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International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2016

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Muhammad Hamid Mahmood
mahmood@phase.cm.kyushu-u.ac.jp

Muhammad Sultan
Department of Agricultural Engineering, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Bosan Road, Multan 60800, Pakistan, muhammadsultan@bzu.edu.pk

Takahiko Miyazaki
miyazaki.takahiko.735@m.kyushu-u.ac.jp

Shigeru Koyama
koyama@phase.cm.kyushu-u.ac.jp

Theoretical and Experimental Analysis of Desiccant Air Conditioning System for Storage of Agricultural Products

Muhammad Hamid MAHMOOD[1,2,5*], Muhammad SULTAN[2], Takahiko MIYAZAKI[3,5], Shigeru KOYAMA[4,5]

[1]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan
E-mail: mahmood@phase.cm.kyushu-u.ac.jp

[2]Department of Agricultural Engineering, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Bosan Road, Multan 60800, Pakistan
E-mail: muhammadsultan@bzu.edu.pk

[3]Faculty of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan
E-mail: miyazaki.takahiko.735@m.kyushu-u.ac.jp

[4]Faculty of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan
E-mail: koyama@phase.cm.kyushu-u.ac.jp

[5]International Institute for Carbon-Neutral Energy Research (WPI-I^{2}CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

* Corresponding Author, E-mail: mahmood@phase.cm.kyushu-u.ac.jp

ABSTRACT

The study emphasizes on the use of desiccant air conditioning (DAC) system for the storage of agricultural products. The chilling sensitivity of the tropical fruits and vegetables makes this system more promising for their optimal storage. The desiccant air conditioning system assisted by Maisotsenko cycle evaporative cooler is proposed in the study to achieve the latent and sensible load of air conditioning. In this regard, the dehumidification evaluation of the honeycomb like polymer based hydrophilic desiccant blocks are carried out by the means of an open-cycle experimental unit. The representative ideal storage zones of three temperature and relative humidity compatible groups of fruits and vegetables are established on the psychrometric chart on the basis of published data. The ideal DAC cycle analysis is accomplished at low regeneration temperature (55°C) for case-I (T = 31°C; RH = 21%) and case-II (T = 13°C; RH = 70%). The dehumidification analysis of the desiccant blocks recommended the time ratio between regeneration and dehumidification modes as 1:1 and 2:3 for the case-I and case-II respectively. The suggested time ratios ensure the dehumidification of the process air up to 2 g/kg of dry air and 4 g/kg of dry air in case-I and case-II respectively. The COP of the system was calculated as 0.90-0.43 and 0.55-0.25 at 30-90 minutes dehumidification with regeneration heat supplies of 1.7-2.3 kW and 2.5-3.5 kW in case-I and case-II respectively. The promising dehumidification by the desiccant blocks resulted in achieving the latent load itself followed by flat plate heat exchanger and Maisotsenko cycle evaporative cooler to achieve the sensible load. However, in case of high sensible loads hybrid DAC system is being recommended in this study.

1. INTRODUCTION

The harvested agricultural products (fruits and vegetables) contain higher moisture contents (60-95%) and have short shelf life under ambient environmental conditions. The postharvest shelf life of these perishable agricultural products can be extended by minimizing the postharvest losses (PHL). The PHL are the losses of quality and quantity (weight) of the agricultural products. In general, the postharvest losses of fruits and vegetables are reported as 20-30% in the literature (El-Ramady *et al*., 2015). However, in case of developing countries (particularly of the tropical belt) these losses become higher as 30-50% of the fresh agricultural products (Atanda *et al*., 2011; Olosunde *et al*., 2015; El-Ramady *et al*., 2015). The key factors responsible for such losses are shown in Figure 1a (Mishra and Gamage, 2007; El-Ramady *et al*., 2015). The preharvest and harvest factors cannot be avoided after the harvesting, however, the postharvest factors can be controlled to slow down the decay process in the agricultural products. The management of the postharvest factors (like temperature and relative humidity) is crucial to keep the harvested products in healthy physiological conditions in order to extend their shelf/storage life with maximum quantity and quality.

The most important postharvest factor on which the quality of agricultural products depends is the temperature of their surrounding environment. The agricultural products perform respiration after harvesting just like before their harvest. The equation (1) better explains the respiration process in the agricultural products (ASHRAE, 2010). It is evident from equation (1) that during the respiration process the ambient air oxygen reacts with the reserve sugar/starch of the harvested products and breakdown it into carbon dioxide, water and consequently heat (about 2667 kJ) is released during this reaction. Furthermore, the heat generation rate during the respiration process in the specific agricultural products can be calculated by the correlation (ASHRAE, 2010) as given in equation (2).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat} \qquad (1)$$

$$Q = \frac{10.7f}{3600}\,(1.8T + 32)^{g} \qquad (2)$$

where Q is heat generation rate in (W/kg), T is temperature in (°C) and f, g are respiratory coefficients. The values of these coefficients for various fruits and vegetables are not tabulated in the manuscript, however these can be found for the particular products from the cited literature (Becker and Fricke, 1996; ASHRAE, 2010). The respiration rate mainly depends on the temperature that means higher the temperature higher will be the reaction rate which ultimately increases the decay/aging process in the products.

