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PERFORMANCE OPTIMIZATION OF A SOLAR-POWERED EVAPORATIVE COOLING SYSTEM

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ABSTRACT
Fruits and vegetables are important sources of digestible carbohydrates, minerals and vitamins A and C. For maximum usefulness and optimum nutritive value, fruits and vegetables are usually consumed when they are fresh and fully matured and harvested. The research work aimed to determine the optimum cooling conditions in a solar-powered evaporative cooling system for maximum preservation of fruits and vegetables. A three-factor, five levels Central composite rotatable design (CCRD) of response surface methodology (RSM) was employed to determine the optimal cooling condition with respect to the three main cooling parameters such as water flow rate), pad thickness and air velocity. The highest cooling efficiency of 80.8% was obtained at water flow rate of 2.5 L/min, pad thickness of 60 mm and air velocity of 1.7 m/s. The optimization of the cooling parameters produced optimum cooling efficiency of 81.05% with desirability of 98.3% from optimal cooling parameters of 2.33 L/min of water flow rate, 61.24 mm of pad thickness and 1.78 m/s of air velocity. The water flow rate and pad thickness had positive significant effects on the cooling efficiency while air velocity has insignificant effect. Cooling efficiency increase with both increased in water flow rate and pad thickness. The model showed that the value of coefficient of determination, R2 (88.86%) was high and p-value of 0.0010 at $\alpha = 0.05$*. Hence the model can be said to be of high significance and can adequately predict the cooling efficiency of solar-powered evaporative cooling system.*

Key words: Evaporative cooler, Response surface methodology (RSM), Optimization, Cooling parameters, Solar-powered, Cooling efficiency.

1 INTRODUCTION
The market for tropical fruits and vegetables has expanded beyond Asia, Hispanic and other ethnic communities around the world as individuals and organizations have become more interested in their personal health, as well as the potentials of vegetables to provide such health building nutrients (Barre et al., 1992). Nigeria is the one hundred and fifty ninth largest producer of fruits and vegetables in the world (FAO, 2018). For this reason, international commerce in fruit and vegetables has so much expanded over the past few decades. Tones of produce are now shipped daily over long distances both within and across countries, and huge investments of resources are being channeled into transportation, storage and marketing to maintain a continuous supply of these perishable commodities (Anyasi1 et al., 2016). This further stress the importance of fruit and vegetables in the economic and industrial development of developing countries, among which Nigeria is one.

The most abundant constituent of fruits and vegetables is water. In their fresh form most fruits and vegetables contain more than 80 percent water with some varieties such as cucumber, lettuce, and melons containing about 95 percent water (Olosunde et al., 2009). Some fruits and vegetable are susceptible to low temperature. These crops are injured after a period of exposure to chilling temperatures below 10–150C but above freezing point (Gross et al. 2002; Olosunde et al., 2015). Therefore vegetables are generally classified as perishable crops. After harvest they shrivel, wither or rot away rapidly, particularly under hot tropical conditions. The damages that occur in these crops are caused primarily by loss of moisture, change in composition and pathological attack (Ndirika and Asota, 1994). Losses of fruits and vegetables occur everywhere from the field to the ultimate consumer and depend on the degree of perishability of the produce. Fresh fruits and vegetable deteriorate easily when stored under ambient condition, mainly due to physiological and microbial activities, which are accelerated at high temperature and low relative humidity of the storage environment. Adequate storage of fruits and vegetables prolongs their usefulness, checks market gluts, provides a wider selection of fruits and vegetables throughout the year and helps in orderly marketing and may increase the financial gain to the producer by reducing subsequent losses.

