Experimental Evaporative Coolers for Vegetable Preservation

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Abstract

Evaporative cooling is a well-known system to be an efficient and economical means for reducing the temperature and increasing the relative humidity in an enclosure. The high cost involved in developing cold storage or controlled atmosphere storage is a pressing problem in several developing countries. Many vegetables need high relative humidity (≥ 70%) with absolutely no exposure to direct heat or sunlight. Annual relative humidity in many parts of India ranges from 35% to 60%. Annual temperatures are also going high in many populated states of India.

Experiments are conducted on natural and forced updraft evaporative coolers. Coolers are made of G.I sheet of 0.5 mm thick. PUF is used as an insulation and it is placed between the G.I sheets in pressed condition to avoid air gap between G.I sheet and foam. Inner volume of each cooler is one cubic feet with a storing capacity of 1 to 1.5 kg of vegetables only.

Experiments are performed on natural draft and forced updraft evaporative cooler to understand the variations in relative humidity, temperatures and quantity of water evaporated in Pune. Shelf life of few vegetables and their important properties are also measured during experiments.

Observations are also compared with the vegetables kept in open air conditions inside and outside the room. Heat balance for actual quantity of water evaporated and heat transmission in evaporative cooler is made. Sensory evaluation of vegetables is also made after conducting the experiments. It is observed that to avoid the problem of shrinkage, wilting and to retain freshness evaporative cooling is a better option in tropical countries. Shelf life of minimum 4 to 5 days is observed for selected vegetables. Natural evaporative cooler performance is found better than the performance of forced updraft cooler.

Experiments are aimed to develop innovative cold storage test rig with the combined use of evaporative cooling, Thermal Energy Storage (TES) concept, ventilation and insulation. These experiments will certainly help to develop low cost cold storages for vegetable preservation at farm end in India.

1. Introduction

Much of the post-harvest loss of fruits and vegetables in developing countries is due to the lack of proper storage facilities. While refrigerated cool stores are the best method of preserving fruits and vegetables they are expensive to buy and run. Consequently, in developing countries there is an interest in simple low-cost alternatives, many of which depend on evaporative cooling which is simple and does not require any external power supply.

This system is based on the principle that when moist but unsaturated air comes in contact with a wetted surface whose temperature is higher than the dew point temperature of air, some water from the wetted surface evaporates into air. The latent heat of evaporation is taken from water, air or both of them. In this process, the air loses sensible heat but gains latent heat due to transfer of water vapour. Thus the air gets cooled and humidified. The cooled and humidified air can be used for providing thermal comfort. [1]

The efficiency of an evaporative cooler depends on the humidity of the surrounding air. Very dry air can absorb a lot of moisture so greater cooling occurs. In the extreme case of air that is totally saturated with water, no evaporation can take place and no cooling occurs. Evaporative cooling is a well-known economical system for vegetable preservation.

2. Evaporative Cooler Performance Parameters

There are four major factors that affect the rate of evaporation.

2.1 Relative Humidity

When the relative humidity is low, the air is capable of taking on additional moisture, and if other conditions are also met, the rate of evaporation will be higher. On the other hand, when the relative humidity is high, the rate at which water evaporates will be low, and therefore less cooling will occur. Under such conditions, evaporative cooling can be effective if a desiccant (e.g., silica gel) is used to remove moisture from the air before it is cooled.

2.2 Air Temperatures

Air with a relatively high temperature stimulates the evaporation rate and is also capable of holding a relatively great quantity of water vapor. With lower air temperatures, less water vapor can be held, and less evaporation and cooling will take place. Locations with high temperatures will thus have higher rates of evaporation, and more cooling will occur.

2.3 Air Movement

Air movement influences the rate of evaporation. As water evaporates from a surface it tends to raise the humidity of the air that is closest to the water's surface. If this humid air remains in place, the rate of evaporation will start to slow down as humidity rises. On the other hand, if the humid air near the water's surface is constantly being moved away and replaced with drier air, the rate of evaporation will increase.

