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Design of Sintered Zeolite Evaporative Cooling System

Luh Putu Ike Midiani [a]
Made Ery Arsana [b]
I Nyoman Gunung [c]

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Abstract

An evaporative cooling system for fruit and vegetable was designed, fabricated, and evaluated in this study. The evaporative cooling system is made of plywood covered with steorofoam. The inside system is made of plywood with dimensions of 30 cm x 30 cm x 30 cm. The inside of the box is covered with steorofoam with a thickness of 2 cm on the front, sides and back. The cooling pad in this evaporative cooling system is sintered zeolite. Sintering zeolite is a new material used to optimize evaporative cooling systems. One suction fan to draw environmental air through the cooling pad and into the controlled room. There is a water reservoir used to collect cooling water and place a cooling water circulation pump. The pump lifts water from the reservoir then sprays the cooling pad through the pipe and then the water is stored back in the reservoir. As water drips through the cooling pad, the suction fan keeps the air moving and blowing through the cooling pad. When passing through the cooling pad, the evaporation process occurs, and the cooling effect takes place. The evaporative cooling system with sintered zeolite cooling pad is capable of controlling temperatures up to 28oC relative to an ambient temperature of 30oC with a relative humidity of up to 94%, compared to a relative humidity value of around 78%. The cooling efficiency of the evaporative cooling system with sintered zeolite cooling pad is evaluated on average to be 82.6%.

Corresponding author:
Luh Putu Ike Midiani,
Mechanical Engineering Department, Bali State Polytechnic, Kampus Bukit Jimbaran,
Badung, Bali 80361, Indonesia.
Email address: putuikemidiani@pnb.ac.id

[a] Mechanical Engineering Department, Bali State Polytechnic, Kampus Bukit Jimbaran, Badung, Bali 80361, Indonesia
[b] Mechanical Engineering Department, Bali State Polytechnic, Kampus Bukit Jimbaran, Badung, Bali 80361, Indonesia
[c] Mechanical Engineering Department, Bali State Polytechnic, Kampus Bukit Jimbaran, Badung, Bali 80361, Indonesia

1 Introduction

Harvested fruits and vegetables that are stored at ambient temperatures with natural humidity in hot areas will spoil quickly, due to the high evaporation of water. Evaporation is active when the surrounding air moves against the flow or natural convection motion (Babaremu et al., 2018; Aste et al., 2017; Tambunan et al., 1999). Environmental air temperature, relative humidity in the air, water temperature and wind speed are factors that are closely related to the occurrence of evaporation. Good storage and preservation methods are needed so that fruits and vegetables avoid evaporation of their moisture content and will last longer (Aked, 2002; Bodbodak & Moshfeghifar, 2016). One way to increase the shelf life of fruits and vegetables is to lower the temperature and maintain the humidity of the storage environment. However, temperatures that are too low can cause damage to harvested fruits and vegetables. As soon as the product leaves the storage space, the breakdown process will start again. Humidity that is too high is also not good for harvested fruits and vegetables. Humidity is too high, causing water to condense on top of fruits and vegetables, increasing spoilage. Thus keeping the product at the lowest safe temperature (0 °C for temperate crops or 10-12 °C for cold sensitive crops) will increase shelf life by lowering respiration rates, lowering sensitivity to ethylene gas and reducing water loss (Zakari et al., 2016; lal Basediya et al., 2013; Krishnakumar, 2002).

Most farmers do not have the financial capacity to purchase and maintain air conditioning machines. Inadequate electricity supply for cold storage and inadequate transportation facilities to bring produce to market are serious obstacles to saving fruit and vegetables from heat spoilage. As a result, there are sharp differences in food supplies between harvest and post-harvest periods. Thus, fruit and vegetable yields are cheap during the harvest season but expensive when yields are scarce. But locally available cold storage will be able to help reverse this trend. Storage of harvested fruit and vegetables in rural areas requires storage of simple and low-cost alternatives, such as simple evaporative cooling systems. Evaporative cooling is one of the oldest and simplest traditional cooling methods. Evaporative cooling system is more environmentally friendly and consumes less energy, can be an alternative to replace vapor compression system (Nkolisa et al., 2018). Evaporative cooling systems generally consist of a porous material that is permeated with water. Hot, dry air is drawn over the porous material. The process of heat and mass transfer will occur when air is in contact with water. The air temperature will decrease with the change of sensible heat into latent heat, i.e. a large amount of heat is transferred from the air to the water to change the water phase to the vapor phase. Increasing the relative humidity of the storage environment will slow down the rate of water loss. The best method to increase relative humidity is to lower the temperature (Ikechukwu-Edeh et al., 2021; Vakiloroaya et al., 2014). Therefore, the aim of this study was to design an evaporative cooling system for the temporary storage of harvested fruits and vegetables in order to increase shelf life before distribution (Ali, 2020; Shashua-Bar et al., 2009).

