ISSN 0511-5728
The West Indian Journal of Engineering
Vol.38, No.1, July 2015, pp.86-95

An Evaporative Cooler for the Storage of Fresh Fruits and Vegetables

Samantha Deoraj [a], Edwin I. Ekwue [b,Ψ], and Robert Birch [c]

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, The University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies
[a]E-mail: samanthadeoraj@hotmail.com
[b]E-mail: Edwin.Ekwue@sta.uwi.edu
[c]E-mail: Robert.Birch@sta.uwi.edu

[Ψ] *Corresponding Author*

(Received 31 January 2015; Revised 2 May 2015; Accepted 02 June 2015)

Abstract: *An evaporative cooler for the storage of fruits and vegetables was designed, built and tested. The system is an economical and efficient method used for the reduction of temperature and increase in the relative humidity for the storage of produce by applying the principles of the evaporative of water. The cooler comprised of two extraction fans, a cooling pad media, a plate-fin heat exchanger, a water tank, a storage and a cooling chamber. The optimal operational parameters were determined by operating the cooler for 180 minutes using three pad media (cedar, teak and coconut fiber), with three fan extraction speeds (4 m/s, 6 m/s and 8 m/s) at two periods of day (morning and afternoon) and the saturation effectiveness of the evaporative pad and temperature differences between ambient conditions and the cooler were measured. The mean saturation effectiveness was 64.42% (cedar), 63.56% (teak) and 53.47% (coconut fiber). The mean values for the temperature difference were 5.00 K (cedar), 4.63 K (teak) and 3.60 K (coconut fiber), showing that cedar was the best material for operating the cooler. The best fan speed was 8 m/s while the cooler operated better in the morning (9.00 a.m.to 12 noon). The evaporative cooler operated at 8 m/s fan speed using the cedar shavings pad was then used to store tomatoes over a 14 day period alongside two other storage methods (refrigeration and ambient conditions). The mean penetration depth of tomatoes was 13.43 mm, 13.82 mm and 18.26 mm for the refrigerator, evaporative cooler and the ambient conditions respectively. The pH and the total solubility solids of the tomatoes stored with the evaporative cooler were the lowest showing that while the refrigerator was the best in terms of maintaining the skin firmness, the evaporative cooler was the best storage method in terms of preserving the acidity of the tomatoes as well as their total solubility solids.*

Keywords: *Evaporative, Cooler, Saturation, Effectiveness, pH, Tomatoes*

1. Introduction

In today's society many individuals strive to maintain a healthy lifestyle consisting of a balanced diet of fresh fruits and vegetables. As the demand for such produce increases, so too does the rate of post-harvest loss, as a result of inadequate facilities to store such produce. It was estimated that the average post-harvest loss in fresh produce in most developed countries is 5% to 25% and 20% to 50% in the developing countries (Kader, 1999). Regionally, harvesting is done early in the morning in order to maximise the lower temperatures because under temperatures of 25°C to 35°C that typically exists in the afternoons, the respiration rate is high thus reducing the storage life. It is important that prompt pre-cooling of fresh produce is done as the produce can potentially deteriorate as much in one hour at 32°C as twenty-four hours at 10 °C (FAO, 2013). Undesirable effects of excessive temperature on produce include accelerated ripening, yellowing, spouting in potatoes and bitter taste in carrots which are directly linked to respiration, transpiration and ethylene production. This is due to the higher respiration rates (Odesola and Onyebuchi, 2009). There is therefore the need to decrease the temperature of the produce thereby decreasing its respiration rates, water loss, ethylene production and sensitivity to it as well as reduce microbial development. According to Odesola and Onyebuchi (2009), low relative humidity increases the transpiration rates, while at high relative humidity, the rate of water evaporation is low hence cooling is low. At high relative humidity, produce will generally maintain its nutritional quality, appearance and flavor with minimal effect on the softening and wilting (Odesola and Onyebuchi, 2009).

The most effective method utilised in storing produce involves refrigerated cool stores. However, many small scale farmers and vendors in the Caribbean region and in most developing countries are unable to incorporate such methods in preserving fruits due to its high cost with respect to installation, energy consumption and maintenance. Currently, the business revenue of many farmers in the region is limited due to the high loss in produce such as pineapples, carrots, tomatoes and guavas because of its perishable properties (Mohammed, 2001). A device can be designed and constructed in order to maximise the shelf life of the produce, thus reducing the losses endured by small scale retailers. This device will allow the appropriate cooling temperatures between 0°C to 21°C (Lerner et al., 2001) necessary to reduce the deterioration process. In order to create such a device, the requirements and parameters affecting the storage life of these produce must be analysed. A major contributing factor to the cooling process incorporates the natural resource, water in conjunction with the process of evaporation. The combination of the evaporation of water can be assisted by an external component such as a suitable air moving device (NAHB, 2001).

Evaporative coolers can be easily constructed using available local materials. They can be easily maintained compared to refrigerated systems as their major mechanical components, the motor, extraction fan and heat exchanger (optional) can be repaired at a low cost. They are environmentally friendly without pollution. Moreover, the refrigerant used is water, whereas existing refrigerated units utilise CFCs, sulphur dioxide and ammonia and these refrigerants are toxic and are contributors to the depletion of the ozone. Evaporative coolers are primarily based on the principle of evaporation which is affected by the flow of air within the system as well as the surface area. The humidity of air which is closest to the water surface is increased as water evaporates from a surface.

