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Energy performance of solar-assisted liquid desiccant air-conditioning system for commercial building in main climate zones

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ABSTRACT

Liquid desiccant air-conditioning (LDAC) system, which consists of a liquid desiccant ventilation system for dehumidification and an air-handling unit for cooling, has become a promising alternative for conventional technology. To evaluate its feasibility and applicability, the simulation of solar-assisted LDAC (SLDAC) in commercial buildings in five cities of four main climate regions were conducted, including Singapore in Tropical, Houston and Beijing in Temperate, Boulder in Arid and Los Angeles in Mediterranean. Results showed that the system's performance was seriously affected by the ratios of building's sensible and latent cooling load. For buildings located in humid areas with low sensible-total heat ratio (SHR), the electricity energy reduction of SLDAC was high, about 450 MW h in Houston and Singapore, which accounted for 40% of the total energy consumption in cooling seasons. The cost payback period was as short as approximately 7 years. The main reason is that the energy required for handling the moisture could be saved by liquid desiccant dehumidification, and the regeneration heat could be covered by solar collectors. For buildings in dry climate with high SHR, the total cooling load was low, but up to 45% electricity of AC system could be saved in Boulder because the chiller COP could be significantly improved during more than 70% operation time. The cost payback period was around 22 years, which was acceptable. However, for the buildings with mild SHR, such as those in Beijing and Los Angeles, the application of SLDAC was not that suitable, in which the electricity energy saved only around 100 MW h and the cost payback period was more than 30 years. The minimum installation area of solar collector should also be fulfilled, or the system would even consume more energy than the conventional ones. It can be concluded that the SLDAC performed best in humid areas and worst in locations with the mild outdoor humidity.

1. Introduction

Due to the rapid development in recent years, the number of air-conditioned buildings and their energy consumption are increasing greatly all over the world [1]. For example, the electricity consumption in commercial buildings accounts for more than 30% of the total energy consumption in Beijing in 2010 [2]. In commercial buildings, about 30–50% of the energy consumption happens in air-conditioning system (AC) to provide a suitable indoor environment, which becomes a big concern [3]. The conventional AC system with vapor-compression refrigeration (VC) has many problems, such as the energy waste, poor control capacity, and healthy issues. The liquid desiccant AC system (LDAC), which includes a liquid desiccant ventilation system for dehumidification and air-handling unit for cooling, is regarded as a promising alternative. Without handling the latent load, the coefficient of performance (COP) of the chillers in LDAC can be significantly improved [4,5]. As the major energy required for desiccant regeneration is low-grade thermal energy [6], introducing in the solar thermal energy to deal with the heat requirement of LDAC in buildings is suitable, especially in areas with abundant solar radiation.

The energy consumption of solar-assisted LDAC (SLDAC) in buildings is seriously affected by the outdoor environment, especially the temperature, humidity and solar radiation. In previous studies, the system's performance under different load profiles was investigated numerically and experimentally. Khalid Ahmed et al. (1997) studied a liquid desiccant dehumidification with a vapor absorption chiller in Saudi Arabia, of which the COP was 50% higher than that of the conventional system [7]. Rane et al. simulated a compression AC with a liquid desiccant system in Mumbai, and found that the COP increased up to 45% [8]. In 2005, Chen et al. [9] analyzed the summer performance of a multi-stage LDAC system driven by hot water under the climate

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Nomenclature

$\dot{m}$	mass flow rate, kg/s
ω	moisture removal rate, kg/kg
ε	effectiveness, –
$\dot{Q}$	energy, kW
h	enthalpy, kJ/kg
η_{solar}	efficiency, –
T	temperature, K
c_p	specific heat capacity, kJ/(kg K)
COP	coefficient of performance
DOF	dry operation fraction
SF	solar fraction
VC	vapor compression air conditioning system
LDAC	liquid desiccant air-conditioning system
SLDAC	solar-assisted liquid desiccant air-conditioning system
RH	relative humidity
SHR	sensible heat ratio
TMY	typical meteorological year