Evaporating cooling is an effective means of providing low air temperature and high relative humidity for cooling produce. An active evaporative cooling system consists of a pad (moist material), fan, storage cabin and water pump (Olosunde et al., 2016). Apart from the general requirements for the efficient operation of an evaporative cooling system, the efficiency of an active evaporative cooler depends on the rate and amount of evaporation of water from the pad. This is dependent upon the air velocity through the pad, pad thickness and the degree of saturation of the pad, which is a function of the water flow rate wetting the pad and the material of construction of the pad (Ndukwu 2011; (Atanda et al., 2011; Olosunde et al., 2016). Minimizing deteriorative reactions in fruits and vegetables enhances their shelf lives, implying that the produce will be available for longer periods; this would reduce fluctuation in market supply and prices. These are favourable indices for food companies that rely on steady supply for processing. There is also every possibility that availability of fruits and vegetables in all seasons at affordable prices would encourage the consumption of fruits and vegetables at the end user's level with a concomitant improvement in the nutritive status of the populace.

Several researchers have investigated the application of evaporative cooling system in extending the shelf life of fruits and vegetables. Onwude et al. (2018) studied the relationship between dimensionless moisture content and shrinkage of sweet potato in terms of volume, surface area, perimeter and illuminated area, they observed that the shrinkage of sweet potato based on computer vision and backscattered optical parameters is affected by the product thickness, drying temperature and drying time. In a related study, Cíntia et al. (2014) evaluate an evaporative cooling system using a water driven ejector, allowing it to be installed in places with plenty of water of evaporative cooling system. It was also observed that the pulse-like disturbance generated by replacing the cooling water at different periods of times did not result in significant affect vacuum destabilization and the temperature rise in the cooling tank. On the other hand, the effects of air velocity, pad thickness and degree of saturation have been studied by different authors. However, none of these studies considered the performance of solar-assisted evaporative cooling system. Therefore, the objective of this paper was to optimize the performance of a solar-powered evaporative cooling system for banana, tomato, mango and carrot and develop mathematical model to predict the efficiency of the cooling system.

2. Materials and Methods

2.1 The Evaporative Cooler

The solar powered evaporative cooling system in this study is intended for small-scale commercial storage of perishable crops, such as mango, tomato, banana and carrots. The solar powered evaporative cooling system consists of a pad end, storage cabin, suction fan, solar panel, control panels, lead acid battery and water distribution components. The water distribution components include a water pump, pipes, overhead and collection tanks Olosunde et al., (2015).

The pad is installed on one side of the cabin, and the suction fan on the other side opposite the pad end. An overhead tank is installed on the top of the cooler from which water drips on to the pad through a lateral pipe laid on top of the pad. There is a collection tank at the bottom of the cooler to collect excess water from the pad. The pump re-circulates the excess water back to the overhead tank. The solar panel powered the fan and the pump and at the same time charges the battery. The battery is used to power the fan and pump in the night when there is no sun light. Plate 1 shows pictorial view of the existing passive evaporative cooling system and solar powered evaporative cooling system.

Plate 1: Pictorial view of the solar photovoltaic powered evaporative cooling systems.

2.2 Features of the Cooler

2.2.1 Pad-end

The pad is held in position by a wooden framework and wire mesh, which covers both sides of the wooden framework. The wire mesh has rectangular large holes to allow for free passage of air to the pad. The framework is of five different thickness of 20, 40, 60, 80 and 100 mm and of size 110 mm x 1130 mm corresponding to one side of the storage cabin.

The framework is constructed with 5 mm thick plywood and the pad is held in between the plywood by nailing them together and by covering with wire mesh. The bottom of the framework is perforated to allow excess water from the pad to flow down to the bottom tank. The inside of the wooden framework is covered with high, density plastic material. This is to protect the plywood from moisture (Olosunde et al., 2015).

2.2.2 Storage cabin

The main framework of the cabin is constructed with 50 x 50 mm thick, hardwood. The walls, roof and floor are constructed with 5mm plywood and insulated internally with 25.4 mm polystyrene materials. It is also covered internally with high, density plastic material to protect the wood from moisture. The outside is painted white to reduce heat absorption. The interior of the cabin is divided into three shelves by horizontal wire mesh. The shelves are of dimensions: 1130 x 600 mm and are reinforced at the edges with 50 mm softwood. The dimensions of the storage cabin are 1130 x 600 x 580 mm (Olosunde et al., 2015).

