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Thermodynamic analysis of a novel evaporation and crystallization system based on humidification processes at ambient temperature

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ABSTRACT

Power consumption in the field of evaporation and crystallization has attracted extensive attentions all over the world. In this paper, humidification and cooling crystallization methods are involved simultaneously to constitute a novel evaporation and crystallization configuration. In light of the thermal processes included, mathematical models based on the mass and energy equilibrium are established. The characteristics of the adopted evaporation and crystallization system (ECS) at the designed parameters are first simulated and analyzed, and the corresponding influence laws from the appointed key parameters are analyzed. Furthermore, a scale and economic analysis is also achieved to explore the application prospect of the evaporation crystallization system. The practicability of the novel evaporation and crystallization system at ambient temperature is verified, with a descent amplitude of 52.88% for the energy consumption of evaporated water within the prescribed range of the air mass flow rate. The simulation results indicate variation of the inlet air parameters, including the relative humidity and temperature, is not effective to improve the thermal efficiency of the evaporation and crystallization system, while an evident reduction for the energy consumption of evaporated water (ECEW) as 45.08 $kWht^{-1}$ is achieved in response to the volume growth of the packings from 15 m^3 to 30 m^3. Finally, it is also found that the cost of heat and mass transfer areas will rise significantly with the increase of the volume although the energy conversion is improved.

1. Introduction

As a result of the serious shortage of mineral resources as well as the environmental pollution, recovery methods of the crystal and relevant evaporation and crystallization devices have attracted more and more attentions all over the world. Actually, kinds of evaporation and crystallization patterns have been introduced to achieve the crystal producing from the exhaust solution [1], such as multiple stage flashing (MSF) [2], multiple effect evaporation (MEE) [3], thermal or mechanical vapor recompression (TVR/MVR) [4–6] and membrane [7].

However, such evaporation and crystallization plants consumed huge amount of energy, thermal energy (MSF, MEE, TVR and membrane) or power (MVR), to achieve the seperation of the crystal from the exhaust solution, and the combustion of the fossil fuel also contribute to the environmental pollution [8,9]. Accordingly, taking the concept of energy conservation into the general evaporation and crystallization methods, self-heat recuperation theory (SHRT) was proposed and developed to enable the recovery both for the internal sensible and latent heat without any additional heat [10,11]. Kotani [12] proposed a conceptual design of an active magnetic regenerative (AMR) heat circulator for self-heat recuperation to realize energy savings. It was found that an AMR heat circulator had significant potential to reduce the total energy consumption in a thermal process. Han [13] focused on the application of self-heat recuperation theory in mechanical vapor recompression evaporation systems when used to concentrate solutions with boiling point elevation. Based on a nonlinear model for the multi-stage MVR system, the stage number, evaporation temperature, heat transfer temperature differences and stage concentration changes on the actual power consumption of the applied steam compressor was calculated and optimized. The simulation results showed that compared to the single-stage MVR and conventional three-effect evaporation system, multi-stage MVR system configurated with SHRT offered advantages as the stage number and evaporation temperatures increases. It can be concluded that the application of SHRT was effective to optimize the energy conversion status within the evaporation and crystallization. However, due to the vacuum condition and the corrosion resulting from the solution, the final investment of the system, mainly including the evaporator and steam compressor, will be very expensive

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Nomenclature

Roman symbols

a	specific area ($m^2\,m^{-3}$)
D	diameter (mm)
h	enthalpy ($kJ\,kg^{-1}$)
H	packing height (m)
k	mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
m	mass flow rate ($kg\,s^{-1}$)
p	pressure (Pa)
Δp	pressure drop ($Pa\,m^{-1}$)
Q	heat load (kW)
Re	Reynolds number
s	solubility ($(g(100\,g)^{-1}$)
S	concentration of solution ($g\,kg^{-1}$);
T	temperature (K)
v	velocity (ms^{-1})
V	volume (m^3)
ω	humidity ratio ($g\,kg^{-1}$)

Greek letters

ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity($kg\,m^{-1}\,s^{-1}$)
ε	void fraction of packing
φ	relative humidity