2 Materials and Methods

Design Principles

The working principle of the evaporative cooling system is the process of converting sensible heat into latent heat. The warm, dry outside air is forced through the pores of the wetted cooling pad. The air passing through the wetted cooling pad is drawn by the suction fan from the environment. Sensible heat is warm and dry air from the ambient that passes through the wetted cooling pad and eventually turns into latent heat due to the evaporation of water that cooling the air (lal Basediya et al., 2013; Amer et al., 2015; Camargo, 2008). To design an evaporative cooling system, several things need to be considered, such as: durability and efficiency of the system, surface area for air movement, incorporation of a water recirculation system for system cohesiveness (Babaremu et al., 2018).

Design Considerations

The design of an evaporative cooling system is carried out by considering the following points [1]:

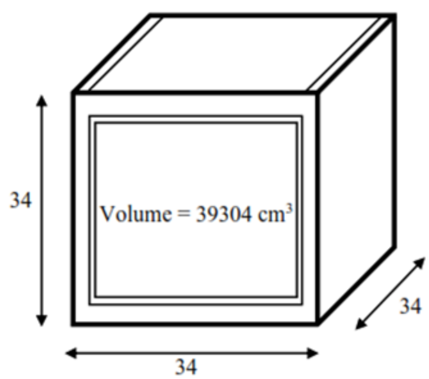
a. System efficiency and durability
b. Surface area for air movement
c. Minimized space for incorporation of water circulation system

Furthermore, the evaporative cooling system design must also be determined:

1. Type of product stored: Tomato
2. Capacity of storage space: 1 kg
3. Storage space cooling load. Cooling load is the amount of heat that must be removed from a room to maintain the temperature of the room so that it is as desired. Calculation of the cooling load involves considering various parameters such as:
   a. Optimal storage temperature: 10 - 20°C
   b. Optimum relative humidity (%) : 85-95%
   c. Approximate cold storage: 1-2 weeks
   d. Ambient conditions: 30°C and 70 % RH

Evaporative cooling system specifications consist of

a. Internal dimensions of cold storage
   Length = 30 cm
   Width = 30 cm
   Height = 30 cm
   Total internal volume = (30 cm x 30 x 30) cm = 27000 cm^3
b. External dimensions of cold storage
   Insulation thickness: 2 cm
   Length = 30 cm + (2 x 2) cm = 34 cm
   Height = 30 cm + (2 x 2) cm = 34 cm
   Width = 30 cm + (2 x 2) cm = 34 cm
   Total external volume = 39304 cm^3
c. External dimensions : 34 x 34 x 34 cm^3
d. Maximum ambient temperature : 30°C
e. Storage room temperature : 20°C



Cooling Load

a. Heat transfer through walls
   If the flow is assumed to be steady, then the heat flow is [8]:

$$Q = UA(T_o - T_i) Kcal/h$$

Where:
U = total heat transfer (Kcal/m^3 hr °C)
A = heat transfer surface area (m^2)

T_o = environment temperature (ºC)
T_i = environment temperature (ºC)
Overall heat transfer coefficient:

$$u = \frac{1}{\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \cdots \frac{1}{h_i}}$$

Where:
h_o = heat transfer coefficient on the outer surface
hi = heat transfer coefficient on the inner surface
x_1, x_2 = wall thickness and insulation material (cm)
k_1, k_2 = thermal conductivity of the wall and insulating material (Kcal/m. hr. ºC)

Thick wall and low conductivity, resistance x/k make the value of u so small that 1/hi and 1/ho have little effect and can be omitted from the calculations. The u value for various types of walls and ceilings ranges from 1.00 to 4 Kkal /m^2.hr. °C [8].