From a search of literature, six major types of evaporative coolers which were constructed were identified (see Table 1). Data was collected on the power consumption, speed of the fan, storage capacity, type of cooling pad, weight and the dimensions and the operational assessment of the devices. The main problem with all the previous designs is that most of them did not mention the material of the cooling pads apart from Thomson and Kasmire (1981) who used Aspen fibre. Diljohn (2010) started the use of local materials of cedar and teak in constructing evaporative coolers, but he operated the cooler at one speed of the fan and also carried out limited testing of the cooler to determine the optimal operating conditions. The main intention of this paper is to continue the work of Diljohn (2010) by designing, construction and testing of an evaporative cooler that could maximise the efficiency of storing produce at a low cost while simultaneously achieving its longevity that a more mechanically suitable device can offer. The design of such a device aims at finding an appropriate balance at increasing the storage life of produce based on the use of a low cost evaporative cooler made with local materials. The optimal conditions for running the cooler will be investigated and compared with the current methods of storing produce.

Table 1. Comparison of some existing evaporative coolers

Comparator	An evaporative cooler for vegetable crops (Thompson and Kasmire, 1981)	Evaporative Cooler (Diljohn, 2010)	EC220W (Amazon.com, 2013)	EXV 115 (Seeley International Pty Ltd, 2013)	PACKA53 (The Home Depot, 2013)
Power Consumption (kW)	1.620	0.026	0.220	0.870	0.150
Speed of Fan (m^3/s)	0.19 – 0.28	0.00273	0.78	2.60	0.22
Storage capacity	272 kg of produce can be stored in storage chamber in 1 to 2 hours	3 kg of produce can be stored in the cooling chamber	NS	NS	NS
Type of Cooling Pad	Aspen Fibre	- Cedar - Teak	NS	NS	NS
Area of Cooling Pad (m^2)	0.743	0.0103	NS	1.375 (2 Pads)	NS
Weight (kg)	NS	NS	9.9	111.1	11.3
Dimensions (W x Dx H) (m)	NS	0.508 x 0.483 x 0.854	0.692 x 0.438 x 1.049	1.016 x 1.219 x 1.168	0.411 x 0.391 x 0.701
Operational Assessment of Device	The device verified the effectiveness of evaporative cooling by testing various produce by varying several parameters.	The maximum efficiency was determined at an average temperature drop of 6.1°C, relative humidity as 24.3% and the overall efficiency as 4.88%.	A portable device, which is used to cool large areas up to 60m^2. Device is durable as it is constructed from U-V ABS plastic.	Device is suitable for cooling commercial or industrial areas and consists of a centrifugal fan, a PSC-variable speed motor. The device uses 90% less electricity than traditional refrigerated systems.	A portable device which does not consist of a pump to moisten the cooling pad. Cools up to 350 square feet for residential purposes

Remarks: *NS: Not specified in the product literature.*

2. Description of the Construction and Operation of the Evaporative Cooler

The system primarily operates on the principle of indirect evaporative cooler. In in-direct evaporative cooling, air is allowed to cool freely, without the addition of moisture to its content, with a heat exchanger. The secondary air is then used in the cooling process of the primary air via the heat exchanger. The wet and dry bulb temperatures within this system are thus reduced (Wescor, 2011). It differs from the direct evaporative cooling where air is allowed to flow through a water soaked material thus allowing evaporation and cooling to occur. The wet bulb temperature and enthalpy are unaffected and the dry bulb temperature reduces as the specific humidity and relative humidity increases (Wescor, 2011). The direct cooling method was not adopted because of the inherent high humidity of local air which leads to very low dry bulb temperature drops.

Components of the evaporative cooler (see Figure 1) are a cooling chamber, 25 cm x 25 cm x 5 cm (10” x 10” x 2”) plate-fin heat exchanger, 12.5 cm (5”) connecting pipe, and a storage chamber. In the cooling chamber, there is an evaporative pad on one end and at the other end, a tapped section with a 25 cm (10”) diameter extractor fan capable of reaching a maximum speed of 10 m/s. At the base of this cooling chamber, is a water storage tank pan with a submersible pump, which delivers water to the top of the evaporative pad via 1.25 cm (1/2”) diameter PVC connecting pipe with 10 holes of diameter 0.8 mm (1/32”). The purpose of these holes is to moisten the evaporative pad to achieve an even distribution of water on the surfaces of the material. The extractor fan attached to the cooling chamber creates a vacuum which removes the water from the evaporative pad and distributes the cool moist air created through the plate and fins of the heat exchanger via a shroud. The shroud was used to ensure that all the cool air created at the cooling chamber was utilised in the cooling process which occurred in the heat exchanger and it prevented turbulent airflow from occurring. A variable transformer regulated the speed of this extraction fan between 4 m/s, 6 m/s and 8 m/s.

The storage chamber consists of three trays for storing produce. A hole of 5 cm (2”) diameter was placed in the center of the base to allow the cool dry air to be created to enter the box via a connecting pipe. The door of the storage box is lined with a sealant material to ensure when the door is closed and the 7.5 cm (3”) diameter extraction fan placed at the top of the storage chamber (see Figure 1) is turned on, there exists a vacuum. During the operation of the evaporative cooler, ambient air is blown through the inlet of the heat exchanger and this air is cooled by the moist air from the cooling chamber. It is at the heat exchanger that the heat transfer takes place between the moist cool air and the ambient air. Ambient air enters the inlet of the heat exchanger and exits at approximately 25^{o}C. The cool ambient air from the outlet of the exchanger is then pulled into the storage box and this is the air that is used to cool the produce.