The other important postharvest factor after the temperature is the relative humidity. Like respiration the harvested agricultural products also perform transpiration. In simple words, the transpiration is the loss of moisture from the product which mainly depends on the relative humidity of the surrounding air. It is responsible for the saleable weight and physical appearance of the agricultural products. Therefore, both the air temperature and the relative humidity have to be controlled and remained within the recommended limits in order to retard the postharvest losses. This can be achieved by keeping the agricultural products in the storage facilities under the ideal storage zone (temperature and relative humidity) environment. Thus, such controlled environment results in maintaining the overall good quality of the products till the end of their storage life.

The most of the storage facilities available today are equipped with conventional vapor compression refrigeration and/or air conditioning systems. However, the postharvest losses of 24% fruits and vegetables in both developed and developing countries are due to the lack of storage facilities (Islam and Morimoto, 2015). Though, some studies reported the higher postharvest losses (about 30-40%) in the developing countries mainly due to lack of storage facilities (Mogaji and Fapetu, 2011; Atanda *et al*., 2011). Moreover, the storage systems built in developed countries are either not readily available or unsuitable for the bulk produce of the fruits and vegetables (Olosunde *et al*., 2015). On the other hand, irrespective of the availability of the storage facilities/space, the conventional refrigeration systems being used in the storage facilities are not only have the demerits of environmental degradation, high energy requirements etc. but also cannot be suitably used for storage of many fruits and vegetables (particularly of tropical areas) due to chilling injury and discoloration (Olosunde *et al*., 2015; Ndukwu and Manuwa, 2015).

The standalone evaporative cooler also cannot be used effectively in humid climatic condition (Olosunde *et al*., 2015; Lal Basediya *et al*., 2013). In this scenario, the desiccant air conditioning (DAC) system with its well-known environmental and energy saving benefits (Sultan *et al*., 2015) can deal the latent and sensible loads of air conditioning distinctly. Such distinction of DAC system makes it more feasible and favorable for the storage of agricultural products without causing chilling injury, off-flavor and discoloration. Therefore, DAC system can be a viable option to be used in storage facilities/structures for on-farm and/or ex-farm storage of the agricultural products. The DAC system can also be used to preserve the agricultural products during their shipments through marines/ships.

In the present study, a desiccant air conditioning system containing two separate set of desiccant blocks, one flat plate heat exchanger (HX), one Maisotsenko cycle evaporative cooler (MEC), and a regeneration heat source unit is proposed to provide the optimal storage conditions. The ideal storage zones for three different compatible groups of fruits and vegetables are developed on the psychrometric chart. The dehumidification evaluation of desiccant blocks was carried out by the means of an open-cycle experimental unit. The experimental system consists of eight desiccant blocks, inlet and outlet temperature and relative humidity measurement gadgets, and dehumidification & regeneration air sources. The system was operated for the dehumidification of inlet air at varying temperature (i.e. 31°C to 13°C) and relative humidity (i.e. 21% to 70%). The low regeneration temperature (about 55 °C) was used to regenerate the desiccant blocks for their cyclic use. The regeneration and dehumidification cycle ratio was set as 2:3 to analyze the performance of the desiccant blocks. Simple psychrometric analysis was made while considering the ideal desiccant air conditioning cycle. Finally, the coefficient of performance of the Maisotsenko cycle assisted desiccant air conditioning (M-DAC) system and regeneration heat input were calculated under the varying environmental conditions. In conclusion, the objective of the study is to perform the theoretical and experimental evaluation of the desiccant air conditioning system in order to ascertain its feasibility to achieve the latent and sensible loads of air conditioning for the storage of agricultural products. The methodology adopted in the study is shown in Figure 1b.

