Development of an active evaporative cooling system for short-term storage of fruits and vegetable in a tropical climate

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Abstract: An active evaporative cooler for short-term storage of fruits and vegetable has been developed to improve the shelf life of fruits and vegetables for small holder farmers in Southern Nigeria. The evaporative cooler uses palm fruit fiber as cooling pad material which is considered a waste in palm oil production in Nigeria and consists of three suction fan, automatic water control switch, water pump and evaporative cooling chambers. The performance of cooler was evaluated in terms of temperature drop, efficiency of the evaporative cooling and cooling capacity. The temperature drop ranged from 4^0C to 13^0C while the relative humidity of the ambient air was increased to 96.8%. The cooler could drop the temperature close to wet bulb depression of ambient air and provided up to 98% cooling efficiency with a maximum cooling capacity of 2,529 W. At an ambient temperature of 37^0C, the evaporative cooler provided the storage conditions of 23.2 temperature and 85.6% – 96.8% relative humidity, which can enhance the shelf life of wide range of fruit and vegetables of moderate respiration rates. The power consumption of the cooler was half that of a typical vapour compression refrigerator of the same volume.

Keywords: cooling capacity, cooling efficiency, evaporative cooling, temperature drop

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1 Introduction

Vegetables and fruits are generally classified as perishable crops, if not quickly preserved when harvested; they shrivel, wither or rot away rapidly, especially under hot conditions (Ndukwu, 2011). The highly perishable ones like leafy vegetables, tomato; asparagus etc, even in storage, has a recommended refrigerated storage life of less than one week. This is because they constitute mostly water. Loss of water from produce is often associated with a loss of quality, as visual changes such as wilting or shriveling and textural changes can take place. Ndirika and Asota (1994) reported that the damage that occurs in fruits and vegetables is primarily by loss of moisture, change in composition and pathological attack. Another aspect to consider when handling fruits and vegetables is the relative humidity of the storage environment. Low temperature and high humidity slows pathological activity, therefore the storage environment for safe preservation of fruits and vegetables must replicate them. Any method that will reduce the temperature and increase the relative humidity of the storage environment relative to the ambient will suppress enzymatic degradation and respiratory activity. It will also reduce the rate of water