2.4 Surface Area

The area of the evaporating surface is another important factor that affects the rate of evaporation. The greater the surface area from which water can evaporate the greater will be the rate of evaporation. A simple example will demonstrate the importance of surface area to evaporation; consider the following two situations. (1) One litre of water placed in a narrow glass container with only about 16 cm2 of surface area exposed to the air; and (2) another litre of water poured into a large shallow pan with about 180 cm2 of surface exposed to the air. If both are left under the same environmental conditions, the large pan of water would dry up much sooner because of the large surface area.

Even though each of these factors has its own separate and significant effect on the rate of evaporation, when combined, their impact is much greater. For example, the first two factors can be discussed together in terms of wet and dry-bulb temperatures. Under conditions where the difference between the wet and dry-bulb temperatures is great, the rate of evaporation will also be great. [3]

The performance of direct and indirect evaporation cooling systems can be assessed on the saturation efficiency (SE), defined as:

$$\varepsilon = \frac{(t_o - t_s)}{(t_o - t_{o,wbt})}$$

Where,
t_o and t_s the dry-bulb temperatures of the air at the inlet and outlet of the system as well as $t_{o,wb}$t, in as the wet-bulb temperature of air at the inlet of the system.

Generally the saturation efficiency of direct evaporative cooling ranges between 60-90%. Typical saturation efficiency values for indirect evaporative cooling systems are in the range of 60-80%. [5, 9]

3. Natural Draft Evaporative Cooler

The system is an enclosed system and air is allowed to pass only through the tray containing water. During this process the warm air will come in contact to comparatively large surface of water. Warm room air will exchange sensible heat to water and during evaporation of water part of latent and sensible heat will be taken from surrounding air causing temperature drop of 3°C to 4°C in the enclosure. To enhance effect of adiabatic evaporation of water insulated enclosure with defined height is provided to get the required updraft chimney effect. Increase in relative humidity of 15 to 25% is observed within the enclosure**.** [4]

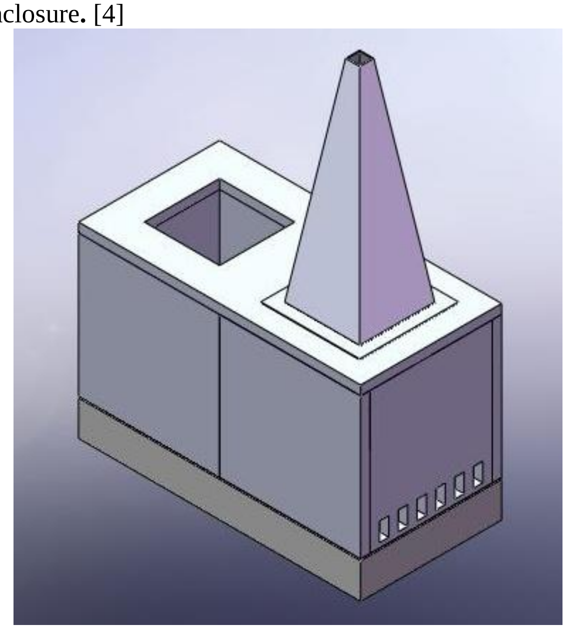


Figure 1. Combined Natural and Forced Updraft Evaporative Cooler

3.1 Thermodynamic Analysis of evaporation of water in Natural Draft Evaporative Cooler

Assumptions made:

1. The system is under steady state and isothermal conditions.
2. The total pressure within the system remains constant.
3. Air as well as water vapour behaves as an ideal gas.
4. There is a slight air movement over the top of tank/tray to remove water vapour which diffuses to that point; however, this movement does not disturb the concentration profile of air in the tank.
5. The water concentration at the surface of water is much more compared to that at the top of the tank (i.e., Cw1> Cw2 or Ca2 > Ca1)