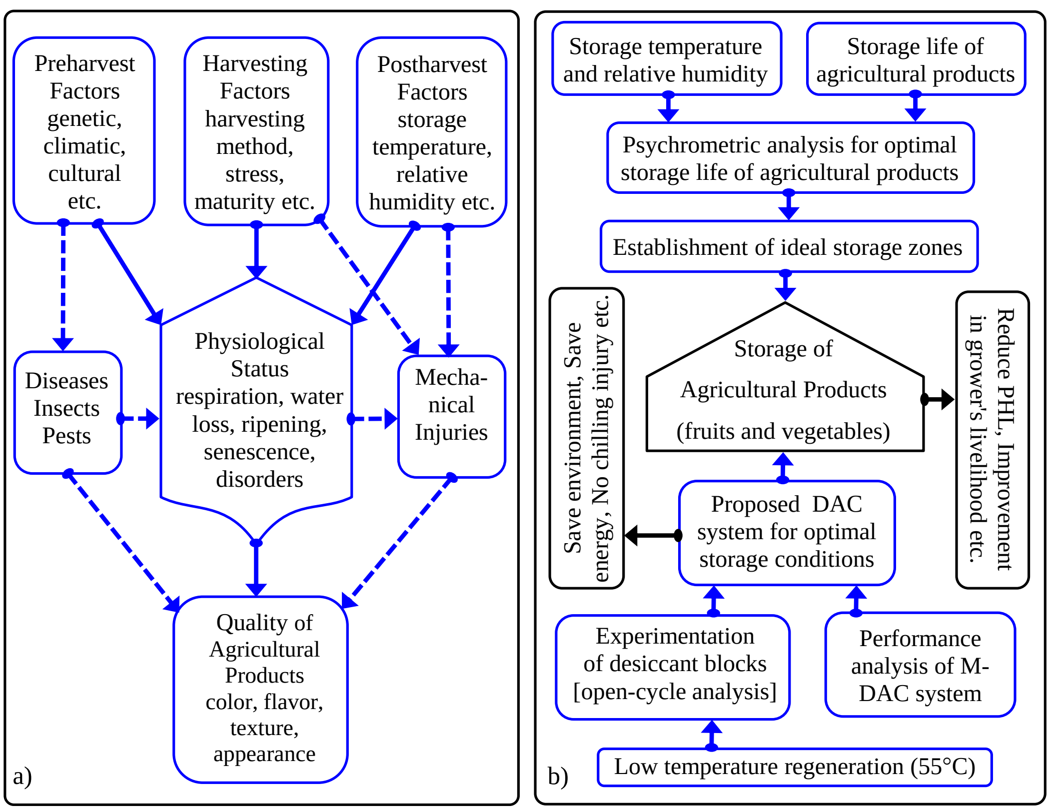

Figure 1: a) Factors affecting the postharvest quality of the agricultural products; b) Illustration of the study objectives and adopted methodology

2. MATERIALS AND METHODS

In the present study, the honeycomb like square shaped desiccant blocks with dimensions of 20 cm x 20 cm x 20 cm are used. The blocks are composed of hydrophilic polymer based sorbent. The desiccant blocks were supplied by the Showa Manufacturing Co., Ltd., Japan.

2.1 Establishment of Ideal Storage Zones

In this study, three different compatible groups of fruits and vegetables according to their temperature and relative humidity are selected for the establishment of ideal storage zones on the psychrometric chart. These groups are termed here as group I, II and III. The major fruits and vegetables belong to these groups (I, II, III) along with their recommended storage temperature (°C), relative humidity (%) and life are given in Table 1 (Kitinoja and Kader, 2002; ASHRAE, 2010). The group I and II are selected because of their sensitivity to the chilling injury. The conventional vapor compression refrigeration system is not recommended in the literature for the storage of chilling sensitive fruits and vegetables. Whereas, the storage of fruits and vegetables of group III need slightly warmth conditions. The better control over temperature and relative humidity is required in case of group III, otherwise, the warmth and humid conditions are always prone to the growth of bacteria and fungi (Lal Basediya *et al*., 2013). Therefore, M-DAC system is proposed in the study for the optimum storage of fruits and vegetables of the group I, II and III. In order to establish the representative ideal storage zone an increment of 3°C is added in the temperature of group I and II. It can be a valid assumption because of chilling sensitivity of agricultural products of the group I and II. Therefore, the representative ideal storage zones developed on the psychrometric chart for the studied agricultural products groups are shown in Figure 2.

2.2 Experimental System and Procedure

The dehumidification analysis of desiccant blocks were carried out by the means of an open-cycle experimental unit placed in the controlled temperature and relative humidity room. The experimental unit consists of eight desiccant blocks, air flow control valves, air blower, heat exchanger, water circulator, constant temperature water bath, inlet & outlet temperature and relative humidity measurement gadgets, and dehumidification & regeneration air sources. The schematic of the experimental unit is shown in Figure 3. The honeycomb like square shaped desiccant blocks (20 cm x 20 cm x 20 cm) composed of hydrophilic polymer based sorbent are used in the experimental unit. The regeneration and process air was supplied by the air circulators (APSITE: PAU-H3200-6KHC, T_{ac} = ± 0.5°C; RH_{ac} = ± 2%) and (PAU-AZ1800SE, T_{ac} = ± 0.05-0.1°C). However, the experimental unit is also equipped with flat plate heat exchanger which is connected to the water bath (ADVANTEC: TBN402DA, T_{ac} = ± 0.1°C) through water circulator (EYELA CTP-3000, T_{ac} = ± 0.1°C). This is an optional arrangement for the provision of high regeneration temperature and it also enable the use of only one air circulator for both the regeneration and adsorption. The inlet and outlet air temperature and relative humidity of the desiccant blocks were measured by the temperature and humidity transmitters (VAISALA: HMT 333, RH_{ac} = ± 1-1.7%; T_{ac} = ± 0.2-0.3°C). The air mass flow rate was determined by measuring the pressure difference across the circular orifice through differential pressure transmitter (TESTO: 6349, P_{ac} = 0.3 Pa). The air flow rate was regulated by variable speed blower (SHOWA: EC-100T-R313, efficiency = 90 %). The data acquisition unit (DAQMASTER: MX 100) was used to record the data for every 10 second interval.