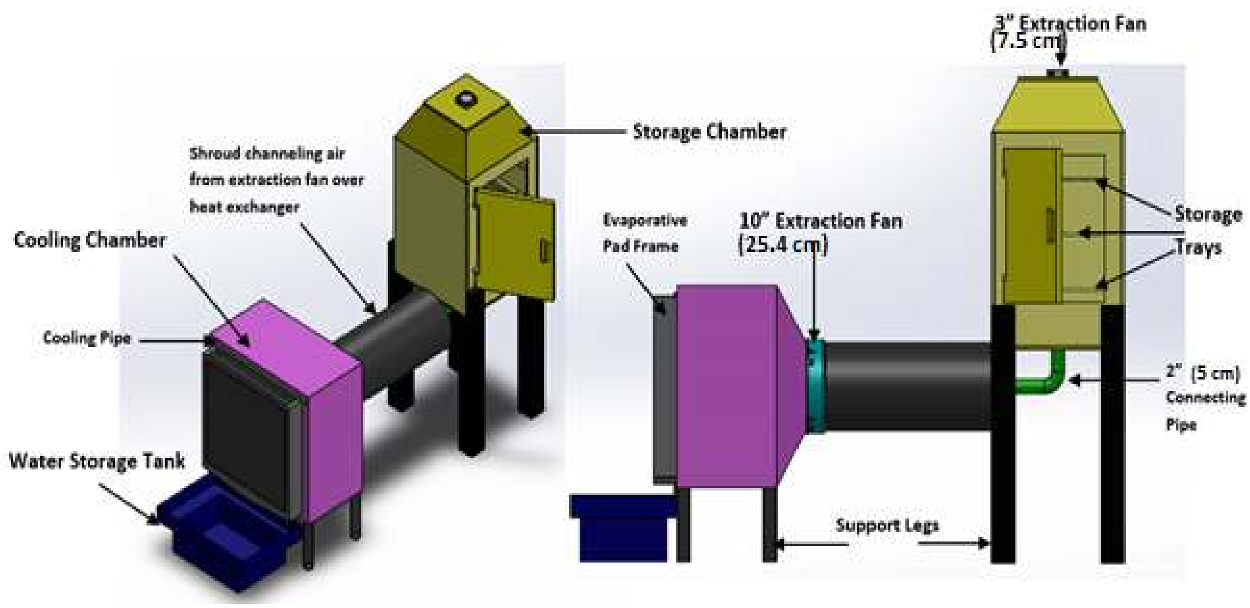

Figure 1. Views of the evaporative cooler with heat exchanger

3. Testing of the Constructed Evaporative Cooler

3.1 Purpose of the Tests

Two tests were carried out. The first test involved the use of a factorial experiment to examine the effect of three (3) types of materials (including cedar shavings, teak shavings and coconut fiber) for an evaporative pad, three (3) different speeds (i.e., 4 m/s, 6 m/s and 8 m/s) for the extraction fan based on the period of the day (morning and afternoon) and time of operation (0 to 180 mins) on two operational parameters of the evaporative cooler (saturation effectiveness of the evaporative pad and the temperature difference between the ambient conditions and the constructed evaporative cooler). This was done to obtain the optimal conditions for operating the evaporative cooler. In the second test, the performance of the evaporative cooler operating at the optimal conditions was compared with that of a refrigerator and traditional methods (storing at ambient conditions).

3.2 Procedure for Testing

Test 1

Cedar shavings, teak shavings and coconut fiber were easily attained from local saw mills. These materials were selected based on their water holding capacity, moisture content and bulk density. Cedar and teak shavings held the shape of the pad and offered little resistance to the development of mold, fungus bacterial growth and foul odors (Essick, 1945). Coconut fiber was selected as typical fibers of 7.70 x 10^{-4} m have a water absorption saturation efficiency of 85% (Toledo et al., 2005). The materials selected possess tolerable rotting resistance, thus a pad constructed of such materials could last for a considerable period (5 months minimum) of time without being changed. The shavings were first air dried for a week and then sifted so as to remove any foreign organic matter such as dried leaves or any other contaminants which could affect the properties of the materials. The following steps were involved:

1) The evaporative pad was inserted into the pad frame.
2) The water tank was filled using regular pipe borne water (T_{avg}= 28.6°C) and the pump was switched on.
3) A variable transformer (variac) was used to regulate the voltage and speed of the extraction fan. The airflow rate was simultaneously recorded with the anemometer from the extraction fan. It was ensured that there was a consistent vacuum in the cooling chamber for the cooling effect so as to reduce loss of heat transfer to the environment.
4) Five thermocouples were connected to the Picolog Software and were able to record the ambient temperature, the temperature exiting the cooling chamber, the temperature entering the storage chamber after being passed over the heat exchanger and mixed with ambient air blown through the inlet of the exchanger, the temperature in the middle of the storage chamber and the temperature exiting the storage chamber every 15 minutes over a time of 3 hours. The main reason for recording the temperatures at the various positions in the system was to effectively analyse and account for the temperatures which the produce would be stored at different levels, as there are three shelves in the storage chamber. A digital temperature and relative humidity probe measured the relative humidity of the ambient air and the storage chamber. A wet bulb thermometer measured the wet bulb temperature of the ambient air. After performing the first test in the morning period (9 a.m. to 12 noon), the system was switched off, the door in the storage chamber was opened and the system was left for an hour to reset. The experiment was then repeated in the afternoon period (i.e., from 1 p.m. to 4 p.m.). The experiments were conducted twice by applying the repeatability and reproducibility principles to evaluate the performance of the system.
5) Steps 1-4 were repeated using different materials at different speeds over a period of 9 days.
6) The saturation effectiveness of the evaporative pad was calculated by using the following equation (ASHRAE, 2007)