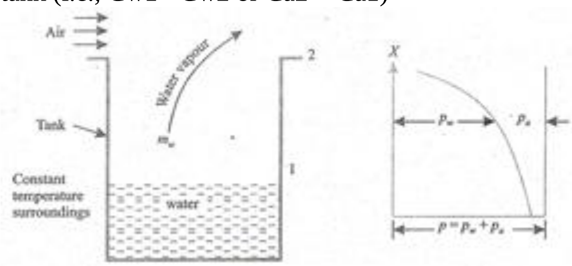


Figure 2. Diffusion of water vapour in air

$$(\dot{m}_w)_{total} = \frac{DAM_w}{G.T} \cdot \frac{p}{(x_2 - x_1)} \ln \left[\frac{p - p_{w2}}{p - p_{w1}} \right]$$

Where,

D= Mass Diffusivity m^2/sec

A= Surface Area in m^2

M_w= Molecular Weight of water

G= Universal Gas Constant

T= Dry Bulb Temperature

P= Atmospheric Pressure

P_{w1}= Partial Pressure of water Vapor at x_1

Pw_2= Partial Pressure of water Vapor at x_2 [8]

$(\dot{m}_w)_{total}$ = Quantity of Water Evaporated in kg/sec

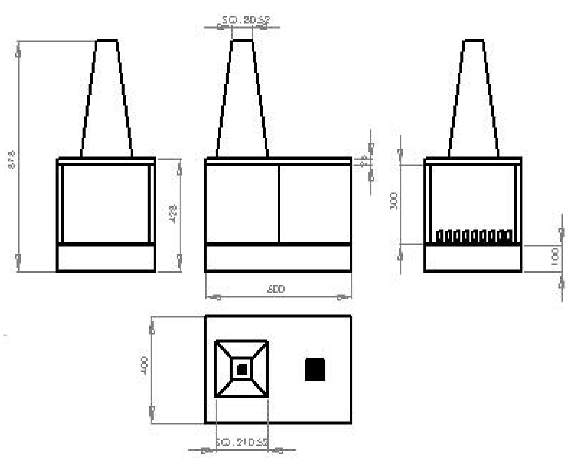


Figure 3. Drawing of Combined Evaporative Cooler

Left Side Chamber: Natural updraft Evaporative Cooler

Right Side Chamber: Forced Updraft Evaporative Cooler

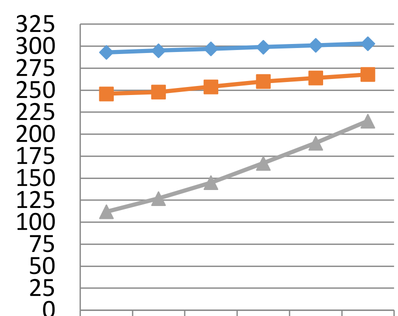
Insulation: PU Foam

Both coolers on mounted on trays containing known quantity of water. MS gauze is placed between trays and coolers to store vegetables on top of it.

Table 1. Experimental results to determine ac tual quantity of water evaporated in Natural Draft Evaporative Cooler

Date	Room RH %	RH % inside Cooler	Water Evaporated
24 & 25 Jan 12	56%	72%	110g (**300g**)
26-28 Jan 12	52%	70%	150g (**600g**)
29-30 Jan 12	45%	68%	160g (**1000g**)

Graph 1 Water Evaporated w.r.t Avg Room Temp & Mass diffusivity



	1	2	3	4	5	6
Avg Room Air Temp K	293	295	297	299	301	303
Mass Diffusivity X E-7 Sq.m	246	248	254	260	264	268
Qty of Water evaporated gm	112	127	145	167	190	215

3.2 Heat Balance/Thermal analysis

PU Foam = 20 mm thick, G. I Sheets = 0.8 mm thick, Average t_0 = 20°C, Average t_i = 17.5°C, k_{foam}=0.025w/mk, $k_{G.I}$= 55w/mk, ho= 12 w/m^{2}k, hi= 16 w/m^{2}k

