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A mathematical model for a thermally coupled humidification–dehumidification desalination process

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Abstract

The humidification–dehumidification process is an interesting technique that has been adapted for water desalination. Previous works experimentally investigated desalination processes in the shell and tube columns, where the humidification and dehumidification were thermally coupled and simultaneously performed at the tube and shell sides, respectively. In this work, a comprehensive steady-state mathematical model was developed for such a humidification–dehumidification desalination process by taking into account the heat and mass balances on both sides of the desalting column, the mass transfer rate at the humidification side, and the heat transfer rate between the dehumidification side and humidification side. Meanwhile, the mass transfer coefficient at the humidification side and the total heat transfer coefficient between the dehumidification side and humidification side were discussed and correlated. The correlations could represent the experimental data very well.

Keywords: Desalination; Humidification; Dehumidification; Mathematical model; Mass transfer coefficient; Heat transfer coefficient

1. Introduction

In many arid zones, coastal or inlands, seawater or brackish water desalination may be the only solution to the shortage of fresh water [1]. Standard desalination processes such as multistage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO) have gained much success in the last half-century. However, their requirements of high initial capital costs and permanent qualified maintenance workers have limited their access to many developing countries [2]. Further, it is not economical to employ them when the capacity is small, especially when there is a need to utilize renewable energy such as solar energy. As a result, small- or medium-scale water desalination units with good flexibility in capacity,

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moderate capital cost, and the possibility of using renewable energy, are of great interest in regions like the northwest zone and many islands of China as well as many other remote arid area across the world where infrastructure is fairly low and the water demand is decentralized.

The humidification–dehumidification process is an interesting technique, which has been adapted for water desalination, where air is used as a carrier gas to evaporate water from the saline feed and to form fresh water by subsequent condensation. It is likely to be the most promising process of solar desalination [3]. Most researchers [4–8] have performed the humidification–dehumidification desalination process in two separate columns, one for humidification and another for dehumidification, with the columns constructed in different structures with various materials. However, separate structure increases both the complexity of the system and the capital cost. Furthermore, in a separate humidification column the latent heat of evaporation for humidification can only come from the sensitive heat of saline water fed to humidify the carrier gas, which limits the amount of the water that can be vaporized, resulting in a limited humidification effect of the carrier gas. At the same time, large amounts of condensation latent heat in another column are nearly lost or partially reused to preheat the saline feed water with low efficiency due to a large temperature difference in such heat transfer processes.

In recent years, Beckman et al. [9] proposed an interesting desalination process known as dewvaporation, in which the humidification and dehumidification process were simultaneously performed in one continuous contact tower. They also developed a simplified mathematical model for such a desalination process, with the assumption that the liquid film temperature is the average temperature of the gas phases [10], which limited the application of the model [11].

In previous works [12,13], thermally coupled desalination processes in the shell and tube columns were experimentally investigated, where the humidification and dehumidification were simultaneously performed at the tube and shell sides, respectively. In this work, a comprehensive mathematical model was developed for such a thermally coupled humidification-dehumidification desalination process. Meanwhile, the corresponding mass and heat transfer coefficients in such processes were correlated and discussed.

2. Mathematical model

2.1. Process description

Briefly, the desalination process focused on here is a carrier gas desalination process where humidification and dehumidification take place in one column. As an example, the shell and tube column was used to perform such a desalination process, which was described in detail in our previous work [13]. In this case, room temperature air is brought into the tube side of the column from the bottom and then flows upward in the tube side. The inside wall of the tubes are wet by preheated feed water, which is fed into each tube at the top of the column through overfall holes in the wall of the tube. As the air moves from the bottom to the top in the tubes, heat is transferred from the shell side to the tube side through the tube wall, allowing the air to rise in temperature and evaporate water from the water coating the inside tube wall. Concentrated water leaves from the bottom of the column, while hot and nearly saturated humid air leaves the column from the top. This hot and humid air exit from the tube side is further externally heated and humidified a little. This hotter saturated air is then sent directly into the shell side of the column from the upper inlet. The shell side of the column, being slightly hotter than the tube side, allows the humid air to cool and condensate, while the condensation latent heat is transferred to the tube side. Finally, water condensate and the dehumidified air leave the shell side of the column from the lower outlet.