$$\varepsilon = \frac{t_1 - t_2}{t_1 - t'} \times 100$$

Where, ε is saturation efficiency (%),
t_1 is dry bulb temperature of entering air (K),
t_2 is dry bulb temperature of leaving air (K), and
t' is the wet bulb temperature of entering air (K)

Test 2

1) **Penetration depth:** Measuring the penetration depth of the sample was an indication of the skin firmness of the tomato and was carried out to compare the effectiveness of the various methods of storage. Measurements were made using the drop cone penetrometer (Hansbo, 1957). The tomato sample was placed on the level gauge, with the dial reading set at zero. The 30° cone was adjusted to move downward by alternating the adjuster on the side on the device until the tip of the cone was slightly touching the tomato sample. The thumb release knob was pressed for 3 seconds and then released. The depth gauge rod was then pressed without being forced in order to attain the depth of penetration of the sample. The samples were tested on the top (opposite end of the stem) as well as on the side (middle).
2) **pH Test:** pH was measured to observe how the acidity of the samples varied based on method of storage and number of days stored. This would assist in determining the most optimum conditions to store tomatoes. A pH meter was calibrated

accordingly before testing. The tomato sample was cut in half and blended in order to attain a solution to test the pH. A 10 cm^3 beaker was used to store the tomato juice and the probe of the pH meter was lowered into it. The reading was noted when the meter gave an indication of "ready" on the screen.

3) **Total Solubility Solids Test**: This physiological test corresponds to the percent of sucrose concentration in the solution. A hand held refractometer was utilized in this test. The scale of the device used is calibrated in °Brix (0 to 32%) in this case based on the stage of development in the tomatoes) which is the measurement unit for dissolved solids. The refractometer was zeroed before testing by washing the glass prism with distilled water, which gave a reading of 0° Brix. The prism was gently wiped with a microfiber cloth and the tomato juice was sprinkled on it. Readings were recorded by looking through the eyecup and adjusting the focus control.

4. Results and Discussion

4.1 Determination of the Optimal Conditions for Operating the Evaporative Cooler

Values of the saturation effectiveness and temperature difference between the ambient conditions and the cooling chamber for the three operating media of the evaporative cooler with the extraction fan operating at three speeds for different periods of the day at different times of operation are shown in Tables 2 and 3, respectively. For most of three materials, the saturation effectiveness and the temperature difference increased with the operating speed of the extraction fans. The values for cedar were in most cases higher than those for the teak, which were also higher than values for coconut fibres. As expected, both parameters also increased with time of testing from 0 to 3 hours. The evaporative cooler operated better in the day than in the afternoon. The mean values of saturation effectiveness and temperature difference for the various experimental variables are shown in Table 4. Both parameters increased with increasing speed of the extraction fan and time of operating the evaporative cooler. Mean values were higher in the morning than in the afternoon and the effectiveness of the materials in the deceasing order was cedar shaving, teak shaving and coconut fibres.

'F' values were obtained from the ANOVA (see Table 5). It shows that the effect of the main effect for the experimental factors on saturation effectiveness and temperature difference was very significant. For both parameters, the time of testing (0-180 mins) was the most important factor that affected the values.

Table 2. Saturation effectiveness of the evaporative cooler with three cooling pad materials and extraction fans operating at three speeds at two periods of the day

Time of Testing (mins)	Cedar shavings with fans operating at			Coconut fibre with fans operating at			Teak shaving with fans operating at		
	4 m/s	6 m/s	8 m/s	4 m/s	6 m/s	8 m/s	4 m/s	6 m/s	8 m/s
0	1.8/5.7*	1.7/10.3	2.0/2.7	1.9/1.4	0.0/4.0	0.4/6.8	2.0/1.3	0.0/2.5	2.0/0.7
30	40.5/24.7	46.5/35.6	57.2/34.7	29.8/31.2	15.5/27.7	17.6/26.1	44.9/19.3	39.3/48.9	48.8/47.9
60	75.6/42.1	69.8/47.0	76.2/55.9	54.0/44.7	29.2/42.8	36.7/42.7	64.8/48.6	66.0/67.4	76.0/70.0
90	92.8/46.0	65.4/89.1	89.1/81.2	69.3/53.4	39.6/54.1	52.9/54.0	71.6/53.9	76.6/77.1	86.8/71.5
120	90.0/45.6	73.4/90.8	95.2/82.5	79.8/64.6	69.2/71.3	69.9/72.5	78.8/62.7	80.9/72.8	88.7/74.8
150	86.9/64.7	88.6/94.5	97.4/88.3	85.2/86.3	92.0/89.2	91.7/89.0	91.1/70.2	99.0/76.1	92.9/87.0
180	98.2/87.7	95.8/94.3	98.8/93.8	90.9/90.0	98.4/93.5	98.8/82.3	87.3/78.3	92.6/78.0	93.8/85.1

* - Values are saturation effectiveness (%) for the morning (9 a.m. to 12 noon)/afternoon (1p.m. to 4 p.m.). The relative humidity of the ambient air ranged from 50.2% to 64.9% while that of the air in the storage chamber ranged from 69.1% to 83.2% throughout the experiments.

