Determination of Mass Transfer Coefficient for Air Humidification in a Packed Bed of Hollow Plastic Spheres: Postprint

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Abstract

Experimental investigations were conducted on the mass transfer coefficient of hollow plastic sphere packed beds in a humidification-dehumidification solar seawater desalination system, and comparisons were made with packed beds composed of other materials. The structural configuration and operational procedure of the experimental apparatus are described, and the relationship between the mass transfer coefficient and various operating parameters is presented. The experimental results demonstrate that these hollow plastic spheres exhibit a high evaporation mass transfer coefficient attributable to their large wetted surface area and internal water-storage porous material. At system cooling water and spray temperatures of 25°C and 80°C respectively, the mass transfer coefficient shows an approximately 8% improvement compared to that of wooden strips. The experimental results further reveal that the influences of spray flow rate and circulating air flow rate on the mass transfer coefficient are generally positive; increases in both spray flow rate and air velocity lead to enhanced mass transfer coefficients, though beyond a certain air velocity, further increases in circulating air flow rate yield diminishing increments in the mass transfer coefficient.

Full Text

Determination of Mass Transfer Coefficient for Air Humidification in a Hollow Plastic Ball Packed Bed

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Abstract

This paper presents experimental measurements of the mass transfer coefficient for a humidification-dehumidification solar desalination device using hollow plastic balls as packed bed material, with comparative analysis against other packing materials. The structure and operational process of the test apparatus are described, and the relationship between mass transfer coefficient and various operating parameters is presented. Experimental results demonstrate that the hollow plastic balls achieve a relatively high evaporation mass transfer coefficient due to their large wetted surface area and internal porous water storage material. When cooling water and spray temperatures are maintained at 25°C and 80°C respectively, the mass transfer coefficient increases by approximately 8% compared to using square wooden strips. Results also indicate that spray flow rate and circulating air flow generally have positive effects on the mass transfer coefficient—both parameters increase the coefficient, though beyond a certain wind speed, further increases in circulating flow yield diminishing returns. Additionally, seawater concentration significantly influences the mass transfer coefficient.

Keywords: desalination; humidification-dehumidification; mass transfer coefficient; solar energy

1. Introduction

Humidification-dehumidification desalination technology is considered one of the most promising methods for efficiently utilizing solar energy to produce freshwater, owing to its numerous advantages: operation without vacuum conditions, low seawater pretreatment requirements, the ability to manufacture components from non-metallic materials, and flexible operating temperature requirements. Consequently, it has become a focal point for researchers worldwide, yielding substantial research outcomes [1-4].

In humidification-dehumidification desalination, the air humidification process is the most critical component. Researchers have developed various humidification beds and tested numerous materials, primarily to enhance the mass transfer coefficient of the evaporation bed. In theoretical studies, Nawayseh et al. [5] theoretically evaluated heat and mass transfer coefficients in humidifiers, presenting their variation with process parameters. G. Prakash [6] defined a "modified heat capacity ratio" for heat and mass transfer in humidification-dehumidification desalination systems, investigating its characteristics while constructing a 700-liter-per-day pilot system that validated the positive relationship between system performance coefficient and mass transfer coefficient. S. Farsad [7] examined solar-powered humidification-dehumidification desalination cycles, proposing thermodynamic and heat-mass balance equations for evaporators, condensers, and auxiliary components, using mathematical derivation to analyze how operating parameters affect water production performance.

Experimental research has also advanced significantly. Bergero (2001) proposed using hydrophobic capillary tubes as contactors, achieving a mass transfer area of 593 m^2/m^3 [8]. Nawayseh (1996) employed wooden strips as evaporator packing material with excellent results [9]. M.M. Farid (2002) and Al-Hallaj S. (1998) experimentally investigated square wooden strip packed beds, comparing horizontal, vertical, and 45° inclined configurations, concluding that proper arrangement could achieve 87 m^2/m^3 mass transfer area with good performance [10-11]. K. Zhani (2013) presented research on using thorn trees and leaves as packing material, deriving empirical formulas for heat and mass transfer coefficients that demonstrated effective enhancement of the humidification process [12]. However, natural biological materials suffer from poor durability, motivating the search for durable packing materials with favorable mass transfer coefficients.

Accordingly, this study selects commercially available hollow plastic balls as packing material, experimentally testing their mass transfer performance and coefficients. These plastic balls exhibit large mass transfer coefficients due to their extensive wetted surface area and porous internal water storage material, making them excellent humidification packing material.

