Study on Solid Desiccant Dehumidification Cooling System for the Storage of Fruits and Vegetables

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Study on Solid Desiccant Dehumidification Cooling System for the Storage of Fruits and Vegetables

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Abstract: *Agriculture sector is a major contributor to meet rising food demand throughout the world. Fruits and vegetables cover a major portion of the food demand. However, about 35-40% portion of the fruits and vegetables is lost because of post-harvest losses. The major reason for the post-harvest losses is improper storage. After harvesting, the fruits and vegetables behave like living organisms and produce sensible as well as latent heat load. Optimum storage could be achieved by removing these heat loads which are a function of environmental conditions like temperature and humidity. Conventional systems like vapor compression-based air-conditioning consume an excessive amount of primary energy. In this principle, Maisotsenko cycle evaporative cooling assisted desiccant air-conditioning (M-DAC) system was explored. The performance of the proposed M-DAC system has thermodynamically investigated the perception of dehumidification potential, cooling capacity, COP, and ideal storage temperature as well as relative humidity ranges. The results reveal that the M-DAC system has achieved dehumidification potential, cooling capacity, and COP of 0.003 kg/kg, 35.5 kJ/kg, and 0.72, respectively.*

Keywords: Desiccant dehumidification; Maisotsenko Cycle; experiments; heat load; fruits and vegetables

1. INTRODUCTION

In recent decades world population is rapidly increasing, thereby corresponding increase in food demand of 70% [1]. The agriculture sector is a major contributor to meet this huge food demand. Pakistan produces 13.67 million tonnes of fruits and vegetables as an agriculture-dependent country, but 35-40% of the production is wasted because of post-harvest losses [2]. The term "post-harvest losses" refers to the degradation of both the quality and quantity of fruits and vegetables after they have been harvested. The significant level of moisture content present in agricultural goods is one of the most prominent factors for post-harvest losses [3–5]. Several factors that contribute to post-harvest losses in fruits and vegetables are shown in Fig. 1.

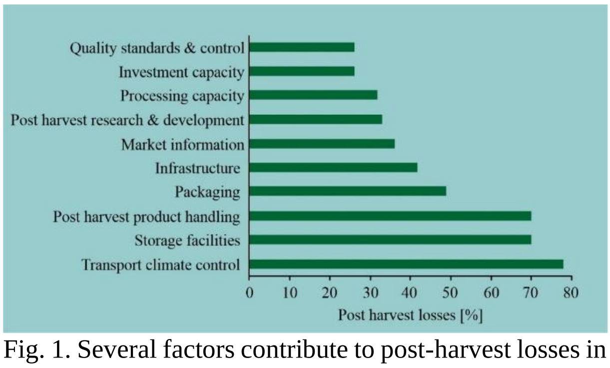

Fig. 1. Several factors contribute to post-harvest losses in fruits and vegetables [6].

Controlling temperature and relative humidity are the most important factors in reducing post-harvest losses. Temperature and relative humidity control are the most important factors in reducing post-harvest losses. The shelf life of fruits and vegetables is a function of storage temperature. High temperature creates a significant effect on the shelf life of fruits and vegetables [7–9]. Similarly, the high temperature has a significant effect on the quality of the fruits and vegetables [10]. The amount of moisture present in the ambient air, expressed as relative humidity, is the primary driver of water loss from harvested products. Agricultural products keep their nutritional quality, flavor, and appearance at high relative humidity levels; however shriveling occurs at low relative humidity levels due to excessive transpiration [11,12].

