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Development of a Cowl-Incorporated Wind-Powered Forced-Air Evaporative Cooler for Preservation of Fruit and Vegetables

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ABSTRACT
This study developed a low cost evaporative cooler powered by a rotating suction cowl, for preservation of fruit and vegetables. The device contained a rectangular cooling chamber with three sides made of jute while the door was made of plywood and lagged inside with jute. A plastic hollow duct vertically connected a rotating suction cowl with the cooling chamber. The continuous rotation of the cowl brought about continuous sucking in of air into the cooling chamber through an air inlet underneath the cooling chamber. The continuous flow of air resulted in cooling by evaporation. The no-load cool air temperatures ranged between 27.3 ºC and 34.5 ºC while the corresponding ambient dry bulb temperatures ranged between 29.1 ºC and 43.9 ºC. The no-load cool air relative humidity ranged between 63.0 % and 87.2 % while the corresponding ambient relative humidity ranged between 40.8 % and 79.5 %. The no-load cooling efficiency was 66.7 %. The evaporative cooler was able to preserve tomatoes for 9 days. The developed evaporative cooler has the potential to perform well in comparison with the existing ones which use electric fans if operated in a windier and less humid region.
Key Words: Cowl, Evaporative cooler, Fruit, Wind-powered, Vegetables, Preservation

I. INTRODUCTION

1.1 Preservation of Fruit and Vegetables

Fruit and vegetables are important food items which contain vitamins and minerals forming an essential part of a balanced diet. They enhance the nutritional quality of diet because of their richness in vitamins and minerals such as ascorbic acid, calcium, iron, iodine, etc [1]. They are very essential for sound health in man and animals as they fight against diseases [2, 3]. Common examples of vegetables and fruit include cabbages, carrots, eggplants, tomatoes, cucumbers, onions, spinach, mangoes, and oranges [4]. Most fruit and vegetables perish few days after being harvested. This causes economic losses. This fact has denied consumers easy access to fresh fruit and vegetables leading to taking processed and chemically-preserved fruit and vegetables, usually tinned, canned, bottled or sacheted as chemically-preserved fruit and vegetables are more readily available.

Chemically-preserved fruit and vegetables, apart from their high cost, pose health hazards to the consumers as a result of the negative side effects of the preservatives: some of these health hazards include cancer, thyroid tumours, hypersensitivity in children and brain tumours [5]. The use of refrigerators could have been a better way of preserving fruit and vegetables but, apart from its dependence on electricity which is either completely unavailable or epileptically supplied in most parts of Africa, it has been observed that several fruit and vegetables including bananas, plantains and tomatoes cannot be stored in the domestic refrigerator for a long period as they are susceptible to chilling injury [3].

The use of evaporative coolers came as a better means of preserving fruit and vegetables than refrigerators. An evaporative cooler is a device that cools air based on the principle of evaporative cooling [6]. Evaporative cooling is the process of reducing the temperature of a compartment by allowing air to flow around a wet surface or wet absorbent material. Examples of absorbent materials are jute, palm leaf and foam.

In extremely dry climates, evaporative cooling of air has the added benefit of conditioning the air with more moisture for the comfort of building occupants. The cooling potential for evaporative cooling is dependent on the wet bulb depression which is the difference between dry bulb temperature and wet bulb temperature [7]. A significant way to improve evaporative cooling is to increase the flow of air around and through a wet absorbent material [8].

Evaporative coolers can be categorized as ordinary and forced-air evaporative coolers. While ordinary evaporative coolers depend on natural air to flow around the wet absorbent material, forced-air evaporative coolers need an external source of power as most of the times fans are incorporated to increase the flow of air in the system. Several authors have worked on forced-air evaporative coolers which use fans, and are therefore electricity-dependent [9, 10, 11, 12, 13, 14, 15]. The foregoing fan-powered evaporative coolers are not very useful in places where there is no electricity supply.