Subscripts

a	air
b	brine
c	crystal
con	condenser
d	dry
cs	concentrated solution
da	dry air
e	evaporator
h	humidifier
i	inlet
l	liquid
ml	mother liquor
o	outlet
p	packing
r	refrigeration
re	remaining
s	solution; solid
w	water; wet

Abbreviation

AMR	active magnetic regenerative
CTE	conventional three-effect
CR	cycle ratio
ECEW	energy consumption of evaporated water
ECS	evaporation and crystallization system
HDH	humidification dehumidification
MEE	multiple effect evaporation
MSF	multiple stage flashing
MVR	mechanical vapor recompression
SHRT	self-heat recuperation theory
TTD	terminal temperature difference
TVR	thermal vapor recompression

[14,15].

Recent years, a novel technology called humidification dehumidification (HDH) was introduced to the separation industry, and extensive investigations have been focused in the field of desalination all over the world due to the high thermal efficiency and ambient operation conditions [16–18]. After establishing the mathematical models for various HDH desalination cycles, Narayan [19] investigated the relevant performance through the platform of Engineering Equation Solver (EES), and several specific methods were proposed to improve the original desalination systems, such as multi-pressure, thermal vapor compression and multi-extraction. In comparison with the original HDH system, the aforementioned measures were verified to be effective to update the performance of the HDH desalination system. Hamed [20] advised mathematical models to simulate the related performance and water production for a solar desalination plant. Two periods were designated to investigate the water production of the proposed system: the first period from 9 am to 17 pm and the second period from 13 pm to 17 pm. The theoretical results indicated that the highest water production emerged in the second period. Furthermore, the corresponding experimental configuration was also structured to study the heat and mass transfer characteristics within the desalination system. Finally, the consistency between the experimental and theoretical results declared the accuracy of the proposed theoretical model involved in the solar HDH desalination system. Huang [21] suggested a novel HDH system to evaporate the solution with a more rigorous mathematical model for the humidification. Based on the established simulation programme for the thermal system, theoretical investigation was achieved to research the influences form critical parameters on the evaporation capacity as well as the gained input ratio. It was found that the reflux ratio and inlet temperature of the solution into the humidifier were proportional to the relevant evaporation capacity, and an optimized air mass flow rate was discovered to maximize the evaporation capacity. For the aspect of the gained input ratio (GIR), it declined with the increase of the air mass flow rate while ascended with the increase of the reflux ratio. Mahdizade [22] proposed a novel HDH desalination unit, constituted with half open-air, open-water architecture. Thermodynamic analysis and corresponding enhancement was conducted and suggested at the fixed top temperatures. Siddiqui [23] introduced the vacuum condition into the HDH desalination unit, and the enhancement effect was validated with an elevated value of GOR. Kabeel [24] test the performance of the HDH desalination system with an indirect solar dryer, and an improvement of 29% for the thermal efficiency was gained when the cycling air flow rate rose. In addition of the thermodynamic investigations, He [25] conducted a thermo-economic analysis for a HDH desalination system, powered by waste heat, and a much lower cost was found compared to that of the solar driven ones.

Packed bed, with high specific surface area, was always applied in the HDH unit, especially the humidification, while the bubble column was also introduced into the humidification and dehumidification processes [26,27]. Rajaseenivasan [28] proposed a biomass driven HDH desalination system, which was made up of bubble column humidifier, dehumidifier, a biomass stove and an air heat exchanger. The relevant experiments were first achieved in the bubble column humidifier to determine the water depth, bubble pipe hole diameter as well as the water temperature. It is seen that the humidifier capacity was augmented with the elevation of the water depth, water temperature, air mass flow rate, cooling water flow rate, and reduction of the diameter for the bubble pipe hole. It is found that the water temperature is critical to control the humidifier performance in comparison with other parameters. Furthermore, better specific humidity was observed with a bubble pipe hole diameter of 1 mm, water depth of 170 mm and water temperature of 333.15 K. Finally, a correlation was concluded to assess