Development of a computer model simulation for predicting the performance of a near infrared reflecting charcoal cooler for on farm storage of mangoes

M. K. Korir, U. Mutwiwa, G. M. Kituu, D. N. Sila

Abstract— Mango (*Mangifera indica L.*) fruit is a valuable fruit in Kenya due to its nutritive value and economic importance. However, at least 40 to 45% of mango fruit is lost during post-harvest handling primarily due to inadequate storage facilities for mango fruit preservation. In this study an improved evaporatively cooled store was developed. The external surfaces of the cooler were sprayed with near infrared reflecting paint (NIR). The mixing ratio of NIR paint and water was 1:2. The dimensions of the cooler were 0.84m x 0.84m x 1.5m. The cooler had a storage space of 0.75m^3 and was constructed from locally available materials including hardwood and charcoal. A 12V fan was used to draw air into the cooler. The charcoal was kept moist by water dripping by gravity from horizontally laid pipes on the roof. A computer simulation model for predicting the performance of the cooler was developed on java platform. The input parameters of the model were inlet air conditions, water conditions and charcoal cooler characteristics. The output parameters of the model included saturation efficiency, dry bulb temperature of the inlet air and cooling capacity. The predicted performance parameters of the cooler included saturation efficiency which ranges from 66.87% to 68.97%, dry bulb temperature of the outlet air which ranges from 24.54ºC to 24.67ºC and cooling capacity which ranges from 105726.44kW/h to 136680.9kW/h. The model results showed that saturation efficiency decreases with increase in inlet air velocity while the cooling capacity increases with increase in inlet air velocity.

Keywords— Computer model simulation, mango fruits, near infrared reflecting charcoal cooler.

I. Introduction

Mango (*Mangifera indica L.*) is an adaptable fruit tree in Kenya, suitable for different agro-ecological zones ranging from sub-humid to semi-arid [1]. Mango tree thrives well at 0 to 1500m above sea level in Kenya although it can grow in higher elevations [2]. In Kenya, an output of 280,884Mt of mango fruit is produced at an estimated production area of 14,387 Ha [3]. Coast and the semi-arid districts of Eastern Kenya are the main production areas of mangoes. Mango fruit is known for its nutritive value and economic importance. It is a potential source of income for resource poor farmer. It is also a source of raw material for industries and foreign exchange earner. However, mango fruits are riddled with challenges along the post-harvest chain. At least 40 to 45% of the fruit is lost along the post-harvest chain [4]. Mechanical damage (bruises), pests and diseases and immature harvesting are the causes of losses. Post-harvest losses are also due to inadequate storage facilities for mango fruits preservation during peak harvesting periods. It is possible to develop effective storage systems and used them to reduce the losses thus improving the net returns for the resource poor farmers [5]. An effective storage of the produce can be achieved by controlling the storage environment. The critical parameters in the modern storage systems include; temperature, moisture and humidity, air velocity, lighting, odour, and pressure [6]-[7]. During storage, it is important to ensure the produce stored is of good quality and free from damages or diseases. Damaged or diseased fruits respire rapidly and consequently produce more heat. In addition, the fruits are exposed to microbial attack [8].

II. Methodology

A. Development of a near infrared reflecting (NIR) charcoal cooler

An improved evaporatively cooled store suitable for preservation of mango fruits was developed and its performance tested in the Department of Biomechanical and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT). The cooler was constructed from locally available materials including hardwood posts (100mm x 50mm), hardwood strips (50mm x 25mm), charcoal, welded wire mesh of wire diameter of 0.24mm and wire spacing of 75mm, coffee tray mesh of wire diameter of 0.5mm and wire spacing of 5mm), and aluminium sheet of gauge 24 and thickness of 0.5mm. The external surfaces of the cooler were sprayed with near infrared reflecting paint (redusol). The mixing ratio of near infrared reflecting paint (NIR) to water was 1:2. The dimensions of the cooler were 0.84m x 0.84m x 1.5m and storage space of 0.75m^3. The cooler has two walls and a doom-shaped roof filled with charcoal layer 0.1m thick. The charcoal was kept moist by water dripping by gravity from a horizontally laid 12.7mm PPR (Polypropylene random copolymers) pipes on

