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A solid-Desiccant Cooling System for Greenhouses

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Abstract— **Solid desiccant systems are of potential interest as a means of cooling greenhouses to temperatures below those achieved by conventional means. This paper presents the study of a solar air conditioning system based on "desiccant evaporative cooling" (DEC) technology for agricultural greenhouse. The energy performance of the greenhouse system, is studied using a numerical simulation in TRNSYS environment. This article aims also to gain knowledge about the performance of desiccant cooling systems coupled to the greenhouse located in Tunisia. The results show an improvement inside greenhouse climate for summer period, with satisfactory thermal comfort of the plants**.

Keywords— Desiccant cooling, greenhouse cooling, Simulation, TRNSYS

I. INTRODUCTION

The agricultural greenhouse aims to create a favorable microclimate to the requirements and the growth of the plants starting from the surrounding climatological conditions. The primary role of the greenhouse is to produce fruits and crops out of season according to the cropping calendars. The microclimate control in a greenhouse has been a complicated procedure since the variables that influence it are several and dependent on each other [1].

The conventional agricultural greenhouse is highly widespread in Mediterranean countries, despite the short comings it presents, precisely the overheating during the day and the intense cooling at night. The thermal behavior of a greenhouse has often been studied, mainly during the night [2].

In order to contribute to a better climatic management of the greenhouse and, in order to reduce losses during the winter. A preliminary study is proposed to improve the thermal energy performances of the greenhouse, initially, the greenhouse was thermally insulated: the sidewalls and the northern roof are built with sandwich panels respectively, then, introducing of a heat shield on the microclimate of the greenhouse. The use of noctural shutter at night provides to reduce the energy consumption and to improve the energetic efficiency of the greenhouse. The contribution of the heat shields reduce heat loss is very satisfactory (about 6 °C), and the relative humidity, during the night, is very important (around 25%).

The growing demand for greenhouse cooling to reduce the overheating of the greenhouse during the thermal summer appears a second problem in the agricultural field. This can be achieved by reducing the high temperatures inside the greenhouses during summer with a cooling system that is less energy intensive and more effective than the conventional ones already used (evaporative pad and fan ventilation systems) [3].

A System based on solar energy seem very promising, there are well adapted for cooling applications, since high solar radiation is in general in phase with high cooling demand [4] The solar cooling, a paradoxical term, is to produce cold from solar energy. The desiccant cooling systems (DEC) are promising solar cooling technologies to ensure a suitable climate conditions. It's an environmentally alternative compared to conventional cooling, when powered by free energy [5]. Lee et al. (2013) [6] conducted a comparison between the compression system and the desiccant cooling system. The results confirm that the desiccant cooling systems can ensure a reduction in carbon dioxide (CO_2) emissions to 13%. Hirunlabh et al.[7] conducted an investigation about the application of the solid desiccant cooling system. The system appeared to be feasible in the hot and humid climatic condition of Thailand. It does report that the system can save 24% of electric energy Hourani et al. [8] presented a hybrid air conditioning system with two-stage evaporative cooling in hot and humid climates that used 100% fresh air to optimize the system. The results showed a reduction of 16.15% in energy consumption and a reduction of 26.93% of water consumption compared to an evaporative cooling system.

This article exposes the results obtained from the study of a solar refreshing system by desiccation coupled to agricultural greenhouse using solid adsorption, or "desiccant cooling" (DEC).

II. DESCRIPTION AND MODELING

A. *Thermal analysis of the greenhouse climate*

The proposed DEC system was modeled in TRNSYS 17 (fig 1). The greenhouse covers a floor area equal to 100 m², 8 m width, 12.5 m long and 3m hight at the center. The structure is all galvanized steel fixed to the ground with stones and concrete. A tomato crop was planted in the greenhouse. The greenhouse was thermally insulated. The south oriented wall and roof of the IG covered with 3 mm thick glass. Sidewalls and the northern roof are built with 0.4 m and 0.6 m thick sandwich panels respectively. At night, shutter aluminum with small blades automatically distributed on the south side.

The greenhouse is considered as a very confined environment and all components of the system exchange between them. To describe the thermal behavior of the greenhouse, there are four components that play important roles in the thermal balance: the cover, the canopy, the soil and the inside air are analyzed.

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The exchanged flows between the greenhouse and its environment are presented in Fig.2.

