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Thermodynamic balancing of the regeneration process in a novel liquid desiccant cooling/desalination system

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ABSTRACT

This paper focuses on thermodynamic balancing of the regeneration process in a hybrid liquid desiccant cooling/desalination system. The thermal balancing technique is investigated by adding a single extraction between the system regenerator and condenser. This technique is considered as a potential method to reduce energy consumption and increase the hybrid system performance, dramatically. The mathematical procedure to model the proposed system using enthalpy pinch is outlined to study the effect of extraction on the hybrid system performance. The hybrid system, with a single extraction and without extraction (zero extraction), is analyzed in terms of the normalized entropy generation, local enthalpy losses, the coefficient of performance, and proper extraction location. The results show that at enthalpy pinch of 20 kJ per kg of dry air, single extraction system performance is 85.7% better than zero extraction. In addition, the single extraction produces 103.2 kg of fresh water per hour as a by-product compared to 94.2 kg per hour for the zero extraction system.

1. Introduction

In coastal areas, there are extreme seasonal variations in temperature and humidity over the course of year; this is why air conditioning is a necessity in these areas. About 70% of produced energy is consumed by air conditioning in these regions. In general, the energy consumption by buildings represents 30–40% of the world's primary energy consumption [1]. In addition, freshwater is turning into a scarce resource in many regions around the world. Population expanding causes an increase in consumption of freshwater, especially in the stressed regions. The mankind is facing a water shortage, with demand expected to surpass supply by 40% in 2030 [2]. Therefore, water purification methods in conjunction with conservation efforts are needed in places where the natural resources of potable water are diminishing [3].

For these reasons, many places are facing two major problems that affect the existence and comfort of its population. These problems are due to high-energy demand and water scarcity. Therefore, cost-effective and environmentally friendly cooling and desalination techniques become an essential requirement. These techniques should be able to effectively utilize waste heat, renewable energy, etc. The desiccant-based hybrid cooling/desalination system [4] can help in solving some of the increasing energy demand [5]. The desiccant-based hybrid system does not use ozone-depleting refrigerants which makes it eco-friendly [6].

Desiccant-based systems for cooling and desalination purposes were investigated in the literature. Hybrid solar still with a desiccant regeneration and desalination of saline water were studied by Modi and Shukla [7]. Su et al. [8] proposed a hybridization between the liquid desiccant dehumidification and solar-powered absorption refrigeration system for cooling and water production. Yang et al. [9] suggested a new method for regenerating liquid desiccant in a cooling system using photovoltaic (PV) capacitive deionization. Kabeel et al. [10] studied an indirect evaporative air cooler with baffles integrated with HDH desalination system. The hybrid system was powered by air and water solar thermal collectors. The liquid desiccant cooling systems were reviewed by Abdel-Salam and Simonson [11]. Moreover, solar-powered absorption chillers involving liquid desiccant cooling systems have been recently reviewed by Shirazi et al. [12]. A novel desiccant system hybridized with HDH for a zero-brine discharge is introduced by Ahmed et al. [13].

Tue et al. [14] introduced a novel desiccant-enhanced direct expansion heat pump, with a coefficient of performance (COP) more than 6. A novel hybrid liquid desiccant cooling/desalination system has been proposed [4] by adding a condenser between the humidifier and regenerator chambers. The benefit of adding a condenser was to recover the heat of outlet scavenging air from the regenerator. This resulted in improving the system performance by 11.25%. Besides the heat recovery, the moisture content in the recirculated air was condensed leading to about 86.4 kg/h freshwater.

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Nomenclature

Acronyms

COP coefficient of performance
HDH humidification dehumidification
HCR heat capacity ratio
NEG normalized entropy generation

Symbols

c_p specific heat capacity at constant pressure (kJ kg^{-1} K^{-1})
h specific enthalpy at a component terminal (kJ kg^{-1})
h^* specific enthalpy in term of dry air mass flow rate (kJ kg_{da}^{-1})
$\dot{H}$ total enthalpy rate (kW)
h_{fg} latent heat of vaporization (kJ kg^{-1})
m slope of humidifier and dehumidifier line (°C kJ^{-1} kg_{da})
$\dot{m}$ mass flow rate (kg s^{-1})
m_r desiccant-to-air mass flow rate ratio (–)
MRR moisture removal rate (kg s^{-1})
$\dot{Q}$ heat input rate (kW)
RR recovery ratio (–)
s specific entropy (kJ kg^{-1} K^{-1})
$\dot{S}$ total entropy (kW K^{-1})
T temperature (°C)

