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https://doi.org/10.5109/4102469

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 6, pp.79-84, 2020-10-22. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
バージョン：
権利関係：

Investigating Applicability of Heat-Driven Desiccant Dehumidification System for Shelf Life Improvement of Fruits and Vegetables

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ABSTRACT: *Fruits and vegetables are considered as highly perishable commodities and deteriorate very rapidly if not handled properly. Present study accentuates on use of desiccant air-conditioning (DAC) system for the storage of fruits and vegetables in challenging climatic conditions of Pakistan. The respiration and transpiration are the factors influencing the products quality and quantity. Post-harvest loss is one of the major concerns in storage life of fruits and vegetables. In this regard, more than half of the population in Pakistan experiencing food insecurity. Under these circumstances, conventional vapor compression air conditioning (VCAC) systems are being used globally to overcome the post-harvest losses but these systems are either expensive or unsuccessful. Therefore, to maintain the post-harvest nutritious value and shelf life of stored fruits and vegetables; a clean, low-cost, and energy efficient DAC system is presented in this study which can be maneuvered on low-grade waste heat, solar thermal energy and biomass.*

Keywords: climate change, food security, dehumidification, air-conditioning, storage

1. INTRODUCTION

Agricultural food products (fruits and vegetables) shows respiration, transpiration and ripening processes after the harvesting too. These products may start deface in a short interval of time due to the presence of high moisture contents (60-95%) and escalate the postharvest losses (PHL) [1,2]. Ambient air temperature and humidity are those major factors that have great impact and contribution in postharvest losses [3]. However, product quality (shape, firmness, color) can be sustained considerably by reducing the PHL [3–6]. Reduction of PHL can be achieved by providing the proper cooling and storage conditions to products straight after their harvest that will ultimately control the nutritional level and increase the shelf-storage life. In view of this, the shelf-storage life of agricultural products can be improved by evading the cooling delays after harvesting, as if lettuce will remain under optimum standard storage conditions in the period of one hour right after the harvest then its storage life can be protracted to 12 days [4,7–11]. The shelf life of fruits and vegetables can be increased by reducing the physiological, chemical and as well as biological changes through controlled temperature and relative humidity in storage structures. The temperature and relative humidity are the crucial factors in cold storages for the quality of fruits and vegetables because these affects directly related with the physiological and biological reactions [3,12–15]. The factors affecting postharvest quality of product is shown in Fig. 1. The preharvest, harvest and postharvest factors causes diseases, mechanical injuries, ripening issues, water loss issues and thus affects the products quality. All these factors are directly connected to the controlled

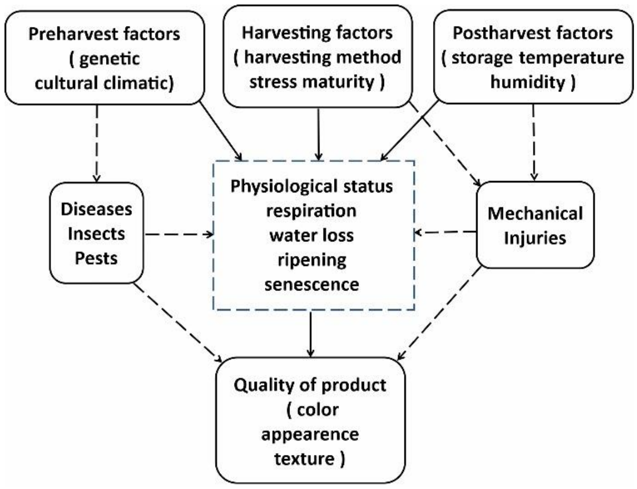

Fig. 1. Factors affecting product quality, reproduced from [1]

environment which should be maintained for better storage life of fruits and vegetables. Higher content of water activity (a_w) present in biological activities is also one of the major factors that directly affects the fresh agricultural products quality [16–21]. Due to extravagant transpiration processes the products quality affected in terms of physical appearance (wilting), net weight, flavor and nutritional value by the loss of moisture happens in a considerable amount [1,6,22,23]. Therefore, management of these factors is crucial for qualitative storage of fruits and vegetables. Conventional vapor compression air conditioning systems are commonly used in storage of agricultural products but these are not suitable for storage of mostly tropical fruits and vegetables at farm because of discoloration and chilling injuries [2,22,24,25]. These conventional systems consume more energy and liberates harmful gases like chlorofluorocarbon (CFC) and affects the environment

[24,26,27]. The postharvest agricultural products respire according to eq 1 [28]