As far as the experimental procedure is concerned, first of all, the ambient conditions of the experiment room were maintained by running its separate air conditioning control unit. The experiments were started with the regeneration of the desiccant blocks. The temperature and relative humidity of the regeneration air stream was maintained at 55°C ± 2°C and 5 % ± 1%, respectively. The regeneration air stream was passed through desiccant blocks for 60 minutes. The low temperature regeneration was selected in order to simulate the conditions that can be available through the use of low grade waste heat, solar energy and biogas. After the regeneration of the desiccant blocks the process air for 90 minutes was moved through them. The process air circulator was adjusted at temperature and relative humidity of 31-13°C and 21-70%, respectively. The time ratio between regeneration air and process air was adjusted as 2:3 for the performance evaluation of the desiccant blocks (Yoshida *et al*., 2013). The initialization of the desiccant blocks was made for each cycle at T= 55°C ± 2°C and RH =5 % ± 1%. The instantaneous data of the experiments were recorded automatically by the data logger. The mass flow rate of the process and/or regeneration air was calculated by the particular orifice equation (3).

$$m_{PA} \text{ or } m_{RA} = C\,A\,\sqrt{2\,\rho\,\Delta P} \qquad (3)$$

where C is orifice flow coefficient [-], A is the area of the orifice (m^2), ΔP is the pressure difference between inlet and outlet of the orifice (N/m^2) and ρ is the density of the air (kg/m^3). In the present experiments diameter of the orifice and orifice flow coefficient are taken as 8 cm and 0.6, respectively.

Table 1: Compatible storage groups (I, II and III) of the agricultural products

Groups	Products	Storage life [weeks]	Products	Storage life [weeks]	T [°C]	RH [%]
I	Okra, Eggplant, Cucumber	1-2	Olive	6	10	85-90
	Pepper	2-3	Potato	20-40		
II	Avocado, Rambutan, Potato (new), Tomato (ripe)	1-3	Guava, Mango, Melon	2-3	13-15	85-95
	Jackfruit, Grapefruit	2-8	Lemon, Pineapple, Banana (green)	4-24		
III	Watermelon, Tomato (mature green)	1-3	White sapote	2-3	18-21	85-90
	Jicama	4-8	Sweet potato	20-35		

(reproduced from ref. Kitinoja and Kader, 2002; ASHRAE, 2010)

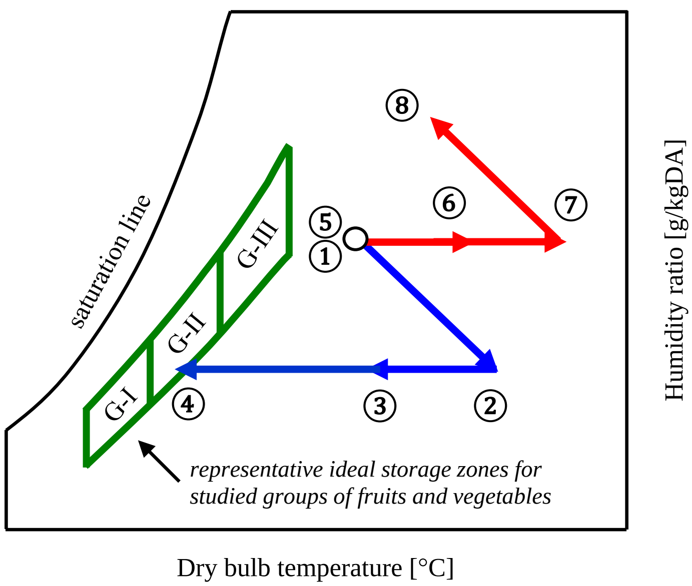

Figure 2: A psychrometric representation of ideal storage zones and typical ideal DAC cycle

2.3 Proposed DAC System

The study proposes a desiccant air conditioning system which consists of two desiccant blocks, one flat plate heat exchanger (HX), one Maisotsenko cycle evaporative cooler (MEC), and a regeneration heat source. The schematic of Maisotsenko cycle assisted desiccant air conditioning (M-DAC) system is shown in Figure 4. Two separate sets of desiccant blocks (I and II) are used in this study to enable their switching during dehumidification and regeneration. The MEC can cool the air to the dew point theoretically. The working principle of the proposed system is as follow: The outdoor air (at state 1) when passes though desiccant blocks (I or II) it becomes dehumidified.

