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Experimental investigations on a solar assisted liquid desiccant cooling system with indirect contact dehumidifier

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ABSTRACT

Challenges on energy and environmental fronts have initiated momentum in increasing the role of renewable energy in air-conditioning industry. Liquid desiccant cooling systems (LDCS), emerging as promising alternative to conventional vapor compression systems, can run on low grade heat which can easily be drawn from solar energy. In the present study a small capacity liquid desiccant evaporative cooling system for small office application is developed. The system is a dedicated outdoor air system (DOAS). Lithium chloride solution is used as a liquid desiccant. The system consists of a dehumidifier, a regenerator, a regenerative evaporative cooler, heat exchangers (solution-solution, air-water, and solution-water) and non-concentrating solar collectors. The dehumidifier in the system is an indirect contact heat and mass exchanger which eliminates the carryover of desiccant. The major energy consumption in the LDCS is for the regeneration process which is tapped from solar energy. The performance of the overall system is presented in terms of its dehumidification effectiveness, moisture removal rate, cooling capacity and thermal COP.

1. Introduction

According to the National Oceanic and Atmospheric Administration (NOAA), the year 2015 was the warmest year since records began in 1880 (HVAC&R Industry, 2016). The number of record-breaking scorching hot summer days in various regions in recent past is alarming (Allouhi et al., 2015). The heating, ventilation and air conditioning demands are expected to rise 6.2% annually (Rafique et al., 2015). Moreover, depleting conventional primary energy resources (like fossil fuels, natural gas, petroleum etc.) along with the consequences of their usage like global warming and pollution are giving rise to growing demand for renewable energy (solar, waste heat, geothermal etc.) based sustainable clean cooling technologies. Foremost amongst the renewable energy sources, solar energy has the highest potential for cooling technologies in tropical/ subtropical climates like India. India, rich in solar energy, receives solar radiation on an average of 200 MW/km^2 with 250–300 sunny days in a year. Daily incident radiation ranges from 4 to 7 kW h/m^2 with 2300 to 3200 sunshine hours per year (Sharma et al., 2012). The coincidental matching of peak cooling load with the maximum solar radiation makes solar energy a very promising candidate for air conditioning (Al-Ugla et al., 2015). An overview and current status of solar energy based cooling technologies has been reported by several researchers in recent years (Henning, 2007; Hwang and Radermacher, 2008; Kim and Ferreira, 2008; Hughes et al., 2011; Chidambaram et al., 2011 etc.). Solar electric refrigeration systems powered by photovoltaic cells are found to be costlier than the solar thermal options (Kim and Ferreira, 2008). Thermally driven cooling systems mainly include closed systems such as vapor absorption system (VAS), adsorption systems and open systems like desiccant systems (solid or liquid). VAS like conventional vapor compression system cools the supply air below the dew point temperature of air to remove moisture which requires lower evaporator temperature than that needed for sensible load removal only. The wetness of tubes due to water condensation over the cooling tubes causes the breeding of mould, bacteria etc., which deteriorates the indoor air quality (IAQ) (Isetti et al., 1997; Xiao et al., 2011). The desiccant systems, in contrast, handle latent and sensible loads independently and thus eliminate reheating of air. Liquid desiccant cooling systems have some advantages compared to the solid ones, such as higher thermodynamic COPs, disinfecting effect, easy storage of regenerated desiccant etc. (Isetti et al., 1997; Factor and Grossman, 1980). Liquid systems improve the IAQ by minimizing microbial growth with the sterilizing effect of desiccant solution. Even fresh water can be produced from humid air with the help of liquid

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Nomenclature

A	area (m^2)
CC	cooling capacity (kW)
COP	coefficient of performance
c_p	specific heat (kJ/kg K)
DBT	dry bulb temperature (°C)
G	mass flow rate of air
h	specific enthalpy (kJ/kg)
I	irradiation (W/m^2)
L	mass flow rate of desiccant
m	mass flow rate (kg/s)
MRR	moisture removal rate (g/s)
OD	outer diameter (m)
p	partial pressure (kPa)
SHWS	solar hot water system
WBT	wet bulb temperature (°C)

Greek letter

ξ	liquid desiccant concentration
ε	dehumidification effectiveness
η	efficiency

Subscripts

a	air
col	collector
d	desiccant
deh	dehumidifier
eq	equilibrium
rec	regenerative evaporative cooler
in	inlet
out	outlet
sol	solution
sc	solar collector
w	water
RHX	regenerator heat exchanger

desiccant using solar energy to mitigate the fresh water shortage in the remote areas (William et al., 2015).