2.2.3 Water re-circulation system

The water re-circulation system consists of a small direct current water pump, (80 watts with a discharge capacity of 6 L/min) and a maximum suction head of 1m and maximum distance of discharge of 5m), a bottom tank (510 mm x 530 mm x 200 mm), pipes and an overhead (510 x 530 x 200 mm). The system is designed to re-circulate the water by the pump, the water to be re-circulated is supplied to the bottom tank either manually or from the overhead tank. The pump delivers the water through a vertical pipe of diameter 19.2 mm into the overhead tank at a height of 1650 mm, which in turn delivers the water through the lateral pipe at pre-determined flow rate onto the pad. Figure 12 shows the closed loop of the panel that regulate the pump flow rate. The horizontal pipe is perforated with a 1mm, diameter hole through which the water drips onto the pad. Excess water that passes down the pad is collected by trough at the bottom of the pad and drains off into the bottom tank to be re-circulated back to the overhead tank again (Olosunde et al., 2015).

2.2.4 Pad thickness

The pad thickness is one of the parameters, whose effect on the saturation efficiency of the cooler is to be investigated. Taye and Olorunisola (2011) suggested pad thickness of 25.4 mm to 50.8 mm of wood wool pad for an evaporative cooler. Five levels of 20, 40, 60, 80 and 100 mm of pad thickness were chosen for investigation in this study. The area of the pad was chosen in such a way that it covers one side of the storage chamber. This was to ensure uniform distribution of the cool and humid air from the wetted pad into the storage chamber to move over and cool the produce inside the storage chamber.

The choice of the material for the pad was based on the following: porosity of the material; water absorption/evaporation rate of the material; availability; cost; ease of construction (Dzivama, 2000).

Olosunde et al. (2009) carried out a study to test three materials (cotton waste, jute and hessian) to be used as pad in an active evaporative cooler. The results showed that the cooling efficiency is highest for jute. Based on the required quality of the pad material, jute material was used for this study.

2.3 Instrumentation

Instruments and various equipment were used to measure and monitor the dependent variables in the course of the research work.

2.3.1 Temperature and relative humidity measurement

Lascar Electronics temperature and RH USB data loggers were used for temperature and relative humidity measurement. Data logger type EL-USB-2 (LASCAR, England, UK) was used for the collection and storage of the temperature and relative humidity data. The data loggers were programmed to record the minimum temperature and maximum relative humidity for every 30 minutes. Data were retrieved from the logger via USB port, on to a Laptop computer (Olosunde et al., 2015).

2.3.2 Air velocity measurement

The air velocity through the pad varies and differs at a point within the pad and was difficult to measure. However, the velocity of the air exiting from the pad, referred to as pad face velocity, was measured. The air velocity was measured by a Smart Sensor Digital Anemometer AR826 (Graigar, China) measuring to an accuracy of 0.3 m/s. The air velocity was measured by placing the air flow meter vane at the back of the cooler where the fan is located and then the value was read directly from the LCD.

2.3.3 Water flow rate measurement

The pump, which was used to circulate the water to the pad, has a regulator through which the rate of water flow to the pad was regulated. The rate of water flow to the pad was measured by collecting the amount of water flowing onto the pad for 30 seconds and then the average value was determined and calculated as the water flow rate in L/min.