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loss, slow or inhibit the growth of molds and bacteria slow the rate of the production of ethylene or minimize the product's reaction to ethylene and other metabolic activities (Katsoulas et al, 2011; Boyette et al, 2010). Fruits and vegetables when properly preserved will prolong their usefulness, provide a wider choice, reduce marketing anxiety and will increase the profit to the producer by reducing losses. Preservation of fruits and vegetable has always been a problem especially in tropical climate with high solar load. Compression refrigerators is being used but it has been observed that several tropical fruits and vegetables like banana, tomatoes, orange, leafy vegetables etc, cannot be stored in the domestic refrigerator because they sustain chilling injury and colour changes (Adebisi et al 2009). The widely used chlorofluorocarbon (CFCs) and hydro chlorofluorocarbon (HCFCs) refrigerants in compression refrigeration systems are partly responsible for ozone layer depletion and exacerbates global warming (Xuan et al, 2012). The World Bank and FAO have advocated cheaper alternative, for the storage of fruits and vegetable based on the principle of evaporative cooling which is simple, and relatively efficient. The principle relies on cooling by evaporation (Adebisi et al, 2009; Xuan et al, 2012). When water evaporates, it draws energy from its surroundings, which produce a considerable cooling effect. Very little amount of energy is consumed to deliver air and water in evaporative cooling, which is much lower than energy used in electrical vapor compression refrigeration systems [9]. Heat in the air is utilized to evaporate the water, resulting in a drop in the air temperature and increase in relative humidity. According to Xuan et al (Xuan et al, 2012) the benefits of evaporative cooling includes substantial energy and cost savings, no CFCs usage, reduced CO_2 and power plant emissions, improved indoor air quality, life-cycle cost effectiveness, greater regional energy independence, etc. An active evaporative cooling system consists of a pad (moist material), fan, storage cabin and water recirculation pump. According to Xuan et al, (Xuan et al, 2012), evaporative cooling is widely used in northwest of China, the Middle East, Indian subcontinent, eastern African, southwestern United States, Australia and northern Mexico however it is still not well explored in Nigeria. Designs of evaporative coolers have been progressive and mostly reported in literature as house air conditioner however; some research have been channel to its utilization for preservation of fruits and vegetables (Redulla, 1984; FAO, 1983; Roy, 1989; Thompson and Scheuerman 1993; Watt, 1997; Jain, 2007 and Neil 2010). Most design available in Nigeria for preservation is of passive type with manual water recirculation system (Ndirika and Asota, 1994; Anyanwu, 2004; Adebisi 2009; Ndukwu, 2011 and Manuwa and Odey, 2012). The disadvantage of this is that the cooler can only work where there is natural movement of the surrounding air unlike the active type and a lot of water is lost. The cooler will also require maximum attention. In this paper, hexagonal shaped active evaporative cooling design is presented, which incorporates water recirculation mechanism with locally sourced low cost and durable cooling pads. This will help farmers and other marketers of fruit and vegetable based agricultural products to be able to store and preserve efficiently their products in the short term. The principle underlying evaporative cooling is the conversion of sensible heat to latent heat. The warm and dry outdoor air is forced through wetted pads that are replenished with water from the cooler's reservoir (Ndukwu, 2011). Due to the low humidity of the incoming, air some of the water evaporates. This evaporation causes two favorable changes: a drop in the dry-bulb temperature and a rise in the relative humidity of the air. This non-saturated air cooled by heat and mass transfer is forced through enlarged liquid water surface area for evaporation by utilizing blowers or fans. Some of the sensible heat of the air is transferred to the water and becomes latent heat by evaporating some of the water. The latent heat follows the water vapour and diffuses into the air (Watt, 1997). In a DEC (direct evaporative cooler), 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) in an ideal process. 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 (Xuanet al, 2012). 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 (Wei, 2009).

2 Materials and method

2.1 Design Considerations of the Evaporative Cooling systems

The following design considerations were made:

1) The evaporative cooler was relatively light in weight for ease of movement;

2) Water re-circulation system was incorporated which is to ensure minimal attention;

3) The evaporative cooler has uniform surface area;

4) The water flow rate from the upper tank was constant;

5) Water recirculation was automatic which is to ensure minimal attention.

2.2 Design calculation

2.2.1 Sizing cooling and storage capacity

The shape of the cooler is assumed regular hexagonal to present a larger projected surface for air circulation (Manuwa and Odey, 2012). The cooler capacity is calculated from simple geometrical equation. The Base area is the area of an equilateral a triangle multiplied by 6.

2.2.2 Heat load design

The cooled and humidified air from the pad is required to remove the total heat load of the evaporative cooler. The most important parameters determining the design of cooling processes and equipment are the processing time and the heat load. The following are the sources of heat to be removed from the cooler.

Heat of conduction: heat entering through the insulated walls and floor.

Field heat of the produce: this is the heat picked up by the produce on the field. It is proportional to the mass of the produce and storage temperature. It is heat extracted from the produce (The heat energy it contains) as it cools to the storage temperature.

Heat of respiration: this is heat generated by the produce as a natural by-product of its respiration.

Infiltrations: this is heat from lights, people, and warm, moist air entering through cracks or through the door when opened.

The various heat load above were calculated using the standard equations in literature (Adebisi et al, 2009; Boyette et al. 2010; Watt, 1997; Rastavorski, 1987).

2.2.3 Air requirement

This is the total volume of air per minute required to remove the total sensible heat load from the cooler. It is calculated using the standard equation in literature (Harris, 1995). Based on the volume of air required, the required axial fan was selected.

