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Performance analysis of a partially closed solar regenerated desiccant assisted cooling system for greenhouse lettuce cultivation

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ABSTRACT

In this paper, a novel scheme of a partially closed solar regenerated liquid desiccant assisted evaporative cooling system has been proposed. The objective of the system is to provide suitable conditions inside greenhouses for cultivation of high value temperate crops like lettuce throughout the year in hot and humid climates of tropics and subtropics. The partially closed system re-circulated a fraction of return air from the greenhouse and ventilated a certain amount of ambient air. A forced parallel flow solar regenerator has been used to re-concentrate the weak desiccant solution. A thermal model has been developed to predict the greenhouse air temperature, vapour pressure deficit and the coefficient of performance of the system. The predicted greenhouse temperature has been compared with that of a reference model study available in literature. A very good agreement is established on comparing the temperatures predicted by the two models with a root mean square error of 0.82 °C and average percentage difference being 2.4%. The COP of the cooling system varied between 0.64 and 0.74 for daylong operation in the most humid month of the year (July). The maximum greenhouse temperature predicted using our proposed model was about 27 °C for year round system operation for the place under consideration (Kolkata). The predicted vapour pressure deficits were also in the optimum range. Thus, optimum or viable lettuce growing conditions were predicted by our model all year around. The study consequently reinforces the viability of cultivation of target plantation (lettuce) in hot and humid climates prevailing in the tropical or subtropical countries like India with our model.

1. Introduction

A greenhouse is a framed structure covered with a transparent material in which the environment can be artificially regulated to optimize the growth of plants. Temperature and humidity are the predominant factors that govern the microclimate inside a greenhouse (Santosh et al., 2017). In the subtropical and tropical countries, the climate remains hot and humid for major part of a year. High temperature is detrimental for the cultivation of high value target crops like lettuce (Lactuca Sativa) which thrive at a temperature between 17 and 24 °C with the maximum viable temperature being 28 °C (Abu-Hamdeh and Almitani, 2016). This can be one of the primary reasons that most of the leading lettuce producing regions (major part of United States of America, Spain, Italy and parts of China) are not located in the hot and humid subtropical and tropical parts of the world (FAOSTAT, 2014). Most horticultural crops like lettuce grow well under air vapour pressure deficit (V.P.D.) of 200–1000 Pa under ranges of optimum temperature (Grange and Hand, 1987). Higher humidity levels (V.P.D. $<$ 200 Pa) promote disease and cause disorders in plant growth, while lower values of humidity (V.P.D. $>$ 1000 Pa) lead to increase in plant water stress making the environment unfit for growth of plantation (Grange and Hand, 1987). Higher than optimum values of humidity during the light period results in advancing the onset of calcium related tipburn in lettuce (Collier and Tibbitts, 1984) and cause saturation of intercellular spaces or "glassiness" (Hand, 1988). So, for the greenhouses located in tropical as well as subtropical regions, the major objective is to reduce the temperature as well as control of humidity for cultivation of lettuce.

Greenhouses can be cooled by using conventional vapour-compression air conditioning systems that are used in buildings. However, use of conventional vapour-compression air conditioning system in a greenhouse is uneconomical besides contributing to global warming. Evaporative cooling is a viable alternative to vapour-compression air conditioning systems. Several studies have been reported which use evaporative cooling in greenhouses, details of which are already available in literature (Kumar et al., 2009; Sethi and Sharma, 2007).

Evaporative cooling systems alone, however, fail to provide sufficient cooling when the ambient humidity is high. Thus, it is important

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to reduce the moisture content of process air and the same can be accomplished by passing it through desiccant materials prior to its entry to the evaporative cooler. A numerical model of Desiccant Enhanced Evaporative (DEVAP) air conditioner which combines an evaporatively cooled liquid desiccant dehumidifier with a dew point indirect evaporative cooler was proposed and experimentally validated by Woods and Kozubal (2013). Simulations showed that for the DEVAP air conditioner, cooling source energy savings were 84% and 39% in Phoenix and Houston respectively compared to that of Direct Expansion air conditioner (Kozubal et al., 2011). Several other papers related to solar air conditioning by using liquid desiccants are available in literature (Factor and Grossman, 1980; Fumo and Goswami, 2002; Gandhidasan, 2004; Gommed and Grossman, 2007; Grossman, 2002; Kapur, 1960; Patnaik et al., 1990).

To maintain the desiccant concentration, the diluted desiccant solution must be regenerated by driving off moisture to an exhaust air. The heat needed to regenerate the desiccant can be obtained from waste heat, solar energy or fossil fuels. An open cycle liquid desiccant absorption refrigeration system was simulated and verified with data available in literature by Collier (1979). The study revealed that ratio of the desiccant solution mass flow rate per unit collector width to the collector length must be small for humid climates. A summer air conditioning system using aqueous solution of lithium chloride as desiccant and employing evaporative cooling was reported by Scalabrin and Scaltriti (1990), which showed that low heating temperatures in the range of 35–50 °C are required for regenerating the desiccant. Alizadeh and Saman (2002a) designed, optimized and provided an experimental study of a forced parallel flow solar regenerator using calcium chloride solution as liquid desiccant. They compared the experimental results with those obtained from a reference model study available in literature (Alizadeh and Saman, 2002b). The study showed that the rate of evaporation of water from diluted desiccant solution increases as water vapour stripping air mass flow rate increases and rate of water loss generally decreases with increasing solution mass flow rate. Studies reported by other authors on solar powered regenerators can be found in literature (Abu-Hamdeh and Almitani, 2016; Elsarrag, 2008; Gandhidasan, 2005). Tropical and subtropical countries receive abundant solar radiation which can be used for regeneration of liquid desiccant solution. The same is expected to drastically reduce the energy consumption required for cooling and dehumidifying greenhouses.