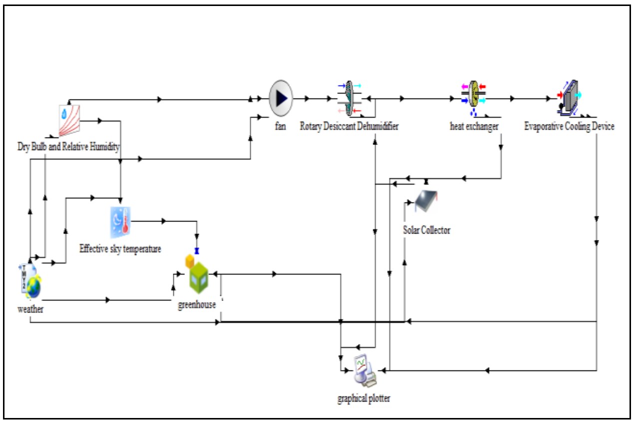

Fig.1 TRNSYS model of the proposed system

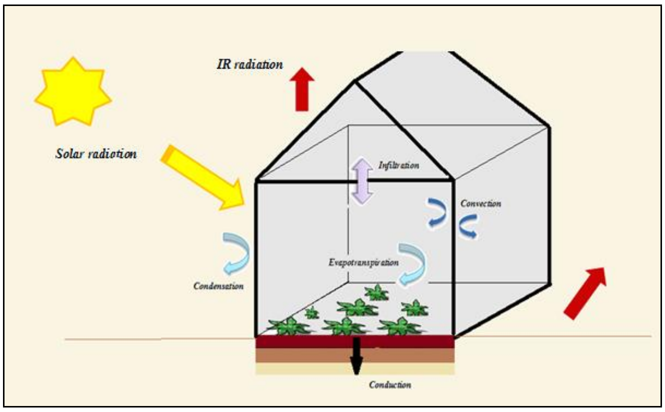

Fig .2 Heat and mass exchanges considered in the greenhouse

The sensible energy balance for the greenhouse is defined by the following equation:

$$C_{pa}\frac{dT_a}{dt} = Q_{surf} + Q_{\inf} + Q_{ven} \qquad (1)$$

Where

Q_{surf} is the total gain from all inside and outside surfaces of the greenhouse.

$Q_{\inf}$ is the total infiltration gains.

Q_{vent} is the ventilation gains produced by the DEC system. It is defined as the cooling capacity supplied to the greenhouse.

Indoor air is also the seat of the water vapor exchange by condensation on the internal faces of the cover, by evapotranspiration from plants, by evaporation over ground and by air change. Neglecting the effect of condensation on the internal face of the cover and by evaporation over ground, the mass balance of the inside air is written as:

$$M_{eff,i}\frac{d\omega_i}{dt} = m_{\inf}(\omega_a - \omega_i) + m_{ven}(\omega_{ven} - \omega_i) + W_{g,i} \quad (2)$$

$M_{eff,i}$ Is the effective water capacity of indoor air

$W_{g,i}$ is the transpiration flow of vegetation cover

B. Desiccant cooling principles

The DEC system contains principally three components: regeneration heat source, the dehumidifier (desiccant material), and the cooling unit(Figs 3 and 4).

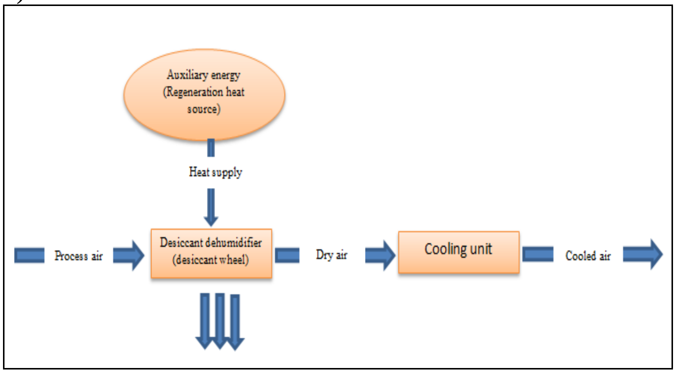

Fig. 3. Desiccant cooling principles

The principle of the system is simple Warm and humid air passes through the desiccant wheel and is dehumidified by adsorption of water (1-2). Its temperature increases and humidity ratio decreases. Desiccant wheel absorbs moisture from air due to pressure difference between pressure of moisture in the air and desiccant materials. Then its temperature is lowered in the rotating heat exchanger (2-3), resulting in a significant pre-cooling of the supply air stream and in the direct humidifier (3-4).
Return air is used to cool down the process air in the heat exchanger (5-6). Then it is heated to regenerate the desiccant wheel (6-7). The regeneration of desiccant material can be made by supplying hot air from any waste heat sources or solar energy, and to allow a continuous operation of the dehumidification process.