2.2.4 Pad design

The pad was made of palm fiber. The pad area, thickness and volume was calculated based on standard equations and can be found in (Gupta et al., 1995).

2.2.5 Water circulation

Water is continuously circulated over and through the pad during operation. A 0.375 kW sump pump was selected based on the height and volume of water tank (Gupta et al., 1995). The pump which has a water delivery capacity of 40 L min^{-1} with maximum delivery head of 30 m was used to lift water from the bottom tank to the top tank (Gupta et al., 1995) at a flow rate of 0.4 L s^{-1}.

2.3 Power requirement

The cooler consist of three small axial air inlet fan of 0.02 kW power each and a sump water pump of 0.37 kW power. The total energy consumption is gotten by addition of all the components.

2.4 Description of the evaporative cooling system

The cooler Figure 1 is made up of 0.24 m^3 hexagonal shaped storage housing structure mounted on a steel frame with stainless wire partitions for storing of fruits and vegetables. The inner (aluminum sheet) walls of the cooler and the outer wall (1 mm gauge mild steel plate) were separated with fiberglass to provide lagging for the system. The outside of the wall is silver colored to increase the reflectivity of the material and decrease the rate of absorption of heat.

Figure 1 Prototype developed active evaporative cooler

Through forced convection, three axial fan mounted adjacent the cooling pad holder forces the air through the wet cooling pad (palm fruit fiber) into the storage chamber. Inside this cold room, the air picks up heat from the fruits and vegetables and the temperature rises due to respiration of the product. To provide for air outlet from the system which is one of the conditions for evaporative cooling, the conditioned air passes through two vents. The two 8 cm diameter vents are located 0.3 m from each other. The vents opens to the atmosphere through 1mm vent holes. Directly at the bottom of this 0.24 m^3 housing is a plastic 20 L water storage tank for storage of water. A 0.37 kW electric water pump lifts the water from the bottom tank through a 2 cm PVC pipe to 20 L upper plastic water tank. The water returns back to the cooling pad (palm fruit fiber) through a 2.5 cm flexible hose equipped with a ball valve to control the rate of water flow. The valve opens into the pads through a perforated 2 cm plastic pipe lined with pinholes that spray water at 10 cm^3 s^{-1} on the pad. Water sprays at the top edges of the pads and distributes further by gravity and capillarity. The water from the pad drains into a trough under the pad. The trough opens into the bottom water tank through 2 cm PVC pipe. The bottom tank is equipped with a floating switch and a control valve. The cooling pad is stuffed inside the 0.009 m^3 cuboids' shaped pad holder made of double walled galvanized steel net. To ensure the ease of maintenance, the two walls were held with two hinges on one side to ensure opening for installing pads. The pad holder was divided into three equal compartments, separated with a perforated galvanized steel plate to prevent sagging of the pad and allow water to pass through. The pad holder was mounted on one side of the cooler with bolt and nut assembly. The inner wall of the pad holder opens into the cooling chamber. Three suction fan of 20 cm swept diameter delivering 0.5 m^3 s^{-1} is mounted adjacent the pad holder for each of the three compartments using the frame and held with a bolt and nut assembly. The fans were lined with 1mm mild steel plates (30 × 100 × 15 cm) by the side welded to the frame of the pad holder to channel the air towards the pad. The three fans were controlled through a rheostat connected to a single one-gang switch. The pump was controlled through locally designed automatic float switch. The switch uses the water level of the bottom tank to switch the pump on and switch it off.