Table 3. Temperature difference between the ambient conditions and the inside of the evaporative cooler with three cooling pad materials and extraction fans operating at three speeds at two periods of the day

Time of Testing (mins)	Cedar shavings with fans operating at			Coconut fibre with fans operating at			Teak shaving with fans operating at		
	4 m/s	6 m/s	8 m/s	4 m/s	6 m/s	8 m/s	4 m/s	6 m/s	8 m/s
0	2.6/0.5	0.1/0.9	0.1/0.2	0.1/0.1	0.0/0.3	0.0/0.5	0.1/0.1	0.0/0.2	0.1/0.1
30	2.6/2.2	2.8/3.2	3.1/2.5	1.5/2.4	0.8/2.2	0.9/2.1	2.5/1.5	2.2/3.8	2.4/4.0
60	5.5/3.7	4.7/4.4	4.4/3.6	2.9/3.7	1.6/3.4	2.0/3.5	4.1/3.5	4.3/5.4	4.6/5.7
90	6.4/3.9	6.3/6.1	6.2/6.4	4.4/4.4	2.3/4.2	3.1/4.3	4.8/4.2	5.1/6.0	5.4/5.7
120	6.9/3.7	7.2/6.4	6.8/6.5	4.5/5.3	4.1/4.9	4.2/5.2	5.4/4.8	5.7/5.7	6.3/5.7
150	7.4/5.0	8.3/7.2	7.4/7.4	5.5/6.6	6.0/5.8	5.8/6.1	6.3/6.6	7.1/6.1	6.9/6.5
180	8.1/6.5	8.7/7.1	7.8/7.2	7.3/5.5	7.5/5.6	6.7/5.1	7.2/6.1	8.0/5.8	8.0/6.2

*- Values are temperature differences (K) for the morning (9 a.m. to 12 noon)/afternoon (1p.m. to 4 p.m.). The ambient temperature ranged from 303 K to 307.4 K (30°C to 34.4°C) throughout the experiments

Table 4. [a]Mean values of the saturation effectiveness (%) and temperature difference between the ambient and evaporative cooler (K) for the different experimental factors

Factor Level	Saturation effectiveness (%)	Temperature difference (K)
Type of pad:		
Cedar shavings	64.4	5.0
Teak shavings	63.6	4.6
Coconut fiber	53.5	3.6
Speed of extraction fan (m/s):		
4	56.8	4.1
6	60.8	4.6
8	63.8	4.6
Time of testing (minutes):		
0	2.6	0.3
30	35.3	2.4
60	56.5	3.9
90	67.7	4.9
120	75.8	4.5
150	87.0	6.5
180	90.9	6.9
Period of the day:		
Morning (9 a.m. -12 noon)	64.4	4.5
Afternoon (1p.m. – 4 p.m.)	56.6	4.3

[a] - Mean values for each factor were obtained by averaging the measured values over the levels of the other three experimental factors.

For both parameters, the time of testing (0-180 mins) was the most important factor that affected the values. For the saturation effectiveness, this was followed by period of the day (morning or afternoon), type of pad and the speed of extraction fan. For the temperature difference, it was followed by the type of pad, speed of fan and period of the day. The most important interaction effects were between type of pad and period of day; speed of extraction fan and period of day and type of pad and speed of extraction fan in that order of importance (see Section 4.3.1).

4.2 Testing of the Evaporative Cooler at the Optimal Conditions

From the first set of results shown in Tables 2 to 5, it was determined that the optimal conditions for operating the evaporative coolers are using the cedar shaving as the media and the speed of operation of the extraction fan as 8 m/s. For comparative purposes, the evaporative cooler was used to store tomatoes for 14 days alongside the refrigeration method operating at 12°C (285 K), 90% to 95% relative humidity and storing at ambient conditions of 25°C (298 K) and between 80% to 85% relative humidity. Table 6 shows the values of the pH, total solubility solids (TSS) and depths of penetration of tomatoes using a penetrometer for the different days for the three methods of storage. Values showed that during the 14-day storage period, while the evaporative cooler more or less maintained the acidity and the TSS of the tomatoes, the refrigeration and ambient conditions made the fruits slightly more alkaline and increased the TSS. Also, the penetration depths of tomatoes stored in the evaporative cooler were slightly greater than those for the refrigeration method but were much lower than the tomatoes stored under ambient conditions.

Table 7 shows the mean values of pH, TSS and penetration depths for the three storage methods and days of storage. The three parameters increased with increasing days of storage. The tomatoes stored in the evaporative cooler had the lowest pH and TSS of the three storage methods. The ‘F’ values were obtained from the ANOVA (see Table 8). It shows that the effect of the main effect for the storage methods and the days of storage on pH, TSS and penetration depths were significant. For penetration depth, the method of storage was more important than the days of storage. For the pH and total solubility solids, the reverse was the case.

4.3 Discussion of the Results

4.3.1 Determination of the Optimal Conditions for Operating the Evaporative Cooler

The first stage of experiments was conducted to determine the optimal conditions for operating the evaporative cooler. The results for the parameters tested are discussed below.

