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DESIGN, CONSTRUCTION, AND PERFORMANCE EVALUATION OF AN EVAPORATIVE COOLING SYSTEM FOR TOMATOES STORAGE

Edward A. Awafo[a]*, Samuel Nketsiah[a], Mumin Alhassan[a], Ebenezer Appiah–Kubi[a]

[a] Department of Mechanical and Manufacturing Engineering, University of Energy and Natural Resources, Sunyani, Ghana

* *Corresponding author: e-mail: edward.awafo@uenr.edu.gh*

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ABSTRACT

An evaporative cooling system was designed and constructed to increase the shelf life of stored vegetables. The evaporative cooler was tested and evaluated using freshly harvested roma tomatoes. The equipment operates on the principle of evaporative cooling which increased the relative humidity and decreased temperature in the preservation chamber. The storage system was made up of wood of 25.4 mm thickness. A side of the system is made of jute sack, which was moistened with water flowing through a series of perforated pipes from a reservoir located at the top of the storage system. The water flowed under gravity. The relative humidity and temperature of the tomatoes were analyzed using tinytag humidity, temperature data logger. The weight loss of the tomatoes was also analyzed using a dial gauge scale. The results revealed that there was significant difference in using the evaporative cooling system for storing tomatoes as compared to ambient conditions. The average cooling efficiency was found to be 81%. The average temperature achieved in the cooling system dropped to an average of 23°C when compared to the average ambient temperature of 33°C, and the relative humidity also increased up to 99% when compared to the average ambient of 59%. The analysis of the evaporative cooling system showed that tomatoes can be stored for more than 6 days with negligible changes in weight, colour and firmness as compared to those under ambient condition, which deteriorated after day 3. The evaporative cooling system was found to be effective and hence can be used by farmers, households, and tomato processing factories for short term storage of fresh tomatoes.

Introduction

The consumption of fruits and vegetables is important due to the nutrients they contain, which can limit the risk of cardiovascular diseases and cancer (Bjarnadottir, 2015). For example, they possess considerable quantities of vitamins A, B, C, D, E and K, which generally help in protecting the human body against diseases and contribute in no small measure to good health (Mogaji and Fapetu, 2011).

Fruits and vegetables, however, are very fragile commodities that cannot be kept for a long period of time because they are highly perishable. It is therefore important that they are properly preserved when harvested to ensure their constant supply with their nutritional value still retained (Afam et al., 2017). In addition, preservation of fruits and vegetables is of great importance because it makes provision for delayed use and eliminates wastage and loss.

The lack of adequate storage facilities, especially at the farm site, is known to be one of the leading causes of postharvest losses of fruits and vegetables in developing countries (Awafo and Dzisi, 2012) leading to reduction in the quality and quantity of the commodity. This also has a direct effect on the distribution, and consumption of the needed supplies for healthy living.

The essence of storage is of great importance because not all the harvested fruits or vegetables will be used immediately after harvest. Therefore, measures of preserving the commodities to extend their shelf life are necessary. Refrigerated storage methods are proven to be the best methods of preserving and prolonging the shelf life of fruits and vegetables. Some of these methods include storage in ventilated shed and at low temperatures. These methods are however expensive to buy and run, especially for smallholder farmers, most of whom live in poor developing countries. The smallholder farmers are not able to afford the cost of purchasing these high-tech storage equipment for their harvested crops. They therefore require low-tech, low-cost storages systems and evaporative cooling principles have been recommended to be used to design such systems (Practical, 2000).

The following are some of the reasons that make evaporative cooling more suitable method than the other methods of preservation of fruits and vegetables at the rural farm level (Amrat et al., 2013):

1. It can be an on-farm cold storage system.
2. It can be made from locally available materials.
3. It is environmentally friendly with no pollution.
4. It requires no high-tech skills to operate and maintain, making it most suitable for rural applications.
5. It is less expensive to install.
6. The energy consumption is very low compared to mechanical compression systems.