1.2 Cowls

The energy of the wind has served for centuries to pump water, grind or mill grain and move boats [16]. A cowl is a hood-shaped covering used to increase the draught through a space such as chimneys, grain bins and livestock structures [17]. It is used to increase the draft of a chimney and prevent backflow. Ventilated grain bins that use cowls are designed to utilize the wind either to force or draw air through the stored grain to dry or to cool it [18]. Cowls can broadly be categorized as stationary cowls and rotating cowls. Rotating cowls are further divided into suction cowls and pressure cowls. The suction cowl backs the direction of wind flow and draws air from the compartment developing negative pressures. This is especially useful in chimneys where smoke is continuously removed from the structure. The pressure cowl faces the direction of wind and draws air into the compartment developing positive pressures [17]. This study developed a simple forced-air evaporative cooler using a suction cowl to prevent dependence on electricity. It provides information on the efficacy of replacement of a fan with a cowl in a forced-air evaporative cooling system for fruit and vegetable preservation.

1.3 Post-Harvest Changes in Quality of Fruits and Vegetables

Ndirika and Asota [18] reported that the damage that occurs in fruit and vegetables is primarily by loss of moisture, pathological attack and change in composition. Other changes that occur include colour change, change in firmness, weight loss, and change in total solids [19, 13]. According to FAO [20], most fresh produce contains between 65 and 95 percent water when freshly harvested. Water is an important constituent of most fruit and vegetables and it adds up to the total weight. Loss of water reduces the weight of the produce. When the harvested produce loses 5 to 10 percent of its fresh weight, it begins to wilt and soon becomes unsaleable. Loss of weight can be in the form of respiratory or evaporative loss. The former, which occurs as a result of respiration, depends mainly on the temperature of the surrounding air. The latter occurs as a result of water vapour deficit of the environment compared to that of the produce [13].

1.4 Factors Accountable for Deterioration in Fruit and Vegetables

The major factors accountable for fruit and vegetable deterioration are pathological, physiological and mechanical activities together with evaporation of water.

1.4.1 Pathological infection

A pathogen is any small organism such as a virus or bacterium which can cause disease [4]. They infest fruit and vegetables leading to their deterioration [13]. Olosunde [21] discovered that pests and insects cause considerable damage to fruit and vegetables through complete removal of the produce or feeding on them.

1.4.2 Physiological activity

Ripening is a sort of physiological activity in plants which transforms mature but inedible plant organs into visually attractive and edible organs. Since the process is normally irreversible, it naturally leads to deterioration and eventual decay of such plant organs [21].

1.4.3 Mechanical injuries

Mishandling of fruit and vegetables causes cracks, cuts, bruises or abrasion: these make them unattractive reducing their shelf lives as a result of drastic deterioration. According to Olosunde [21] and Aworh *et al.* [22], mechanical damage also considerably accelerates the rate of water loss from produce resulting in higher respiration and ethylene production rate, increased damage and lower level of ascorbic acid. The foregoing results in alteration in taste and nutritive value.

1.4.4 Evaporation of water

The higher the rate of evaporation, the lower the moisture content and shelf life of an agricultural produce [13, 21].

1.5 Factors Affecting the Rate of Evaporation

The factors affecting the rate of evaporation are mainly air temperature, air movement, relative humidity and wet-surface area.

1.5.1 Air temperature

Post-harvest respiration is a deterioration process [23]. It results in the depletion of reserve carbohydrate by oxidizing them to carbon (IV) oxide, water and energy [19] as represented in equation (1).

$$C_6H_{12} + 3O_6 = 6CO_2 + 6H_2O + 67Kcal\ (energy) \quad (1)$$

Deterioration of fruit and vegetables during storage depends largely on temperature. Throughout the period between harvest and consumption, temperature control has been found to be the most important factor in maintaining product quality. Respiration and metabolic rates are directly related to room or air temperatures within a given range. The higher the rate of respiration, the faster the produce deteriorates [24].