Greek

Δ difference
ε effectiveness (–)
Ψ enthalpy pinch (kJ kg_{da}^{-1})
ξ desiccant solution concentration (kg_s kg_{sol}^{-1})
ω humidity ratio (kg_{H_2O} kg_{da}^{-1})
φ relative humidity (–)

Subscripts

1, 2, … desiccant solution stream state points
a, b, … air stream state points
ave average
bot bottom
da dry air
ex extraction point
f dehumidifier
gen generated
ht heater
hx heat exchanger
i inlet
id ideal
max maximum
min minimum
n condenser
o outlet
opt optimum
pw freshwater
r regenerator
s desiccant
sol solution
st strong concentration
tan′ correspondent point at humidifier line to the tangent point at air curve
tan tangent point at air curve
w weak concentration

The aforementioned studies were conducted to improve cooling/desalination systems. Moreover, some efforts suggested an implementation of the balancing principle to improve the system performance by minimizing entropy generation. Thiel et al. [15] have studied irreversibility by drawing a clear distinction between the finite mean driving force of a transport process and its variation with the spatial distribution. Narayan et al. [16] studied the effect of thermal balancing using extraction technique on the performance of HDH desalibnation systems. Notably, the thermal balancing principle has been applied to systems that involve heat and mass exchangers. In particular, it was successfully tested to improve the performance of HDH systems *via* some mass extractions between the system humidifier and dehumidifier. Chehayeb et al. [17] have broadened the concept of single extraction that was proposed earlier by Narayan et al. [16] to the multiple air extractions and injections, in order to thermodynamically balance the HDH system. Miller and Lienhard [18] introduced enthalpy rates to balance the HDH system components by extracting water or air from one component and injecting into the other.

Müller–Holst [19] proposed an extraction HDH system by varying the ratio of water-to-air mass flow rate continuously, thereby decreasing the stream-to-stream temperature difference to achieve thermal balancing. Another novel approach for thermodynamic balancing was presented by Zamen et al. [20] by proposing a multi-stage HDH system. They introduced a new performance parameter, called “temperature pinch”. Schlickum [21] patented a three-stage HDH system, in which the liquid stream was connected in series while the air stream was separately recirculated for each stage. Hou [22] reported a two-stage solar multi-effect HDH system. Different designs for a closed-air open-water HDH system with and without extractions are investigated by Elmutasim et al. [23].

Brendel [24] invented an HDH system that is driven by forced convection. In which, water is extracted at several points from the dehumidifier and injected into the humidifier to provide thermal balancing. Thiel and Lienhard [25] have shown that it is required to consider both the concentration and temperature profiles in order to optimize heat and mass exchangers (HME). Younis et al. [26] have also studied extracting air from two points in the humidifier and injected into the dehumidifier. The enthalpy-temperature diagram is frequently used to demonstrate the impact of extraction on HDH systems [20], whereas the temperature pinch approach was used earlier [27] to evaluate a system maximum performance.

Narayan et al. [28] have investigated thermodynamic balancing in HDH system by extracting and injecting water or air from the dehumidifier into the humidifier or the other way around. Mistry et al. [29] reported that reducing entropy production results in maximizing the performance of HDH performance. Miller and Lienhard [18] investigated the impact of extraction on balancing the enthalpy profiles in HDH systems. McGovern et al. [27] reported a 300% increase in HDH performance by incorporating a single water extraction. They also found that the recovery ratio enhancement was from 7% to 11%. Analogous to temperature pinch, Narayan et al. [16] presented enthalpy pinch approach to balance HME, wherein both temperature and concentration profiles are considered. Through experimentation, Narayan et al. [30] reported a 54% increase in the performance of an HDH system by using a single air extraction.

Noticeably, the literature has focused on HDH for carrying out the thermal balancing principle. There is no study on the effect of extraction technique in liquid desiccant cooling systems. This is because, applying extraction is not possible in the conventional liquid desiccant cooling systems due to the lack of condenser in such systems, unlike the