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Experimental and numerical study on the regeneration performance of LiCl solution with surfactant and nanoparticles

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ABSTRACT

The paper experimentally and numerically investigated the enhancement of LiCl falling film regeneration performance in a plate type regenerator by adding surfactant polyvinyl pyrrolidone (PVP) and multi-walled carbon nanotubes (MWNTs). Experimentally, by adding surfactant PVP and adopting mechanical methods, steady nanofluid containing MWNTs was successfully fabricated. The regeneration characteristics of LiCl/H_2O solution, LiCl/H_2O-PVP solution and LiCl/H_2O-MWNTs nanofluid were identified quantitatively. Compared with the regeneration rate of the LiCl/H_2O solution, the values of the LiCl/H_2O-PVP solution and nanofluid are on average 24.9% and 24.7% greater. These enhancements can be attributed to the increase of mass transfer area and decrease of falling film thickness, which is caused by a decrease in contact angles. However, adding 0.1 wt% MWNTs to the LiCl/H_2O-PVP solution has negligible influence on the regeneration rate. The three solutions have nearly the same mass transfer coefficients under comparable operating conditions. Theoretically, a mathematical model was built with the consideration of film contraction to describe the simultaneous heat and mass transfer processes in the regenerator. The calculated falling film wetting areas agree well with the measured ones, with a relative difference of less than 6%. The mean absolute relative deviation between the computational regeneration rates and experimental ones for the LiCl/H_2O solution, LiCl/H_2O-PVP solution and LiCl/H_2O-MWNTs nanofluid are 9.01%, 3.95% and 4.22%, respectively, which demonstrates the accuracy of the developed model. The experimental data and newly developed numerical model are helpful for the study of regeneration enhancement and system design of liquid desiccant cooling systems.

1. Introduction

The regenerator is one of the main components in a liquid desiccant cooling system (LDCS), which is promising technology for air-conditioning due to its energy saving potential and accurate temperature and humidity control [1]. During the process of regeneration, low-grade energy, such as solar energy and waste water heat [2], can be utilised. Given the high proportion of energy (30% to 50%) consumed by air-conditioning systems [3], the attractions of LDCS are clear. To further enhance heat and mass transfer performance during the regeneration or dehumidification process, various physical and chemical methods have been proposed by researchers.

Surface modification is the most direct way to enhance mass transfer during regeneration. Some novel configurations, such as constant curvature surface (CCS) [4], surface treatment tubes [5,6], film-inverting structures [7,8] and plate-fin structures [9], have been studied by previous investigators. Most of these surface modification methods attempt to change the flow pattern on the absorber or regenerator to increase turbulent flow and ensure a greater contact area for heat and mass transfer. Aside from configuration enhancement, surface treatment with super-hydrophilic coating is also an effective way to improve the surface wettability of the regenerator or dehumidifier [10].

Other methods focus on modification of the liquid desiccant itself rather than the configuration of components in the LDCS, such as adding surfactant or nanoparticles to the solution. For the surfactant, a minor amount of certain chemical substances, such as 2-ethyl-1-hecanol [11], 2-methyl-1-pentanol [12] and n-octanol [13], was mixed into the desiccant solution. Different degrees of mass transfer enhancement were experimentally observed in previous studies [11–13]. Most researchers attributed the enhancement mechanism to Marangini convection. However, the attribution of the trigger mechanism for Marangini convection is still controversial. Some possible explanations, such as the Kashiwagi model [14], salting-out model [15], solubility model [16] and vapour surfactant theory [17], have been proposed.

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Nomenclature

c_p	heat capacity (kJ/(kg K))
D	rim part length (m)
g	gravitational acceleration (m^2/s)
h	enthalpy (kJ/kg)
L	dehumidifier length (m)
Le	Lewis number
$LDCS$	liquid desiccant cooling system
m	mass flow rate (kg/s)
MWNT	multi-walled carbon nanotube
p	pressure (Pa)
Pr	Prandtl number
PVP	polyvinyl pyrrolidone
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
w	absolute humidity (g/kg)
T	temperature (°C)
X	concentration (%)

Greek symbols

α_h	heat transfer coefficient (W/(m^2 K))
α_m	mass transfer coefficient (kg/(m^2 s))
β	shrinkage angle (°)
δ	Film thickness (m)
γ	vapourisation latent heat (kJ/kg)
μ	dynamic viscosity (Pa s)
θ	contact angle (o)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ξ	deformation factor
Δ	change value

Subscripts

a	air
cal	calculated result
exp	experimental results
e	equilibrium
h	heat transfer
i	inlet
m	mass transfer/main part
o	outlet
r	rim part
s	solution
w	cooling water

However, only a partial enhancement phenomenon could be explained this way, rather than all surfactants.