An evaporative cooling system was designed and constructed, and its performance, using freshly harvested tomatoes, was studied and analysed. This paper presents the results from the studies and makes recommendations on how to improve the system studied.

Theory and principle of evaporative cooling system

The underlying principle of evaporative cooling is the conversion of sensible heat to latent heat. Typically, evaporative cooling is a physical phenomenon whereby liquid evaporates into air, releasing latent heat, which results into the cooling of the object or medium that the air comes into contact with (Rusten, 1985). During this process, the moisture content of the air is increased, and the process is called direct evaporative cooling (DEC). The process of direct evaporative cooling is shown in Figure 1.

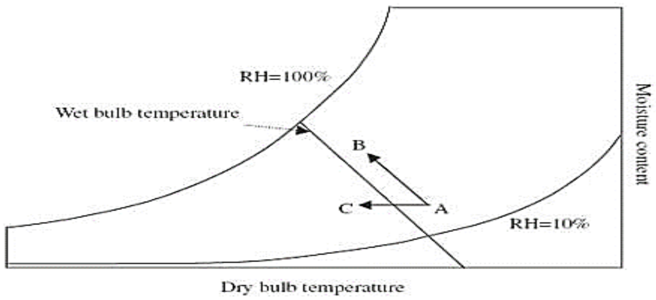

Figure 1. Direct and Indirect Evaporative Cooling Processes (Amrat et al., 2013).

The process can be represented on a psychrometric chart by a displacement along a constant wet bulb temperature line as shown by line AB in Figure 1. If the cooled air or the remnant water is used as a primary circuit of a heat exchanger, and the air to be cooled circulates in the secondary circuit of the heat exchanger, the secondary-circulation air temperature will decrease but its moisture content will remain constant as a displacement as shown by line AC in Figure 1. This process is called indirect evaporative cooling (IEC). Since the air temperature drops, its relative humidity will increase, but less than during the DEC process. DEC and IEC form the basis of two types of evaporative cooling systems. DEC systems decrease air temperature by direct contact with a water surface or with a wetted solid surface, or even with sprays. However, wetted solid surfaces, such as jute canvas and gunny bags ceramic jars and filaments are more water economical than the water pond or sprays.

Figure 2 shows a schematic direct evaporative cooling system. For direct evaporative cooling, water is vapourised inside the air streams and the heat and mass transferred between air and water decreases the air-dry bulb temperature (DBT) and increases its humidity, keeping the enthalpy constant (adiabatic cooling). The minimum temperature that can be reached is the thermodynamic wet bulb temperature (WBT) of the incoming air. The effectiveness of this system is defined as the rate between the real decrease of the DBT and the maximum theoretical decrease that the DBT could have if the cooling were 100% efficient and the outlet air were saturated. Practically, wet porous materials or pads provide a large water surface in which the air moisture contact is achieved, and the pad is wetted by dripping water onto the upper edge of vertically mounted pads.

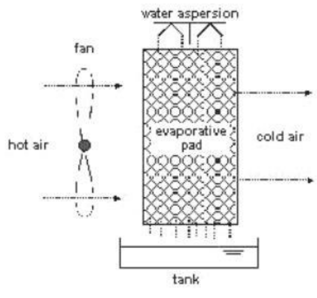

Figure 2. Direct evaporative cooling (DEC) (Camargo, et al., 2007)

In contrast to this process, indirect evaporative cooling uses some form of heat exchanger that uses the cool moist air, produced through evaporative cooling, to lower the temperature of drier air (Narayanan, 2017). This cool dry air is then used to cool the environment, and the cool moist air is expelled.

Four major factors that affect the rate of evaporation are air temperature, air movement, surface area and relative humidity of the air.