a. Surface area = A = 2 x (34 x 34) = 2312 cm^2 (Length, wide)
b. Total surface area = 4624 cm^2 = 0.462 m^2
c. Environment temperature (T_o) = 30 ºC
d. Room temperature (T_i) = 20 ºC
e. Thickness of the plywood = 2 cm = 0.02 m
f. Thermal conductivity of plywood = 0.112 W/m.ºC
g. Thickness of the steorofoam = 2 cm = 0.02 m
h. Thermal conductivity of steorofoam = 0.033 W/m.ºC

Overall heat transfer coefficient:
1/u = (0.02/0.112) + (0.02/0.033) = 0.179 + 0.61
u = 0.785 W/m^2.ºC
Heat transfer through the building materials:

$$Q = 0.785\ x\ 0.4624\ x\ (30 - 20) x 24$$
$$Q = 87.12 \frac{watt}{24h}$$

b. Heat transfer through the top
   a. Surface area = A = 34 x 34) = 1156 cm^2 = 0.116 m^2
   b. Thickness of the plywood = 2 cm = 0.02 m
   c. Thermal conductivity of plywood = 0.112 W/m.ºC
   d. Thickness of the steorofoam = 2 cm = 0.02 m
   e. Thermal conductivity of steorofoam = 0.033 W/m.ºC

   Heat transfer through the top :

$$Q = 0.785\ x\ 0.116\ x\ (30 - 20)\ x\ 24$$
$$Q = 21.85 \frac{watt}{24h}$$

c. Heat transfer through the bottom
   a. Surface area = A = 34 x 34) = 1156 cm^2 = 0.116 m^2
   b. Thickness of the plywood = 2 cm = 0.02 m
   c. Thermal conductivity of plywood = 0.112 W/m.ºC
   d. Thickness of the steorofoam = 2 cm = 0.02 m
   e. Thermal conductivity of steorofoam = 0.033 W/m.ºC

   Heat transfer through the bottom:

$$Q = 0.785\ x\ 0.116\ x\ (30 - 20)\ x\ 24$$

$$Q = 21.85 \frac{watt}{24h}$$

d. Total heat transfer

$$Total\ heat\ transfer = heat\ transfer\ through\ walls + top + bottom$$
$$Q = 130.82 \frac{watt}{24h}$$

e. Product load[14]
Product cooling = weight of the product x specific heat of product x temperature difference
= 1 kg x (3985.1 J/kg °C) x (30-20)
= 9516.4 Kal/24 h

f. Respiration load during cooling [14]
Average temperature = (30 + 20) / 2 = 25 °C
Respiration heat load = weight of the product x heat respiration
= 1 kg x 0.086 W/kg = 73.94 Kal/h

g. Total heat load = heat transfer through surface + product cooling + respiration load
= 130.82 + 9516.4 + 73.94 = 9721.16 Kal / 24 h

h. Miscellaneous load calculation
Service load can be taken as 10 per cent of the total i.e., lights, fans, etc. Therefore, total heat load during cooling = 10693.28 Kal / 24 h
The overall heat load = 10693.28 + 1069.328 = 11762.6 Kal / 24 h

i. Total heat load calculation
Assuming refrigeration operates for about 16 hours/ day, the refrigeration capacity
requirement = 11762.6 / 16 = 735.16 Kal / 24 h
= 3.078 kJ / 24 h = 0.0356 W

j. Volume of reservoir
The water distribution consists of pipes, water tanks and water pumps. The reservoir volume is provided to keep the water pump submerged, hence the reservoir volume
= 30 x 30 x 15 = 13.5 liter

k. Design and selection of suction fan
The determination of fan capacity was in equation [6]:
Fan capacity = 8 cfm/sqft × bottom area
= 8 cfm/sqft × 1.25 sqft = 10 cfm
Factor of safety is 10% of fan capacity given as = 10% x 10 = 1 cfm
Required fan capacity = 10 + 1 = 11 cfm