1.5.2 Air movement
As water evaporates from a surface, it tends to raise the humidity of the air that is close to the water 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 is constantly being moved away and replaced with drier air, the rate of evaporation will either remain constant or increase.

1.5.3 Relative humidity of air
Relative humidity is the measurement of the amount of water vapour in the air as a percentage of the maximum quantity that the air is capable of holding at a specific temperature [6].
Mathematically, relative humidity, R_H, can be represented by equation (2).

$$R_H = \rho_{av}/\rho_{sv} * 100\ \% \qquad (2)$$

where,
ρ_{av} is actual vapour density, (kg m^{-3});
ρ_{sv} is saturation vapour density, (kg m^{-3}) [25].

At high relative humidity, produce maintains its saleable weight, appearance, nutritional quality and flavour, while softening, wilting, and juiciness are reduced. When the relative humidity is low, only a small portion of the total possible quantity of water vapour that the air is capable of holding is being held, and also the air is capable of taking additional moisture [25]. According to Basediya *et al.* [23], high humidity should be used with low temperature storage because humidity and warmth or high temperature in combination favour the growth of bacteria and fungi.

1.5.4 Surface area
The greater the surface area from which the water evaporates, the greater the rate of evaporation [25, 13]. This implies that the greater the surface area of the wet absorbent material used in an evaporative cooler, the more effective the evaporative cooling of the compartment.

II. MATERIAL AND METHODS

2.1 Design Considerations
The design of the experimental wind-powered forced-air evaporative cooler involved the conceptualization of suitable components such as the suction cowl and the duct. The following design considerations were employed:

i. incorporation of a rotating suction cowl instead of an electric fan;
ii. use of jute pad which is the most efficient locally available common absorbent material;
iii. making the frame from hardwood instead of steel in order to reduce cost;
iv. lagging of the wooden door with jute pad which is kept moist by frequently wetting it so as to reduce heat gain from the surroundings; and

The focus of this research work was to verify the feasibility of the proposed design concept. Hence, emphasis was placed on functionality rather than optimization of the parameters that were considered to affect the performance of the entire system.

2.2 Choice of Materials
The wind-powered evaporative cooler has various parts made of different materials such as jute, plastic, steel, galvanized iron, and wood. The materials were chosen based on some design criteria which are mainly availability, functionality, durability and economy.
Jute is a bast fibre, like hemp, and flax. It is a natural and vegetable fibre [26]. It is very cheap to produce, and its production levels are similar to that of cotton. Coarse fabrics made of jute are called hessian, or burlap in America. Jute is biodegradable [27]. Jute fibre has some unique properties like heat insulation, low thermal conductivity and high porosity [28, 29]. Olosunde [21] researched on absorbent materials like Jute, Hessian and cotton wastes and concluded that jute had the highest cooling efficiency.

The water reservoir, control valves, water distribution pipes and the duct were made of plastic. Plastic was chosen because it is water resistant. It is also lighter and relatively cheaper than some common materials such as steel. The cooling chamber was made of hardwood. Hardwood was chosen rather than softwood because hardwood is more resistant to decay and insect attack. Wood is a common material and relatively cheaper than steel. The cowl was made of galvanized iron, while its support and duct support were made of steel. The cowl support and duct support were silver-coated to make them resistant to corrosion as a result of harsh weather conditions.

2.3 Design and Description of the Wind-powered Evaporative Cooler

The major components of the wind-powered evaporative cooler are the cooling chamber, cowl, cowl support, duct and the duct support (Figure 1) while Figure 2 is the front view.