Subscripts

a	air
s	solution
I	interface
in	inlet
out	outlet
da	outdoor air
w	water
wb	wet-bulb
hot	hot water
cold	cold water

of Beijing with the average COP of 1.1. Liu et al. analyzed the performance of LDAC with energy recovery from exhaust air, and found that its electricity consumption was 75% of that in the conventional system in summer in Beijing [10]. In 2007, Li et al. [11] investigated a SLDAC with the solar collector/regenerator (C/R), and found that the energy consumption was 25–50% less than that of the conventional system in Hong Kong. Alizadeh [12] tested a SLDAC in the tropical climate, and the overall electrical COP was approximately 6. In 2008, Katejanekarn and Kumar [13] simulated the operation performance of SLDAC in Thailand, and indicated that the system could reduce the relative humidity by about 11%. In 2011, Audah et al. [14] investigated the feasibility of a solar-powered liquid desiccant system under humid climates, and found that the energy cost was about 1/3 of that in the conventional system. In 2011, Jain et al. [15] developed an experimental setup to study the performance of liquid desiccant dehumidification in India, and found that the performance was limited by the moisture transfer characteristics of the interface. In 2014, She et al. [16] developed a new energy-efficient refrigeration system subcooled by liquid desiccant dehumidification and evaporation, and indicated the COP could significantly increase of 20%.

Literature review indicates that most previous studies investigated the application of SLDAC in a particular area, and the comprehensive analysis and comparison of different climate regions was limited. To evaluate the feasibility and applicability of SLDAC, it is necessary to analyze its operation performance under different climates. The climates on planet Earth can be divided into six categories: Temperate, Polar, Arid, Mediterranean, Tropical and Mountainous. Due to the cold weather and few inhabitants, the AC system is generally not required in Polar and Mountainous regions. Therefore, five cities within four climate regions were selected in this paper, including Singapore in Tropical, Houston in Temperate (Low latitude), Beijing in Temperate (High latitude), Boulder in Arid and Los Angeles in Mediterranean. The distribution of main climate zones and locations of cities selected in our research are indicated in Fig. 1.

The environment temperature, relative humidity (RH) and solar radiation of typical meteorological years (TMY) of these cities were summarized in Fig. 2. The selection of TMY refers to the study of Crawley [17]. As the AC system usually operates in commercial buildings in cooling seasons, only the parameters from May to October are shown. As shown in Fig. 2(a) and (b), both the highest temperature and RH occur in Singapore, with the annual average of 27.5 °C and 84.5%, and keep steady in the cooling seasons. The outdoor temperature and humidity are also high in Houston. The outdoor temperature and RH of Los Angeles are steady from May to October, with the annual average of 16.7 °C and 67.5%. Though the average temperature in cooling seasons of Boulder is close to that of Los Angeles, the humidity in Boulder is quite low due to the much dryer weather. From Fig. 2(c), Boulder and Los Angeles have the highest daily solar radiation, about 27.5 MJ/m^2 in cooling seasons, and the followings are Houston. However, the solar radiation of Singapore is the lowest in these five cities, which is lower than 20 MJ/m^2.

With a selected typical commercial building, this paper first investigated the AC load profiles of buildings in five cities, i.e. Singapore, Houston, Beijing, Boulder and Los Angeles. Then, via system modelling, the energy requirement of the solar-assisted liquid desiccant air-conditioning system in different regions were studied and compared with that of the conventional system (vapor-compression refrigeration), and the relationship between the electricity use and solar collector installation area was provided. Furthermore, the operation performance of SLDAC, including the COP and solar fraction of the whole AC system, and dry operation fraction of the chiller, was investigated. Besides, a brief economic analysis of the application of SLDAC was conducted to evaluate its feasibility and applicability in different cities.

2. Methodology

2.1. Load profile of commercial building

The typical commercial building selected in our simulation was north–south orientation. It has 3 floors of retail (1600 m^2/floor), 2 floors of car-park (1600 m^2/floor) and 24 floors of office (545 m^2/floor for 5/F–15/F and 515 m^2/floor for 16/F–26/F). The cooling load profile of the building was simulated with Energy-plus, which served as an input data for simulating the operation performance of SLDAC. As shown in Fig. 3, to make the results comparable, the typical floor layout and building façade of the selected building in all five cities were the same.

The different thermal properties of building envelopes in different cities were set according to the guidance from local governments [18]. The default parameters for occupant density schedules, minimum outdoor air requirement, lighting power density and equipment power density were derived from the Energy Commercial Reference Building Models by the U.S. government [19]. The thermal conductivity of building envelopes and several basic settings were summarized in Table 1.

The indoor temperature set point was selected as 25 °C [20], and a consistent 1 m^3/m^2 h air infiltration was applied. The simulation period was the cooling season, from May to October, and