The isenthalpic dehumidification of the process air (state 2) is shown in Figure 2. The dehumidified air is then enters to the HX for sensible cooling of the process air (state 3). Afterwards, further sensible cooling of the process air is accomplished through the MEC. The MEC provides the required conditioned air (state 4) for the storage of agricultural products. On the regeneration side, the outdoor air (state 5 or 1) passes through the HX to recovers the heat of adsorption (state 6) of the dehumidified process air. The regeneration air is further heated by adding the heat through heat source. Finally, the heated air (state 7) passes through the desiccant blocks for their regeneration.

The dehumidification data of the desiccant blocks were obtained through open-cycle experimental unit. The further analysis of the isenthalpic dehumidified process air is carried out by the fundamental heat and mass transfer equations (4-8) of the DAC system.

$$T_3 = T_2 - \varepsilon_{HX}\,(T_2 - T_5) \tag{4}$$

$$T_4 = T_3 - \varepsilon_{MEC}\,(T_3 - T_{1,wb}) \tag{5}$$

$$T_6 = T_5 + \left(\frac{T_2 - T_3}{m_{RA}/m_{PA}}\right) \tag{6}$$

where, the subscripts (1-7) define the different states of process and regeneration air as shown in Figure 4. The wet bulb effectiveness of MEC (ε_{MEC}) and HX (ε_{HX}) are taken as 0.6 and 0.9, respectively (Sultan *et al.*, 2016). The specific heat capacity (C_p) of the air is taken as 1.006 kJ/kg·K. The mass flow rate of process air (m_{PA}) and regeneration air (m_{RA}) was determined as 0.1 kg/sec (with 10% variation) during the desiccant block dehumidification and/or regeneration open-cycle experiments. The heat input to the regeneration air through heat source is determined by equation (7). Lastly, the coefficient of performance (COP) of the proposed system is calculated by the equation (8).

$$\text{Heat input} = m_{RA}\,C_p\,(T_7 - T_6) \tag{7}$$

$$\text{COP} = \frac{m_{PA}}{m_{RA}}\left(\frac{h_5 - h_4}{h_7 - h_6}\right) \tag{8}$$

3. RESULTS AND DISCUSSION

3.1 Desiccant block dehumidification

The open-cycle desiccant block experimental unit was operated under varying inlet air temperature and relative humidity conditions in order to ascertain the dehumidification performance of the adsorbent. These inlet conditions are represented by case-I (T = 31°C; RH = 21%) and case-II (T = 13°C; RH = 70%) as shown in Figure 5. However, the regeneration of the adsorbent was carried out at same temperature (55°C ± 2°C) and relative humidity (5%) in both cases. The time ratio during the regeneration (60 minutes) and dehumidification (90 minutes) modes were also kept same in case-I and case-II. The air mass flow rate was 0.1 kg/sec (±10 %) during the experiments. The outlet air temperature and RH profiles corresponding to the inlet conditions of case-I and case-II are shown in Figure 5. It is examined that almost equilibrium conditions reached after 60 minutes dehumidification in case-I as shown in Figure 6. It is because of higher inlet air temperature and lower relative humidity (dry conditions). Referring to the Figure 7, there is no further dehumidification after 60 minutes, and it does not remain isenthalpic. Therefore, the time ratio between regeneration and dehumidification process is suggested as 1:1. The optimized time ratio for these conditions ensures the dehumidification of the process air up to 2 g/kg of dry air.

On the other hand, the desiccant block performs higher dehumidification up to 4 g/kg of dry air in case-II due to cold and humid conditions. The desiccant block has affinity towards such humid conditions. The preset time ratio (2:3) is optimal for case-II as it ensures the isenthalpic dehumidification up to 2 g/kg of dry air at the end of the dehumidification mode (90 minutes). But, such higher dehumidification does not guarantee the higher coefficient of performance of the system. The almost same outlet air humidity ratio values during each cycle confirms the reliable performance of the desiccant blocks in the long run as shown in Figure 6. Therefore, it can be concluded that the