2. Experimental Apparatus Structure and Working Principle

To test the mass transfer coefficient of the hollow plastic ball packed bed, we designed a single-effect humidification-dehumidification solar desalination system as shown in [Figure 1: see original paper]. The system operates with forced air circulation, consisting of two independent processes: evaporative humidification and cooling dehumidification. The incoming seawater temperature is adjustable, as are the circulating air velocity and cooling water flow rate. [Figure 2: see original paper] shows photographs of the experimental setup and the packing materials. The working principle is as follows: cooling seawater is pumped into the system and enters the finned condenser in the dehumidifier, then exits from the top of the dehumidifier. To minimize heat loss from discharged brine, the seawater volume in the humidifier remains essentially constant through internal recirculation. Seawater enters the upper portion of the humidifier through a spray distributor, spraying onto the hydrophilic porous hollow plastic ball packed bed. Un-evaporated concentrated brine flows through drainage holes to the bottom of the humidifier, where a standpipe maintains a constant water level for recirculation. When the water volume exceeds the standpipe height, brine discharges from the system.

The high-temperature humid air generated in the humidifier enters the dehumidifier through the upper duct, where freshwater is produced via condensation. The cooled humid air returns to the humidifier through the lower duct under fan action, completing the cycle. Produced freshwater drains from the dehumidifier bottom into a collection tank.

The humidifier and dehumidifier share identical structures: 1200 mm height, 650 mm diameter, with 260 mm diameter ventilation ducts for humid air. The hydrophilic porous plastic balls measure 26 mm in diameter, packed to 400 mm height in the humidifier. The solar water heating system plate heat exchanger has 5 m^2 area. Feed and circulation pumps have maximum flow rates of 1.50 m^3/h, with adjustable actual flow rates. To compare mass transfer coefficients between hollow balls and wooden strips, we also designed a wooden strip packed bed as shown in [Figure 2: see original paper], using 2 cm × 3 cm rectangular fir strips with 2 cm spacing.

3. Calculation Method for Mass Transfer Coefficient

Nawayseh [5] defined the mass transfer coefficient in humidifiers and provided the calculation formula as follows:

Here, G is the humid air mass flow rate (kg/s), H is the enthalpy of humid air or water (kJ/kg), K is the packed bed mass transfer coefficient (kg/m^2s), a is the packed bed specific surface area (m^2/m^3), and V is the packed bed volume (m^3). Reference [5] also provides the relationship between humid air enthalpy, humidity ratio, and air temperature:

where W is the humidity ratio of humid air (kg/kg dry air) and T is temperature (°C).

By measuring temperatures T and flow rates L at various points, enthalpy values H can be calculated. Using equations (4)-(7), the air flow rate G, heat loss coefficient *U_{loss}*, overall heat transfer rate *U_{cond}*, and humidifier mass transfer coefficient *Ka* can be determined. If convective heat transfer between humid air and the condenser in the dehumidifier, as well as heat loss from the dehumidifier to surroundings, are neglected, then $G(H_3\text{-}H_4)$ in equation (1) approximates *m_{{{eh}}_{{fg}}}, *where* m_e* is freshwater production rate in the dehumidifier (kg/s) and *h_{fg}* is the latent heat of water condensation at average condensation temperature (kJ/kg).

4. Experimental Results and Analysis

4.1 Effect of Spray Temperature on Mass Transfer Coefficient

In the humidifier, incoming seawater temperature decisively influences system water production performance. Therefore, we first tested the mass transfer coefficient at various spray temperatures while maintaining spray flow rate at 0.167 kg/s, circulating air flow at approximately 0.19 m^3/s, and cooling water flow at 0.267 kg/s.

[Figure 3: see original paper] presents measured mass transfer coefficients for both hollow plastic balls and square wooden strips at different cooling water temperatures (10°C, 15°C, and 25°C). Results show that, with constant humid air flow, cooling water flow, and temperature, the humidifier mass transfer coefficient depends primarily on spray temperature, increasing essentially linearly with it. This occurs because higher spray temperatures produce higher humid air temperatures, increasing water vapor content per unit volume. According to the governing equations, when temperature increases from 50°C to 80°C, humid air humidity ratio rises sharply from 87.25 g/kg dry air to 425.08 g/kg dry air.

At lower spray temperatures, hollow plastic balls show no advantage over wooden strips. However, as spray temperature increases, the mass transfer coefficient for plastic ball packing increases more rapidly. At 80°C spray temperature, the *Ka* product (specific surface area × mass transfer coefficient) for plastic balls improves by 4.6%, 7.6%, and 7.9% at cooling water temperatures of 10°C, 15°C, and 25°C respectively, with more pronounced enhancement at higher cooling water temperatures. These results demonstrate that the plastic hollow balls, with their extensive wetted surface area and porous internal water storage material, achieve superior humidification compared to wooden strips. Combined with their low cost and excellent corrosion resistance, they represent better packing material for humidification-dehumidification desalination systems.