Traditional storage solutions rely on vapor compression, which consumes a significant amount of primary energy while also degrading the environment using toxic refrigerants [13,14]. Furthermore, these systems, particularly for agricultural products, are unable to manage optimal temperature and relative humidity conditions [15,16]. In this regard, evaporative cooling (EC) and desiccant air-conditioning (DAC) systems are two alternative energy efficient as well as environmentally friendly options. Direct EC, indirect EC, and Maisotsenko cycle EC (MEC) systems are the EC systems [17]. The MEC is a thermodynamic process that lowers the ambient air temperature by utilizing psychrometric renewable energy found in the air[18,19]. Two thermodynamic mechanisms provide the cooling effect in the MEC system: evaporative cooling and heat transfer, in which the ambient air temperature approaches the dew point temperature rather than the wet-bulb temperature [20,21]. But the scope of standalone EC systems has been found limited, particularly in humid regions [3]. To address this limitation, a desiccant air-conditioning (DAC) system is an emerging option in humid areas [22–24]. The DAC system deals with sensible and latent load simultaneously, thereby cool and dehumidify the process or ambient air. The standalone DAC system could not achieve the optimum storage criteria required by fruits and vegetables for their storage. In this principle, MEC-assisted DAC (M-DAC) system could be a viable option for the storage of fruits and vegetables. The M-DAC system deal with sensible load via MEC, and latent load via DAC system, thereby provide more cooling potential. American Society of Heating, Refrigerating and Air-Conditioning Engineers determines the optimum temperature and relative humidity ranges of -5 to 25°C and 85-95%, respectively for fruits and vegetables to provide efficient storage [25]. Fig. 2 shows a psychrometric illustration of ideal temperature and relative humidity zones for fruits and vegetables based on Multan's hourly climate (Pakistan).

In this study, the desiccant dehumidification system was developed at a lab scale. The experimental data is collected by performing various dehumidification and regeneration process. The developed system performance was investigated from a thermodynamic point of view from viewpoints of dehumidification potential, cooling capacity, and coefficient of performance (COP) for the storage of fruits and vegetables. In addition, heat (sensible and latent) produce from fruits and vegetables was determined.

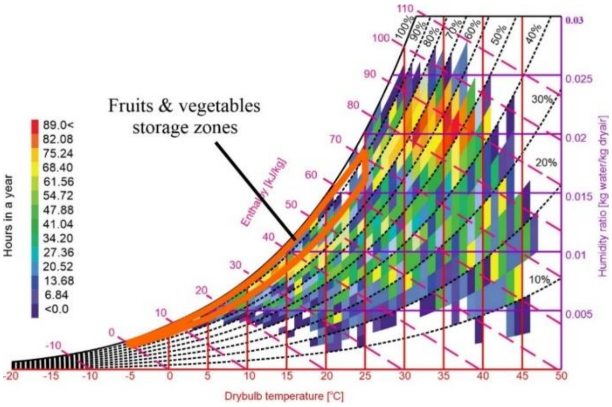

Fig. 2. psychrometric illustration of ideal temperature and relative humidity zones for fruits and vegetables based on Multan's hourly climate (Pakistan).

2. MATERIALS AND METHODS

2.1 Experimental Section

A desiccant experimental system with an open cycle was developed. It included a heater, fan, desiccant material, accessories, sieves, anemometer, temperature, and relative humidity sensors. The primary component of the DAC system is a sieve because desiccant material is placed on it. Polyacrylic polymer and mesh are used to create sieves. For the desiccant system, a total of 18 sieves were employed, each in the shape of a rectangular block. Each sieve is 250mm x 145mm x 3mm, and 68g of silica gel is placed on top of each sieve. The total weight of the silica gel utilized in this experiment was approximately 1.22 kg. The pictorial representation of the developed desiccant dehumidification system is shown in Fig. 3(a).

The DAC system's experimental approach is that ambient air enters the desiccant unit and is converted to dry and hot due to the release of adsorption heat. Later, moisture absorbed during the dehumidification process causes the desiccant material to become saturated. As a result, the regeneration process is carried out to supply a regeneration stream for the desiccant material to complete the cycle. Fig. 3(b) shows a schematic diagram of the experimental setup.