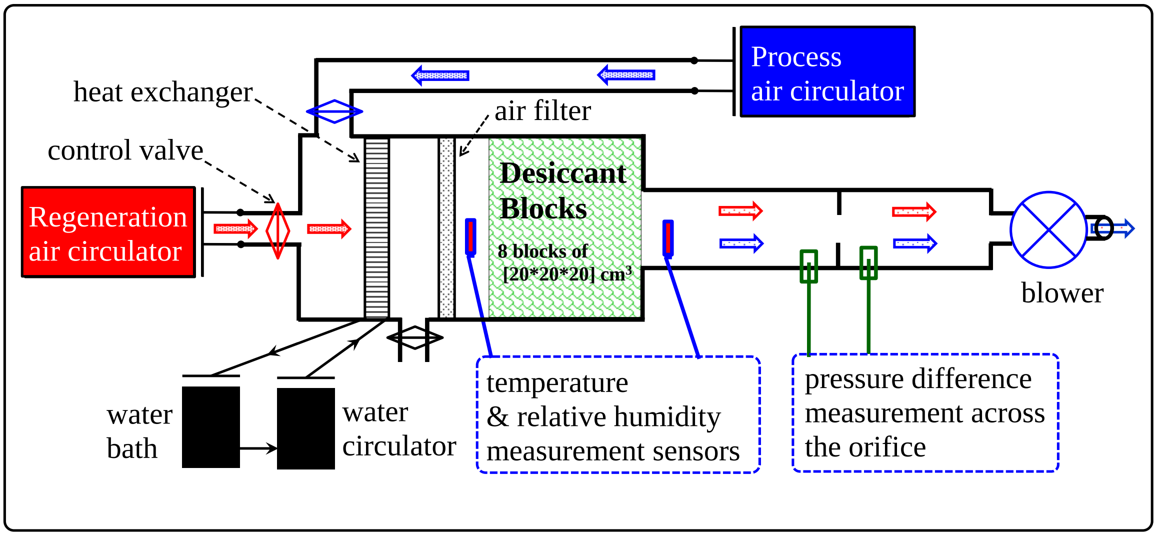

Figure 3: Schematic of the desiccant blocks open cycle experimental unit

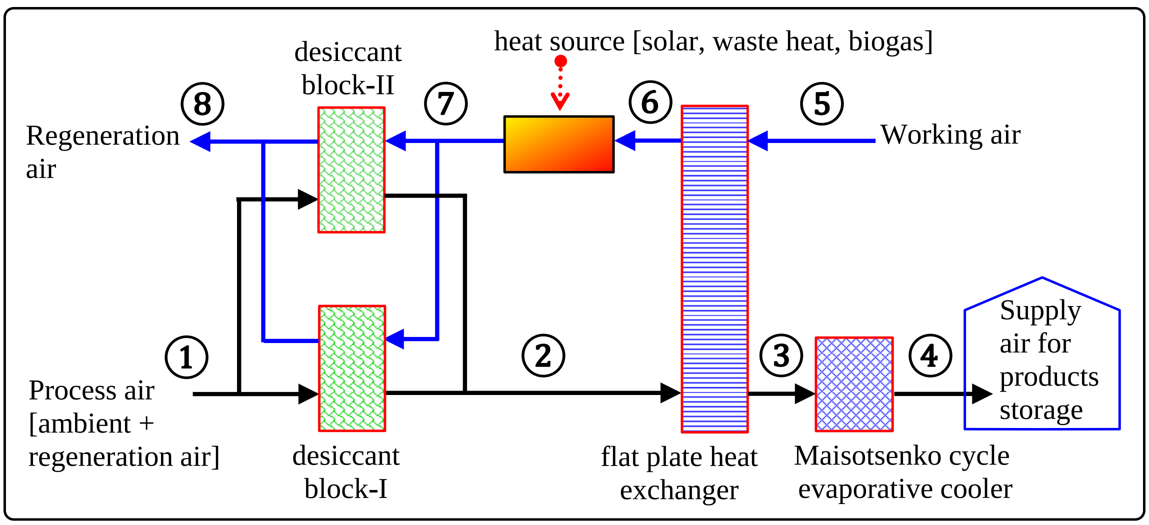

Figure 4: Schematic of the proposed DAC system

studied desiccant blocks can reasonably achieve the latent load of the air conditioning for the storage of fruits and vegetables. The low regeneration temperature (55°C) was used in order to simulate the conditions that can be available through the use of low grade waste heat, solar energy and biogas etc.

3.2 Performance Analysis of the Proposed DAC System

The performance of the proposed DAC system on the basis of the open-cycle desiccant block experimental data is carried out by the fundamental heat and mass transfer equations (4-8). The wet bulb effectiveness of the HX and MEC are taken as 0.9 and 0.6, respectively. The regeneration temperature is 55°C in both cases (I and II). It is worthy to mention that the temporal variation of the system COP (as given in Figure 8 a,b) was estimated by considering the process and regeneration air flow simultaneously. In contrast with the proposed desiccant blocks system as presented in Figure 4, the system analyses are more related to the rotary system. The coefficient of performance (COP) and the heat supplied through external heat source for the regeneration of the desiccant blocks are calculated for both the studied environmental conditions (case I and II) as shown in Figure 8 (a,b). The relative difference in COP and heat supplied in both the cycles of each case (I and II) are also plotted in order to ensure the reliable cyclic performance of the DAC system. The COP of the system was calculated as 0.90-0.43 and 0.55-0.25 at