Several studies have been reported on solar desiccant assisted evaporative cooling of buildings, however only very few works have been done on solar desiccant assisted evaporative cooling of greenhouses (Banik and Ganguly, 2017). The effect of transpiration on greenhouse microclimate has not been taken into account in a similar solar desiccant assisted evaporative cooling system available in literature (Abu-Hamdeh and Almitani, 2016). Canopy transpiration is an important phenomenon for a mature crop particularly when the ambient insolation is high and when desiccants are used to dehumidify supply air. In another similar work, the humidity of the greenhouse air has not been predicted (Davies, 2005). All previous research works on greenhouse cooling technology using desiccants have been carried out for open air cycle systems where the conditioned greenhouse air is completely exhausted to the atmosphere (Abu-Hamdeh and Almitani, 2016; Banik and Ganguly, 2017; Davies, 2005; Lychnos and Davies, 2012). However, no research paper has been reported in literature that predicts the greenhouse air temperature, vapour pressure deficit and coefficient of performance (COP) on employing a partially closed solar regenerated liquid desiccant assisted evaporative cooling system, while incorporating the effect of transpiration.

The aim of the present study is to develop a thermal model based on linearization of sensible and latent heat exchanges in a solar regenerated liquid desiccant assisted evaporatively cooled greenhouse. The model predicts the greenhouse air temperature, vapour pressure deficit and coefficient of performance of the cooling system, incorporating the effects of shading and crop transpiration. The cycle is partially closed, re-circulating a fraction of return air and ventilating a certain amount of ambient air. A comparison has been made between the predicted temperature values obtained from our model and those from a similar model available in literature (Abu-Hamdeh and Almitani, 2016). A key motive of this research is to propose a method for greenhouse evaporative cooling employing liquid desiccants regenerated by using solar energy, which would give satisfactory performance for growing high value temperate crops like lettuce in hot and humid tropical/subtropical climates throughout the year. The final objective of this study is the use of the predicted values for efficient greenhouse climate control.

2. Proposed methodology

2.1. Description of the system

The schematic diagram of the proposed system is shown in Fig. 1. It consists of an arched gabled roof greenhouse (28 m × 8 m × 4 m) oriented in the east-west direction for cultivation of lettuce, a crop with low tolerance to high temperature.

The return air and ambient air are mixed with the help of an air-mixing plenum. Then, this process air (corresponding to position 1′ in Fig. 1) is drawn into the desiccant pad made of flattened and ridged sheets of cellulose paper with various flute angles. An aqueous solution of lithium chloride with a concentration of 0.4 kg per kg of water is used as the desiccant (Davies, 2005). Concentrated lithium chloride solution is pumped from the tank and sprayed into the process air, bringing about dehumidification by absorbing moisture from the air. The desiccant solution becomes weak due to absorption of moisture from the process air and is collected in another tank as shown in Fig. 1. The latent heat of condensation and heat of dilution of the desiccant solution is released during the dehumidification process. Thus, in order to remove this heat, cold water is supplied from a cooling tower through pipes embedded in the desiccant pad.

In order to regenerate the desiccant solution, a forced parallel flow solar regenerator/collector similar to the one proposed by Alizadeh and Saman (2002a) is used. It consists of a flat inclined blackened surface (a plate of copper sheet metal electroplated using a nickel layer underneath and thin black chrome coating at the top) over which the weak desiccant solution to be concentrated trickles down as a thin film. The bottom of the solar regenerator/collector is insulated by polystyrene and the top is covered by a single glazing leaving an air gap. The regenerator is installed in two halves to allow a fraction of incident ambient insolation on the roof into the greenhouse as shown is Fig. 1. An air stream which flows parallel to the liquid desiccant film is forced into the regenerator by using axial fans at the inlet of the collector in each half. Spray nozzles at the top of the collector are used to distribute the weak liquid desiccant evenly over the surface. Solar energy heats up the weak desiccant solution allowing the water to evaporate which is carried away by the forced air stream and exhausted to the atmosphere. This regenerates the concentrated strong desiccant solution which is collected in a tank. A heat exchanger is used to preheat the weak desiccant solution before entering the regenerator by using the hot strong desiccant solution. In the heat exchanger, the strong desiccant solution is also simultaneously cooled, thereby, lowering its vapour pressure. This cooling helps to increase the performance of the dehumidifier (Fumo and Goswami, 2002).

The dehumidification process is followed simultaneously by sensible cooling of the process air due to the cold water pipes embedded in the desiccant pad. After the initial cooling, the air exiting the desiccant pad (corresponding to position 2 in Fig. 1) is further sensibly cooled by employing a dew point indirect evaporative cooler. The dry and cool air (corresponding to position 3 in Fig. 1) is then supplied to the greenhouse. The dew point indirect evaporative cooler is similar to the one used by Riangvilaikul and Kumar (2010). At the exit of the greenhouse, an exhaust fan is installed which guides the return air into a duct which brings it to the air mixing plenum for further conditioning.