4.2 Effect of Circulating Air Flow Rate on Mass Transfer Coefficient

Circulating air flow rate is another important factor for enhancing mass transfer coefficients. We tested mass transfer coefficient variation with air flow rate under different spray flow rates and seawater temperatures, with cooling water temperature at 8-10°C and flow rate at 0.217 kg/s.

First, we examined air flow rate effects at different spray flow rates (0.183, 0.167, 0.117, and 0.088 kg/s) with fixed spray temperature at 75°C. [Figure 4: see original paper] shows the mass transfer coefficient variations for both hollow plastic balls and square wooden strips, where the horizontal axis L/G represents the ratio of spray flow rate to air flow rate. Under constant spray flow, smaller L/G values indicate larger circulating air flow rates.

Results show that the *Ka* product for plastic ball packing generally exceeds that for wooden strips. For example, at 0.167 kg/s spray flow and $L/G = 0.0015$, *Ka* increases by 17%.

Additionally, at low air flow rates, mass transfer coefficients generally increase with flow rate. However, beyond approximately 0.19 m^3/s, further increases yield limited improvement and sometimes even cause reduction. Therefore, fan power requires optimization. Higher spray flow rates permit appropriately increased fan power. Results also indicate that smaller spray flow rates produce lower mass transfer coefficients, but beyond 0.167 kg/s, the coefficient increase slows. At spray flow rates of 0.167 kg/s and 0.183 kg/s, mass transfer coefficients remain essentially unchanged, demonstrating that spray flow cannot be arbitrarily increased.

Subsequently, we tested air flow rate effects at different spray temperatures with fixed seawater flow at 0.167 kg/s. [Figure 5: see original paper] presents results for both packing materials. Findings show that mass transfer coefficients generally increase with air flow rate across all spray temperatures, with higher temperatures yielding higher coefficients. The Ka product for plastic balls typically exceeds that for wooden strips—for instance, increasing by 8.8% at 80°C spray temperature and $L/G = 0.0015$.

4.3 Comparison of Mass Transfer Coefficients Across Different Packing Materials

In humidification-dehumidification desalination, the air humidification process is most critical. Previous researchers have developed various humidification beds and tested numerous materials to improve evaporator mass transfer coefficients. As listed in , Nawayseh (1996) studied wooden strip packing using natural convection [9], while Al-Hallaj (1998) investigated square wooden strips under both natural and forced convection, comparing horizontal, vertical, and 45° inclined configurations [10-11].

Technical specifications of three experimental systems from Malaysia and Jordan

Parameter	Nawayseh [9] (Pilot)	Al-Hallaj [11] (Pilot)	Al-Hallaj [11] (Bench)	This Work
Condenser heat exchange area (m^2)	4 (single)	8 (double)	0.6 (single)	4
Humidifier surface area (m^2)	-	-	-	-
Humidifier specific surface area (m^2/m^3)	87	-	-	-
Solar collector area (m^2)	-	-	-	5
U_{loss} (W/m^2K)	-	-	-	-
Air velocity (m/s)	-	-	-	3.6-4

[Figure 6: see original paper] compares our experimental mass transfer coefficients with results from Nawayseh and Al-Hallaj. At low seawater flow rates, plastic balls exhibit lower mass transfer coefficients than wooden strips due to inferior wetting characteristics. However, as seawater flow increases, the complex surface geometry of plastic balls yields progressively better performance. At 4 m/s air velocity and 0.196 kg/s spray flow, the mass transfer coefficient improves by 7%. Since plastic balls are non-toxic, corrosion-resistant, and can withstand long-term seawater immersion—advantages wooden strips cannot match—they represent an excellent packing material choice.

5. Conclusions

This study designed and tested a humidification-dehumidification desalination system using specially designed hollow plastic balls and square wooden strips as packing materials. System performance under various operating conditions was measured to determine mass transfer coefficients. Results demonstrate that plastic balls, with their extensive wetted surface area and porous internal water storage material, achieve superior humidification compared to wooden strips. At cooling water and spray temperatures of 25°C and 80°C respectively, the mass transfer coefficient improves by 7.9% over wooden strips. Across different spray temperatures and flow rates, plastic ball packing consistently yields higher mass transfer coefficients, confirming their suitability as packing material for humidification-dehumidification desalination systems.

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Note: Figure translations are in progress. See original paper for figures.