C, which is abundant from renewable energy and waste heat sources, has not been effectively utilized [5]. Therefore, exploring efficient methods of salt-water separation which uses ultra-low grade heat becomes increasingly appealing from a sustainable perspective.

As the core component of vacuum flashing salt-water separation device, vacuum evaporator has become a research focus in recent years. Dan Zhang [6] investigated static flash evaporation of NaCl solution when the superheat degree was between 1.7 and 53.9 K. It was reported that vapor quality is improved with the increasing initial solution height, while the vapor production per unit mass of NaCl solution decreased, because the increasing static pressure of bottom liquid restrains the flash process. Besides, it was also found that vapor quality is increased linearly with increasing the superheat degree. Furthermore, through adopting the spray flash evaporation method proposed by O. Miyatake et al. [7–8], A. Günther [9] and Sami Mutai [10] injected atomized liquid spray into the low pressure environment to accelerate the flashing process. The interaction between the flash and liquid atomization was studied, which indicates that flash intensifies the atomization effect and reduces droplets' size even when the superheat degree was relatively small. Consequently, the flash evaporation rate and ratio are improved and the non-equilibrium temperature difference is reduced. However, the researchers [9,10] focused on improving the conversion

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Nomenclature

HP	heat pipe
m	condensed water mass (kg)
P	heat pipe average power (W)
P_s	evaporator pressure (kPa)
P_l	condenser pressure (kPa)
t	elapsed time (s)
T	heat source temperature (°C)
T_c	cooling water temperature (°C)
T_{hp}	heat pipe surface temperature (°C)
T_s	initial superheat degree (°C)
T_x	adsorbent bed temperature (°C)
η	water separation ratio (%)

rate from sensible heat to latent heat, rather than enhancing the separation ratio fundamentally. Therefore, the single stage separation ratio is only 0.8–1.4%ofthe traditional vacuum flash desalination devices.

In order to discover the relationship between heat and temperature variations in the flash process of droplets, C.M. Augusto [11] and Wenlong Cheng et al. [12] conducted the researches on the formation and the temperature variations of the droplets during the vacuum flashing. The results showed that, during the static flash evaporation, the droplets' final temperature is decreased when the pressure gets lower or the droplets become smaller. It is reported that it takes more time to reach the lowest temperature when droplets' original temperature is high. Other researchers [1,2] studied the temperature distribution of lithium chloride droplets during the vacuum flashing process. It was found that the radiant heat significantly promotes the flash evaporation. Therefore, the heat supply in a timely manner to the flash evaporation is the critical requirement for maintaining the evaporation intensity. In terms of that, heat pipes (HPs) can be used as an ideal media in the heat transfer process due to their high heat transfer coefficient even better than the heat conductivity of metals. Xuehua Guo [13] and Qian Yang [14] applied the gravity HPs into single stage vacuum evaporators. Heat within engine jacket water is absorbed by HPs, and then transferred to seawater, which forms a falling film on the HP's cold side surface. Because the solution absorbs heat continuously during the falling process, the superheating is well maintained. It is mentioned that the single stage separation ratio reached up to 8–30% [13,14]. In other literatures, H. Jafari Mosleh [4] applied HPs to a novel solar-driven desalination device, which achieved fresh water yield of 0.933 $kg \cdot m^{-2} \cdot h^{-1}$ and improved the utilization ratio from 22.5% to 65.2%.

In order to maintain the low pressure during the flash evaporation, steam generated in the evaporator must be transferred into liquid form quickly. Compared to the traditional direct condensation using cooling water, solid adsorption technology can dramatically reduce the steam pressure to a lower level in the system. Its potential in desalination has attracted wide attention in recent years. National University of Singapore made some remarkable achievements on the application of solid adsorption in desalination [15–18]. Solid adsorbent was introduced into the process to replace the traditional condensing system, which lowers the evaporation temperature to 4–5 °C. Based on that, they remarkably reduced the condensing pressure and increased the stage number of MED (Multi-effect Distillation) to achieve 1.5–2 times of the water producing ratio.