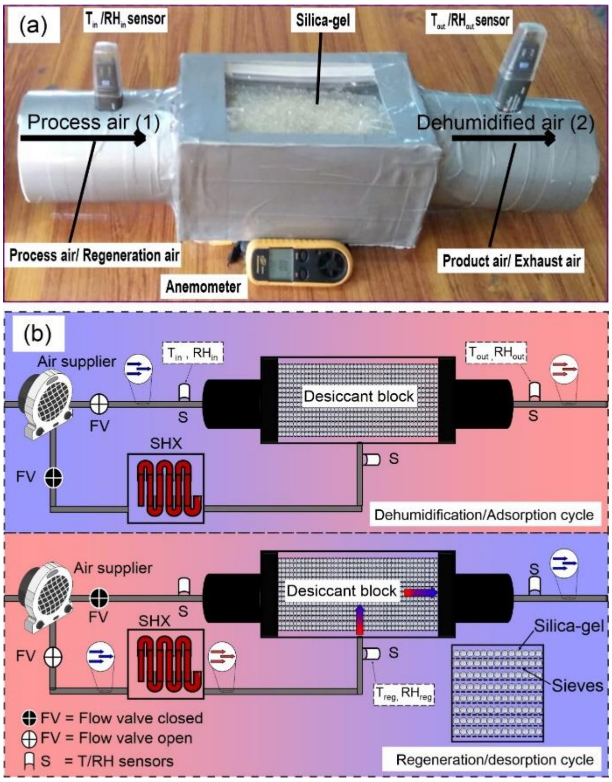

Fig. 3. (**a**) Pictorial representation of developed DAC system (**b**) schematic diagram describing the working of the developed DAC system [26].

2.2 Data Reduction

The performance of the developed DAC system is investigated using experimental data from the desiccant dehumidification process. The process air is dehumidified and transferred via a sensible heat exchanger (SHX), which is calculated using Equation (1) [8,26]. The SHX's product air passes through the MEC unit, which is calculated according to Equation (2) [27,28]. Equations (3) are used to calculate dehumidification potential.

$$T_3 = T_2 - \varepsilon_S(T_2 - T_1) \quad (1)$$
$$T_4 = 6.70 + 0.2630(T_3) + 0.5298(W_3) \quad (2)$$
$$\Delta W_{deh} = W_{in} - W_{out} \quad (3)$$

Cooling capacity and COP can be calculated from Equations (4) and (5) for the M-DAC system. The enthalpy of air can be calculated from Equation (6) [29].

$$Q_{c,M-DAC} = h_1 - h_4 \quad (4)$$
$$COP_{M-DAC} = \frac{Cooling\ capacity}{Heat\ input} = \frac{h_1 - h_4}{h_7 - h_6} \quad (5)$$
$$h = 1.006T + W(2501 + 1.86T) \quad (6)$$

where, subscript 1-4, 6, 7 is air states as represented in Fig. 4. T is air temperature [°C], ε_S is effectiveness of heat exchanger [0.9], W is humidity ratio [kg/kg], ΔW_{deh} is dehumidification potential [kg/kg], $Q_{c,M-DAC}$ is the cooling capacity of the M-DAC system [kJ/kg], COP_{M-DAC} is coefficient of performance for the M-DAC system, and h is the enthalpy of air [kJ/kg].

2.3 Heat Load Calculations

A major portion of the cooling load is described by the heat loads added by the products (fruits and vegetables) to be stored. In most cases, the product is precooled to remove the field heat before being transferred to cold storage to be stored at the desired temperature and relative humidity. The product that has been packed tightly into cold storage still respires and transpires, releasing heat and moisture. The latent heat of condensation of moisture and the heat of respiration must be removed from the cold storage. The heat of respiration is removed by sensible cooling, and the heat of moisture is removed by the latent heat of condensation at that temperature. A load of sensible cooling and latent heat of condensation are calculated by Equations (7-9) [30].

$$Q_s = m \times C_p(\Delta T)/t \quad (7)$$

$$Q_l = m \times h_{fg}/t \quad (8)$$

$$h_{fg} = 334 \times a \quad (9)$$

where, Q_s is sensible heat produce by-product [kW], m is mass of product [kg], C_p is the average specific heat of product below and above freezing temperature [kJ/kg °C] available in the literature [31], ΔT is temperature difference between initial and final temperature of product [°C], t is storage time [hours], Q_l latent heat produced by the product [kW], h_{fg} is latent heat of condensation [kJ/kg], and a is the fraction of water content present in the product, respectively available in the literature [31].