Description of Evaporative Cooling Systems

The evaporative cooling system is mostly made of plywood covered with steorofoam. The inside is made of plywood with dimensions of length 30 cm x width 30 cm x height 30 cm. The inside of the box is covered with steorofoam with a thickness of 2 cm on the front, sides and back. Furthermore, steorofoam and the outside of the box are coated with aluminum insulation to increase reflectivity and reduce the rate of heat absorption. One suction fan with a size of 15 cm x 15 cm, 35 watts, speed of 2750 RPM is used to draw environmental air through the cooling pad and into the controlled room (Farfán et al., 2022; Riangvilaikul & Kumar, 2010). There is a water reservoir with a capacity of 9.75 liters which is used to store cooling water and place a cooling water circulation pump. An 8 watt electric pump lifts water from the reservoir then sprays the cooling pad through a PVC pipe with an inner diameter of 1.5 cm, then the water is collected again in the reservoir. Cooling pads are held in place with wire mesh to allow air to pass through the pads easily. The cooling pad material is sintered zeolite powder, cylindrical in shape. Figures 1, 2 and 3 show the schematic diagram, evaporative cooling system and zeolite sintering cooling pad respectively (Cuce & Riffat, 2016; Farfán et al., 2021).

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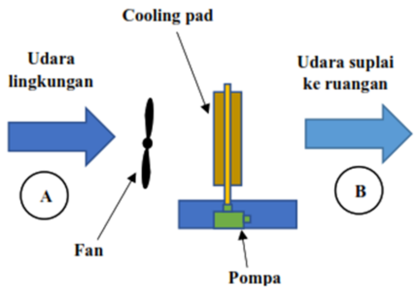

Figure 1. Schematic of evaporative cooling system

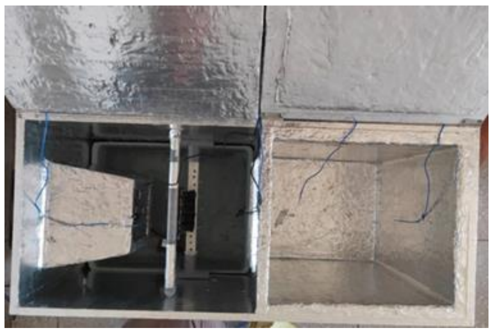

Figure 2. Evaporative cooling system

Figure 3. Sintering zeolite cooling pad

3 Results and Discussions

Testing of Evaporative Cooling Systems

The performance of the evaporative cooling system is tested to determine the effect of evaporation, its effectiveness and efficiency before being filled with vegetables or fruit to be stored. Tests include measurements of humidity, ambient air temperature and conditioned room temperature. The effectiveness of the sintering zeolite cooling pad is based on the cooling saturation efficiency (SE). The cooling efficiency for sintering zeolite is calculated using the following formula (Zakari et al., 2016):

$$SE = \frac{T_{1(db)} - T_{2(db)}}{T_{1(db)} - T_{1(wb)}}$$

Where:
$T_{1(db)}$ = dry bulb outdoor temperature, ^oC
$T_{2(db)}$ = dry bulb cooler temperature, ^oC
$T_{1(wb)}$ = wet bulb outdoor temperature, ^oC

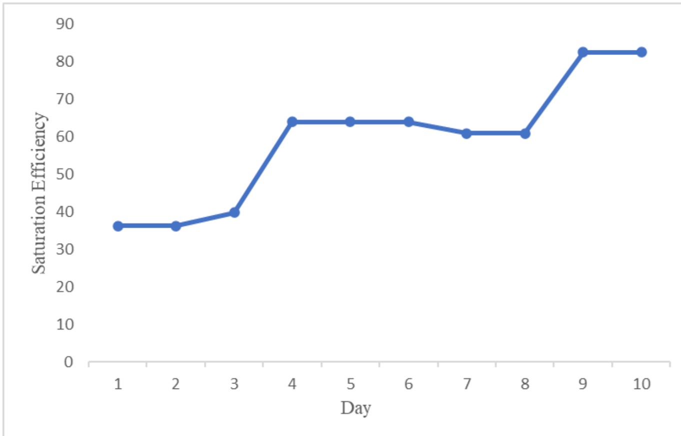

Figure 4. Saturation Efficiency of the Evaporative Cooling System

From Figure 4, it can be concluded that the no-load evaporative cooling system is capable of achieving fairly high cooling efficiency within ten days of no-load performance evaluation. The evaporative cooling system is able to achieve a cooling efficiency of 82.6%, this shows that the evaporative cooling system is very effective so it is worth testing using a load (Rehman & Mohandes, 2008; de'Gennaro et al., 2003).

