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Modelling and experimental verification of a solar-powered liquid desiccant cooling system for greenhouse food production in hot climates

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A B S T R A C T

Experiments and theoretical modelling have been carried out to predict the performance of a solar-powered liquid desiccant cooling system for greenhouses. We have tested two components of the system in the laboratory using $MgCl_2$ desiccant: (i) a regenerator which was tested under a solar simulator and (ii) a desiccator which was installed in a test duct. Theoretical models have been developed for both regenerator and desiccator and gave good agreement with the experiments. The verified computer model is used to predict the performance of the whole system during the hot summer months in Mumbai, Chittagong, Muscat, Messina and Havana. Taking examples of temperate, sub-tropical, tropical and heat-tolerant tropical crops (lettuce, soya bean, tomato and cucumber respectively) we estimate the extensions in growing seasons enabled by the system. Compared to conventional evaporative cooling, the desiccant system lowers average daily maximum temperatures in the hot season by 5.5–7.5 °C, sufficient to maintain viable growing conditions for lettuce throughout the year. In the case of tomato, cucumber and soya bean the system enables optimal cultivation through most summer months. It is concluded that the concept is technically viable and deserves testing by means of a pilot installation at an appropriate location.

1. Introduction

Energy is closely linked to food. In the US, for example, food production and processing accounted for 15.7% of the total energy consumption in 2007 [1]. In addition, the use of energy resources from fossil fuels is a major contributor to climate change which is likely to hinder agriculture and threaten food security in the future. In its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC) noted that temperature increases of just 1–2 °C would be sufficient to reduce crop productivity in low latitudes, especially in regions subject to seasonally dry or tropical climates [2]. Moreover, the low latitudes are home to many developing nations whose populations are expected to grow by some 70% by 2100 [3]. The combination of climate change and increasing food demand make it very important to research intensive means of growing food that can help adapt to warming conditions. Technologies that can achieve this using only renewable energy inputs are especially interesting.

One approach that could aid adaptation to climate change is the provision of artificially cooled environments for the cultivation of crops. The use of greenhouses to provide protected growing environments is increasing around the world. Some greenhouses are cooled using evaporative cooling (pad and fan) or fogging systems. These systems are limited, however, with regard to the lowering of temperature achievable.

A previous study put forward a concept for an enhanced greenhouse system making use of solar energy and liquid desiccant [4]. Desiccant cooling is a well established refrigeration method though more commonly realised with solid rather than liquid desiccants. The latter have the advantage of allowing larger amounts of air to be handled. In addition, it is possible to move the liquid desiccant to a solar regenerator by pumping. Therefore, liquid desiccants are particularly interesting for solar applications requiring large amounts of low-grade cooling.

The earliest reported experiments with liquid desiccant cooling were those of Baum et al. [5] and Kakabaev et al. [6] based on the theoretical work of Kakabaev and Khandurdyev [7]. Since then research has focused on the investigation of the performance of the regenerator and the desiccator, essential components of any liquid desiccant cooling systems (LDCS). Several authors investigated the various types of solar liquid regenerator by performing experiments [8–13] while others investigated the different types of structures

Abbreviations: EvCool, evaporative cooling; LDCS, liquid desiccant cooling system; NTU, number of transfer units; RH, relative humidity.

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Notation

List of symbols

A_1	parameter, K m^{-1}
A_2	parameter, m^{-1}
A	regenerator surface area, m^2
a	absorptivity
C_{pa}	specific heat capacity of air, J kg^{-1} K^{-1}
h_{fg}	latent heat of evaporation, J kg^{-1}
I_R	solar irradiance, W m^{-2}
K_c	overall heat loss coefficient of greenhouse cover, W m^{-2} K^{-1}
$\dot{m}_a$	air mass flow rate, kg s^{-1}
$\dot{m}_{abs}$	water rate of absorption, kg s^{-1}
$\dot{m}_{ev}$	rate of evaporation, kg s^{-1}
T_a	air temperature, °C
T_{amb}	ambient temperature, °C
$T_{amb,wb}$	ambient wet bulb temperature, °C
T_{gh}	temperature inside greenhouse, °C
T_w	temperature of cooling water, °C
$\dot{V}_a$	ventilation rate, m^3 s^{-1}
W	width of greenhouse, m
x	distance from inlet, m
X	mass concentration, kg kg^{-1}

Greek variables

γ	plant transpiration coefficient
η	effectiveness
ρ_a	absolute density of air, kg m^{-3}
τ	transmissivity of greenhouse roof
ω	absolute humidity, kg kg^{-1}

used in desiccators [14–28]. Liquid desiccant cooling technology has been investigated extensively for applications such as cooling of human dwellings, commercial buildings and hospitals [29–32]. The chemical compounds used as desiccants are lithium salts (LiCl, LiBr), calcium chloride or mixtures of LiCl, $CaCl_2$ and triethylene glycol.