3. PROPOSED MAISOTSENKO CYLE EVAPORATIVE COOLING (MEC) ASSISTED DESICCANT AIR-CONDITIONING (DAC) SYSTEM

A dedicated MEC-assisted DAC (M-DAC) system is comprised of a solid silica gel-based dehumidification unit and a sensible heat exchanger, a MEC device, and a heat source. Ambient air travels through a desiccant block, which dehumidifies it and raises its temperature to near the desiccant block's regeneration temperature (condition 1-2). Similarly, hot, and dehumidified air travels through a sensible heat exchanger, which reduces the temperature of the air somewhat while maintaining the humidity ratio (condition 3). The process air then goes through the MEC device, which reduces the temperature to that of the ambient air, which is optimal (condition 4). Ambient air conditions are intended for the regeneration of desiccant blocks. Ambient air is gone through a heat exchanger as a return air which transfers the heat of process air into the regeneration air, slightly increasing its temperature without influencing the humidity ratio (condition 6). Fig. 4 shows a schematic design of the proposed M-DAC system. The regeneration air is heated by a low-grade heating source (ideally a solar collector, although biomass or waste heat from operations can also be employed), which raises the temperature of the regeneration air even more (condition 7). The desiccant block desorbs the solid desiccant (i.e., silica gel) and absorbs its moisture, transferring the sensible heat into the desiccant unit, which is subsequently delivered to the process air (condition 8), completing the cycle.