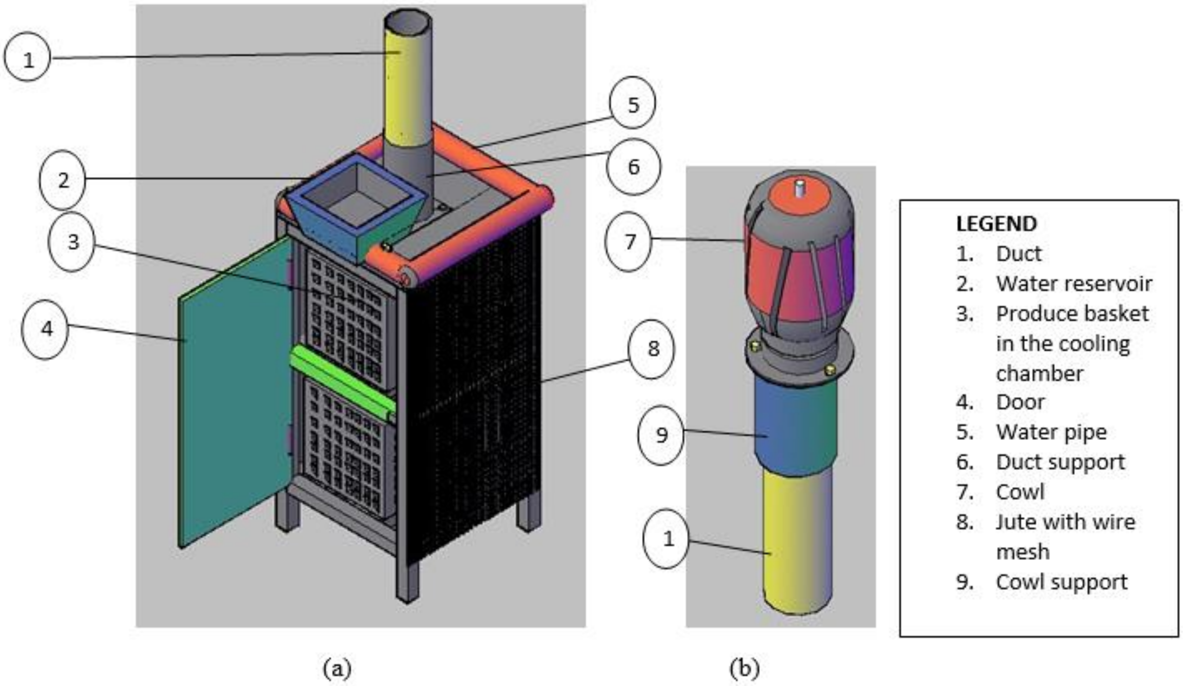


Figure 1: Conceptual design of the cowl-incorporated evaporative cooler: (a) the cooling chamber, water distribution system, duct support and part of the duct that connects to the cowl; (b) part of the duct from the cooling unit, cowl support and the cowl.

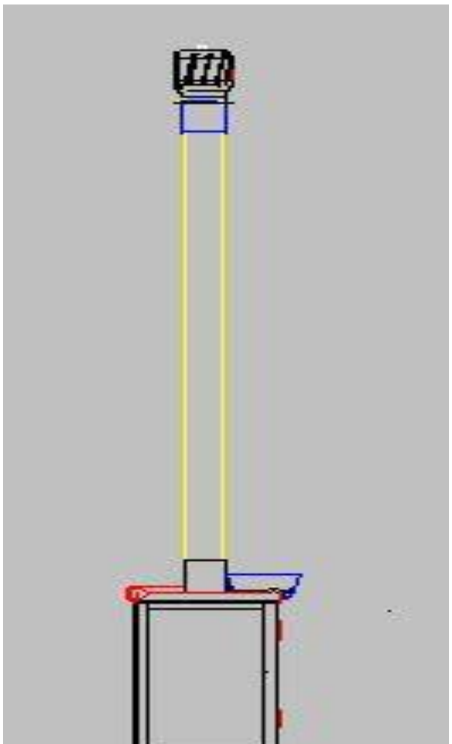


Figure 2: Front view of the evaporative cooler.

