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Suggested solution concentration for an energy-efficient refrigeration system combined with condensation heat-driven liquid desiccant cycle

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ABSTRACT

This paper presents a hybrid energy-efficient refrigeration system enhanced by liquid desiccant evaporative cooling technology for subcooling the refrigerant, where the liquid desiccant cycle is driven by the exhausted heat from the condenser and three commonly used liquid desiccants: LiCl, LiBr and $CaCl_2$ aqueous solutions are considered here. The solution concentration for the proposed hybrid energy-efficient refrigeration system should be determined and optimized carefully for better performance. Sensitive study of solution concentration involved in the hybrid system is conducted at different condensation temperature. The results indicates that under standard working condition (i.e., condensing temperature is 50 °C), the optimum solution concentration is 0.31 for LiCl aqueous solution, 0.45 for LiBr aqueous solution and 0.42 for $CaCl_2$ aqueous solution, while the maximum *COPs* are nearly same. When the condensing temperature is 45 °C, the optimum solution concentration should be set at 0.27 for LiCl aqueous solution, and 0.41 for LiBr aqueous solution and 0.37 for $CaCl_2$ aqueous solution, while condensing temperature is 55 °C, it is 0.35 for LiCl aqueous solution, 0.49 for LiBr aqueous solution and 0.45 for $CaCl_2$ aqueous solution. The simple fitting formulas are obtained, and performance improvement potential is discussed.

1. Introduction

Liquid desiccant air-conditioning system combined with evaporative cooling was proposed as an alternative to the traditional vapor compression air conditioning system due to its advantage in effective removal of air latent load, utilization of low grade heat and reduction of the electricity consumption [1]. Dehumidifier and regenerator, as very essential components of the liquid desiccant air-conditioning system, were studied theoretically and experimentally in past decades [2,3]. Peng and Zhang [4] designed a new solar liquid collector/regenerator, and simulation results showed that regeneration efficiency increased by 45.7%. An idea improving the wettability over the surface of a cylindrical dehumidifier channel was proposed and also was verified experimentally [5]. Fibrous sheets were attached to the inner surfaces of the channel to sustain the complete wetting of the heat and mass transfer area. Kabeel [6] investigated the regeneration of liquid solution using cross flow of air stream with falling film of desiccant on the surface of a solar collector/regenerator.

Many research works have been carried out recently to study the performance of various liquid desiccant cooling systems. Kozubal et al. [7] proposed a liquid desiccant air conditioner, which consisted of two stages: a liquid desiccant dehumidifier and an indirect evaporative cooler. It reduced peak electricity demand by 80% and total source energy use by 40%–80% respectively, compared to a conventional air conditioner. Woods and Kozubal [8] presented numerical and experimental study of a proposed liquid desiccant air conditioner. Integration of a liquid desiccant system into an evaporative cooling-assisted all fresh air system was suggested by Kim et al. [9]. Simulation results showed that the proposed system consumed 51% less cooling energy compared to the conventional VAV (Variable Air Volume) system. A new type of frost-free air-source heat pump system with integrated liquid

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Nomenclature

B	atmospheric pressure (Pa)
COP	coefficient of performance
cp	specific heat capacity (kJ/kg K)
G	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
H	height (m)
L	length (m)
Le	Lewis number
M	molar mass (kg/mol)
NTU	number of mass transfer unit
P	vapor pressure (Pa)
T	temperature (°C)
ΔT_{sc}	subcooling degree (°C)
W	width (m)
X	mass concentration (%)
x	molar concentration (%)

Greek symbols

η	effectiveness
ω	humidity ratio (kg/kg)
θ	reduced temperature

Subscripts

a	air
amb	ambient
$base$	baseline
c	critical point
con	condenser
m	mole
r	regeneration
ref	refrigerant
s	solution
sc	subcooling
w	water

desiccant dehumidification was proposed [10], and the comparison results showed that COP of the frost-free air-source heat pump system was 30%–40% higher than that of heat pump heating integrated with an electric heater humidifying system. The effect of variable fresh air ratios on the performance of a liquid desiccant air conditioning was studied by Niu et al. [11]. Results showed that the maximum power saving ratio was 58.9% when the fresh air ratio was 20%. Gupta et al. [12] compared the relative performances of three different thermally driven, environmentally friendly cooling systems, and it was found that the desiccant cooling system outperformed the others at the heat source with the temperature above 90 °C.