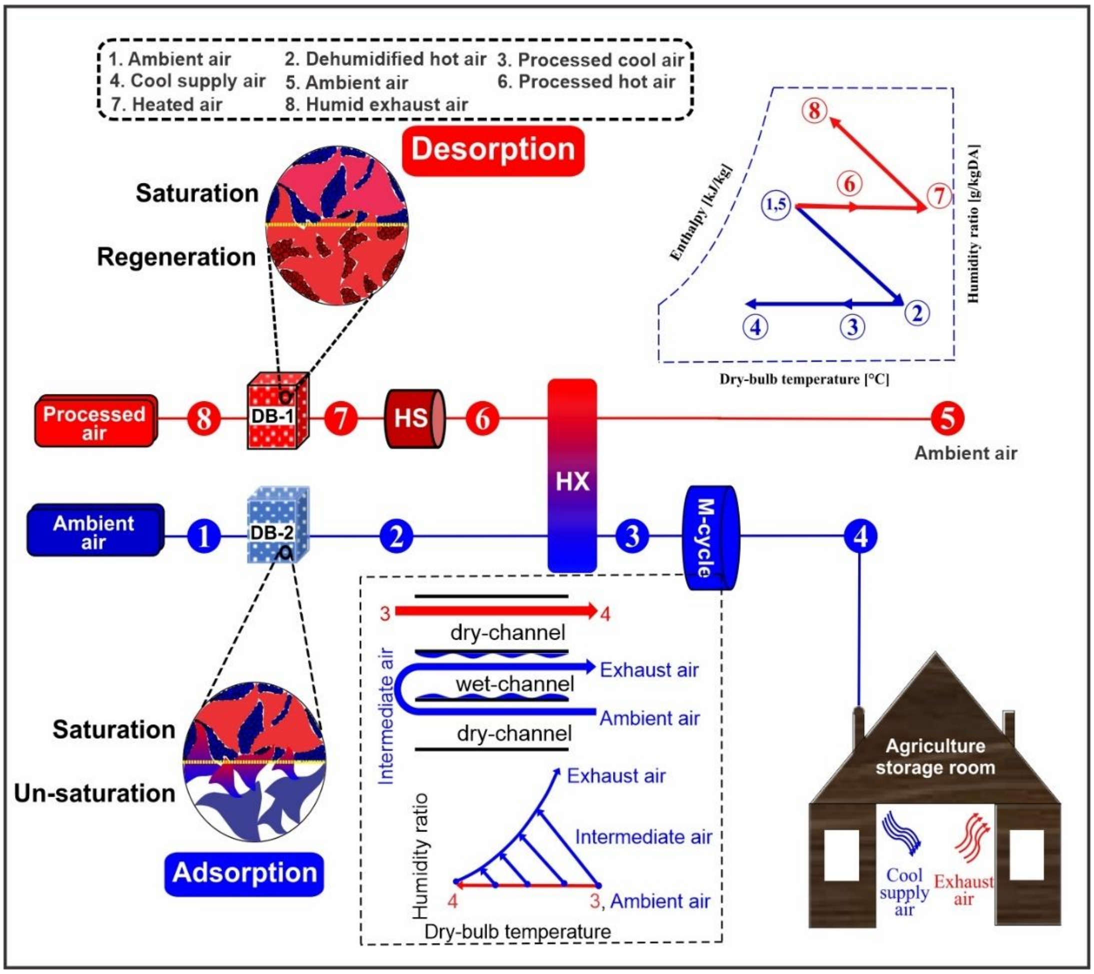

Fig. 4. Schematic representation of the proposed M-DAC system [26].

4. RESULTS AND DISCUSSION

The fruits and vegetables produce sensible as well as latent heat which needs to be removed for optimum storage. Fig. 5 shows the sensible heat produced by fruits (apple, banana, grape, and mango) concerning various ΔT. The sensible heat generated by fruits increased with ΔT. In the case of mango, at 3°C the sensible heat was found 0.14 kW, but at 15°C the sensible heat was 0.72 kW. A similar increasing trend was observed in other fruits. Fig. 6 shows the sensible heat produced by vegetables concerning various ΔT. The sensible heat produced by vegetables (broccoli, cabbage, cucumber, and tomato) increased with ΔT. In the case of, cabbage, at 3°C the sensible heat was found 0.72 kW, but at 15°C the sensible heat was 3.63 kW. A similar increasing trend was observed in other vegetables.

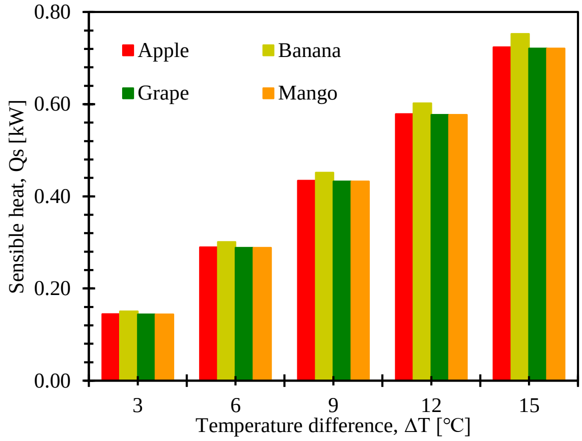

Fig. 5. Sensible heat produced by fruits concerning temperature difference, ΔT.

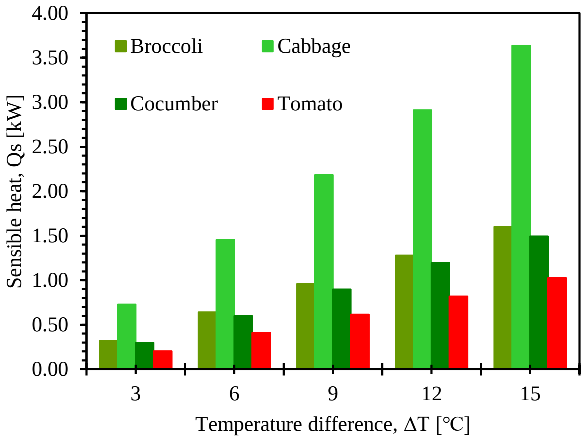

Fig. 6. Sensible heat produced by vegetables concerning temperature difference, ΔT.

Fig. 7 shows latent heat produced by fruits. The maximum latent heat of 4.90 kW was observed by the banana indicate maximum moisture content present as compared to other selected fruits. Fig. 8 shows the latent heat produced by vegetables. The maximum latent heat of 25.34 kW was observed by cabbage which represents excessive moisture content present in it as compared to other selected vegetables.

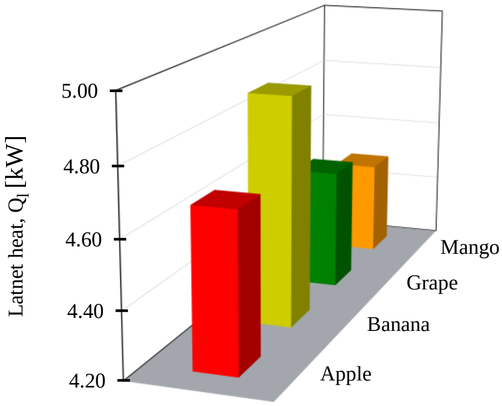

Fig. 7. Latent heat produced by fruits.