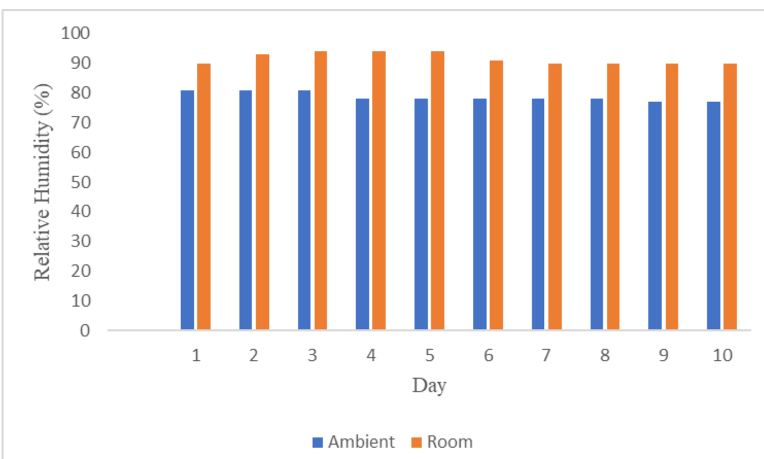

Figure 5. Relative humidity of ambient and cooler room

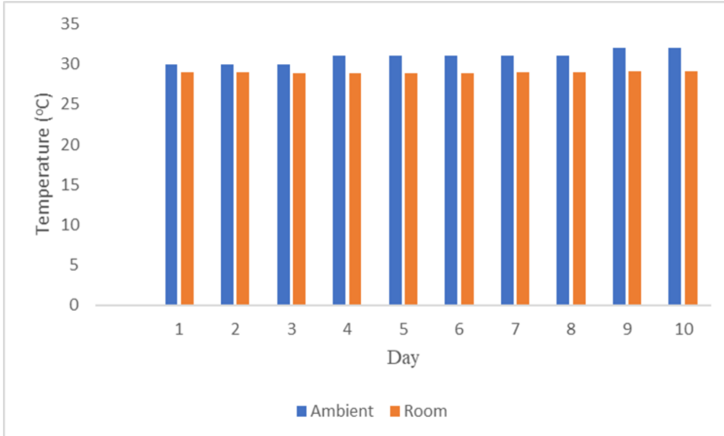

Figure 6. Temperature of ambient and cooler room

Figure 5 shows the results of measuring relative humidity using a digital hygrometer. Measurement of environmental relative humidity and conditioned room humidity is carried out at no-load conditions. Analytically, the evaporative cooling system shows an increase in relative humidity in the conditioned room compared to the surrounding environment. Figure 6 shows relative humidity of the evaporative cooling system ranging from 78 to 94%, which is in good agreement with ASHRAE (Handbook, 1996). ASHRAE states that the relative humidity required for storing vegetables ranges from 85 to 90%, if the relative humidity is below, it will reduce the shelf life of fresh vegetable storage (Nikolajsen et al., 2006; Hänel, 1976).

The temperature of the conditioned environment and room was measured using a digital thermometer. Measurement of ambient temperature and conditioned room temperature is carried out at no-load conditions. The results of temperature measurements are shown in Figure 6. ASHRAE recommends storing fruits and vegetables between 16 and 25 °C with an ambient temperature of 17 and 28 °C. It can be calculated that the temperature difference between the environment and the storage room is around 1-3ºC. Figure 3 shows the temperature difference between the environment and storage room ranging from 1-3ºC. These results indicate that the evaporative cooling system that has been made refers to ASHRAE (Handbook, 1996). This implies that evaporative cooling systems with higher relative humidity than ambient conditions can be recommended for fruit and vegetable storage (Hatfield & Prueger, 2015; Atkin & Tjoelker, 2003).

4 Conclusion

The designed evaporative cooling system was successfully made by utilizing zeolite sintering as a cooling pad. The evaporative cooling system e has been tested according to the specified standards and produces good and appropriate performance. So this evaporative cooling system can be recommended as a fruit and vegetable storage.

Conflict of interest statement
The authors declared that they have no competing interest.

Statement of authorship
The authors have a responsibility for the conception and design of the study. The authors have approved the final article.

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