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Performance analysis of a novel heat pump type air conditioner coupled with a liquid dehumidification/humidification cycle

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ABSTRACT

In recent years, liquid desiccant air-conditioning system (LDAC) has shown a great potential alternative to the conventional vapor compression systems. LDAC not only greatly improves the indoor air quality by controlling the humidity and temperature independently, but also deceases the electrical energy consumption of the conventional air conditioner. In this work, the liquid desiccant and humidification cycle is driven by the exhaust heat of the compressor. Cycle performance of a small-scale heat pump type air conditioner coupled with a liquid desiccant/humidification cycle has been theoretically and experimentally evaluated by the present study. Parametric analysis on cycle performance of the present cycle is carried out through both theoretical and experimental methods, and lithium chloride aqueous solution is used as the working fluid of the solution cycle. The thermodynamic analysis results show that while the evaporating temperature of the present cycle increases to 15 °C, the energy consumption decreases by about 22.64% when compared with conventional air conditioner. Theoretical results also indicate that the coefficient of performance (COP) of the novel system has a potential improvement of about 35.3%. Based on the theoretical results, experimental analyses of this novel cycle under summer and winter working conditions are carried out. In addition, comparison of the humidification and dehumidification ability as well as COP of the present novel system and the traditional one are carried out. Researching results of the present study provide important reference for investigator of this field.

1. Introduction

With the rapid development of urbanization, air conditioning system (ACS) has been widely applied, especially in the household area. However, because of the high commercial energy consumption, it brings some problems at the same time, such as the energy crisis, climate change and greenhouse effect. All these problems have generated a need to develop a more energy-saving system.

Energy consumption of ACS in buildings takes up a large proportion of total social commercial energy consumption. Therefore, the energy saving technology of air conditioners gains great concern. In terms of ACS, the heat pump type air conditioners are widely used in buildings, such as residences, schools and supermarkets. Many researchers focus on this area. Zheng et al. [1,2] investigated the thermal performance and economic analysis of seawater heat pump systems in areas of severe cold during winter, and developed mathematical models of a helical coil heat exchanger, which was very helpful in the designing and optimizing of the subsea heat exchangers. In order to predict the effects of multifactor internal parameters on the COP and total heat transfer areas, an optimization analysis of a steam operated double effect water-LiBr absorption heat pump is presented with mathematical models by Zheng et al. [3]. Wu et al. [4] investigated the applicability of air source absorption heat pump in different regions, and gave some improvement options. Liu et al. [5] proposed a combined heat pump transformer system operating with a water/lithium bromide working pair, and developed a computational model to investigate its performance, which showed that the exergy coefficient of performance is around 71.1%. Gao et al. [6] studied the optimization of a small-scale ACS integrated with a ground source heat pump, and results showed that the optimization strategy saved the energy consumption by 9.59% in a typical spring day and 2.97% in a typical summer day.

According to ASHARE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) published in 2013, the acceptable thermal temperature and relative humidity (RH) ranges for human occupancy are 20–28 °C and 40–60% respectively.

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Nomenclature

T	temperature, K or °C
h	specific enthalpy, kJ kg^{-1}
M	mass flow rate, kg s^{-1}
Q	heat flow rate, kW or W
q	air flow rate, kg s^{-1} or m^3 s^{-1}
d	humidity ratio of air, g/kg of air
P	vapor pressure, Pa
m	moisture removal rate, kg h^{-1}
r	latent heat of water vaporization, kJ kg^{-1}
C	specific heat capacity, kJ (kg °C)$^{-1}$
k	heat transfer coefficient, W(m^2 K)$^{-1}$
A	heat transfer area of air-cooler, m^2
ACS	air conditioning system
LiCl	lithium chloride
LDAC	liquid desiccant air conditioner
AC	air conditioner
RH	relative humidity
COP	coefficient of performance
EER	energy efficiency ratio
LMTD	logarithmic mean temperature difference
Δt	temperature difference