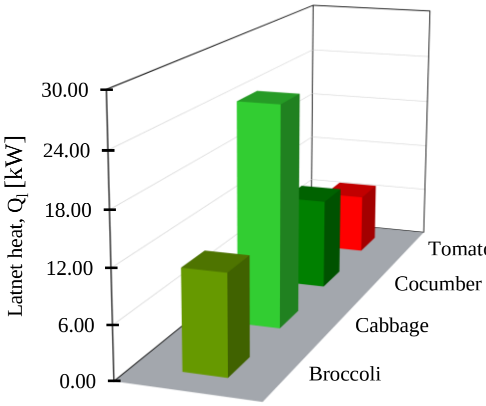

Fig. 8. Latent heat produced by vegetables.

On an experimental basis, the desiccant dehumidification performance was examined for various processes and regeneration air conditions cycles. Fig. 9 shows experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of temperature for the developed DAC system. The output temperature of the DAC system ranges from 43.4°C to 59.1°C. Fig. 10 shows experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of relative humidity for the developed DAC system. The output relative humidity of the DAC system ranges from 23.6% to 41.6%.

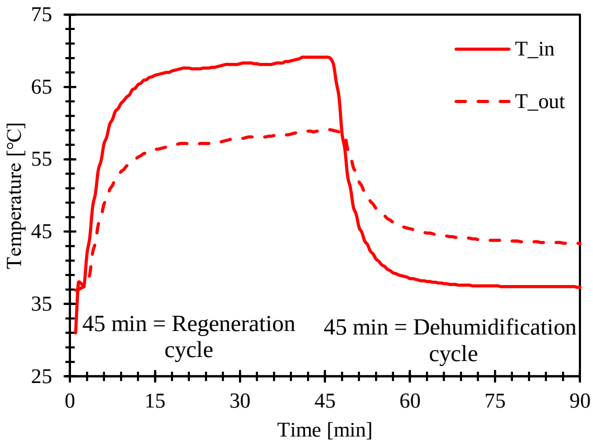

Fig. 9. Experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of temperature for the developed DAC system.

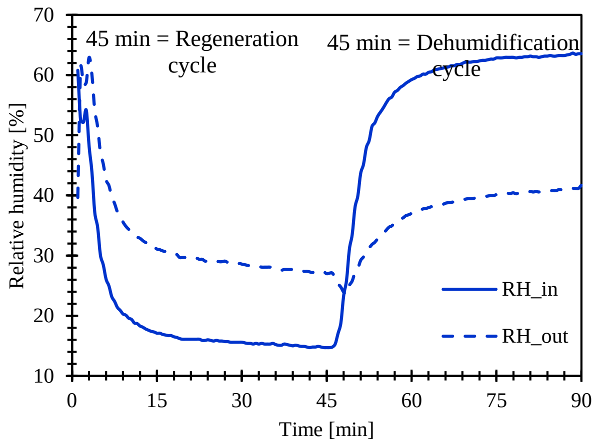

Fig. 10. Experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of relative humidity for the developed DAC system.

Fig. 11 shows experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of humidity ratio for the developed DAC system. The output humidity of the DAC system ranges from 0.02 kg/kg to 0.03 kg/kg. The dehumidification potential of the DAC system of 0.003 kg/kg was observed. Fig. 12 shows output temperature and relative humidity profiles of the dehumidification cycle by the proposed M-DAC system. The output temperature and relative humidity range from 16.7°C to 24.6°C, and 62.8% to 92.8% by the proposed M-DAC system, respectively.