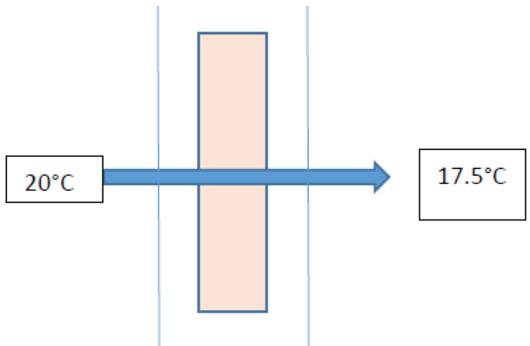


Figure 4. Heat Transmission through wall

Q = U. A. (to – ti) .. Watts

Q = 1.058. 0.568. (2.5) = 1.5 ≈ 2 w

Heat penetrated in a day = 2J/s. 24. 3600 = 172.8 kJ
Amount of heat absorbed by evaporating140 gram of water:
1 gm. of water evaporated = 2.466 KJ is absorbed.
Hence, 140 gm. of water = 345 KJ heat is absorbed/Day [6]

Table 2. Heat balance

Heat Absorbed .. KJ	Heat Removed .. KJ
345 KJ	1) Transmission Heat = 172.8 KJ
	2) m. Cp △ t = 10KJ (Veg)
	3) m. Cp. △ t = 12.6KJ (water)
	4) 345 – (1+2+3) = 345 – 195.4 = 149.6 KJ Heat Loss

3.3 Important Observations:

Vegetables kept in Natural Updraft Cooler found better than open room conditions.
Controlled near adiabatic saturation conditions are possible.
Shelf life of 6 to 7 days is observed for Cauliflower and Cabbage.
For cut Cauliflower & Cabbage shelf life is reduced to 3 to 4 days.

4. Forced Updraft Evaporative Cooler

The system is an enclosed system with 1 ft^{3}volume inside. PU Foam is used as an insulation. Construction is similar to Natural Draft Cooler only the chimney is replaced by fan. Air near the tray containing water is sucked with the help of fan to enhance the effect of adiabatic evaporation. Quantity of water evaporated is increased but increase in relative humidity of 10 to 12% is only observed within the enclosure.

Figure 5. Forced Updraft Cooler

Figure 6. Vegetable Storage on tray

Gauze is placed above the tray containing known quantity of water. Vegetables are placed over a gauze.

4.1 Thermodynamic Analysis

Assumptions made:

1. The system is under steady state and isothermal conditions.
2. The total pressure within the system remains constant.
3. Air as well as water vapor behaves as an ideal gas.
4. Air flow steadily over water surface at constant velocity.

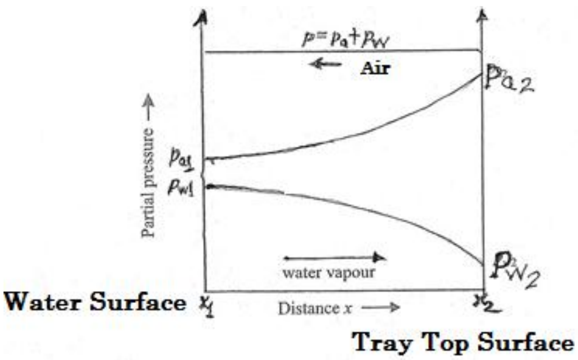


Figure 7. Distribution of partial pressures of water vapor and air

$m_w = h_{mp} . A. (p_{w1}- p_{w2})$ …. Kg/sec

where,

h_{mp} = Mass Transfer Coefficient based on pressure difference.