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

Ambient oxygen reacts with the sugar of the product and produces water and oxygen. So, the respiration heat is released and agricultural products consume oxygen for respiration and respiration rate (Q) can be calculated using relationship given below

$$Q = \frac{10.7\theta_1}{36\times10^5}(1.8T + 32)^{\theta_2} \quad (2)$$

The main reason behind all the PHL is the lack of proper storage facilities at the farm level and this entails the eminence of eco-friendly, low-cost cooling technologies functions with renewable energy such as Desiccant air conditioning (DAC) system which has the ability to deal with the both loads (sensible and latent) precisely [29,30]. This distinction of the DAC system to deal both the loads can be used for the storage of agricultural food products (fruits and vegetables) and it is proposed in this study. The working and efficiency of DAC systems has been reported in the literature [3,17,24,31–35].

2. METHODOLOGY

The methodology adopted for the study includes the development of ideal storage zones for various agricultural food products on psychrometric chart as shown in Fig. 2. All the products in groups belong to the same temperature and relative humidity zones. The bananas, bitter melon, and breadfruit relates to the same group in terms of required temperature and relative humidity for better storage. Also, the sapodilla, sugar apples, sweet potatoes, cucumbers, onions, mushrooms, cabbage, papayas, pineapples and garlic are categorized into groups. The desiccant air conditioning system can achieve the controlled temperature and humidity conditions. Air dehumidification data was obtained from the DAC system installed at Department of Agricultural Engineering, Bahauddin Zakariya University, Multan to analyze the performance of DAC system and to check the applicability of the proposed system for the optimal storage of agricultural food products. The proposed DAC system includes two processes (dehumidification (1-2-3-4) and regeneration (1-5-6-7)) as shown in Fig. 3. Ambient humid air enters in desiccant unit at stage 1 and exit at stage 2 after dehumidification. In this, the desiccant wheel absorbs the moisture from the ambient air and dehumidifies it. Flat plate heat exchanger with effectiveness of 0.9 is used in this system. Maisotsenko cycle (M-cycle) evaporative cooler of effectiveness (0.6) is installed with DAC system to provide the required storage conditions for agricultural food products. In the proposed system, the dehumidification performance of silica gel based desiccant air conditioning system was analyzed using the equations given below

$$T_{dp} = T - (\frac{100-RH}{5}) \quad (3)$$

$$h = 1.006T + X(2501 + 1.86T) \quad (4)$$

$$q_{eq} = m(h_{out} - h_{in}) \quad (5)$$

$$X = 0.62\frac{p_v}{p_{atm}-p_v} \quad (6)$$

$$\Delta X = X_{in} - X_{out} \quad (7)$$

$$T_3 = T_2 - \varepsilon_{HX}(T_2 - T_1) \quad (8)$$

$$T_4 = T_3 - \varepsilon_{M_{cycle}}(T_3 - T_{1wb}) \quad (9)$$

where T_{dp} represents dew point temperature (°C), h represents enthalpy, X represents humidity ratio, q_{eq} and