2.5 Experimental tests

Experimental tests were undertaken with palm fruit fiber as the cooling pad at air velocities of 4.0 m s^{-1}. the cooler was loaded with 2 kg of pumpkin (cucurbita) and amaranthus leaf and another set up inside the shade to study the effectiveness of the design. The test facility was located under an open shade built under a whistling pine tree. This is to reduce direct action of the sun and expose the cooler to natural air. The tests were carried out in January and February of 2013; this period presented the extremes of the temperature within the year. During the period of the test the relative humidity of the environment varied from 28% to 80% with the ambient temperature reaching 45°C. The palm fruit fiber was stuffed into the pad holder at a pad thickness of 30 mm and a parking density of 20 – 22 kg m^{-3}. After the pad was place, the upper water tank was opened at a water flow rate of 10 cm^3 s^{-1}. The water flows through the pad into the bottom tank and re-circulates back through the pump for one hour to saturate the pad with water before the cooler was loaded with vegetable. The cooler was then loaded with vegetable, the speed of 4.0 m s^{-1} was set with the rheostat and the fan turned on. The thermocouple (omega data logger, HH1147) (±0.1–^{0}C) was positioned through the hot wire terminals inserted into the cooling chamber. One of the terminals was covered with cotton wool soaked inside the water to measure the wet bulb temperature

(Anyanwu,2004). The air speed of the fan was determined with vane microprocessor (AM-4826) digital anemometer (±0.1 m s^{-1}). Two ABS temperature and humidity clock (±0.1^{0}C and 1.0%) was positioned inside the shade and another outdoor where there is no shade to record the temperature and humidity of the ambient. Two analogue thermometers were inserted inside the two tanks to measure the water temperature. The data were logged every one hour. The relative humidity and the enthalpy of the cooler were obtained from the psychometric chart. In addition, the wet bulb temperature and the enthalpy of inside the shade and the ambient were calculated also from the psychometric chart.

2.6 Performance evaluation

The cooling capacity and cooling efficiency defined by Equation (1), Equation (2) and Equation (3) is a widely used index for evaluating the performance of direct evaporative cooling media (Ndukwu, 2011; Xuan et al., 2012; Watt, 1997). They were used as follows:

Cooling efficiency (ℓ)

$$\ell = T_{db} - T_s/T_{db} - T_w \quad (1)$$

Cooling capacity (Qb)

$$Qb = 1.08 \times Vsc \times (T_db - T_s) \quad (2)$$

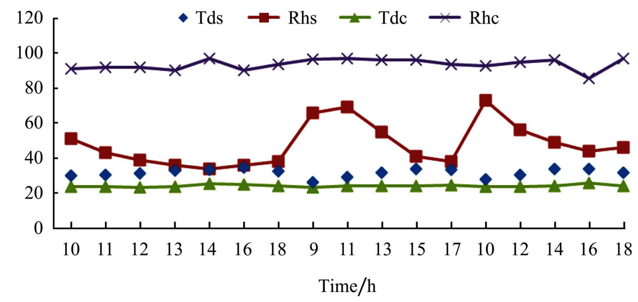
Equation (2) was converted to S.I unit and modified as follows

$$Qi = 670.66 \times Vsi \times (T_{db} - T_s) \quad (3)$$

where, T_{db} is ambient dry bulb temperature (^{0}C); T_w is ambient wet bulb temperature (^{0}C); T_s is dry bulb temperature of cooler storage space; Qi is the cooling capacity in S.I units; Vsc is the flow rate of air (CFM); Vsi is the flow rate of air ($m^3 s^{-1}$)

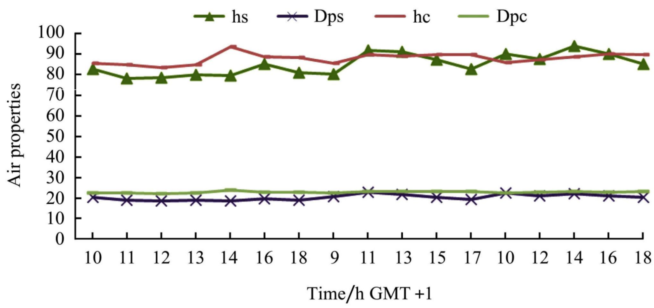
3 Results and discussion

The results on the observation of a typical three consecutive days were presented in Figure 2, Figure 3 and Figure 4. Figure 2 and Figure 3 show the hourly air properties of ambient air and cooler air. It is clear from Figure 2 that at 13:00 hours (GMT +1), the ambient air of 32.8^{0}C temperature with 36% relative humidity could be brought to 23.2^{0}C temperature and 90.4% relative humidity at the first day. It shows that the cooler could drop the ambient temperature very close to its wet bulb temperature of 21.96^{0}C. The maximum temperature drop observed was 13^{0}C.