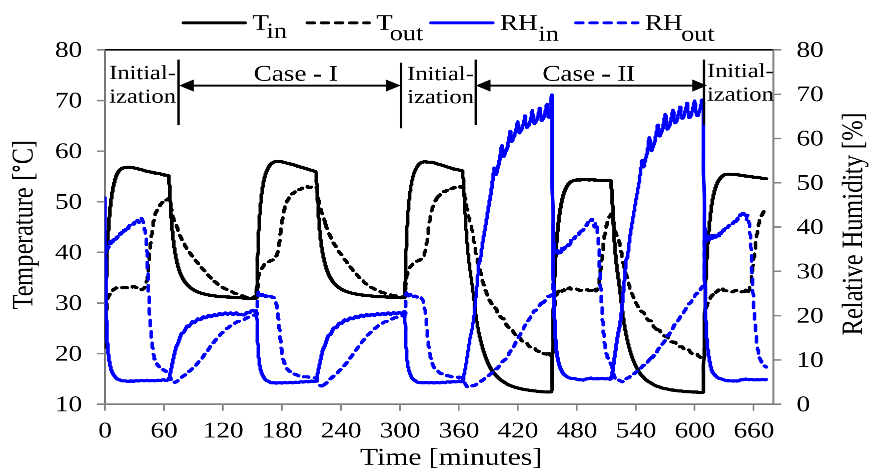

Figure 5: Regeneration and dehumidified air temperature and relative humidity profiles

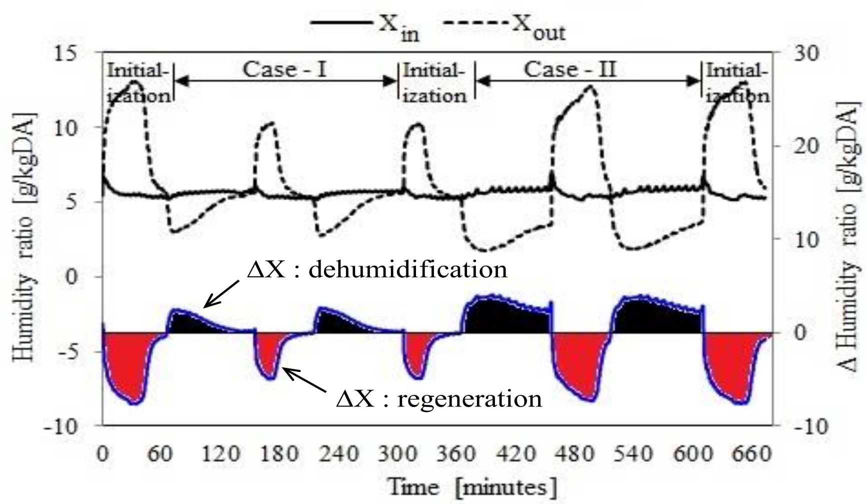

Figure 6: Dehumidification performance of the desiccant block

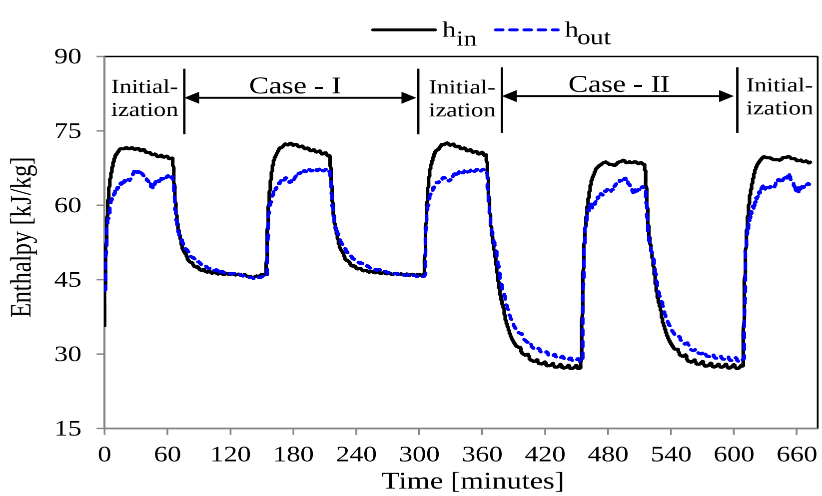

Figure 7: Enthalpy profiles of regeneration and dehumidified air in case-I and case-II