Materials and Methods

Construction of the Evaporative Cooling System

Materials used for the construction of the evaporative cooling system were:

1. **Jute sack:** This was made with cotton, designed to absorb, and hold water, and give maximum surface area for air and water contact. As air was forced through the jute sack, natural evaporation of water created cooled and humidified air.
2. **Wood:** The wood was used to construct the framework of the evaporative cooling system. Wood was chosen because of its availability, light weight, and cost effectiveness.
3. **PVC Pipe:** This is a plastic material that was used as a medium to transport water from one point to the other. The PVC pipe was chosen because of its resistance to corrosion and comparative low cost.
4. **Valve and valve socket:** These were used to regulate the flow of water through the PVC pipes.
5. **Suction fan:** This was used for the suction of air from the surrounding of the evaporative cooling system through the wet cooling pad into the cooler space. The 3 installed suction fans on the evaporative cooling system had the following specifications each: 12 V, 0.15A and 1.8 W.
6. **Pump:** A pump with power rating of 373 W was used to pump back the dripped water into the reservoir.

Measuring Instruments

Tinytag Humidity, Temperature Data Logger

Both the temperature and relative humidity readings were taken using tinytag RH-temperature data logger. The readings were taken 4 hourly intervals with the help of an automated data logger.

The tinytag humidity, temperature data logger monitors temperatures from -40 to +85°C using a built-in sensor. This accurate and reliable unit is ideal for monitoring in outdoor and industrial applications. It has the following features:

- built-in temperature sensor,
- case waterproof to ip68,
- user programmable alarms,
- user-replaceable battery,
- 32,000 reading capacity,
- high reading resolution,
- fast data offload ,
- low-battery monitor.

Camry dial spring gauge

This was used to measure the weight of the tomatoes both under ambient condition and in the cooler unit. Thus, the original weight and the new weight respectively, to help determine the physiological weight loss.

Testing of the evaporative cooler

The evaporative cooler was subjected to both no load and load tests. A control test was also carried out to fully ascertain the performance of the evaporative cooler.

The control test

A sample of the same type of tomatoes were taken and tested under ambient environmental conditions of temperature and relative humidity. Firmness as well as physiological weight loss were determined.

No load test of evaporative cooler

This was done by testing the system without loading tomatoes to ascertain whether there was a temperature drop and increase in relative humidity as compared to that of ambient condition.

This was done to ensure that the cooling chamber has achieved a suitable condition for the storage of the tomatoes, thus pre-conditioning.

Load test of the evaporative cooling system

The evaporative cooling system was loaded with the same quantity of tomatoes as kept under ambient condition. The temperature and relative humidity of the cooling unit were monitored throughout the experiment with the help of a data logger. Assessment of the physiological weight loss, colour change and firmness of tomatoes were also carried out daily.

To determine the physiological weight loss, the tomatoes were weighted each day and the difference between the measured weights for each three consecutive days was recorded. The procedure was repeated until the tomatoes begun to deteriorate. The total average of the differences was estimated. The percentage weight loss was then estimated using the equation 1

$$\text{Percentage weight loss} = \frac{\text{original weight} - \text{new weight}}{\text{Original weight}} \times 100\% \quad (1)$$

Construction of the evaporative cooler

Using the materials discussed in section 3.1, the evaporative cooler was constructed. The framework was made of wood with dimensions 1.02 m × 0.61 m × 0.61 m. Within the framework, are three shelves with intervals of 0.30 m from each other. A jute sack runs from the top to the bottom of the framework held in place by a wire mesh. At the back of the jute sack are three suction fans mounted on platforms in line with the three shelves. PVC pipes were also used to construct the piping network (water distribution system) of the evaporative cooler. The piping network is connected to two water reservoirs and a pump. Figures 3 shows the general overview of the constructed evaporative cooling system.

Figure 3. General overview of the evaporative cooler

Results and discussion

Data collected from both ambient and evaporative cooler conditions were computed and analyzed to fully evaluate and ascertain performance of the system.

Evaporative cooler efficiency

The effectiveness of the saturation of the jute pad was used as a measure of the cooling efficiency.