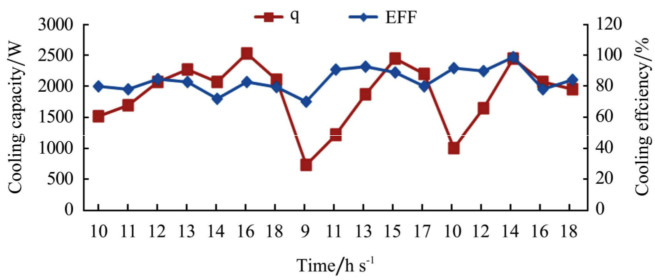
Note: Tdc – dry bulb temperature of the of the air leaving the pad; Tds- ambient dry bulb temperature; Rhc- relative humidity of air leaving the pad; Rhs – ambient relative humidity

Figure 2 periodic variation in air properties for a typical three days period for the evaporative cooler



Note: hs is enthalpy of the air entering the pad (kJ kg^{-1}); Dps is dew point temperature of air entering the pad; hc is enthalpy of the air leaving the pad (kJkg^{-1}); Dpc is dew point temperature of air leaving the pad

Figure 3 Periodic variation in air properties for a typical three days period for the evaporative cooler



Note: q = cooling capacity (W); EFF = efficiency (%)

Figure 4 Periodic variation in cooler efficiency and cooling capacity for the cooler media

The relative humidity of the cooler was observed around 85.6% – 96.8% throughout the experiment, which shows the maximum possible level of saturation of air by humidification. Xuan et al., 2012 noted that 100% relative humidity was not achievable in direct evaporative cooling systems because 100% saturation is impossible. This is because the pad is loosely packed, and the process air can easily escape between the pads without sufficient contact with the water. In addition, the contact time between air and water is not long enough which results that heat and mass transfer might be insufficient (Manuwa and Odey, 2012). The cooler temperature was maintained at 23.2 – 25.8^{0}C and at this condition, the wet bulb temperature of the ambient ranged from 21.96 – 23.98^{0}C. During this period, the ambient temperature of the shade ranged from 29.9 – 37^{0}C while the relative humidity ranged from 34% – 73%. It was observed that the lowest temperature drop of 4^{0}C for the cooler occurred when the ambient relative humidity was highest at 73%. The enthalpy of the cold air ranges from 83.22 – 93.5–kJ kg^{-1} while the dew point temperature ranges from 22.15 – 23.85^{0}C (Figure 3).In addition, the cooling efficiency of the pad media ranged from 77%–98% while the cooling capacity ranged from 733 – 2529 W as shown in Figure 4.

The curve of cooling capacity and efficiency revealed that the higher cooling capacity and efficiency was achieved with the higher temperature and lower relative humidity of ambient air in the afternoon when the solar load is highest. This is desirable, because this is when much cooling is required due to the high solar load. At the above prevailing tropical condition, the active evaporative cooler was able to preserve freshly cut leafy pumpkin and amaranthus for more than eight days before visible colour changes was noticed which is the effect of micro-organism as a result of warmed up temperature in high relative humidity.

4 Conclusions

An active evaporative cooler was designed, developed and evaluated for its effectiveness in short-term storage of fruits and vegetables. The cooler was portable with a volume of 0.24 m^3. The developed evaporative cooler was able to drop the cooler temperature close to the wet bulb temperature of the ambient and increase the relative humidity to 96.8%. The cooler was tested with highly respiring cut pumpkin and amarnthus leaf and achieve favorable temperature and relative humidity for safe storage for 8 days.

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