2.4 Design of Experiment

Design Expert software (Version 11.0. 1, Stat-Ease Inc, Minneapolis, MN 55413, USA) was used in this study to design the testing and optimizing the performance of the solar-powered evaporative cooling system. The experimental design employed in this work was a five-level-three factor full factorial design. Central Composite Response Design and 20 (i.e. 8 + 2*3 + 6) test runs were performed for fresh banana, tomato, mango and carrot samples each. Water Flow Rate (WFR), Pad Thickness (PT) and Air Velocity (AV) were selected as independent factors for the optimization study. Five levels of water flow rate (0.5, 1.5, 2.5, 3.5 and 4.5 L/min), path thickness of (20, 40, 60, 80 and 100 mm) and air velocity of (0.7, 1.2, 1.7, 2.2 and 2.7 m/s) were chosen. The response chosen was the cooling efficiency. Six replications of centre points were used to predict a good estimation of errors and testing were performed in a randomized order. The actual and coded levels of each factor are shown in Tables 1 and 2. The coded values were designated by –2 (minimum), −1, 0 (centre), +1, +2 (maximum), −α and +α. Alpha is defined as a distance from the centre point which can be either inside or outside the range, with the maximum value of 2n/4, where n is the number of factors. It is noteworthy to point out that the software uses the concept of the coded values for the investigation of the significant terms, thus equation in coded values is used to study the effect of the variables on the response. The empirical equation is represented in equation (1) as:

$$Y = \beta_0 + \sum_{i=1}^{2} \beta_i X_i + \sum_{i=1}^{2} \beta_{ii} X^2{}_i + \sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta_{ij} X_i X_j \qquad (1)$$

Y = Response (Cooling Efficiency)

β_0 = Constant term

$\sum_{i=1}^{2} \beta_i$ = Summation of coefficient of linear terms

$\sum_{i=1}^{2} \beta_{ii}$ = Summation of quadratic terms

$\sum_{i=1}^{2}\sum_{j=i+1}^{2}\beta_{ij}$ = summation of coefficient of interaction terms
X_iX_j = independent variables

Table 1: Levels, codes and intervals of independent variables used for the experiment

Factors	Units	Codes	Levels					Interval of Variation
			-2	-1	0	1	2	
Water flow rate	L/mm	A1	0.5	1.5	2.5	3.5	4.5	1.0
Pad thickness	mm	A2	20	40	60	80	100	20
Air flow rate	m/s	A3	0.7	1.2	1.7	2.2	2.7	0.5

2.5 Sample Preparation and Storage experiment

Fresh samples of banana, tomato, mango and carrot were procured from the market and washed clean to remove dirt and any other foreign materials. The experiment was conducted for each of the product at the optimum operating condition of the SPECSS established in the first experiment. Mango (20.6 kg), tomato (16.8 kg), banana (18.2 kg) and carrot (12.0 kg) were stored in the SPECSS chamber. On the first day of the experiment, one analysis was carried out for each of the quality factors to be assessed. Three samples were used for each quality assessment, and the experiments were done in three replicates. Subsequently analysis was carried out at three days intervals. Under this experiment too, the maximum shelf life of each of the produce stored in the cooler was established.

Data loggers were programmed to record temperature and relative humidity at 30 minutes intervals within the chamber until a steady condition was reached. This indicated the temperature depression and maximum humidification achieved by the SPECSS.

2.6 Performance Criteria

The performance efficiency of the cooler for the storage of banana, tomato, mango and carrot were evaluated. These crops were selected because of their perishability after harvest. Quality assessments of the produce stored inside the cooler were determined. Some quality parameters for effective storage were used to assess the effect of the storage environment on the crops. The fruits and vegetables were analyzed for their chemical changes based on the AOAC (2012) methods. The quality assessment tests that were carried out include changes in: physiological weight, total titratable acids, redox potential, total soluble solids and firmness.

2.7 Determination of Effect of Water Flow Rate, Pad Thickness and Air Velocity on the Saturation Efficiency of the Solar Powered Evaporative Cooler.