2.3.1 The cooling chamber

The cooling chamber is a rectangular cabin which has two equal divisions having dimensions of 600 by 600 by 500 mm each. It is the unit where the fruit or vegetables to be preserved are kept. Each division contains a plastic basket where the produce to be preserved is kept.

2.3.2 The cowl, cowl support, duct and duct support

The selected cowl is a globe type. It has a circular section to enable it to rotate about a fixed duct below it. It has an internal diameter of 0.225 m and an external diameter of 0.285 m. It has a height of 0.3 m and a mass of 2.25 kg. The steel cowl support with predetermined inner diameter of 0.152 m corresponding to the outer diameter of the duct was designed for strength based on equations 3 to 7 through which the maximum design strength of 125 MPa and minimum thickness of 7.5×10^{-7} m were obtained. The thickness used was 2 mm.

$$S_d = S_y/N \quad (3)$$

$$S_{max} = F_c/A \quad (4)$$

$$A = \pi (D^2 - d^2)/4 \quad (5)$$

$$t = (D - d)/2 \quad (6)$$

$$\tau_{max} = S_{max}/2 \quad (7)$$

where, S_d is design strength, (MPa); S_y is yield strength approximately equal to 250 MPa; N is factor of safety which was taken as 2; S_{max} is maximum normal stress, (Pa); F_c is cowl weight, (N); A is area of cross section of the cowl support, (m^2); τ_{max} is maximum shear stress, (Pa); D is outer diameter, (m); d is inner diameter selected as 0.152 m, and ; t is minimum thickness, (m) [30, 31, 32].

The PVC duct bears the cowl support and the cowl. It is stiff enough to stand and withstand the effects of wind flow. It is a 2-mm thick pipe with an inner diameter of 152 mm and a height of 3300 mm. The steel duct support is of 1.5 mm thickness. Table 1 specifies the major components of the device.

Table 1: Specification of components.

Item	No	Part Name	Material	Specification (mm)
1	1	Globe-type Suction Cowl	Galvanized iron	225 ID; 285 OD
2	2	Duct	Plastic	152 ID; 1 T; 3300 H
3	1	Water Reservoir	Plastic	0.02 m^3
4	3	Pipe	Plastic	25 ID; 1 T; 600 L
5	2	Control valves	Plastic	25 ID; 2 T
6	-	Pad	Jute	600 by 10 by 1000
7	3	Wire Mesh	Steel	600 by 1 by 1000
8	1	Door	Plywood	500 by 15 by 900
9	4	Frame Stand	Hardwood	50 by 50 by 1200

***NB: ID = inner diameter; OD = outer diameter; T = thickness; H = height; L = length**

2.4 Air Flow in the Evaporative Cooler

Figure 3 shows the direction of air movement in the wind-powered evaporative cooling system. The jute wall has pores, and there is air inlet at the bottom of the cooling chamber. As the suction cowl rotates, it sucks in air continuously into the cooling chamber through the air inlet and the pores of the soaked jute wall bringing about cooling by evaporation.

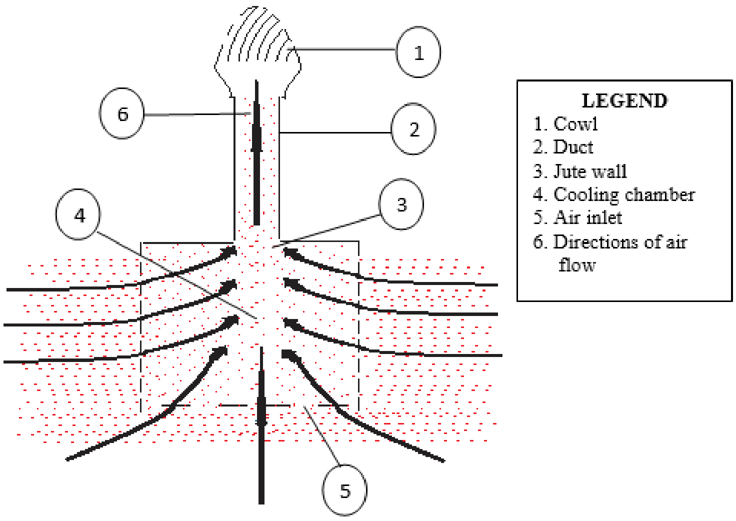


Figure 3: Air flow in the wind-powered evaporative cooling system.