To incorporate the merits of the abovementioned technologies to fully utilize ultra-low grade heat and strengthen the evaporation intensity, the authors [19] developed a novel vacuum evaporator, which includes two separation processes: the spray flash prime evaporation and the second evaporation reheated by the HPs and assisted by the solid adsorption. The water separation process and the fresh water yield per unit volume are improved greatly. When solid adsorbent beds were added into the system, the vacuum pressure was maintained at a very low level, and eventually the vapor generated in the evaporator was absorbed by the adsorbent beds quickly. In this paper, a series of water separation experiments of NaCl solution with 3% salinity are reported, which identifies the heat and mass transfer characteristics, when the HPs and the adsorbent beds are adopted and integrated into the novel single stage vacuum evaporator for salt-water separation.

2. System description and working principle

2.1. Experimental rig setup

The experimental rig mainly consists of an evaporator, two adsorbent chambers, a condenser, a water circulation loop and two vapor channels. A schematic diagram of the setup is shown in Fig. 1 and the picture of the rig is seen in Fig. 2.

The evaporator is mainly composed of two blind plates and a toughened glass tube in between, the toughened glass tube is with the dimensions of inner diameter D = 135 mm, height H = 450 mm as well as HPs with the dimensions of external diameter D = 10 mm, wall thickness T = 0.5 mm, length L = 400 mm. Because of the cylindrical spray region, the HPs are plugged through the holes on the blind plate in a regular hexagon form including one drainage hole as shown in Fig. 3. Sintered water-copper HPs, water as working fluid, are adopted in the experiment. The metal powder-sintering method is implemented in the internal wall of the HPs, resulting in strong hydrophilic and hydrophobic characteristics at the hot end and cold end respectively, which helps to improve the heat transfer performance significantly [20]. The HP performance parameters and thermocouple arrangement on the HPs are shown in Table 1 and Fig. 4 respectively. A centrifugal nozzle head with the aperture of 0.3 mm used in the experiments can generate micro droplets with the diameters of 5–10 μm under a pressure between 20 and 70 bars.

The adsorbent bed is made up of five sets of U-shaped aluminum finned stainless steel-made tube in each adsorbent chamber. 8 kg of 'Type A' fine pored silica gel with the diameters of 0.5–1.5 mm is packed between the fins by the wire mesh. Thermocouple arrangement on the adsorbent bed is shown in Fig. 5. There are 8magnetic valves in the water circuits to switch hot water and cold water pathways.

T thermocouples with the precision of ±0.5 °C are used for temperature measurement. Pressure gages with range of 0–20 kPa and accuracy of 0.1% are set in the evaporator and condenser. Because the adsorbent chamber has a large flow area and it is close to the evaporator and condenser, the measured value of pressure also stands for the adsorbent chamber pressure.

The working principle of the experimental setup is as follows. The high pressure in the centrifugal nozzle atomizes the preheated solution into micro droplets and sprays them into the vacuum evaporator. After two separation process including the spray flash evaporation and the HP reheating second evaporation, steam is transferred to the adsorbent bed 'A' through adsorption. The remaining concentrated solution is pumped out. Adsorbent bed B is heated by hot water at the same time, and the vapor desorbed will condensation in condenser. The adsorbent bed 'A' and 'B' is set to perform desorption or adsorption alternatively by switching the valves, ensuring the continuity of the experiment [21]. The temperature and pressure of both adsorption and desorption process will change with the heat and mass transfer process. According to the mass balance, the mass of adsorption is equal to the mass of desorption and the mass of condensed water in one operation cycle.

2.2. Experiment parameters

The experiment examines the influence of the adsorbent beds and HPs in the heat and mass transfer process. The main parameters involved are the water temperature T in the heating tank1, the cooling