Nanofluid is defined as a steady lyosol containing nanoparticles with a size of less than 100 nm [18]. Methods for the preparation of nanofluid can be divided into two groups: one-step and two-step. The former fabricates and disperses nanoparticles simultaneously into a base fluid [19]. Generally speaking, this method performs better than the two-step method. Nevertheless, the complicated manufacturing processes involved and low production output restrict its large-scale application. In the two-step method, nanoparticles are produced by physical and chemical synthesis techniques [19]. Subsequently, the prepared nanoparticles are dispersed into a base fluid by various methods. This method has been widely used in both research and commercial applications due to its low cost. Because of its outstanding thermal physical properties, nanofluid has become a hot research area in recent years.

Numerous studies have concentrated on heat transfer enhancement by adding nanoparticles into water or other base fluids. Both single phase and multiphase heat transfer experiments and numerical studies were carried out to uncover the heat transfer characteristics in nanofluid. Different levels of improvement in terms of the heat transfer coefficient were revealed [20]. Compared with the large amount of research concerning heat transfer, investigations focusing on mass transfer are relatively scarce. Mass transfer studies of nanofluid have concentrated on gas absorption and liquid mass diffusion [21,22]. The types of gas absorption mainly include bubble type and falling film. Falling film water vapour dehumidification, which is the research focus of this study, belongs to the latter type.

Kang et al. [23] studied the absorption performance of $LiCl/H_2O$ solution with the addition of Fe and carbon nanotubes in a tube type absorber. They adopted Arabic gum as a surfactant and used an ultrasonic vibrator to obtain stable nanofluid dispersion. The experimental results showed that the mass transfer enhancement of carbon nanotubes was greater than that of Fe, by a factor of up to 2.48 at a concentration of 0.1 wt%. Kim et al. [24] performed a similar study with the addition of SiO_2 nanoparticles. They found that the nanoparticles could be steadily dispersed into the $LiBr/H_2O$ solution only when the concentration of SiO_2 was less than 0.01 vol%. Otherwise, distribution stabilisation was required. Mass transfer improvement could be increased up to 18% at the SiO_2 concentration of 0.005 vol%, which was caused by Brownian motion, as stated by Kim et al. [24]. Fe_3O_4 was adopted by Zhang et al. [25] to study the falling film absorption experimentally. Their results indicated that the absorption enhancement ratio increased with the increase of the mass fraction of Fe_3O_4 and a decrease in particle size. The enhancement ratio reached up to 2.28 at a concentration of 0.05 wt% for 20 nm nanoparticles. The working pair of $LiBr/H_2O$ was replaced by NH_3/H_2O in the study conducted by Yang et al. [26]. Three kinds of nanoparticles, Al_2O_3, Fe_2O_3 and $ZnFe_2O_4$, were added into the base fluid of NH_3/H_2O solution. They found that the absorption rate was weakened by adding poorly dispersed nanoparticles or only adding surfactant. The absorption performance of Fe_2O_3 could be increased by 70% with the matched surfactant under certain circumstances. Pineda et al. [27] studied CO_2 absorption performance in a tray column absorber using methanol with the addition of Al_2O_3 and SiO_2 nanoparticles. During the preparation of nanofluids, an ultra-sonicator was used for the dispersion of nanoparticles. Pineda et al.'s results indicated that the maximum enhancement ratios for Al_2O_3 and SiO_2 were 9.4% and 9.7%, respectively. In addition to experimental studies, some researchers have conducted numerical studies. Ali et al. [28,29] numerically investigated dehumidification performance in vertical and inclined plate falling film absorbers with the addition of Cu-ultrafine particles.

However, apart from Ali et al. [28,29], all of the preceding studies of gas absorption focus on absorption refrigeration operated in a closed loop; for example, the operation pressures of Kang et al. [23] and Kim et al. [24] were both 0.01 bar. However, mass and heat transfer in the LDCS occur in an open loop at atmospheric pressure. Furthermore, no study has paid attention to the regeneration process, which is an indispensable part in the LDCS, and Ali et al. [28,29] did not take the dispersion of nanoparticles into consideration, which is a practical and serious problem in nanofluid research.

In this study, a stable 0.1 wt% $LiCl/H_2O$-MWNTs nanofluid was first fabricated by adding surfactant PVP and adopting mechanical