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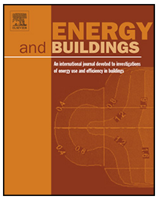

Performance assessment of a membrane liquid desiccant dehumidification cooling system based on experimental investigations

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ABSTRACT

A membrane-based liquid desiccant dehumidification cooling system is studied in this paper for energy efficient air conditioning with independent temperature and humidity controls. The system mainly consists of a dehumidifier, a regenerator, an evaporative cooler and an air-to-air heat exchanger. Its feasibility in the hot and humid region is assessed with calcium chloride solution, and the influences of operating variables on the dehumidifier, regenerator, evaporative cooler and overall system performances are investigated through experimental work. The experimental results indicate that the inlet air condition greatly affects the dehumidification and regeneration performances. The system regeneration temperature should be controlled appropriately for a high energy efficiency based on the operative solution concentration ratio. It is worth noting that the solution concentration ratio plays a considerable role in the system performance. The higher the solution concentration ratio, the better the dehumidification performance. However simultaneously more thermal input power is required for the solution regeneration, and a crystallization risk in the normal operating temperature range should be noted as well. The system mass balance between the dehumidifier and regenerator is crucial for the system steady operation. Under the investigated steady operating condition, the supply air temperature of 20.4 °C and system COP of 0.70 are achieved at a solution concentration ratio of 36%.

1. Introduction

In the hot and humid region, air conditioning plays an important role in handling both sensible and latent cooling loads. The main design criteria for air conditioning systems are thermal comfort, indoor air quality, energy efficiency and associated environmental effect [1]. Mechanical vapour compression is the most common applied technology, in which dehumidification is accomplished by cooling air to the dew point temperature, and consequently extra energy is consumed to reheat the airstream for the desired supply temperature [2]. It has been reported that energy consumption of an air conditioning system exceeds 50% of the total energy usage of a building in the hot and humid climate [3]. On the other hand, the associated risks of mechanical vapour compression system such as leakage, bacterial breeding, and fungi due to water condensation on the cooling coil surface, have been noticed with prominent effects on indoor air quality and ' health. To address the drawbacks, many innovative dehumidification cooling systems have been developed with efficient independent temperature and humidity controls and simultaneously less energy consumption. Desiccant cooling has been regarded as one of the environmental-friendly air conditioning approaches without overcooling and reheating problems [4]. In theory, desiccants which are classified into solid and liquid materials, remove moisture from an airstream through natural sorption process. Compared with the solid desiccant system, the liquid desiccant dehumidification (LDD) system has been a more promising and economical choice due to its flexibility in utilizing low-grade energy sources [5] and capability of independent humidity and temperature controls [6]. Moreover, the LDD system is capable to provide high quality supply air as liquid desiccants can filter the bacteria, microbial contaminations, viruses and moulds [7]. In terms of energy conservation, 19% reduction in the annual primary energy consumption could be achieved with an LDD system for an office building in Miami, Florida [8]. Regarding to the economical aspect, 40% of the operation cost can be saved with an LDD system compared to a conventional air conditioning system [9].

Generally, the LDD system performance is influenced by many factors, including liquid desiccant characteristic, packing type

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Nomenclature

Symbols

c_p	Specific heat capacity (J/kg K)
C_{sol}	Desiccant solution concentration
h	Specific enthalpy (J/kg)
$\dot{m}$	Mass flow rate (kg/s)
$\mathrm{m_{float}}$	Flow meter float weight (kg)
$\dot{M}_a$	Mass addition rate (g/s)
$\dot{M}_r$	Mass removal rate (g/s)
P	Pressure (Pa)
$\dot{Q}_{cooling}$	System total cooling output (W)
$\dot{Q}_{DH\_cooling}$	Dehumidifier cooling output power (W)
$\dot{Q}_{RE}$	Regenerator thermal input power (W)
T	Temperature (°C)
T_{wb}	Wet bulb temperature (°C)
T_{w_f}	Hot water supply temperature (°C)
$\mathrm{T_{w\_r}}$	Hot water return temperature (°C)
U_X	Measured variable uncertainty
U_Y	Calculated variable uncertainty
v	Volumetric flow rate (L/min)
$\bar{V}$	Average air velocity (m/s)
$\mathrm{V_{float}}$	Flow meter float volume (m^3)
$\mathrm{X_i}$	Measured variable
Y	Calculated variable

Greek letters

ε_{DH}	Dehumidification effectiveness
ε_{EV}	Evaporative cooling effectiveness
ρ	Density (kg/m^3)
ω	Humidity ratio of air flow (kg/kg_{dryair})