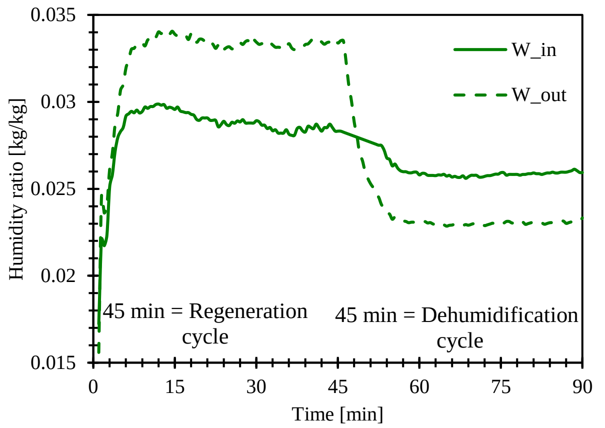

Fig. 11. Experimental regeneration (1-45min) and dehumidification (46-90min) cycle profiles of humidity ratio for the developed DAC system.

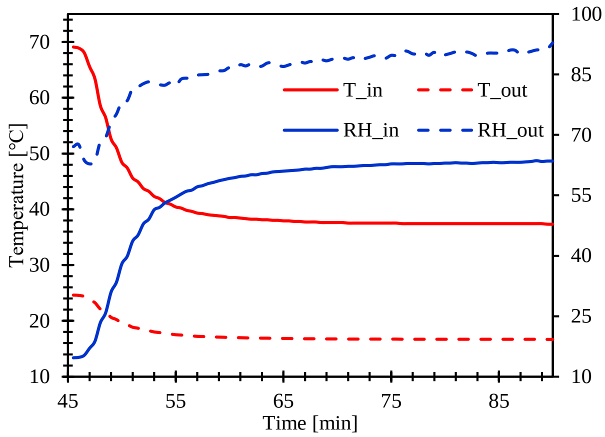

Fig. 12. Output temperature and relative humidity profiles of dehumidification cycle by the proposed M-DAC system.

It can be seen from Fig. 2 the optimum temperature and relative humidity zones for storage of fresh fruits and vegetables lie between the output of the proposed M-DAC system. Therefore, the M-DAC system can be used for the potential application of storage of fruits and vegetables. Fig. 13 shows cooling capacity and coefficient of performance for the dehumidification cycle achieved by the proposed M-DAC system. The maximum cooling capacity and COP of 35.5 kJ/kg, and 0.72 were observed by the proposed M-DAC system.

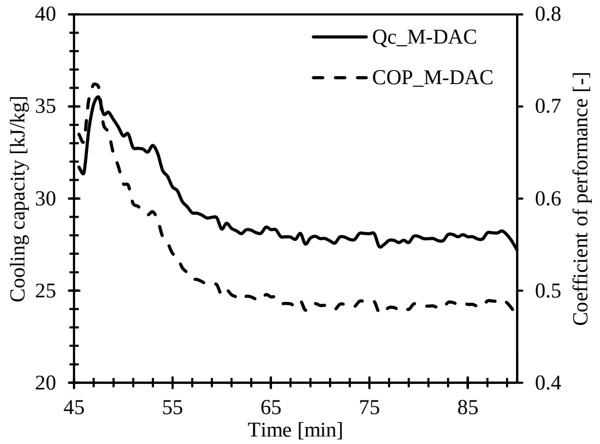

Fig. 13. Cooling capacity and coefficient of performance for dehumidification cycle achieved by the proposed M-DAC system.

CONCLUSIONS

In the current study, Maisotsenko cycle evaporative cooling assisted desiccant air conditioning system (M-DAC) was thermodynamically investigated for potential application of fruits and vegetable storage. Fruits and vegetables produce sensible and latent heat loads which need to be removed from the storage house for providing optimum storage conditions. The sensible and latent load produced by fruits and vegetables has been investigated in this study. In addition, the experimental performance of the solid desiccant air conditioning system was analyzed at the various process and regeneration conditions. The feasibility of the proposed M-DAC system was investigated from perspectives of dehumidification potential, cooling capacity, coefficient of performance (COP), an ideal temperature as well as relative humidity storage ranges. The results concluded that dehumidification potential, cooling capacity, and COP of 0.003 kg/kg, 35.5 kJ/kg, and 0.72 were observed. Moreover, the output temperature and relative humidity ranges of the proposed M-DAC system have been observed in the ideal storage range of fruits and vegetables.

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Conflict of interest

The authors declare no conflict of interest.

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