Greek symbols

ε	mass concentration of LiCl solution
∂	uncertainty

Subscript

mo	moisture
s	solution
c	critical point
H_2O	pure water
a	air
i	inlet
o	outlet
la	latent heat
se	sensible heat
di	diluted solution
con	concentrated solution
re	refrigerant
m	mass
v	volume
co	cooling capacity
he	heating capacity
id	indoor
od	outdoor
max	maximum
min	minimum

However, most heat pump type air-conditioners remove water vapor by cooling the air below its dew point temperature. Under this situation, the outlet air temperature is too low to meet the acceptable thermal temperature. Another aspect, due to the condensation of water vapor in air, the surface of evaporator is damp during its run-time, which provides an appropriate condition for bacteria and mildew breeding. In addition, few conventional air conditioners have the humidifying capacity. In winter working condition, the heating process will decrease the relative humidity of air inevitably. The dry air environment may weaken the immunologic mechanism of human, and make people feel thirsty even sick. In addition, the sensible temperature of indoor occupant will decrease with an increase in moisture loss of human body. To overcome the drawbacks of the conventional air-conditioners, more attentions are paid to the liquid desiccant dehumidification system.

As Jain et al. [7–10] presented that the new AC should have the function to control the temperature and humidity independently. Compared with the conventional air conditioner, the liquid desiccant dehumidification has more advantages and potential to be adopted. Because of the fluidity property, it is feasible to combine the vapor compression refrigeration system with the desiccant system. Much of the thermal energy required in the regeneration process can be drawn from the renewable energy, which means the diluted desiccant can be reused in the system. Moreover, it can not only dehumidify the air, but also release water vapor in it, when the cycle is reversed. In 1995, Lof.G first proposed and experimentally tested a liquid desiccant system, in which triethylene glycol was used as hygroscopic solution. Lazzarin [11] analyzed and simulated the performance of a temperature-and-humidity independent controlling air-conditioning system applied in a supermarket. The research showed the energy consumption of the hybrid system reduced by 60%. Elmer et al. [12] and Buker et al. [13] proposed novel liquid desiccant air conditioning systems in built environment applications. Aly et al. [14] proposed a solar-power open absorption cycle modeling with two different desiccant solutions and investigated the effect of different operating parameters on the change in the overall performance of the system. Xiong et al. [15] experimentally studied a two-stage liquid desiccant dehumidification system using a lithium chloride solution and a calcium chloride solution respectively in two stage dehumidifier. Rafique et al. [16–18] analyzed the performance of a desiccant evaporative cooling system under hot and humid conditions. Woods and Kozubal [19] presented a numerical model and experimentally studied on a desiccant-enhanced evaporative air conditioner. Angrisani et al. [20] made some improvements on an innovative desiccant air conditioning system based on experimental investigations.

According to the study of Yi [21], the surface water vapor partial pressure of desiccant solution increased with temperature. Bouzenada [22] experimentally studied the effect of the difference in relative humidity between the inlet and outlet air and the concentration range of inlet and outlet desiccant liquid on the performance of the dehumidifier. Mohan [23] designed a liquid desiccant vapor compression hybrid system, and concluded the effect of varying room air temperature and specific humidity on its performance. In order to improve the efficiency of reutilization, the solution needs to be heated before the regenerating process. And there are many methods to achieve this, for example, Rafique et al. [24] used a heater to increase the temperature before the solution entering the regenerator.

Because the regeneration temperature of solution is in the range of 45–75 °C, the solution cycle can be driven by renewable energy or waste heat [25,26]. In 1961, Sheridan first put up with a solar liquid desiccant dehumidifying system, in which lithium chloride was chosen as the medium. In 2003, Gommed and Grossman [27] built a solar liquid desiccant air conditioner (SLDAC) in Mediterranean city, and ran the performance test for 5 months. The result showed thermodynamic coefficient of performance of the system is around 0.8. Li [28] proposed a new system and divided it into two modules, respectively the solar thermal regeneration part and fresh air cooling dehumidification part. But the system was limited by the sunlight intensity, and the system could only be used in the strong solar radiation area. In the study of Zhang et al. [29], a compound type of liquid desiccant air