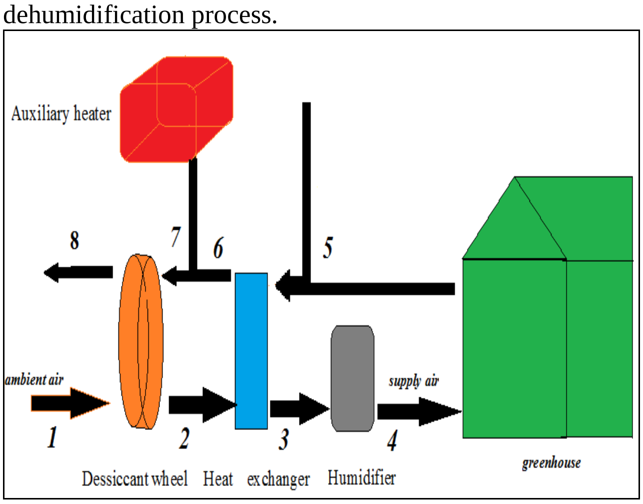

Fig.4. Desiccant cooling installation

1) Desiccant wheel

The property of desiccant wheel is to absorb moisture from the air. For the operation of the desiccant wheel, the approach of Maclaine-Cross and Banks has been selected, referred to as an analogy theory in the relevant [9] [10]. On the basis of the expressions that Jurinak [11] has provided for the combined potentials F1, F2:

$$F_1(T,\omega) = \frac{-2865}{T^{1.490}} + 4.344 * \omega^{0.8624} \quad (3)$$

$$F_2(T,\omega) = \frac{T^{1.490}}{6360} - 1.127 * \omega^{0.07969} \quad (4)$$

2) Sensible heat exchanger

The sensible heat exchanger is used to cool the warm air (transfer the heat of sorption in the dehumidified supply air stream to the exhaust air stream). The effectiveness of the sensible heat exchanger is:

$$\varepsilon_{ex} = \frac{T_5 - T_6}{T_5 - T_2} \quad (5)$$

3) Humidifiers

In the process air stream, after heat recovery and before regeneration air stream, an humidificateur is used. The effectiveness of the humidifier in the process air stream is:

$$\varepsilon_{ev} = \frac{T_3 - T_4}{T_3 - T_{wb}} \quad (6)$$

4) Solar system

The solar system is used to ensure an amount of heat for the reactivation (regeneration) of the desiccant wheel. The required energy is obtained by :

$$Q_{reg} = m_{reg}\left(h_8 - h_7\right) \quad (7)$$

5) Cycle performance

The performance of the desiccant cooling system is measured by calculating the coefficient of performance. This is given by the relation:

$$COP = \frac{Q_{cool}}{Q_{elec}} = \frac{m_{pr}\left(h_{out} - h_4\right)}{Q_{elec}} \quad (8)$$

Where h_{out} represents the enthalpy of the outside air and $h_{\sup}$ indicates the enthalpy of the air blown into the greenhouse.

Q_{elec} represents the energy consumption of the system

III. Results and Discussion

A. Ambient climatic condition of the greenhouse

The results obtained for the greenhouse studied were performed for the climate of Tunis, over all the year, using the numerical software TRNSYS. Ambient and inside air temperature are an important parameters which influence the performance of the desiccant cooling system. The DEC cycle is a novel open heat driven cycle which can be used both to cool and dehumidify air using water as refrigerant in direct contact with air. The term 'open' is used to indicate that the refrigerant is discarded from the system after providing the cooling effect to the ambient air. This is why the interior and external conditions of air influence significantly the performance of the system.

Figs 5 and 6 presented the inputs of our model. Firstly, Figure.5 show the ambient and the inside greenhouse temperatures wish is presented by the maximum and the minimum temperatures for one year. As indicated in this figure, we notice that the difference between the day and the night in the winter is probably 30°C to 60 °C. For the greenhouse temperature above 32 °C (wish is the temperature imposed by the user) the greenhouse needs a cooling in this interval of time.