However, some of the above compounds are expensive, scarce or toxic. It has been shown that magnesium chloride ($MgCl_2$) is an interesting non-toxic compound for use in greenhouse cooling applications especially for installations near the sea coast [33]. Magnesium chloride is the second most abundant salt in seawater and is the principal constituent of bitterns, the supernatant brine that is a by-product from solar salt works. Seawater bitterns have properties similar to those of pure solutions of magnesium chloride and so they have potential as liquid desiccants [34].

Thus, though a number of authors have investigated solar-powered liquid desiccant cooling systems, so far very few have focussed on the greenhouse application or on the use of $MgCl_2$ as the desiccant. The aim of the current study is to investigate the technical feasibility of these ideas with the help of experiments and modelling. The specific objectives are: (i) to build and test prototypes of the regenerator and desiccator in the laboratory; (ii) to compare the results with the predictions of theories based on studies from the literature that used other liquid desiccants; (iii) using a computer model based on the theory, to predict the performance of the cooled greenhouse at large scale in a range of hot climates represented by some coastal cities (Mumbai, Chittagong, Muscat, Messina, Sfax and Havana); and (iv) thus reach conclusions about what is technically possible with the system with regard to lowering of temperatures and the extensions of the growing seasons of typical crops. In contrast to the earlier preliminary study [4], this work takes into account the properties of a specific liquid desiccant ($MgCl_2$). In addition, it includes experimental verifications carried out in the laboratory, and detailed modelling of mass and heat transfer enabling the sizing of the main components to be calculated.

2. Theory

This section introduces the system and its components and describes the theory that has been used to model each component and thus provide the basis for the predictive model.

2.1. System concept

The concept of the cooled greenhouse system is shown schematically in Fig. 1. The essential parts of the system are the regenerator, the desiccator, and the greenhouse including the evaporative pad. There are three process fluids: air, liquid desiccant and cooling water. The desiccator and evaporative pad are both wetted porous media, permeable to air. Atmospheric air enters the system through the desiccator where it is dehumidified as it comes in contact with the liquid desiccant. The lowered humidity means that the cooling effect of the evaporative pad downstream is enhanced. As a result of absorbing water from the air, the liquid desiccant becomes less concentrated. The solar regenerator provides the necessary latent heat to drive off water from the liquid desiccant and thus restore its concentration and desiccant property. The solar regenerator may be placed on the greenhouse roof or on the ground. After leaving the regenerator, the concentrated desiccant is returned to the desiccant pad. To remove the latent heat of condensation and the heat of dilution of the liquid desiccant, the desiccant pad includes cooling tubes carrying cooling water provided at the ambient wet bulb temperature. This cooling water may be supplied from the sea or from a cooling tower. The air is drawn through the system by an exhaust fan.

2.2. Regenerator

The regenerator is of open type, consisting of a tilted black surface exposed to the sun with desiccant solution running over it. This is the simplest and cheapest arrangement and therefore considered potentially interesting for the greenhouse application where large areas will be required. Following a survey of theories that have been presented in the literature [5,7–13,35–49], it was decided to adopt the theory of Collier [35] which has already been applied successfully by other researchers [7,11,50]. This approach applies heat and mass balance to a differential control volume at some position x from the inlet of the regenerator to formulate an ordinary differential equation, the solution to which gives an expression for the rate of evaporation per unit area of the surface. The regenerator theory is presented in detail in Appendix A and Ref. [51].

2.3. Desiccator

Fig. 2 shows the detailed arrangement of the desiccator which contains several sections of porous medium (CELdek®) each inserted between bundles of cooling tubes. Based on the relevant inputs (i.e. conditions and flow rates of the inlet air, liquid desiccant and cooling water) the theoretical model predicts the mass flux of water absorption and the properties of the fluids at the outlet. The approach is based on the work of Liu and associates [21–23,52] and