2.5 Key Performance Evaluation Equations

The following are the major key performance equations (8 to 10) for the evaporative cooling system.

$$\eta_{cooling} = (T_{db} - T_s)/(T_{db} - T_{wb}) * 100\ \% \quad (8)$$

where,

$\eta_{cooling}$ is evaporative cooling efficiency, (%)

T_{db} is dry bulb temperature, (ºC)

T_{wb} is wet bulb temperature of the ambient air, (ºC)

T_s is temperature of cool air, (ºC).

$$W_L = W_1 - W_2 \quad (9)$$

where,

W_L is loss in weight of the fruits or vegetables stored, (kg)

W_1 is initial weight of the fruits or vegetables stored, (kg)

W_2 is final weight of the fruits or vegetables stored, (kg)

$$L = 100 W_L / W_1 \quad (10)$$

where,

L is percentage weight loss (%).

III. RESULTS AND DISCUSSION

3.1 The Developed Wind-powered Evaporative Cooler

Plates 1 to 4 show the various components of the evaporative cooler.


Plate 1: The cowl

Plate 2: The cowl and its support.

Plate 3: The cooling sub-system.

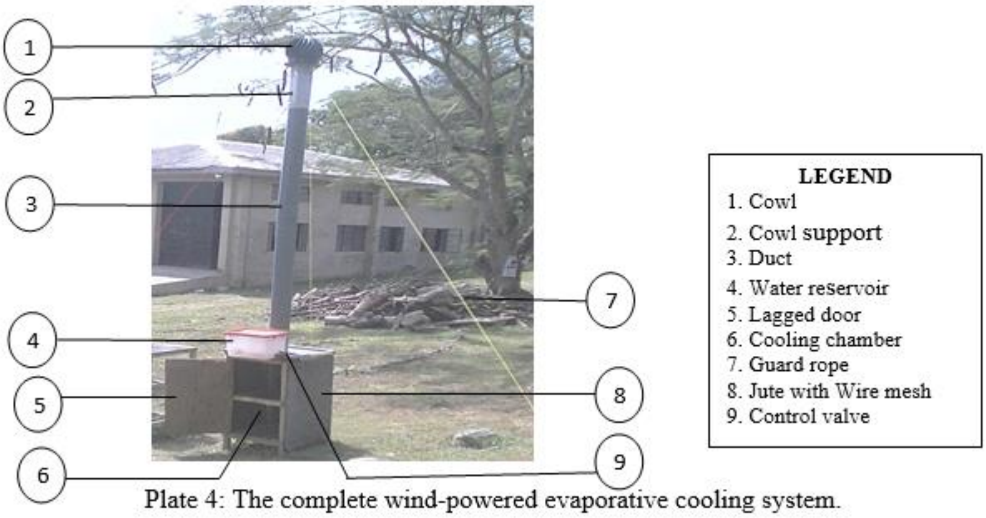


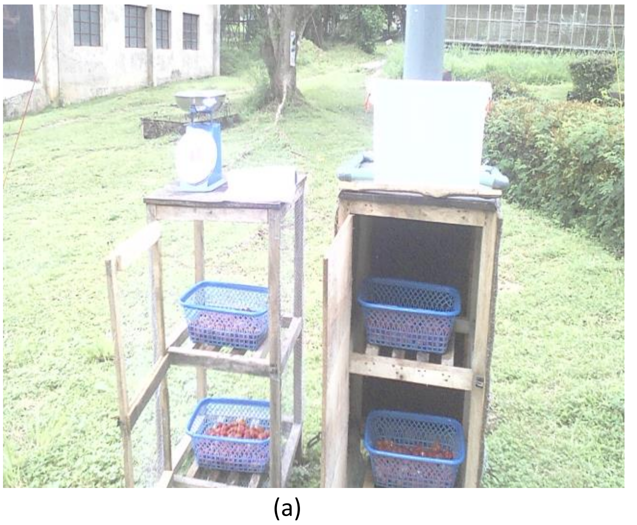
Plate 4: The complete wind-powered evaporative cooling system.