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the roof. The excess water was collected by gutters located at the bottom of the walls and channeled to the water reservoir (Fig. 1). A 12V shurflo pump with a capacity of 13.2l/min and 2.7m head (model 2088-443-144; City, Mexico) was used to pump water from the reservoir to overhead tank approximately 2m from the ground. The amount of water used to moisten the charcoal was monitored using a 12.7mm multi-jet vane wheel dry type water flow meter. The air was drawn into the cooler by a 12V fan centrally located on one of the sides directly opposite the door. All the lateral sections of the walls were completely covered to ensure one direction flow of the inlet air. The variation in the inlet air velocity was achieved by the use of slide rheostat (Type, D-4; Amps, 8; Ohms, 2.8; No, Y-95; Yambishi Electric Co. Tokyo Japan) connected in series with the fan. The air velocity was measured using EMPEX digital electronic anemometer wind Messe (model FG-561, Japan). The dry bulb temperature and relative humidity of the inlet air was measured using Tinytag Ultra 2 data logger (model TGU-4500, Gemini Data Loggers Limited, United Kingdom). The fan and the pump draw power from a 70Ah battery being re-charged by a 125W solar panel. A charge controller (Apple 15, Sundaya International/Singapore) was used to control the battery from overcharging.

B. Computer model development

A computer model for predicting the performance of the developed evaporative cooler was developed on java platform. The inputs parameters of the model were inlet air condition, dry bulb temperature (°C), wet bulb temperature (°C), specific humidity (kg/kg of dry air) and velocity (m/s); water condition, water temperature (°C) and water flow rate (l/s); charcoal cooler characteristics, length of the evaporative pad (m), evaporative pad thickness (m), height of the evaporative pad (m) and wetted area per unit volume of charcoal material (m^2/m^3). The output performance parameters of the cooler predicted by the model included saturation efficiency (%), outlet air dry bulb temperature (°C) and cooling capacity (kW/h). The dry bulb temperature and specific humidity of the inlet air were measured on hourly basis from 8a.m to 6p.m. Wet bulb temperature and specific humidity were computed using psychometric calculator. The air properties were evaluated at the selected condition D (Table I).

C . Ambient condition

Daily dry bulb temperature (T_{db}) and relative humidity (RH) data of Jomo Kenyatta University of Agriculture and Technology (JKUAT), Juja, Kenya (latitude, -1.1°; longitude, 37.02°; altitude, 1211m above the sea level) for the month of January, February and March were collected and grouped into 5 categories. The most occurring ambient condition D of mean maximum T_{db} of 30.5°C and RH of 60% were selected for analysis. All air properties were evaluated based on this condition (Table II).

TABLE II
AIR PROPERTIES AT AMBIENT CONDITION D

Air properties	
cpa	1005J/kgK
cpv	1865J/kgK
Ka	0.02644W/mK
Pr	0.7135
v	$16.09\times10^{-6}m^2/s$
d	$1.164kg/m^3$

D Geometrical dimensions of the evaporative pad and set up

Fig. 1 shows geometrical dimensions of the charcoal pad. The arrangement of the pads and the flow of air in the cooler is represented in Fig. 2. The ambient air was blown horizontally through one side of the pad and exit on the other side

E. Mathematical formulations

The area through which air enters the pad is taken as face area. The total face area of the two pads is determined based on equation 1.

$$A_{ft} = 2(L \times H) \quad (1)$$

A_{ft} = total face area through which the air enters the pads (m^2); L = length of the pad (m); H = height of the pad (m)
The total volume of the pads is given by,

$$\vartheta = 2(L \times H \times I) \quad (2)$$

ϑ = total volume of the pads (m^3); I = thickness of the pad (m)
Total wetted surface area for the charcoal pads can be determined using equation 3.

$$A_w = \vartheta \times A_v \quad (3)$$

A_v = wetted area per unit volume of charcoal material (m^2/m^3)

TABLE I
WEATHER DATA OF JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY, JUJA, KENYA FOR THE MONTH OF JANUARY, FEBRUARY AND MARCH, 2013

Ambient condition	Maximum, T_{db} (°C)	Total days	Mean Maximum, T_{db} (°C)	Mean RH (%)	Mean T_{wb} (°C)
A	Below 25.5	3	24.1	80.6	21.5
B	25.6 to 27.5	9	26.4	76.4	23.2
C	27.6 to 29.5	23	28.7	66.8	23.9
D	29.6 to 31.5	35	30.5	60	24.4
E	Above 31.6	20	32.2	52.4	24.6