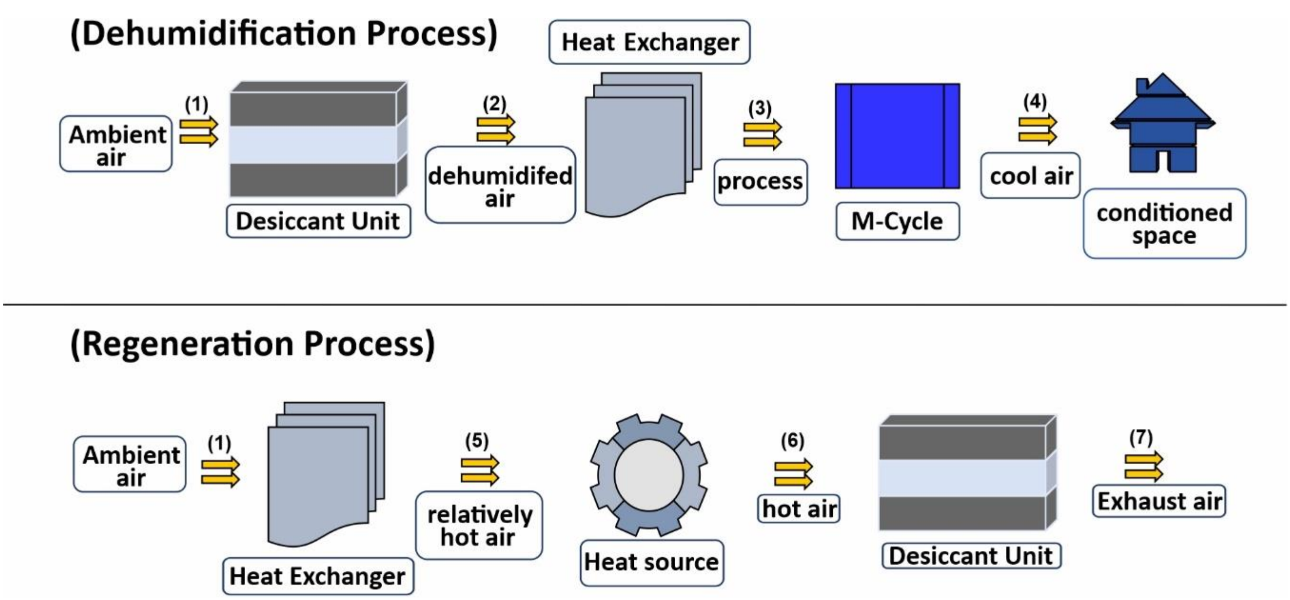

Fig. 2. Proposed desiccant air conditioning system for storage of fruits and vegetables

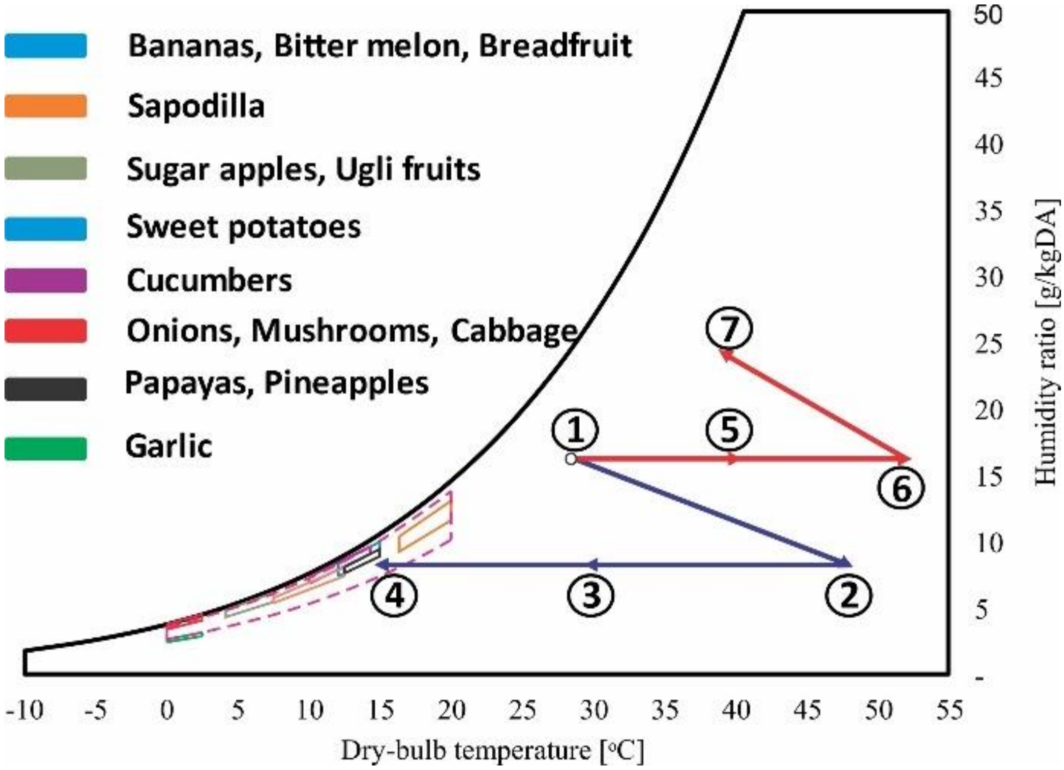

Fig. 3.Ideal storage zones for fruits and vegetables [2]

m represents the isosteric heat of adsorption and mass flow rate, respectively. The ambient air passes through solid desiccant-based dehumidification unit which slightly increases the temperature and dehumidifies the air. The process air passes through sensible heat exchanger which reduces the temperature, without affecting humidity ratio of the process air. This process air is used for product storage in a storage chamber. For regeneration process, either ambient air or return air from the storage chamber can be used for the regeneration of the solid desiccant (i.e. silica gel). The ambient air was used in this case. Ambient air passes through the sensible heat exchanger which transfers the heat from the process air (in dehumidification cycle) to the ambient air slightly increasing its temperature. The regeneration air passes through a heating source (usually a solar collector, but biomass, low grade waste heat from different sources, etc. can be used) which increases the temperature of the regeneration air. The regeneration air desorbs the silica gel solid desiccant, increasing the temperature of the silica gel which is transferred to the ambient air (in dehumidification cycle), hence completing the cycle. The regeneration air absorbs the moisture and is released from the desiccant as exhaust air. The detailed results and discussion are given below in next sections