The inside and outside relative humidity, are indicated in Figure.6. The relative humidity of the inside air, during the day, reached extremely low values (less than 25%), causes many infections to the crops. To limit the lowering of the humidity and to promote the development of fungal diseases, a ventilation action of the greenhouse is required in this period.

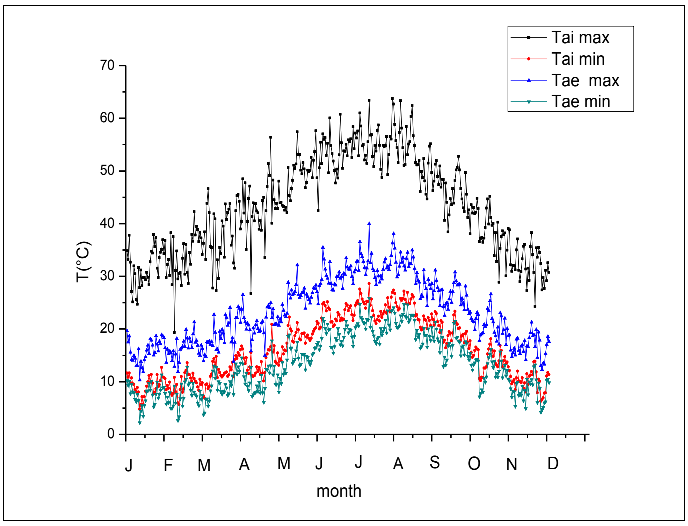

Fig.5. Maximal and minimal ambient and greenhouse air temperature

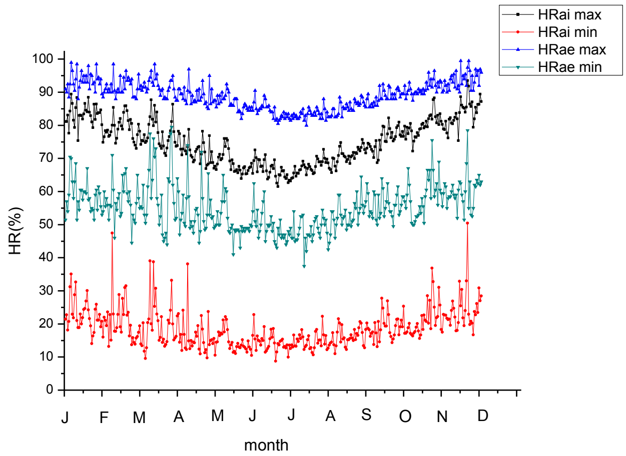

Fig.6. Maximal and minimal ambient and greenhouse air relative humidity

B. Efficiency of the DEC system

The results are presented for the 4th day of the month of July taken as a typical day. The interior temperature (Fig.7) does not exceed 20°C in the greenhouse, at the beginning of the evening. On the contrary, during the day, the reduction of the convective exchanges inside the greenhouse lead to a rise in the temperature of the inside air, the temperature is very high reached 65°C. So, the cooling action is required. When the DEC system start, the temperature of supply air is in the range of 22°C (daytime). The indoor temperature is around 32°C; while if no cooling system is used it exceeds 65°C. The supply air is 10°C cooler that the outdoor temperature. An average difference of 12°C between the inside air (cooled greenhouse) and treated air is obtained.

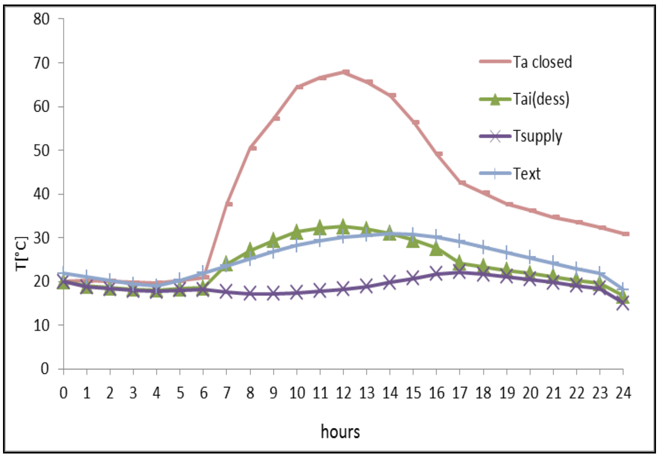

Fig.7. Variation of the air temperature

The variation of the temperature in the various points of the installation is shown in (Fig.8).