Liquid desiccants are hygroscopic salt solutions that can absorb water vapor from the air. A liquid desiccant has the potential to dehumidify air to 20% relative humidity. The physical properties of some liquid desiccants, such as LiBr, LiCl and $CaCl_2$ aqueous solutions, had been investigated by many researchers [13–16]. Conde [13] reported on the properties of the aqueous solutions of lithium and calcium chlorides, particularly on empirical formulations of their thermophysical properties required in the industrial design of sorption equipment. Pátek and Klomfar [14] presented a set of computationally efficient formulations of thermodynamic properties of LiBr–H_2O solutions at vapor–liquid equilibrium in the form of explicit separate functions of temperature and mixture composition. Mass transfer performance of two commonly used liquid desiccants, LiBr aqueous solution and LiCl aqueous solution, was compared in the literature [17] on the basis of the same solution temperature and surface vapor pressure. Gao et al. [18] experimentally investigated on the heat and mass transfer between air and LiCl solution in a cross-flow dehumidifier. Aly et al. [19] presented the modeling and simulation of a solar-powered desiccant regenerator used for an open absorption cooling system. Lithium chloride and calcium chloride solutions were applied as the working desiccants in the investigation. Jain et al. [20] developed an experimental setup to study the performance of liquid desiccant dehumidification system using calcium chloride and lithium chloride as desiccants. Liu et al. [21] discussed the effects of regeneration modes (i.e., hot air or hot desiccant-driven regeneration) on the performance of a liquid desiccant packed-bed regenerator, employing LiBr, LiCl and $CaCl_2$ aqueous solutions.

A new energy-efficient refrigeration system subcooled by liquid desiccant dehumidification and evaporation was proposed in our previous paper [22]. In this paper, the proposed system performance with three commonly used liquid desiccants: LiCl aqueous solution, LiBr aqueous solution and $CaCl_2$ aqueous solution is analyzed and compared. The suggested solution concentrations for the three different solutions are obtained according to different condensing temperature. Correlations between the suggested solution concentrations and condensing temperatures are concluded and the energy saving potential of the proposed system using three different solutions is discussed.

2. Physical properties of LiCl, LiBr and $CaCl_2$ aqueous solutions

The physical properties of the commonly used liquid desiccant are rather different. In the regeneration and dehumidification processes, three parameters of liquid desiccant are crucial: the vapor pressure p_s, the equivalent humidity ratio ω_s and the specific thermal capacity cp_s. The temperatures and vapor pressure of humid air and liquid desiccant should be same, when liquid desiccant is in equilibrium with the humid air. The equivalent humidity ratio of liquid desiccant ω_s can then be determined with the equilibrium status of air, as shown in the following equation [21].

$$\omega_s = 0.622^* \frac{p_s}{B - p_s} \tag{1}$$

where, B is the atmospheric pressure.

For LiCl and $CaCl_2$ aqueous solutions, the vapor pressure above liquid desiccant $p_s(X_s,T)$ is calculated using the following equations [13].

$$p_s(X_s, T) = p_w(T)^* \pi^* f(X_s, \theta) \tag{2}$$

$$f(X_s, \theta) = A + B^* \theta \tag{3}$$

$$A = 2 - \left[1 + \left(\frac{X_s}{\pi_0}\right)^{\pi_1}\right]^{\pi_2} \tag{4}$$

$$B = \left[1 + \left(\frac{X_s}{\pi_3}\right)^{\pi_4}\right]^{\pi_5} - 1 \tag{5}$$