Table 5. ‘F’ values in the analysis of variance for saturation effectiveness (%) and temperature difference between the ambient conditions and the evaporative cooler (K)

Sources of Variation	Degrees of freedom	Saturation Effectiveness	Temperature Difference
Type of pad	2	73.5	165.5
Speed of extraction Fan	2	24.3	17.3
Time (minutes)	12	347.1	314.2
Period of the day	1	89.8	4.5
Type of pad x speed of extraction fan	4	15.3	14.3
Type of pad x time (minutes)	24	6.8	3.0
Types of pad x period of day	2	29.0	31.3
Speed of extraction fan x time (minutes)	24	0.6	1.0
Speed of extraction fan x period of Day	2	28.7	30.1
Time (minutes) x period of Day	12	3.8	8.6

Table 6. pH, total solubility solids (ºBrix) and penetrometer depths (mm) for evaporative cooler operating at optimal conditions compared with refrigeration and storage of tomatoes at ambient conditions

No. of days	Method of Storage								
	Refrigeration			Evaporative cooler			Ambient conditions		
	pH	Total solubility solids (ºBrix)	Penetration depth (mm)	pH	Total solubility solids (ºBrix)	Penetration depth (mm)	pH	Total solubility solids (ºBrix)	Penetration depth (mm)
0	3.87	3.2	11.8	3.91	3.1	12.5	3.89	3.2	11.3
3	3.91	3.3	13.2	3.94	3.3	12.3	3.91	3.3	15.7
5	3.89	3.2	13.2	3.95	3.1	13.0	3.91	3.3	17.5
7	3.90	3.5	11.3	4.09	3.3	12.0	4.10	3.3	17.8
9	4.25	3.4	12.0	4.29	3.2	13.5	4.40	3.6	17.7
11	4.20	4.2	14.0	4.29	3.4	15.2	4.45	3.5	20.7
13	4.40	3.9	15.2	3.27	3.9	16.5	4.41	4.4	24.5
14	4.41	3.2	15.0	3.91	4.4	15.7	4.44	3.4	19.5

Table 7. Mean values for the pH, total solubility solids (TSS) and penetrometer depth (mm) for the different experimental factors

Factor Level	pH	Total solubility solids (ºBrix)	Penetration depth (mm)
Method of storage:			
Refrigerated	4.11	3.63	13.42
Evaporative cooler	4.05	3.46	13.82
Ambient conditions	4.22	3.53	18.26
Day of storage:			
0	3.89	3.15	11.98
3	3.92	3.28	13.72
5	3.91	3.20	14.56
7	3.98	3.36	13.72
9	4.32	3.41	14.39
11	4.30	3.70	16.61
13	4.40	4.07	18.72
14	4.04	3.65	16.72

Table 8. 'F' values in the analysis of variance for the pH, total solubility solids (TSS) and penetrometer readings (mm)

Sources of Variation	Degrees of Freedom	pH	Total Solubility Solids (ºBrix)
Method of Storage	2	19.18	3.54
Day of Storage	10	28.18	12.88
Method of Storage x Day of Storage	20	11.13	5.09

1) Type of Material Used to Construct the Evaporative Cooling Pad

The values of the saturation effectiveness and temperature difference were the greatest for the pad constructed from cedar shavings, followed by teak shavings and then coconut fiber. The results indicated that cedar shavings was marginally better than teak. The effectiveness of the evaporative pad depends significantly upon the material which has a clean wet surface as well as minimum air flow resistance. Cedar and teak shavings used in the experiment were approximately 1.12 x 10^{-4} m thick and 0.0381 m to 0.0508 m in length. From the experiments, cedar shavings were able to spread the water rapidly by capillary action and allowed a substantial percentage of air to enter than the other materials. Also, the surface area of the shavings and fibers which is exposed to moist conditions affects the rate of cooling the system that would experience. For a larger moisten surface area, a greater amount of cooling occurred.

The microscopic structure and orientation of the grains in the shavings can account for the ability of the materials to allow a considerable amount of heat transfer to occur which in turn produced a significant decrease in temperature. The grains in the cedar wood are straight and have a medium/ fine texture whilst teak has a considerably coarse texture and medium sized pores with grains being tangential (Green et al., 1999). Coconut fiber, however, offered considerable resistance to air flow due to the porosity and permeability of the fiber itself.

2) Time (minutes) for the Operation of the Evaporative Cooler

This was the most important experimental factor on the temperature difference and saturation effectiveness (see

Table 5). This trend is directly correlated to the variation of the wet bulb and dry bulb temperature with time. As time increased, the cooling effect increased within the system for the different materials. The maximum temperature difference which was attained was 8.72 K, at 180 minutes of operation. Also, the relative humidity inside the storage chamber increased with increasing speed for the cedar and teak shavings and decreased with the coconut fiber. The maximum relative humidity attained was from the cedar and teak shavings at 83.2% and 80.30% respectively. For teak, the maximum was 77.9%.

This is in accordance to the fact that achieving 100% relative humidity in evaporative cooling cannot occur as the pads are loosely packed thus allowing air to easily escape without having sufficient contact with the water (Xuan et al., 2012). This was observed with the coconut fiber pad, because of the texture of the coconut fiber, the contact time between the air entering the cooling chamber and the water from the pipe wetting over the pad was not long enough regardless of the system being in operation for 180 minutes. Thus, the heat and mass transfer was insufficient, which accounts for the low relative humidity attained contrary to the behavior of cedar and teak.