The saturation efficiency was calculated for the pad using equation 2 as mentioned in Stabat, *et al.* (2001).

$$\epsilon = \frac{T_{l,db} - T_{e,db}}{T_{l,db} - T_{e,wb}} \quad (2)$$

where:

ϵ – direct evaporative cooling saturation efficiency, (%)

$T_{e,db}$ – entering air dry-bulb temperature, (°C)

$T_{l,db}$ – leaving air dry-bulb temperature, (°C)

$T_{e,wb}$ – entering air wet-bulb temperature (°C) estimated using psychrometric chart

$$\in = \frac{23.43-28.50}{23.43-23.49} = 81\%$$

Therefore, the cooling efficiency of the evaporative cooling system is 81%.

During the analysis, it was observed that the tomatoes under ambient condition started deteriorating after day one while that of the tomatoes kept inside the evaporative cooler remained almost unchanged after day six.

The result also showed that the average cooling efficiency of the system was 81%. This implies that the evaporative cooling system was very effective, and hence it will increase the shelf life of fresh tomatoes.

Temperature and relative humidity

The temperature and relative humidity of both the system and ambient condition were monitored throughout the experiment. As shown in Figure 4, the result showed that the average storage temperature of tomatoes achieved in the system ranges from 23.0 to 27.0°C, meanwhile, the temperature of the ambient ranges from 25.90 to 33.20°C.

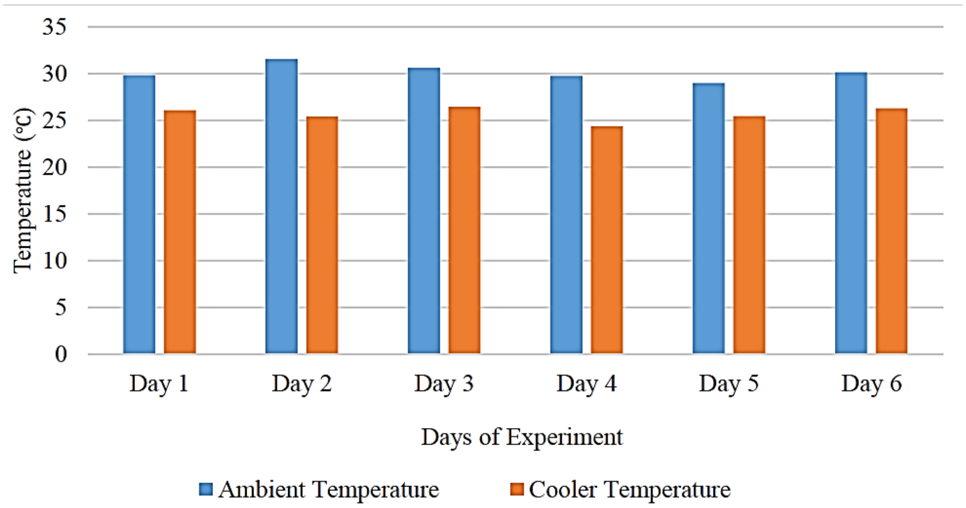

Figure 4. Daily average relative temperature for both ambient and cooling system

Also, it was observed that the relative humidity achieved in the evaporative cooler ranged from 81% to 96% as presented in Figure 5. This was an increase of 13% to 40% in the system's relative humidity in relation to that under ambient conditions.