Current research in liquid desiccant technology has been reported by several authors (Rafique et al., 2015; Yin et al., 2014; Luo et al., 2014; Mohammad et al., 2013; Mei and Dai, 2008). Lof (1955) was probably the first to develop and conduct experimental study on a liquid desiccant system. He used TEG as a liquid desiccant. The performance of such systems immensely depends upon the type of liquid desiccant used. Several researchers have experimentally studied LDCS utilizing various desiccants like aqueous solutions of lithium chloride (LiCl), potassium formate (KCOOH), calcium chloride ($CaCl_2$) lithium bromide (LiBr), triethylene glycol (TEG) etc. (Koronaki et al., 2013; Liu et al., 2011; Mei and Dai, 2008; Longo and Gasparella, 2005; Ertas et al., 1992). Among the commonly used liquid desiccants LiCl has the best performance (Mei and Dai, 2008). Well-established correlations pertaining to thermo-physical properties of LiCl are reported in the literature (Conde, 2004; Ahmed et al., 1998).

Numerous performance studies have been carried out on liquid desiccant systems both experimentally and using simulations (Longo and Gasparella, 2005; Gommed and Grossman, 2007; Moon et al., 2009; Jain et al., 2011; Das and Jain, 2013, 2015a). The dehumidifier is the most important component of a liquid desiccant system which is either adiabatic or internally cooled. The experimental performance of adiabatic and internally cooled dehumidifiers has been compared by Bansal et al. (2011). The effectiveness varies between 0.38 and 0.55 without cooling and between 0.55 and 0.706 with simultaneous cooling. Most of the adiabatic and internally cooled dehumidifiers considered by the researchers are direct-contact type where air and desiccant comes in direct contact with each other. The commonly used air-desiccant direct contacting equipment are packed towers, spray towers, falling films etc.

Widely used packed bed structures are known for their large contact area and contact time. In this, desiccant sprayed from the distributor located at the top, flows down by gravity wetting the packing. It is exposed to the process air along the packing surface. Liu and Jiang (2009) have studied the effect of the air and the solution stream flow-pattern on the dehumidifier and regenerator effectiveness. Investigations on heat and mass transfer between desiccant solution and air in a counterflow packed tower have been conducted by Kim et al. (2015). In spray tower, liquid desiccant fed from the nozzle distributor fixed atop, dissociates into tiny droplets and interacts with the air. Large surface area obtained for heat-mass interactions between air and sprayed desiccant droplets enhances their effectiveness. Their COP is reported to be 0.7–0.83 (Scalabrin and Scaltriti, 1990). However, the chances of solution droplet carryover are high (Jain and Bansal, 2007). In falling film designs the liquid desiccant flows by gravity along the wetted wall in the form of thin films and directly contacts the air. The solid surfaces are generally tubes or plates, placed vertically (Kumar et al., 2011). These devices have low pressure drop, high contact area per unit volume and low initial cost (Kim et al., 2003). Possibility of carryover is comparatively less in wetted wall (Ronghui et al., 2014). Droplet filters or mist eliminators have been used to abate the entrainment of desiccant droplet in the supply air (Kathabar, 1998). However, this method causes higher air-side pressure drop and requires frequent maintenance. Numerous attempts have been made to contain the carryover of desiccant (Rane et al., 2005; Lowenstein et al., 2006; Kumar et al., 2011). A low-flow falling film contactor has been developed by Lowenstein et al., 2006 which claims to eliminate desiccant carryover in supply air stream. A wicking material is attached to the contact surface of plastic plates to enhance the solution distribution. In the contacting device developed by Rane et al. (2005), circular wire mesh disks are rotated over partially filled liquid desiccant trays. The device having high surface density of 465–600 m^2/m^3 can operate at low liquid flow rate. The carryover is contained by keeping low air velocity of 1–2.4 m/s. The wire mesh packings developed by Kumar et al. (2011) improved the performance of spray tower by 30% without increasing air-side pressure drop and claims to limit carryover.

Energy savings potential of liquid desiccants in evaporative cooling-assisted systems has been studied by Kim et al. (2013). Various potential liquid desiccant cycles are identified and analysed with a simulation model by Das and Jain (2015b). The effect of hot water temperature on the performances of the cycles is investigated at ARI conditions. Mohammad et al. (2013) reviewed the available hybrid liquid desiccant systems. Recent research developments in membrane contactors for liquid desiccant systems to subside the carryover of desiccant have been reported by Huang and Zhang (2013).

The moisture picked up by the liquid desiccant in the dehumidifier is removed in the regenerator for reuse. Low regeneration