Subscripts

air	Air
eq	Equilibrium condition
in	Inlet
out	Outlet
S	Saturation
sol	Solution
w	Water

Abbreviations

COP	Coefficient of performance
DH	Dehumidifier
EV	Evaporative cooler
LDD	Liquid desiccant dehumidification
LDDC	Liquid desiccant dehumidification cooling
MLDD	Membrane-based liquid desiccant dehumidification
MLDDC	Membrane-based liquid desiccant dehumidification cooling
RE	Regenerator

and operating condition [10]. For the selection of a liquid desiccant, several parameters should be considered, such as boiling point elevation, energy storage density, regeneration temperature, thermo-physical property, availability and cost [11]. Halide salts are the most commonly selected desiccants, for instance lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride ($CaCl_2$). Among them, LiCl is mostly preferred due to its favourable equilibrium water vapour pressure in the dehumidification process [12]. Nonetheless, LiCl solution usually crystallizes at large vapour pressure depression [13]. On the other hand, $CaCl_2$ is regarded as the cheapest and most readily available desiccant. Better mass transfer potential in the regeneration process is obtained with $CaCl_2$ solution compared to LiCl solution under the same operating condition [14]. Besides, weak organic acid salts such as potassium and sodium formate are good alternatives [7] and ionic liquids become promising for the specific achievable dew point temperature at a comparatively lower driving temperature [13]. With respect to the regeneration of liquid desiccant solution, it can be performed by either heating dilute solution or inlet air to the required regeneration temperature. By comparison, heating dilute solution is proved to be more efficient in the solution regeneration process [15].

The LDD packing arrangement is another critical factor influencing the dehumidification performance [16]. The available packing types are namely, wetted wall, spray tower, packed column and membrane-based, which provide the solution and air flow in different patterns including parallel, counter and cross flows. The wetted wall, spray and packed towers have been popular options for the dehumidification purpose [17]. However, these direct contact packing types have a major problem of liquid desiccant droplet carryover, which could be harmful to occupants' health, building structure and indoor equipment [18]. To eliminate this problem, a membrane-based liquid desiccant dehumidification (MLDD) system is adopted, which involves an indirect contact process for dehumidification. Membranes acting as selective barriers allow heat and moisture transfers between the solution and airstream but prevent the carryover of liquid desiccant solution into the supply airstream [18]. Membranes are categorized into dense and porous types depending on the pore dimension. The dense membrane is hydrophilic for vapour transportation, while the porous membrane with a more open volume and larger pores is hydrophobic [19]. With respect to the form, membranes can be constructed as flat sheets with a simple structure and easy fabrication, or hollow fibres with a large packing density and high effectiveness but a more complex design.

A liquid desiccant dehumidification cooling (LDDC) system is defined as a hybrid air conditioning system combining a liquid desiccant dehumidification unit to handle the latent cooling load and a cooling unit to deal with the sensible cooling load [20]. A variety of cooling technologies can be integrated with the LDD system, such as vapour compression, vapour absorption and evaporative cooling. Among them, the evaporative cooling system has been widely applied because of its lower installation and running costs [21]. Compared with a vapour compression air conditioning system, the reduction in energy consumption of an evaporative cooler is over 75% [22]. Generally, the evaporative cooling is classified into direct and indirect types. The effectiveness of the direct evaporative cooling system is in the range of 70% to 90%, while the effectiveness ranges only from 40% to 60% for the indirect system. The direct evaporative cooling system adds moisture to the cooled supply air, whereas the indirect evaporative cooling system provides only sensible cooling to the supply air without any moisture being added, which is more preferred in the humid climate [23].

The selection of an evaporative cooling unit for an LDDC system depends on climate condition, supply air demand, cost and etc. The feasibility of an LDDC system with an indirect evaporative cooling unit is evaluated by experimental work in [24], in which the indoor air temperature reduces from 33.8 °C to 22.3 °C and the relative humidity decreases from 68.6% to 35.5%. With the similar design concept, a drop of 7.5 °C in the indoor air temperature is achieved in [25]. In response to the climate condition and air conditioning requirement in Hong Kong, a hybrid liquid desiccant air conditioning system is developed by integrating both direct and indirect evaporative cooling means [26], whose performance is investigated by theoretical modelling. The LDDC system with an evaporative cooling unit is proved with remarkable energy and cost saving potentials [27]. By installing an evaporative-cooling assisted LDDC system for an open office building in Seoul, South Korea, 12% saving of the annual primary energy consumption could be