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Parameter analysis and optimization of the energy and economic performance of solar-assisted liquid desiccant cooling system under different climate conditions

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ABSTRACT

Operation conditions significantly affect the energy and economic performance of solar-assisted liquid desiccant cooling systems. This study optimized the system control parameters for buildings in different climates, i.e., Singapore (hot and humid), Beijing (moderate) and Boulder (hot and dry), with a multi-parameter optimization based on the Multi-Population Genetic Algorithm to obtain optimal system performance in terms of relatively maximum electricity saving rate with a minimum cost payback period. The results indicated that the selection of operation parameters is significantly influenced by climatic conditions. The solar collector installation area exhibited the greatest effect on both energy and economic performance in humid areas, and the heating water flow rate was also important. For dry areas, a change in desiccant concentration had the largest effect on system performance. Although the effect of the desiccant flow rate was significant in humid cities, it appeared to have little influence over buildings in dry areas. Furthermore, the requirements of the solar collector installation area in humid areas were much higher. The optimized area was up to 70 m^2 in Singapore compared with 27.5 m^2 in Boulder. Similar results were found for the flow rates of heating water and the desiccant solution. Applying the optimization, humid cities could achieve an electricity saving of more than 40% with a six-year payback period. The optimal performance for hot and dry areas of a 38% electricity saving with a payback period of 14 years was also acceptable. The results facilitate anyone faced with choosing suitable operational parameters under different climate conditions.

1. Introduction

The rapid spread of air-conditioned buildings has led to a surge of interest in energy efficient technology [1]. The conventional air-conditioning system with vapor-compression refrigeration (VCR) has many problems, including energy waste, poor humidity control and health issues [2]. Liquid desiccant cooling systems (LDCSs) have thus become a promising alternative that dehumidify outdoor air to handle the entire latent load [3]. Due to their lower regeneration temperature, LDCSs can run on low-grade thermal energy such as solar energy [4].

The main concerns of designers and engineers faced with the option of using solar-assisted LDCSs (SLDCSs) in buildings focus on energy saving and economic performance [5]. Numerous researchers have experimentally and numerically investigated the performance of SLDCSs under different operation conditions (see the field study on hot water-powered LDCSs in Beijing by Chen et al. [6], the investigation of solar-assisted liquid desiccant ventilation systems in Pathumthani by Katejanekarn and Kumar [7], the energy savings and economic benefits of open-cycle desiccant dehumidification in Hong Kong by Li et al. [8], the study of liquid desiccant dehumidification combined with refrigeration systems by She et al. [9] and the investigation of the annual performance of sprayed LDCSs in Beijing by Liu et al. [10]). Several studies have explored how to improve the performance of solar collectors such as solar heat exchangers filled with a porous medium [11], solar receivers with double-layer ceramic foam [12] and nanoparticle fluid for flat-plate solar collectors [13].

As system performance depends on various operation conditions, parameter optimization has drawn increasing attention in LDCS research. To optimize the moisture removal rate of a packed tower dehumidifier, McDonald et al. [14] developed several simplified

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Nomenclature

A	area (m^2)
I	solar radiation (W/m^2)
$\dot{m}$	mass flow rate (kg/s)
ω	moisture removal rate (kg/kg)
$\dot{Q}$	energy (kW)
h	pressure head (Pa)
η_{solar}	efficiency (–)
t	temperature (K)
c_p	specific heat capacity (kJ/(kg K))
sf	local resistance coefficient
COP	coefficient of performance
VC	vapor-compression refrigeration
LDCS	liquid desiccant cooling system
TMY	typical meteorological year
ESR	electricity savings rate