3) Speed of the Extraction Fan

The temperature difference increased for the pads constructed of cedar and teak shavings with an increase in speed of the extraction fan whilst the opposite occurred for coconut fiber (see Tables 2 and 3). Saturation effectiveness of the pad also increased for cedar and teak shavings. However, the saturation effectiveness for coconut fiber decreased with increasing speed. Increasing the speed of the fan was directly related to the rate at which water was removed from the materials and dispersed throughout the air. The increase in fan speed resulted of an increase in the water content in the air, which was directly related to the rate that water was removed from the shavings and the cooling effect which occurred. The coconut fiber was able to produce higher temperature differences and saturation efficiencies at 4 m/s because of the air voids present in the fiber itself, at a lower speed it was able to cool more effectively than it would at a higher speed as the rate of evaporation was less.

4) Period of the Day

The results for analysis variance are given in Table 5. This indicated that the period of the day was the second most important experimental factor on the saturation effectiveness. Period of the day however, had the least contribution to the temperature difference of the system. The results indicated that there was an interaction between the morning and afternoon periods for the behavior of the cedar and teak pads. The cedar material performed better during the morning period whereas teak produced the higher saturation effectiveness in the afternoon period. Thus, the ambient conditions throughout the day such as relative humidity, wet bulb temperature and dry bulb temperature affected the efficiency of the system in relation to the physical and microscopic properties of the materials. This trend was also observed in previous research conducted by Dağtekin et al. (2009), which indicated that the maximum temperatures attained inside as well as outside for the evaporative cooler was at 11.00 hours to 14.00 hours. The cedar pad provided the largest temperature difference in the morning period compared to the afternoon, whilst teak behaved in the opposite manner. This is as a result of the variation of the ambient dry bulb/wet bulb temperature over time. However, the overall ideal operating speed was at 8 m/s as this produced a substantially high saturation effectiveness than the other speeds and a reasonable temperature difference.

4.3.2 Testing of the Evaporative Cooler at the Optimal Conditions

The best method of storage affecting the firmness of the samples was the refrigerated conditions followed by the evaporative cooler and ambient conditions. It can be stated that for the refrigerated and evaporative cooler samples, the enzyme activity was in fact lower in comparison to those stored in ambient conditions. This finding was in accordance to the theory that the enzyme activity is a function of temperature (Cantwell, 2008). The storage temperatures for the refrigerator and evaporative cooler, were responsible for the decrease in the enzyme activity. The enzyme responsible for the breakdown of pectin in the cell wall is the peptidase enzyme. At these conditions the pectin in the cell wall was present which reinforced the cell wall fibers thus allowing it to remain firmer than those in the ambient condition. The tomatoes stored under ambient method of storage had the greatest penetration depths.

The pH content was greatly affected by the number of days the samples were left in storage followed by the TSS and the penetrometer readings. The pH content of the samples gradually increased as the storage period increased. However, the ambient conditions had the highest value of pH followed by refrigerated methods and the evaporative cooler. Thus, the evaporative cooler was the ideal method of storage in preserving the acidity of the tomatoes as well as its TSS content. The rise in the pH of the samples indicates the direct relationship that the acid concentrations in the samples decline with the level of maturity (Gordon et al., 2011). The decline in the level of acidity in the tomatoes is directly related to the increase in the sugar content as ripening increases as seen in the experiments conducted. The soluble content (°Brix) was used to assess the quality of the tomatoes. The physical color was visually observed and indicated that the tomatoes in the refrigerated and evaporative cooler were at development stages 5 and 6 throughout the test (90% surface covered was red-orange in color). However, the samples under ambient conditions quickly reached development stage 6 where the surface area of the tomatoes were 100% covered in a ruby red.

5. Conclusions

The following can be concluded from the study:

1) An effective way of storing fruits and vegetables could be the use of evaporative coolers using local materials like cedar shavings, teak shavings and coconut fiber as pad. It was found that Cedar shavings would be the best material in terms of saturation effectiveness and lowering the ambient temperature required for storage. The fan speed of 8 m/s produced the best results.
2) Tomatoes were tested under refrigerated, evaporative cooling and ambient conditions. The best method for storing produce in terms of skin firmness was the refrigerator followed by the evaporative cooler. The pH and the total solubility solids (TSS) of the tomatoes stored with the evaporative cooler were the lowest showing that while the refrigerator was the best in terms of maintaining the skin firmness, the evaporative cooler was the best storage method in terms of preserving the acidity of the tomatoes as well as their total solubility solids. Storage under the ambient conditions was the worst condition for the pH, TSS and penetration readings.

References:

Amazon.com. (2013). *Amazon.com.* Accessed November 12, 2013. http://www.amazon.com/Luma-Comfort-EC220W-Evaporative Cooling/dp/B007SNRZHS/ref=sr_1_5?ie=UTF8&qid=1384812 660&sr=8-5&keywords=swamp+coolers.

ASHRAE (2007). *ASHRAE Handbook Fundamentals*, SI Edition. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Cantwell, M. (2008), *Impact of Ripening and Storage Conditions on Ripe Tomato Quality*. Assessed February 25, 2015. http://ucanr.edu/datastoreFiles/234-1181.pdf

Dağtekin, M., Cengiz K., and Yılmaz Y. (2009), "Performance characteristics of a pad evaporative cooling system in a broiler house in a Mediterranean climate", *Biosystems Engineering* Vol.103, No.1, pp.100-104.

