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Thermal investigation and performance analysis of a novel evaporation system based on a humidification-dehumidification process

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ABSTRACT

A novel humidification-dehumidification (HDH) system is designed to enhance the evaporation capacity. A more rigorous mathematical model of humidifier is proposed. A simulation programme of the whole system is built. Theoretical investigation is performed to investigate the effect of various parameters on the evaporation capacity and gained input ratio. The results demonstrate that the reflux ratio and inlet solution temperature of the humidifier are proportional to the evaporation capacity. An optimum mass flow rate of air exists for which the evaporation capacity is maximized. The gained input ratio (GIR), defined as the ratio between the total latent heat of evaporated water and the external heat input, decreases with the increase in air mass flow rate and increases with the increase in the reflux ratio. The optimum value of the gas-liquid ratio for maximum evaporation capacity is near 1.17, regardless of conditions. A multi-index comprehensive evaluation is introduced to assess the overall performance of the system. And a practical case is carried out to illustrate how to select the optimum operational parameters under different circumstances.

1. Introduction

With industrial development and increases in the population, ensuring adequate water supplement is becoming an important problem. The rapid development of industry also results in more wastewater emissions. Treating industrial wastewater reasonably and effectively and exploiting non-traditional water becomes a urgent task.

Evaporation is one of the most typical unit operation and the most commonly used water treatment operation in industry, and it is not only widely used in wastewater treatment, desalination, but also in food, pharmaceutical, chemical and so on. However, evaporation is also an energy-intensive process [1], so it is important to develop a low energy evaporation technology. There are three main evaporation technologies including multi-stage flash (MSF), multi-effect evaporation (MEE), and vapour compression evaporation (VCE), currently. Vapour compression evaporation can be divided into mechanical vapour compression (MVC) and thermal vapour compression (TVR) categories [2,3]. However, some disadvantages resulting from the evaporation technologies mentioned above seem to be apparent, such as high original investment, large bulk, high manufacturing precision, and manufacturing difficulties [4].

Because of high energy consumption and other disadvantages of conventional evaporation technologies, new technologies have been putting forward. Humidification-dehumidification (HDH), which mimics the natural water (rain) cycle [5], is a promising technology applied for both desalination and industrial water treatment. It leverages the phenomenon that air can be mixed with a large quantity of water vapour and the increased ability of air to carry water vapour at higher temperature [6]. Due to this characteristic, HDH system can operate at ambient temperature and pressure, making it easy to maintenance. There is no rotary equipment and only one evaporation chamber in system, which means lower manufacturing level requirement and original investment. Additionally, the system, in which low temperature evaporation can be conducted without decompression, is available for the evaporation of thermal sensitive substance. In that, HDH has received ongoing attention of experts and scholars, and an increasing number of investigations have been carried out in recent years.

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Nomenclature

A	transfer surface area (m^2)
c_p	Specific heat at constant pressure (kJ/kg·°C)
D	diameter of humidifier (m)
G	mass flux of air (kg/m^2·s)
h	heat transfer coefficient (kJ/m^2·°C)
H	height of packing in humidifier (m)
i	enthalpy (kJ/kg)
k	mass transfer coefficient (kg/m^2·s)
k_a	unit volume mass transfer coefficient (kg/m^3·s)
L	mass flux of solution (kg/m^2·s)
Le	Lewis factor
m	mass flow rate (kg/s)
Q_{in}	heat stream into the system (kw)
r	reflux ratio
r_0	latent heat (kJ/kg)
T	temperature (°C)
U	overall heat transfer (kJ/m^2·°C)
V	packing volume (m^3)
w	humidity ratio (kg_{vap}/kg_{dryair})
W	weight
x	actual value of index
Z	dimensionless index

Subscripts

a	air
c	convection heat transfer
de	dehumidifier
g	dry air
he	heater
l	solution
m	mass transfer
p	packing
s	saturation
sa	saturated at the temperature of air
ssa	supersaturated at the temperature of air
sl	saturated at the temperature of solution
v	vapour
w	water

Nawayseh et al. [7,8] built two units in Jordan and Malaysia, they studied the heat and mass transfer in the humidifier and condenser to develop appropriate correlations for heat and mass transfer coefficients through experiments. Based on these results, a simulation programme was built to predict the performance of the desalination units, and the results of the simulation were in agreement with the experimental results.

He et al. [9] performed a parametric study of a humidification-dehumidification desalination system using low-grade heat sources. The performance of the system was evaluated at different operation pressures, a balance point came up at which the water production of the system reached the maximum value. He [10] also proposed a novel water-power cogeneration plant based on humidification dehumidification system coupled with the organic Rankine cycle. Energy analysis at different operation parameters was achieved. And the results showed that the performance of the whole system is really sensitive to the operation parameters of the HDH desalination system.

Farsad and Behzadmehr [11] applied the design of experiments method to analyse a humidification-dehumidification desalination system. Sensitivity analysis of the main parameter was performed, and the regression function was constructed to make predictions for the distilled water.

Hamed et al. [12] investigated the humidification-dehumidification desalination system theoretically and experimentally. A theoretical simulation model was developed based on the experimental data. The calculated results showed that when the system was operated 4 h in a day with prior preheating, it displayed higher productivity.

Moumouh et al. [13] investigated a humidification-dehumidification desalination system using theoretical and experimental approaches. A mathematical model was developed to predict the productivity of the system. The results obtained from the theoretical model were in notably good agreement with experiment results.

A novel humidifier-dehumidification was designed and tested by Deniz and Çınar [14]. Thermal and electrical energy were both delivered via solar energy. An energy-exergy analysis was conducted based on an experimental study, and the enviro-economic properties were also investigated.

Coupling of a cascade solar still with a humidification–dehumidification system was investigated experimentally by Tabrizi et al. [15]. The effects of different operating conditions and configurations on the thermal performance and productivity of the solar system were studied. The results showed that the presence of a humidification-dehumidification system caused an increase in the daily productivity from 28% to 141%.

Nada et al. [16] combined humidification dehumidification system with air-condition system, aiming to save energy and product fresh water. Four systems with different configurations were proposed. And comparison study was performed to identify systems configurations that have the highest fresh water production rate, highest power saving and highest total cost saving.

A humidification dehumidification desalination system powered by solar energy is theoretically investigated by Yıldırım and Solmuş [17]. Mathematical model of system is developed. Three different heat configurations, only air heating, only water heating and air-water heating were investigated and compared.

Li and Zhang [18] studied a hollow fibre membrane-based humidification–dehumidification desalination system. A theoretical model for the whole system simulation is developed and validated. The effects of various parameters on system performance are examined. According to the study, the hot saline water flow rate, the inlet air flow rate and the packing fraction should be optimized to improve the performance of the system.

An active solar humidification-dehumidification desalination system integrated with geothermal energy was developed by Nabil et al. [19]. A geothermal water tank was used to heat water inside the humidification chamber. Experimental research was conducted and an analytical model was also developed to compare the effect of solar energy and combined solar-geothermal energy on accumulated productivity.

A bubble column humidification dehumidification desalination system integrated with the different solar collectors is analysed by Rajaseenivasan et al. [20]. Three systems with different solar collector were separately tested. Experimental research was conducted to study effect of mass flow rate of air and cooling water on performance of the system.

Zubair et al. [21] optimized a humidification-dehumidification (HDH) desalination system integrated with solar evacuated tubes.