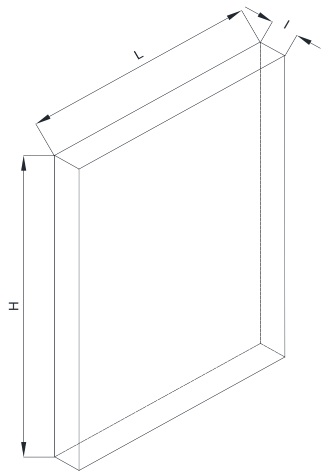

Fig.1 Evaporative pad dimension

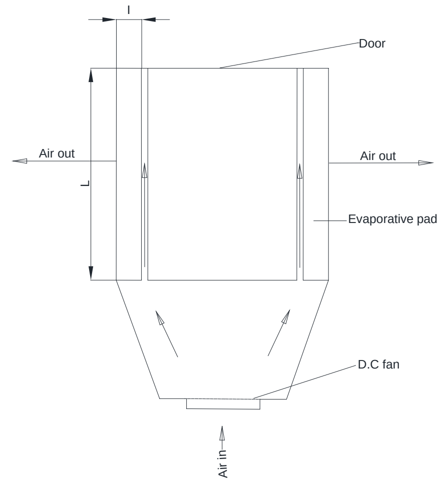

Fig. 2 Top view of the charcoal cooler showing evaporative pads set up and air flow

= 500m^2/m^3; A_w = total wetted area for the charcoal pads (m^2).

Characteristic dimension is given by,

$$l_c = \frac{\vartheta}{A_w} \qquad (4)$$

l_c = characteristics dimension (m)

Heat transfer coefficient can be determined using equation 5 [9].

$$Nu = 0.10\left[\frac{l_c}{l}\right]^{0.12} \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.33} \qquad (5)$$

Nu = Nusselt number (dimensionless); Re = Reynolds number (dimensionless); Pr = Prandtl number (dimensionless)

Reynolds number is given by equation 6 [10]

$$\mathrm{Re} = \frac{v_a l_c}{v} \qquad (6)$$

v_a = air velocity of air through the charcoal pad (m/s)

Saturation or cooling efficiency is evaluated using equation 7 [9]

$$\eta = \left[1 - \exp\left(-\frac{h_c A_c}{m_a c_{pu}}\right)\right] * 100 \qquad (7)$$

η = saturation or cooling efficiency (%); m_a = mass flow rate of air through the pad (kg/s); c_{pu} = specific heat of humid air (J/kgK).

c_{pu} is given by,

$$c_{pu} = c_{pa} + wc_{pv} \qquad (8)$$

c_{pa} = specific heat of air (J/kgK); c_{pv} = specific heat of the water vapour (J/kgK); w = specific humidity (kg/kg of dry air)

Dry bulb temperature of outlet air can then be calculated using equation 9 [10].

$$t_2 = t_1 - 0.01\eta(t_1 - t_{wbt}) \qquad (9)$$

t_1 = dry bulb temperature of the inlet air (°C); t_2 = dry bulb temperature of the outlet air (°C); t_{wbt} = wet bulb temperature of the inlet air (°C)

Cooling capacity of the cooler is evaluated based on equation 10 [10].

$$Q_c = m_a c_{pa}(t_1 - t_2) * 3.6 \qquad (10)$$

Q_c = cooling capacity (kJ/h)

III. Results and Discussion

Fig. 3 shows the developed near infrared reflecting (NIR) charcoal cooler loaded with mango fruits. This study focused on predicting the performance of the NIR charcoal cooler at no load condition based on computer model simulation (Fig. 4).

Fig.3 The near infrared reflecting (NIR) charcoal cooler loaded with mango fruits

The predicted saturation efficiency ranges from 66.87% to 68.97%. The Cooling capacity ranges from 105726.44kW/h to 136680.9kW/h. The dry bulb temperature of the outlet air ranges from 24.54°C to 24.67°C. The saturation efficiency and cooling capacity varies with inlet air velocity. The saturation efficiency decreases with increase in inlet air velocity. Figure 5 shows variation in saturation efficiency with inlet air velocity at one hour interval. Further, at higher velocities, air has lesser contact time with water causing less evaporation

[10]. The dry bulb temperature of the outlet air increases with decrease in saturation efficiency. The dry bulb temperature of the outlet air is directly affected by the saturation efficiency [10]. The cooling capacity increases with increase in air velocity.