3.2 Testing of the Wind-powered Evaporative Cooler

A shed was created over the wind-powered evaporative cooler so that the water soaking the jute would be kept cool to increase the efficiency of the evaporative cooler (Plate 5). Water was manually supplied to the water reservoir about an average of 4 times during the day so as to keep the jute moist. No-load tests were carried out on the device.

Plate 5: The experimental set-up showing the wind-powered evaporative cooler under a shed.

Equal weights of tomatoes were kept inside the control chamber placed beside the evaporative cooler, and the conditions were examined concurrently. Plate 6 is the complete experimental set-up. The tomatoes preserved were examined three times daily for colour changes, weight changes (using a weighing balance) and change in firmness. A multi-function device was used to measure the cool air relative humidity, ambient relative humidity, cool air dry bulb temperatures, ambient dry bulb temperatures and the wind speeds. On the tenth day, the tomatoes that had got spoilt were separated.



(a)

(b)

Plate 6: (a) The control chamber (left) and the evaporative cooler (right) with the door opened temporarily; (b) the door of the evaporative cooler was closed as expected during evaluation.

3.3 No-load Test Results

The evaporative cooler was tested without being loaded. The temperatures and the relative humidity were measured three times daily (around 8 am, 12 noon and 4 pm) for four days.

3.3.1 Temperature and relative humidity readings

Figure 4 graphically compares the temperatures of the cooling chamber of the wind-powered evaporative cooler and the ambient conditions.

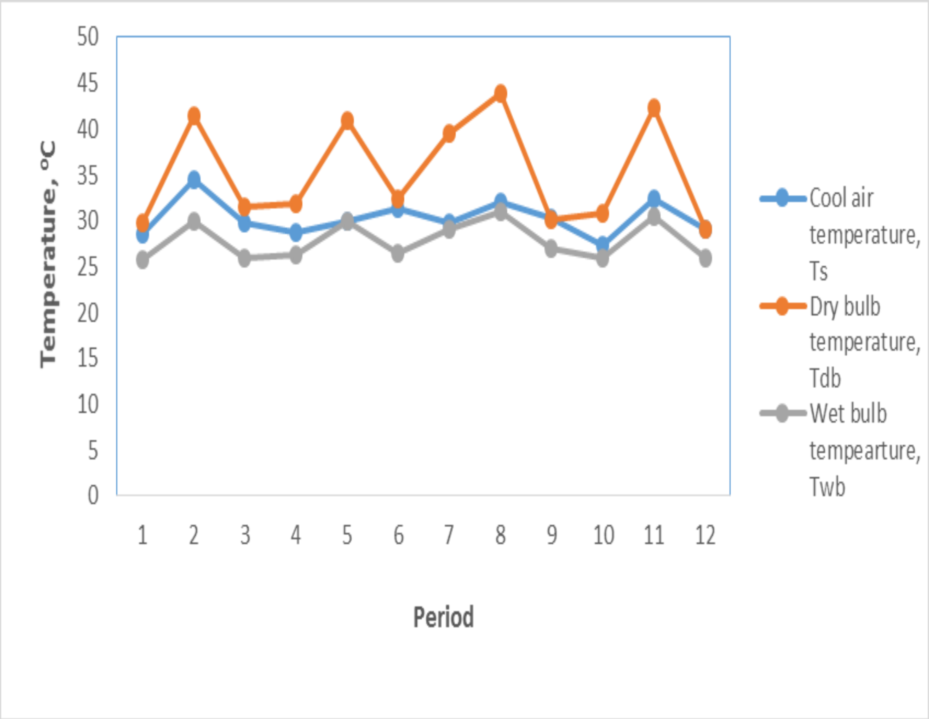


Figure 4: Comparison of the no-load temperature readings.