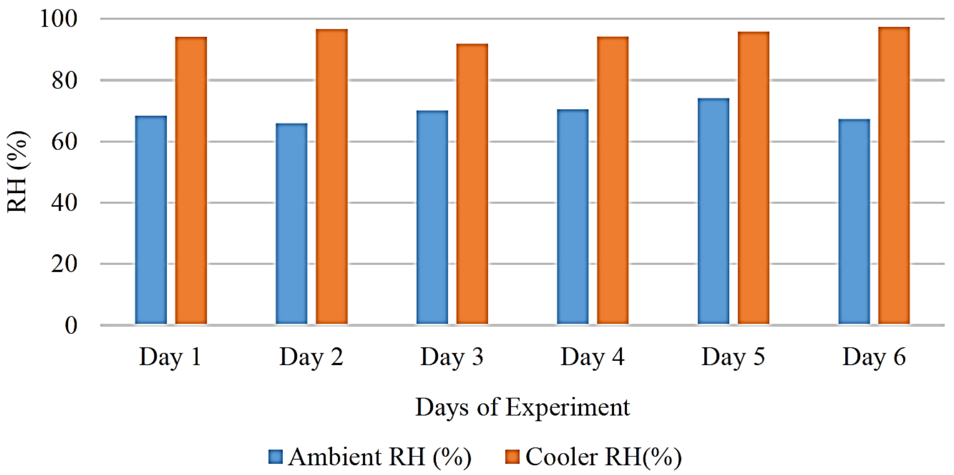

Figure 5. Daily average relative humidity for both ambient and cooling system

Physiological weight loss of tomatoes

Figure 6 shows the daily weight loss of the tomatoes during the experiment. The percentage weight loss of tomatoes in the evaporative cooling system and ambient ranged from 3.85% to 15.38% and 16.67% to 66.67% per day, respectively. The evaporative cooling system with mean weight of 650 g gave less loss of weight as compared to the ambient condition with mean weight of 150 g gave the highest loss of weight. Hence, the evaporative cooling system proves to be better in preserving fresh tomatoes than storing them under ambient conditions.

Burden and Wills (1989) reported that water is an important constituent of most fruits and vegetables, and it adds up to the total weight. Loss of water will definitely reduce their weight and begin to wilt and soon becomes unusable, hence it is paramount to maintain the weight of fresh tomatoes to extend their shelf.

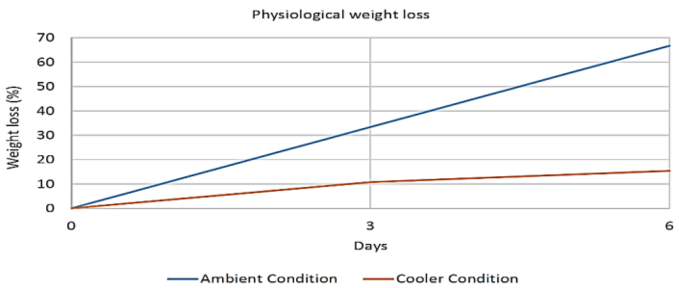

Figure 6. Physiological weight loss

Colour change

Tomatoes grown for consumption, should among other quality criteria, have appealing colour (Kader, 1999). Therefore, colour change is a measure of qualitative loss of the commodity.

The roma variety of tomatoes, with average sizes of about 60 mm in diameter, were freshly harvested in May 2020 and used for the test. The colour changes of the tomatoes were monitored for both samples kept under ambient conditions and in evaporative cooling system. The tomatoes for both ambient and the evaporative cooler were of the same colour (dark red) at the beginning of the experiment, as shown in figures 7 and 8 respectively.

Figure 7. Tomatoes for ambient condition at start

Figure 8. Tomatoes in cooler at the start of experiment

On day three, it was observed that those under the ambient condition had changed from dark red to yellowish red with the onset of yeast infection (Figure 9). However, those kept in the evaporative cooler remained unchanged (Figure 10).

Figure 9. Tomatoes under ambient on Day3

Figure 10. Tomatoes in cooler on Day 3

It was also observed that the tomatoes stored in the evaporative cooling system still retained their colour after day six (Figure 12) with no appreciable colour changes noticed in most of the tomatoes, whiles those kept under ambient conditions had deteriorated completely (Figure 11).

Figure 11. Tomatoes under ambient on Day 6

Figure 12. Tomatoes in cooler on Day 6

Firmness

Firmness of fruits is another important parameter for determining the quality of fruits. Loss of firmness leads to quality loss. The tomatoes stored in the evaporative cooler still retained their firmness but those kept under ambient conditions started to lose their firmness after day one, and after day three most of the tomatoes started rottening. The change in firmness in the tomatoes was noticed also through their change in shape.