Diljohn, T. (2010), *Design, Build and Maximise Efficiency of an Evaporative Cooler for the Storage of Produce*, Unpublished B.Sc. Mechanical Engineering Project, University of the West Indies.

Essick, B. (1945), *Pad for Evaporative Coolers*, Los Angeles, California Patent 2,39l,558. December 25.

FAO (2013), *FAO Corporate Document Repository*, Accessed October 24, 2013. http://www.fao.org/wairdocs/x5403e/x5403e0b.htm#TopOfPage

Gordon E. A., LeStrange, M. and Barrett, D.M. (2011), "Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes", *Journal of the Science of Food and Agriculture*, Vol.91, No.7, pp.1175-1181.

Green, D.W., and Kretschmann, J.E. and Winandy, D.E. (1999). *Mechanical Properties of Wood.* General Technical Report (GTR), Madison, WI: SDA Forest Service, Forest Products Laboratory, 4.1-4.45.

Hansbo, S. (1957), "A new approach to the determination of the shear strength of clay by the fall-cone test", *Proceedings of the Royal Swedesh Geotechnical Institute*, Stockholm, Sweden, pp.1-48.

Kader, A.A. (1999), "Fruit maturity, ripening and quality relationships", *Proceedings of International Symposium on Effect of Pre-and Post Harvest Factors on Storage of Fruits* (Editor: L. Michalczuk), ACTA Horticulture 485, ISHS, 203 – 208.

Lerner, B. R., and Dana, M.N. (2001), *Storing Vegetables and Fruits at Home*, Purdue University Cooperative Extension Service, West Lafayette, Assessed February 25, 2015. http://www.hort.purdue.edu/ext/ho-125.pdf

Mohammed, M. (2001), *Optimizing Postharvest Handling and Maintaining Quality of Fresh Pineapples*, Inter-American Institute For Co-operation in Agriculture, Trinidad and Tobago. February 25, 2015. http://www.iica.int/Eng/regiones/caribe/trinidadytobago/Documents/pineapple_publication.pdf

NAHB (2001), *NAHB Research Center*, Accessed Septemeber 1, 2013. http://www.toolbase.org/TechInventory/TechDetails.aspx?ContentDetailID=749&BucketID=1&CategoryID=6.

Odesola, I.F. and Onyebuchi, O. (2009), "A review of porous evaporative cooling for the preservation of fruits and vegetables", *The Pacific Journal of Science and Technology*, Vol.10, No.2, pp.935-941.

Seeley International Pty Ltd. (2013), *Breezair*. Accessed November 12, 2013. http://www.breezair.com/us/help-me-choose/model-specifications.

The Home Depot (2013), *The Home Depot*. Accessed November 12, 2013. http://www.homedepot.com/p/Port-A-Cool-KuulAire-470-CFM-3-Speed-Portable-Evaporative-Cooler-for-350-sq-ft-PACKA53/203191797#.UosU3_mfhSA.

Thompson, J., and Kasmire, R.F. (1981), "An evaporative cooler for vegetable crops", *California Agriculture*, March, pp.20-21.

Toledo, F.R.D., Ghavami, K. and England, G.L. (2005). Free, restrained and drying shrinkage of cement mortar composites reinforced with vegetable fibres. Cement and Concrete Composites 27 (5): 537–536.

Wescor (2011), *Evaporative Cooling Basics.* Accessed October 7, 2013. http://www.wescorhvac.com/Evaporative%20cooling%20white%20paper.htm

Xuan, Y.M., Xiao, F., Niu, X.F., Huang, X. and Wang, S.W. (2012). Research and application of evaporative cooling in China, a review. Renewable and Sustainable Energy Reviews, Vol. 16, Issue 5, 3535-3546.

Authors' Biographical Notes:

Samantha Deoraj *is a graduate of the Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, The University of the West Indies in 2014 majoring in the Energy stream with a keen interest in renewable energy as well as applying engineering methods to sustain the environment. She is currently a Graduate Mechanical Engineer at The National Gas Company of Trinidad and Tobago.*

Edwin I. Ekwue *is presently Professor and Head of the Department of Mechanical and Manufacturing Engineering and*

Coordinator of the Biosystems Engineering program at The University of the West Indies, St Augustine, Trinidad and Tobago. He is a member of the Editorial Board of the West Indian Journal of Engineering and the Journal of Mechanics of Interactions. His specialty is in Water Resources, Hydrology, Soil and Water Conservation and Irrigation. His subsidiary areas of specialisation are Structures and Environment, Solid and Soil Mechanics, where he has teaching capabilities. Professor Ekwue had served as the Deputy Dean (Undergraduate Student Affairs), the Deputy Dean (Post-graduate Affairs and Outreach), the Chairman of Continuing Education Committee, and the Manager of the Engineering Institute in the Faculty of Engineering at The UWI.

Robert Birch *is an Instructor in the Department of Mechanical and Manufacturing Engineering at The University of the West Indies, St Augustine, Trinidad and Tobago. He is a registered Professional Engineer (R.Eng) and Project Management Professional (PMP) with over sixteen years of industrial and teaching experience. He has a BSc. (Eng) and MPhil in Agricultural Engineering from The University of the West Indies and is presently pursuing a PhD in Mechanical Engineering. Mr. Birch is a member of the Institution of Agricultural Engineers (UK). His interests are in Field Machinery and Heavy Equipment Design, Fluid Power Technology and Soil-Machine interaction.*

■