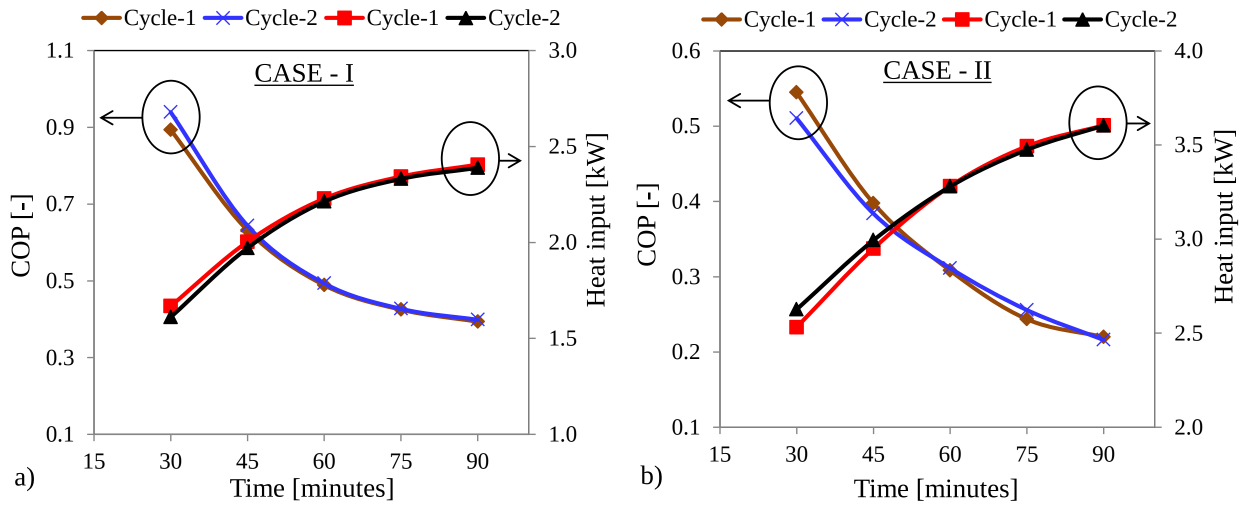

Figure 8: a) COP of the DAC system and heat supplied for regeneration of desiccant block in case-I; b) COP of the DAC system and heat supplied for regeneration of desiccant block in case-II

30-90 minutes of dehumidification time in case-I and case-II respectively. The corresponding regeneration heat supplies are increased as 1.61-2.40 kW and 2.53-3.60 kW as shown in Figure 8 (a,b).The decreasing COP and increasing regeneration heat supplies are due to the reduction in the heat of adsorption with increasing cycle time. However, these can be optimized by minimizing the dehumidification cycle time 60 minutes in case-I. The COP of the system in case-II is less as compared to case-I because of higher supply of regeneration heat. The negligible relative differences in COP and also in heat input for both the cycles of the case (I and II) confirms the sustainable dehumidification performance of the desiccant blocks. The desiccant blocks used in the proposed system achieved the latent load; whereas, the HX and MEC achieved the sensible load of air conditioning for optimal storage of agricultural products. However, this study proposes the use of hybrid DAC system in case of high sensible loads.

4. CONCLUSIONS

The present study addresses the theoretical and experimental evaluation of the desiccant air conditioning system for agricultural applications. The system achieves the latent load by desiccant itself whereas sensible load was accomplished by the Maisotsenko cycle evaporative cooler. The factors affecting the postharvest losses of the agricultural products are highlighted. The optimal storage zones for three compatible groups of fruits and vegetables are established on the basis of temperature and relative humidity. In this regard, a desiccant air conditioning system assisted by Maisotsenko cycle evaporative cooler has been proposed to achieve the latent and sensible load of the air conditioning. The dehumidification evaluation of honeycomb like hydrophilic polymer based desiccant blocks was done by the means of an open-cycle experimental unit under two different environmental conditions. These environmental conditions are represented by case-I (T = 31°C; RH = 21%) and case-II (T = 13°C; RH = 70%) in the study. The regeneration of desiccant blocks was made at low temperature (55°C) in order to simulate the conditions that can be available through the use of low grade waste heat, solar energy and biogas. The regeneration and dehumidification cycle ratio is recommended as 1:1 and 2:3 for case-I and case-II respectively. The suggested time ratios ensure the dehumidification of the process air up to 2 g/kg of dry air and 4 g/kg of dry air in case-I and case-II respectively. The ideal DAC cycle was established on the psychrometric chart to attain the latent and sensible loads of air conditioning for optimal storage of agricultural products. Finally, the coefficient of performance of the proposed DAC system and supply of regeneration heat was calculated using the fundamental heat and mass transfer equations. The COP of the system was calculated as 0.90-0.43 and 0.55-0.25 at 30-90 minutes of the dehumidification time in case-I and case-II respectively. The corresponding calculated regeneration heat supplies are increased as 1.61-2.40 kW and 2.53-3.60 kW. The results of the study showed that the desiccant air conditioning system can achieve the latent load of air conditioning efficiently by means of desiccant itself. However, the performance of MEC for the regulation of sensible load of air conditioning was partly affected when humid air is employed.

NOMENCLATURE

COP	coefficient of performance [-]	Q	respiratory heat [W/kg]
DA	dry air	RA	regeneration air
DAC	desiccant air conditioning	RH	relative humidity [%]
f, g	respiratory coefficients [-]	T	temperature [°C]
G	group of agricultural products	X	humidity ratio [g/KgDA]
h	enthalpy [kJ/kg]	ε	effectiveness of devices [-]
HX	flat plate heat exchanger	Δ	Difference (in - out)
m	air mass flow rate [kg/sec]		
M-DAC	Maisotsenko cycle assisted DAC system	**Subscripts**	
MEC	Maisotsenko cycle evaporative cooler	ac	accuracy
P	pressure	in	inlet conditions
PA	process air	out	outlet conditions
PHL	postharvest losses [%]	wb	wet bulb

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