Conclusions

For the studies presented in this paper, an evaporative cooling system was designed and constructed for preservation of fresh fruits and vegetables, which was tested using freshly harvested tomatoes. The evaporative cooling system worked on the principle such that warm dry air was cooled and humidified by passing through a wet jute sack.

The evaporative cooling system was powered with electric power from the national electricity grid. The evaluation of the system was carried out to ascertain the average drop in the temperature during the no-load test where the temperature recorded ranged from 28.1 to 25.2°C.

The cooling efficiency of the cooler was found for load condition to be 81%. The tomatoes were stored both in the cooling system and under ambient conditions to deduce the effectiveness of the system, taking the physical phenomenon such as the system relative humidity, weight loss, colour and firmness of tomatoes into consideration and evaluating them. The percentage weight loss of the tomatoes was much in the ambient (16.67 to 66.67%) compared to those stored in the cooler (3.85 to 15.38%).

The loss of firmness was more obvious in the tomatoes stored under ambient conditions than those stored in the evaporative cooling system.

Analysis revealed that the use of evaporative cooling system in preserving fresh tomatoes was highly significant. The testing of the evaporative cooling system showed that the tomatoes could be stored for at least 6 days without deteriorating compared to those of under ambient conditions, which started deteriorating only after day 1. The evaporative cooling system was thus found to be effective and is recommended for use by rural farmers, households, and tomato processing factories for short term storage of fresh tomatoes.

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OCENA PROJEKTU, BUDOWY I DZIAŁANIA SYSTEMU CHŁODZENIA EWAPORACYJNEGO W PRZECHOWYWANIU POMIDORÓW

Streszczenie. System chłodzenia ewaporacyjnego został zaprojektowany i skonstruowany w celu przedłużenia terminu przydatności do spożycia warzyw. Chłodziarka ewaporacyjna została zbadana i oceniona przy zastosowaniu świeżo zebranych pomidorów odmiany Roma. Sprzęt działa na zasadzie chłodzenia ewaporacyjnego, które zwiększa wilgotność względną i zmniejsza temperaturę w komorze przechowalniczej. System przechowywania został zbudowany z drewna o grubości 25,4 mm. Bok systemu składa się z worka jutowego zwilżonego wodą płynącą przez perforowane rurki ze zbiornika umieszczonego na szczycie systemu przechowywania. Woda płynęła pod wpływem siły ciężkości. Wilgotność względna i temperatura pomidorów mierzone były za pomocą rejestratora danych. Utrata wagi pomidorów analizowana była za pomocą czujnika zegarowego. Wyniki pokazały istotne różnice w przechowywaniu pomidorów w systemie chłodzenia ewaporacyjnego w porównaniu do warunków otoczenia. Średnia wydajność chłodzenia wynosiła 81%. Średnia temperatura osiągnięta w systemie chłodzenia spadła średnio do 23℃ w porównaniu do średniej temperatury otoczenia wynoszącej 33℃, a wilgotność względna również zwiększyła się do 99% w porównaniu do średniej z otoczenia wynoszącej 59%. Analiza systemu chłodzenia ewaporacyjnego wykazała, że pomidory mogą być przechowywane przez więcej niż 6 dni z nieistotnymi zmianami w wadze, kolorze i jędrności w porównaniu do pomidorów przechowywanych w warunkach otoczenia, które uległy pogorszeniu się po 3 dniach. Stwierdzono skuteczność system chłodzenia i możliwość zastosowania go przez rolników, gospodarstwa domowe i przedsiębiorstwa przetwarzające pomidory w krótkoterminowym przechowywaniu świeżych pomidorów.

Słowa kluczowe: system chłodzenia ewaporacyjnego, termin przydatności do spożycia, ocena wydajności, projekt i budowa, przechowywanie pomidorów