Subscripts

a	air
s	solution
in	inlet
out	outlet
cw	cooling water
hw	heating water
f	friction loss
d	local and device loss

regression models using Statistical Analysis Software. In 2009, Liu et al. [15] conducted a performance analysis of an internally cooled dehumidifier, and found that the desiccant concentration and mass flow rate were the main factors influencing performance. In 2011, Sanjeev et al. [16] experimentally investigated the influence of heating water temperature and solution concentration on dehumidification performance. Gandhidasan and Mohandes [17] developed a numerical model based on an artificial neural network to predict the relationship between the inlet and outlet parameters of a packed bed dehumidifier. An artificial neural network model was proposed by Mohammad et al. [18] for predicting the moisture removal rate and dehumidification effectiveness with inlet parameters. In 2014, Seenivasan et al. [19] optimized five control parameters to enlarge dehumidification effectiveness using the Taguchi method. However, previous studies have been constrained by several limitations. For example, the parameter optimizations of the whole LDCSs, rather than the dehumidifier/regenerators, were limited, especially for solar-assisted systems. In addition, research on the economic analysis of LDCSs has been insufficient.

Several of the operation parameters of SLDCSs are determined by the weather, building construction and government specifications, which cannot be adjusted by designers or engineers. For example, the fresh air flow rate is determined by the occupant density and schedule, and the air temperature and solar radiation are determined by the weather conditions. However, other parameters, including the mass flow rate of the desiccant solution and initial desiccant concentration, the solar collector installation area, the mass flow rate of water through the collector (heating water) and the mass flow rate of water through the cooling tower (cooling water), can be changed by engineers to reduce energy or cost consumption. Thus, to improve system performance, the control parameters were optimized via a self-developed system model based on the Multi-Population Genetic Algorithm (MPGA) to obtain a relatively minimum payback period with the maximum electricity saving through an SLDCS. The internally cooled/heated dehumidifier/regenerator was applied in this system. Three cities with different climates were selected for study, including Singapore (hot and humid), Beijing (moderate) and Boulder (hot and dry). The environmental temperature and relative humidity (RH) of these cities in cooling seasons are summarized in Fig. 1.

2. Methods

2.1. System description

An air-conditioning system was combined with vapor compression cooling and liquid desiccant dehumidification in this research. As Fig. 2(a) shows, the outdoor air was dehumidified to handle the latent load, and then mixed with the return air. The mixed supply air was then cooled with the cooling coils. As only a sensible load was handled in the cooling coils, the cooling water temperature increased, which significantly improved the chiller COP. The supply air was then distributed into the air-conditioned room by VAV boxes and managed via the temperature controllers. The energy consumption and cost of the dehumidification system, chillers, pumps, fans and cooling tower were all considered.

The details of the liquid desiccant dehumidification system are presented in Fig. 2(b). The internally cooled dehumidifier and internally heated regenerator were applied in this system. The desiccant solution flowed through the dehumidifier to dehumidify the outdoor air, and the procedure was cooled indirectly with the water from the cooling tower. To ensure that all of the extra moisture could be removed in the dehumidifier, a cooling coil was included to adjust the solution temperature and reach the required moisture removal rate. Then, the dilute solution was heated with water from the solar collectors and regenerated through contact with the exhaust indoor air. The hot water from the solar collector flowed through the regenerator and an electric heater was used as an auxiliary.

The design parameters of the system components are summarized in Table 1. Centrifugal pumps were used in the proposed system, the flow rate and pump head of which were selected according to the air-conditioning system and case building requirements.

For the all-air handling system, the supply/return air conditions, the control strategy for the VAV box and the energy consumption of the chillers were simulated in Energy-plus. For the desiccant dehumidification system, as the fluids were circulating in the system, four nested iteration loops were used to calculate the fluid temperatures and other outlet parameters, including the loops for the temperature of the solution entering the regenerator, for the hot water temperature, for the cooling water temperature and for the temperature of the solution entering the dehumidifier. These nested loops were developed and solved using C program, as described in the literature [21].

A typical office building was selected for our research. It had 29 floors, a total area of 15,805 m^2 and a north–south orientation. The layout of a typical floor is shown in Fig. 3. The construction details, thermal properties, energy density and schedules were derived in the energy codes from the U.S. government [22]. The daily operation time for the air-conditioning system was 7:00–19:00 weekdays and 7:00–15:00 Saturdays. The indoor sensible and latent loads of the building were predicted by Energy-plus. The thermal inertia of the office building was determined using the properties of building envelopes, weather conditions and schedule, which were considered and calculated in the simulation with Energy-plus.