The results showed that the dry bulb cool air (in the cooling chamber) temperatures ranged between 27.3 and 34.5 °C while the corresponding ambient dry bulb temperatures ranged between 29.1 and 43.9 °C. It was also observed that the depression was high in the afternoons compared to the other periods of the day. The cool air relative humidity ranged between 63.0 and 87.2 % while the corresponding ambient relative humidity ranged between 40.8 and 79.5 %. Figure 5 illustrates the difference between the two conditions.

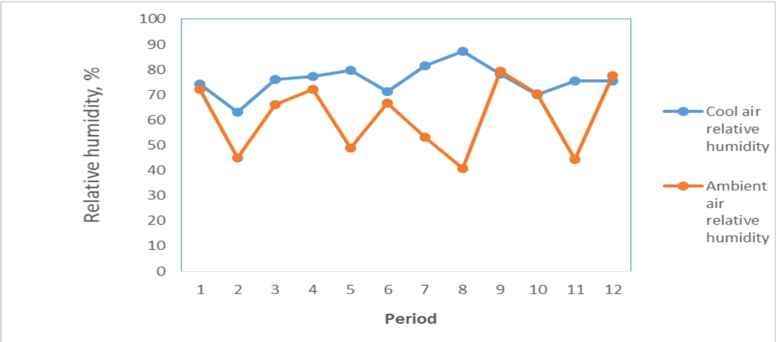


Figure 5: Comparison of the no-load relative humidity readings.

3.3.2 No-load cooling efficiency

The no-load cooling efficiency was calculated for each experimental run using the equation 2 as depicted by Figure 6. The average cooling efficiency calculated from the average T_{db} (35.3 °C), T_s (30.3 °C) and T_{wb} (27.8 °C) was 66.7 %.

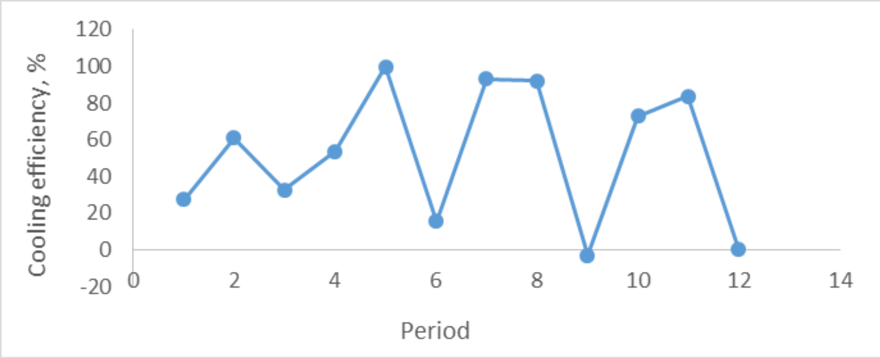


Figure 6: No-load cooling efficiency.

IV. CONCLUSIONS

This study examined the development of a cowl-incorporated wind-powered forced-air evaporative cooler. Results from experiments conducted show that:

i. the evaporative cooler no-load cool air temperatures ranged between 27.3 and 34.5 ºC while the corresponding ambient air dry bulb temperatures ranged between 29.1 and 43.5 ºC .

ii. the no-load cool air relative humidity ranged between 63.0 and 87.2 % while the corresponding ambient air relative humidity ranged between 40.8 and 79.5 %.

iii. The no-load average cooling efficiency was calculated as 66.7 %.

iv. The developed evaporative cooler has the potential to perform well in comparison with the existing ones which use electric fans if operated in a windier and less humid region.

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