Part of the moisture of the outside air (T1) is extracted by a material desiccant in the desiccant wheel, inducing an increase in the dry air temperature (point T2). This temperature is then lowered by passing through a heat exchanger (point T3) with the return air, which is previously cooled in a humidifier. The air is then cooled in a humidifier (T4).

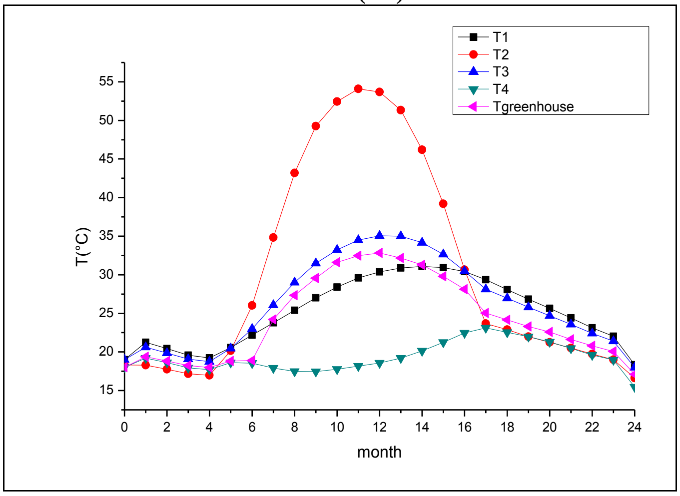

Fig.8. Variation of the temperature in the various points of the installation.

C. Economic evaluation

In the economic analysis, DEC cost, energy cost and payback period in comparison with expected service life cycle of the installation are investigated with taking into account the interest and the inflation. The project lifetime is 22 years. The inflation rate of fuel prices in Tunisia varies from 2% to 8% and the discount rate is 8%.

The annualized cost (Ca) has been calculated as given by Eq. [9]:

$$C_a = C_{inv} + C_{re} \tag{9}$$

The investment cost (C_{inv}) is given by Eq. (10)

$$C_{inv} = C_{ac} + C_{op} + C_{main} \tag{10}$$

Where C_{ac} represents the annualized capital cost, C_{inv} is the investment cost

The annual electricity cost C_{re} for fans is given by:

$$C_{re} = R * W * C_e \tag{11}$$

The payback duration (PD) is defined as

$$PD = \frac{\text{initial investment system cost}}{\text{cost of energy gain}} = \frac{C_{inv}}{C_{SE}} \tag{12}$$

An economic analysis shows that the optimized DEC system is attractive and rentable since the payback period is 1.02 years.In our case the payback period is very small compared to the life of the dryer (22 years).

D. CONCLUSION

The objective of this work was to study the possibilities of modeling technology for greenhouses on TRNSYS software to take advantage of this dynamic simulation environment. This article also aims to gain knowledge about the performance of desiccant cooling systems coupled to the greenhouse located in Tunisia. The cooling period is then from Mai to September in Tunisia. In this study, a desiccant cooling system is coupled to insulate greenhouse in order to maintain greenhouse's daytime temperature within an optimal range to maximize the tomato crops production

The numerical results show that the diurnal variation of the temperature inside the greenhouse with DEC system decrease and atteint 33°C (favorable temperature for plants growing). The supply air is 10°C cooler that the outdoor temperature. An average difference of 12°C between the inside air (cooled greenhouse) and the treated air was obtained. Economic analysis shows that the DEC system is attractive and rentable since the payback period is 1.02 years. In our case, the payback period is very small compared to the life of the dryer (22 years).

NOMENCLATURE:

C_{ai}	Heat capacity of air (J/Kg.K^{-1})
Tai	Air temperature (°C)
RH	Relative humidity (%)
Q	Heat (KJ/hr)
h	Enthalpy
M_{eff}	Effective water capacity of indoor air
$W_{g,i}$	The transpiration flow of vegetation cover
ω	Specific humidity (kg water / kg dry air)
C_{inv}	The investment cost
C_{ac}	Annual capital cost ($)
C_{op}	Operation cost ($)
C_{main}	Maintenance cost ($)
C_{re}	The annual electricity cost ($)
F1-F2	Potentials lines
TRNSYS	Transient System Simulation program
DEC	Desiccant evaporative cooling
inf	Infiltration
ven	Ventilation
surf	Surfaces
C_{op}	Operation cost ($)
C_{main}	Maintenance cost ($)
C_{cc}	Capital cost($)
a	Air
i	Inside

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