3. RESULTS AND DISCUSSION

In this study, the proposed DAC system is investigated for the optimum storage of agricultural food products (fruits and vegetables). The DAC system works in two cycles namely regeneration and dehumidification in same process i.e. 30min for regeneration and 30min for dehumidification. In DAC, the air is dehumidified due to water vapor pressure deficit between air and desiccant sides. The phase of water vapor changes from vapor to liquid, so it must to release the heat equivalent to heat of condensation. For that purpose, mostly desiccant dehumidification processes must include the HX process in order to achieve and recover the heat for regeneration process. The performance of silica gel-based desiccant dehumidification system was experimentally tested with two arrangements (cross flow and axial flow). Fig. 4(a) shows the experimental relationships of temperature and relative humidity for cross flow arrangement at 20:20 min. When regeneration temperature increases then supply air temperature also increases thus relative humidity decreases. The air enters at relative humidity of about 40-50% and exit at about 30-40%, so it is clear that it has the potential to dehumidify the air at maximum efficiency. While, the Fig. 4(b) shows the experimental relationships of temperature and relative humidity for cross flow arrangement at 30:30 min. It is clear from the figure that the air enters into the system at relative humidity of about 30-50% and exit at about 10-30%, so with the increasing time of dehumidification and regeneration, it dehumidifies a lot. And also, the RH for the storage of fruits and vegetables at temperatures 15-25ºC varies for each fruit and vegetable (bananas, cucumbers, sapodilla, sugar apples, sweet potatoes, garlic, papayas, pineapples). The most important point in DAC system is that the dehumidification cycle. It can also be said that the regeneration cycle can be more shortened by employing higher regeneration temperature. Adsorption kinetics phenomenon is one of the main factors for this kind of behavior. Fig. 5. describes the wet bulb temperature and humidity ratio profiles in both regeneration and dehumidification cycles in DAC system. It is clear from the figure that the system works very efficiently to increase the shelf life of fruits and behavior of processes. It shows a huge potential and the required level of transpiration, fermentation and respiration for fruits and vegetables can be maintained and achieved by the exposure of dehumidified air must be longer than the regeneration cycle in order to establish an efficient

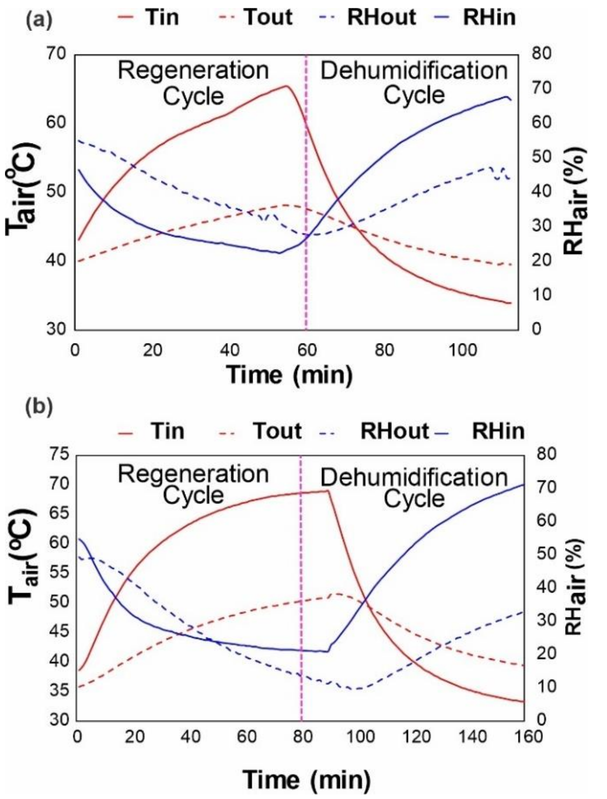

Fig. 4. Experimental profiles of cross flow arrangement of DAC system with (a) 20:20 min and (b) 30:30 min

dehumidification system. In Fig. 6(a) , the air enters at relative humidity of 30-50% and exits at about 20-40% and thus indicates the effectiveness of proposed DAC system. The DAC can be used in many applications with this arrangement of proposed system. Fig. 6(b) shows the dehuumidifcation and regeneration cycles at 30:30 and 40:40 min. The air enters at relative humidity range 20-50% and exits at about 15-40%. From the above discussion, it is clear that the dehumidifed air conditions are very crucial for the performance of desiccant air conditioning system.

