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Solar liquid desiccant regeneration and nanofluids in evaporative cooling for greenhouse food production in Saudi Arabia

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ABSTRACT

This article is about using solar energy and liquid desiccant to provide evaporative cooling systems of spaces occupied by plants in high ambient humidity climate. The system took full benefit of the regeneration of liquid desiccant by pure solar energy. The effect of airflow on the predicted and measured average daily maximums of greenhouse temperatures obtained using desiccant system and those obtained with conventional evaporative cooling for the month of June was investigated and reported. The desiccant evaporative cooling system lowered the average daily maximum temperatures in the greenhouse by about 6 °C relative to conventional evaporative cooling system. Furthermore, shell and tube heat exchanger configuration was adopted to simulate pipes implanted in the desiccant pad and fed with nanofluids supplied from a cooling tower. The effects of changing volume fractions of nanoparticles on energy effectiveness and heat transfer coefficient of an assumed shell and tube heat exchanger have been analyzed and discussed. Improvements on convective heat transfer coefficient of 7.20–14.40%, 6.20–12.30%, and 5.50–9.01% were obtained for 0.01–0.04 volume concentrations of Al_2O_3-W, Fe_3O_4-W, and ZnO-W nanofluids, respectively. In addition, energy effectiveness has been analyzed and enhancements of 27.50–50.10%, 25.01–40.10%, and 24.00–32.02% were obtained for volume fractions from 0.01 to 0.04 of ZnO, Fe_3O_4, and Al_2O_3 nanoparticles, respectively, suspended in water with constant mass flow rates of fluids. Dynamic indicators (life cycle and annualized life cycle costs) were applied to evaluate the economic-effectiveness of this energy supply system. The total life cycle cost was found to be $11,206 and the annualized life cycle cost for this system was found to be 1317 $/year.

1. Introduction

The theory of cooling using liquid desiccant is that a hygroscopic liquid is carried into contact with air, in an apparatus known as a dehumidifier (Agami et al., 2007). The air turns out to be drier and this resort to increase its comfort value. Improved comforts conditions are prerequisite to higher ventilation rates. In humid climates, a much bigger load must be removed from the outdoor air before being supplied to the inside space in order to attain more quality of the inside air. In other words, reducing humidity of the outside air through the cooling season will enhance indoor air quality by restraining condensation and decreasing augmentation and distribution of bacteria. Refrigeration equipment are usually used to attain the required dehumidification. The other method of dehumidification is by using liquid or solid desiccants. Most current systems use solid rather than liquid desiccants.

Desiccants are used primarily to decrease the water vapor content in humid air. The choice of desiccant is a key consideration. Desiccants typically used in the past included ethylene glycol, calcium chloride, lithium bromide and lithium chloride. Lithium salts are however, limited in global supply; and currently they are in high demand for the electric battery market. Ethylene glycol is toxic to humans, as are lithium salts to a lesser extent.

Liquid desiccant systems usually composed of a conditioner or an absorber for air dehumidifying by absorbing water vapor from the air using the concentrated desiccant. To maintain the desiccant capacity of the liquid, it has to be regenerated to drive off moisture out of the dilute solution to an exhaust air. The exhaust air is generally heated to put forward regeneration of desiccant. This technique is well known in the scientific literature; for example, researchers reported regenerating a solution of lithium chloride in a solar still in 1963 (Hollands, 1963). Researchers in this field have adopted different designs for regenerator in their studies. The kind of apparatus used for air–liquid contacting is usually falling film (Jain et al., 1999; Howell, 1987; Luo et al., 2015), spray (Patnaik et al., 1990; Scalabrin and Scaltriti, 1990; Chung et al.,

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1999; Koronaki et al., 2014) or packed towers (Fumo and Goswami, 2002; Oberg and Goswami, 2000; Gandhidsan, 2005; Elsarrag, 2007; Mohammad et al., 2013). Although, falling film, spray towers and packed towers have been researched the latter received more attention (Elsarrag, 2006). Experimental models have been developed and compared with theoretical models. Various studies concerned to the usage of liquid desiccant in a packed column or tower could be found in (Al-Sulaiman et al., 2007; Tao et al., 2012; Xiu-Wei et al., 2012; Gandhidsan, 2004; Liu et al., 2015).

The heat needed for the desiccant regeneration can be supplied by waste heat, solar energy or fossil fuel. Utilizing solar energy for regenerating dilute desiccants has been getting a great deal of consideration recently (Qi et al., 2014; Elsarrag et al., 2016). Performance studies on open solar regeneration systems in hot humid climates and the potential of thermal storages were conducted (Elsarrag, 2008; Katejanekarn and Kumar, 2008; Tu et al., 2010; Lychnos and Davies, 2012a, 2012b; Riangvilaikul and Kumar, 2010; Mohammad et al., 2013; Jason and Eric, 2013).