A= Surface area of water

P_{w1} = Partial Pressure of water vapor at x_1

P_{w2} = Partial Pressure of water vapor at x_2

m_w = Mass of water evaporated in kg/sec [8]

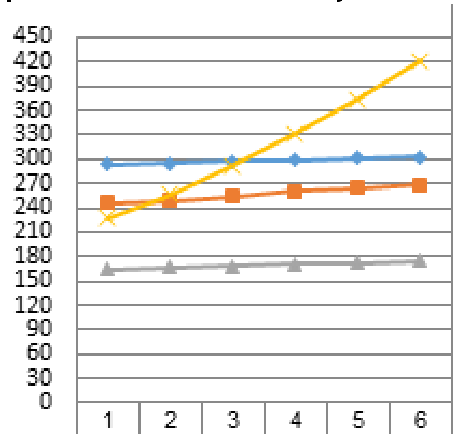
Table 3. Experimental results to determine actual quantity of water evaporated in Forced Up-Draft Evaporative Cooler

Date & Time 10 AM	RH % at Room	RH % Inside Cooler	Water Evaporated in 7 Hr
24 & 25 Jan 12	46%	65%	180g **(300g)***
26-28 Jan 12	48%	62%	210g **(500g)***
29-30 Jan 12	42%	52%	245g **(500g)***

- Bracket quantity is the water available in Tray
- Atm. Pr.= 0.93725 bar, Air Velocity = 1m/sec

Forced updraft cooler consumes more power than forced downdraft cooler. Loss of moisture from vegetables is observed in forced updraft cooler. Retainment of relative humidity within the enclosure is difficult in forced updraft evaporative cooler. Continuous non-interrupted power supply is necessary in forced updraft evaporative cooler. But, laminar flow ventilation within enclosure is possible by using forced updraft cooler.

Graph 2. Water Evaporated w.r.t Average Room Air temperature & Mass Diffusivity



	1	2	3	4	5	6
Avg room air Temp	293	295	297	299	301	303
Mass Diffusivity E -7Sqm/sec	246	248	254	260	264	268
Kinematic Viscocity Sq.m/sec	164.2	166.2	168.3	170.3	172.6	174.8
Water Evaporated gm in 7 Hours	227	257	292	332	374	422

Graph 2 indicates that amount of water evaporated will increase with rise in air velocity and average room air temperature. But, increase in absolute humidity within the enclosure is difficult for given air velocity in Forced Updraft Evaporative Cooler. Both, increase in air velocity and average room temperature will enhance the mass diffusivity.

Table 4. Sensory Evaluation after 7 days (5-12 February 2012)

Natural Draft Cooler (Area =0.210 Sq.m)	Forced Draft Cooler Area= 0.095 Sq.m	Open Room	Open Room Cut Vegetables

Water Evapora-ted 150-190 gm in 24 Hours	Water Evaporated 240-310 gm in 7 Hours(v =1 m/sec)	Avg Room Temp Variations 18°C - 22°C	Avg Room RH% 25-45%
Cabbage & Flower more hard, Better	Cabbage & Flower became Soft, Separation, Not O.K	Blackening Spots 20% on Flower & Soft, Cabbage 10% Yellowish	Moisture Loss More, 70% Wastage or Loss, No Fres-hness

Condition of Vegetables after 7 Days in Coolers

Figure 8.
a) Natural Up-Draft Cooler b) Forced Up-Draft Cooler

Figure 9. Condition of Vegetables after 7 Days kept in Open Room

5. Conclusion

Lower RH% & Higher Temp lead to more moisture loss in vegetables. It will result into shrinkage, wilting and loss of freshness. Higher RH% and higher temperature lead to rottening of vegetables. It will make vegetables more susceptible to the attack of micro-organisms. For given conditions performance of Natural draft Cooler is found better than Forced Draft Cooler. Experimental results ascertain the fact that keeping low temperature of 15°C +/- 2°C and RH 70 – 80% will definitely enhance the shelf life of vegetables for all seasons. Findings are useful to construct innovative low cost cold storage for vegetable preservation with combined concepts of evaporative cooling, thermal energy storage and passive insulation.

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