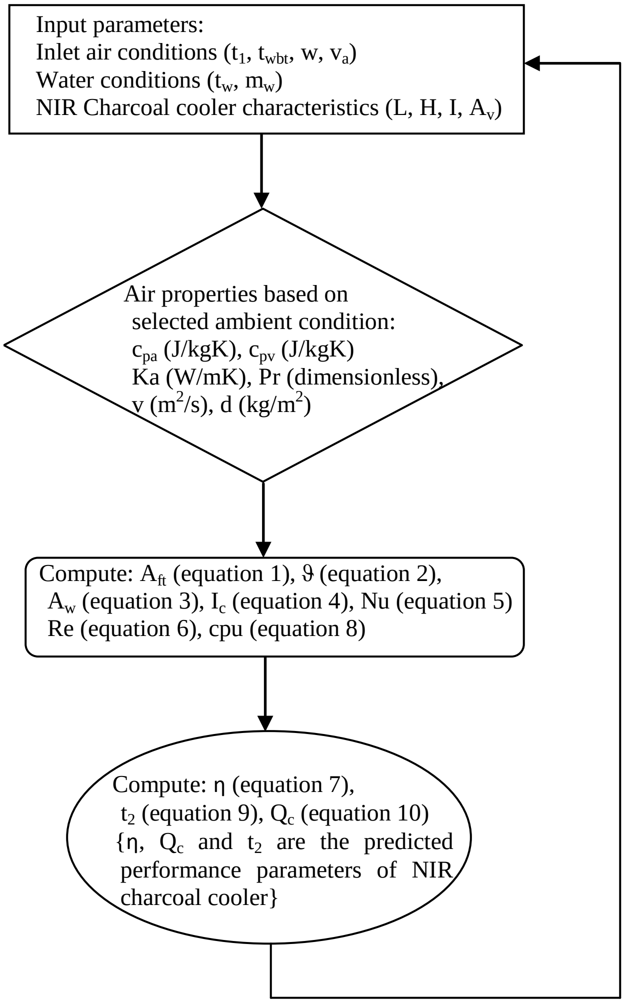

Fig. 4 A schematic computer model simulation for predicting the performance of near infrared (NIR) charcoal cooler.

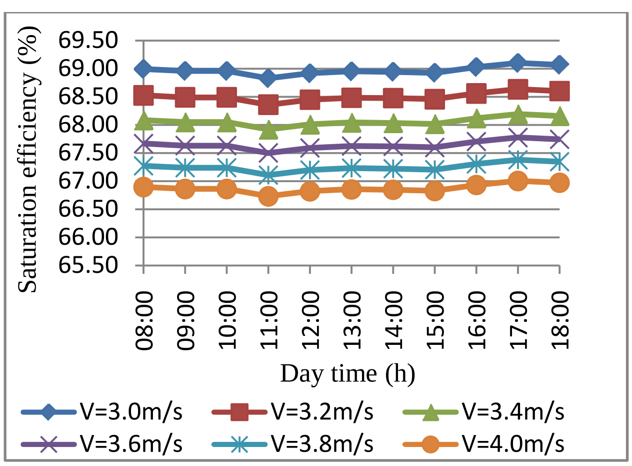

Fig. 5 Variation in saturation efficiency with inlet air velocity at one hour interval

Fig. 6 shows variation in cooling capacity with inlet air velocity at one hour interval.

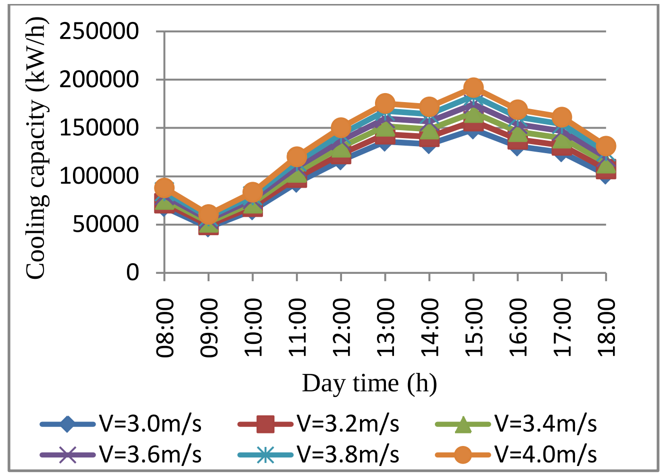

Fig. 6 Variation in cooling capacity with inlet air velocity at one hour interval

IV. Conclusion

The predicted saturation efficiency of the near infrared reflecting (NIR) charcoal cooler at no load condition decreases with increase in inlet air velocity and it ranges from 66.87% to 68.97%. The dry bulb temperature of the outlet air ranges from 24.54ºC to 24.67ºC. Cooling capacity increases with increase in inlet air velocity and it ranges from 105726.44kW/h to 136680.9kW/h. This shows that large mass of air can be cooled at high inlet air velocity but at low saturation efficiency

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