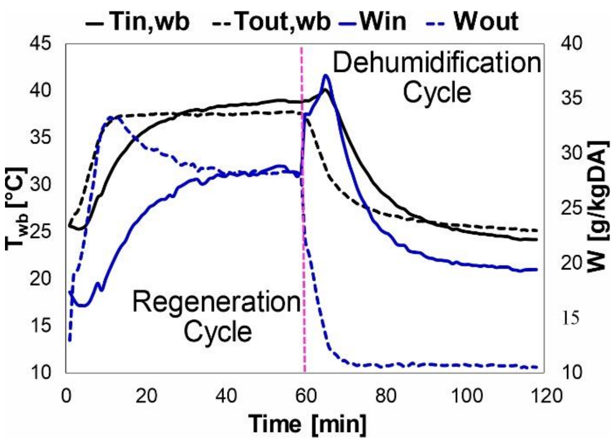

Fig. 5. Experimental profile of wet bulb temperature and humidity ratio

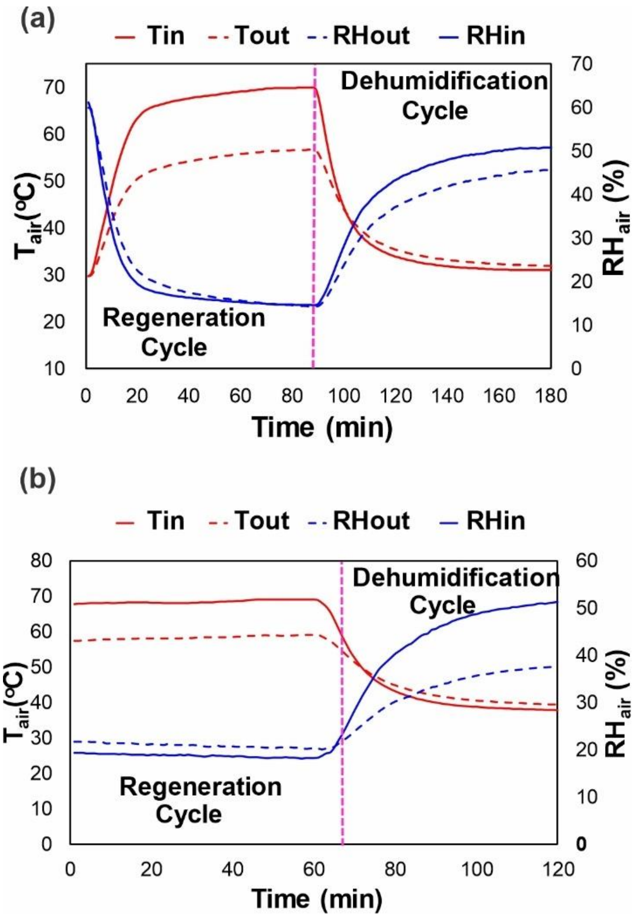

Fig. 6. Experimental profiles of axial flow arrangement of DAC system with (a) 30:30 min and (b) 45:45 min

4. CONCLUSIONS

In this study the applicability of proposed DAC system for storage of agricultural food products (fruits and vegetables) has been investigated. The ideal storage zones for agricultural food products was developed on psychrometric chart. The dehumidification performance of DAC system is analyzed by obtaining the inlet and outlet conditions data for two arrangements (cross flow and axial flow). The experimental profiles of temperature and relative humidity in both the cycles of DAC (regeneration and dehumidification) was established to check the performance of desiccant dehumidification. Flat plate heat exchanger is used to recover the heat of adsorption. Maisotsenko cycle was installed with DAC system to achieve the required zones for storage. From all above relations, it has been seen that DAC system can be an optimal solution for the storage of agricultural food products at farm. This low-cost and environmentally friendly system is the best option to increase the shelf-storage life and to overcome the food security issues.

Acknowledgements

All this work is part of the Ph.D. research of Mr. Ghulam Hussain (1st Author). This research work has been carried out in the Department of Agricultural Engineering, Bahauddin Zakariya University, Multan-Pakistan. This research was funded by Bahauddin Zakariya University, Multan-Pakistan under the Director Research/ ORIC grant titled "Thermodynamic evaluation of low-cost air-conditioning systems for various applications" awarded to Principal Investigator: Dr. Muhammad Sultan.

Conflict of interest

The authors declare no conflict of interest.

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