Saudi Arabia is rich in solar irradiance and this natural resource could replace the existing fossil energy. The dry air can also be subsequently cooled by evaporating water into it. Evaporative cooling is one of the choices considered corresponding to mechanical vapor compression for air conditioning applications. As for energy consumption, evaporative coolers use much less electric power than vapor compression systems (Gebrehiwot et al., 2013). These systems are commonly utilized in regions with dry and temperate climates in place of conventional air-conditioning devices due to the lower initial cost and energy consumption. Also, its use has been extended to regions under humid weather conditions by incorporating with a desiccant chamber for air dehumidification before the evaporation process. Coupling desiccant dehumidification with evaporative cooling expands the range for comfort cooling (Bom et al., 1999) including greenhouse applications. Cultivating crops in greenhouses could reduce the total irrigation demand by many times. Where farmers used evaporative cooling pads, they could even extend their growing season out to 10 months a year. Water can be used as a medium for evaporative cooling and is gaining significant traction (Jim, 2009). Evaporative cooling typically requires a low ambient relative humidity to provide for the mass exchange (water to air) yielding a resulting energy exchange (heat from air to water). The challenge evaporative cooling faces is its application in climates which have higher relative ambient humidity.

The performance and comfort provided by desiccant cooling depends on several factors including: the choice of desiccant, the ambient temperature and humidity, the system configuration and design of the components. Innovations in dehumidifier design beside advances in absorptive materials have increased the attraction towards desiccant technology (Dieng and Wang, 2001). Consequently, the desiccant equipment cost and size continue to decrease and hence finding a market place. However, desiccant cooling also suffers from some drawbacks. It is a psychrometric process and as such limited in the temperature depression it can achieve. As a result, the practical and commercial applications of solar liquid desiccant cooling remain relatively few.

Enhancing the efficiency of the heat exchange process is usually accomplished by increasing of area of the heat transfer. However, this approach makes heat exchanger systems larger and massive. As the thermal conductivity of solid particles is greater than conventional fluids therefore, recently, the uses of solid particles in conventional liquids have been considered to improve heat transfer of these fluids (Saghafifar and Gadalla, 2015). But increased pressure drop, sedimentation, and fouling are the setbacks that make this practice less attractive. The latest developments in nanomaterial's technology have supplied potentials to prevail over these problems by generating particles in required nanometer size. Nanofluid is the suspension of nano class particles (generally less than 100 nm) in conventional liquid. Research articles in literature show that thermal conductivity enhanced, and hence thermal performance, by nanoparticles suspension in base fluids (Sundar et al., 2013; Rizvi et al., 2013). However, the heat exchanger's effectiveness relies on the convective coefficient of heat transfer of the operating fluids which, in turn, depends on density, viscosity, specific heat and thermal conductivity of the fluid.

The main aim of this study was to simulate numerically and to verify experimentally the air temperature in an evaporative cooling for greenhouse food production in Saudi Arabia using solar liquid desiccant regeneration. The research project's key motive was to overcome the challenge of establishing a system of effective liquid desiccant cooling system that is powered by solar energy for a greenhouse in high humidity climates. The regeneration of desiccant was carried out with a solar system that was used to heat and regenerate the diluted desiccant. The change in air temperature as it goes through the greenhouse was measured and estimated using a mathematical computer simulation based on an energy balance for that greenhouse. The second objective was to investigate the influence of various nanofluids as cooling fluids on the effectiveness of the heat exchange process in the desiccant pad and eventually their effect on the measured air temperature inside the greenhouse.

2. System assembly

2.1. Experimental setup

The main target in this study was to develop a whole system integrated mass and energy model for a cooling system using desiccants and evaporative cooling, able to function in varying and given temperature and humidity conditions. The main task consisted of both experimental work, generating the data, and modeling work, taking the data and creating mathematical relationships between the inputs (temperature, humidity, flow rates) and outputs (temperature). An experimental facility was designed and constructed in Saudi Arabia with fresh air inlet and exhaust, allowing space for the associated personnel, instrumentation and data logging facilities to generate the data necessary for the development of the predictive models for dehumidification and evaporative cooling. The green house has a width of 10 m and length of 30 m with a plan area of 300 m^2. Reducing the humidity of the air was achieved using liquid desiccant which can be regenerated. Air flow rates examined were between 3 and 30 kg/s. The desiccant pad (dehumidifier) placed immediately before an evaporative cooler which, in turn, placed upstream of the greenhouse inlet. Desiccant used was aqueous solutions of calcium chloride. The desiccant pad, $1.5 \times 1.5 \times 0.4$ m, was constructed with porous medium allowing air to pass through it. It comprised of particularly fattened and ridged sheets of cellulose paper with various flute angles, one flat (30°) and one steep (60°) that have been joined together. The process air was drawn into the desiccant pad using a centrifugal blower and is consequently caused into close contact with the desiccant liquid. The dehumidification process was carried out by spraying the liquid desiccant into the process air to absorb the humidity from the air then the liquid desiccant falls to a sump and pumped back to the nozzles to be sprayed back to the air again. The solution becomes diluted as a result of absorbing humidity from the air stream. The concentration of desiccant solution decreases as the water content increases. Heat, corresponding to the heat of desiccant dilution and the condensation latent heat, was released as moisture was taken away from the incoming air stream. For this reason, 12 copper tubes (15 mm outside diameter) fed with cooling fluid supplied from a cooling tower were embedded in the desiccant pad. The cooling tower lowers the