The basic format of the experiment involved an interaction study of the effects of the three parameters on the saturation efficiency of the cooler. These parameters are combined in a split-split plot experiment. Five levels of Water Flow Rate (WFR), Pad Thickness (PT) and Air Velocity AV were used. Split-split plot design is uniquely suited for a three-factor experiment. It can therefore be applied to this experiment, where three variables were investigated. In this experiment, the three variables were divided as follows. The pad thickness was considered as the main plot and had five levels, which were tested randomly. It was therefore referred to as the main plot. Five levels of water flow rate and five levels of air velocity were assigned and tested randomly against the five levels of pad thickness. They were therefore considered as the subplot and sub-subplot, respectively. Three two-way combinations (e.g., PT vs. WFR, PT vs. AV and

WFR vs. AV) and one three-way combination were considered in this study. The experimental layout is presented in Table 2 and carried out in three replicates.
Selection of the variable and their levels was influenced on ranges suggested by various researchers. Xuan et al., (2012), and Umbarker et al. (1991) have recommended pad face velocities for various pad materials like celdek, fluted paper pads and cement coated pads as 1.25 to 1.7 m/s for pad thickness ranging from 50 mm to 100 mm.

2.8 Statistical Analysis

Analysis of variance was carried out as described by Gomez and Gomez (1983). Analysis of variance (ANOVA) is one of the principal statistical research tools in many scientific disciplines, which provides a summary of complex patterns of data in a convenient tabular form. The analysis of variance is specifically chosen in this study to examine the variation in the results of the performance efficiency of the cooler obtained under experimental variables and their interactions. Statistical software (SPSS version 17.0, IBM corporation, USA) with split-split plot program was used for analysis on a personal computer. The Duncan multiple range test (DMRT) and Tukey HSD were used for the comparison test. They are more appropriate for the test of experimental variables with many levels.

3.0 Results and Discussion

3.1 Interactive effect of pad thickness and water flow rate on performance efficiency

The average summary of the efficiency results at the various cooling conditions combinations is presented in Table 2.

Table 2: Tests result of cooling efficiencies at various interactions of the cooling conditions

Run	Coded and Actual factors			Response
	Water flow rate (L/min)	Pad thickness (mm)	Air flow rate (m/s)	Efficiency (%)
1	0(2.5)	0(60)	-2(0.7)	65.0
2	-1(1.5)	-1(40)	-1(1.2)	69.2
3	1(3.5)	-1(40)	-1(1.2)	65.0
4	-1(1.5)	1(80)	-1(1.2)	75.0
5	1(3.5)	1(80)	-1(1.2)	66.7
6	0(2.5)	-2(20)	0(1.7)	47.5
7	-2(0.5)	0(60)	0(1.7)	58.3
8	0(2.5)	0(60)	0(1.7)	80.8
9	0(2.5)	0(60)	0(1.7)	80.6
10	0(2.5)	0(60)	0(1.7)	80.7
11	0(2.5)	0(60)	0(1.7)	80.8
12	0(2.5)	0(60)	0(1.7)	80.6
13	0(2.5)	0(60)	0(1.7)	80.5
14	2(4.5)	0(60)	0(1.7)	62.5
15	0(2.5)	2(100)	0(1.7)	50.8
16	-1(1.5)	-1(40)	1(2.2)	68.3
17	1(3.5)	-1(40)	1(2.2)	56.7
18	-1(1.5)	1(80)	1(2.2)	70.8
19	1(3.5)	1(80)	1(2.2)	58.3
20	0(2.5)	0(60)	2(2.7)	74.2

From the result of the interactive effect of pad thickness and water flow rate presented in Table 2, there is a significant effect of the interaction between Pad thickness (PT) and Water flow rate

(WR) on efficiency considered as an independent variable. In this case they are all significant p = 0.00 ($p < 0.05$), so we can conclude that pad thickness and water flow rate did have a significant effect on the independent parameter. Since p-value = 0.00< 0.05 we reject the null hypothesis. Therefore, at the 0.05 significance level, there is enough evidence to conclude that level of pad thickness and water flow rate have a significant interaction effect on mean value of the efficiency. The effect of the interaction between pad thickness and water flow rate on the performance efficiency of the solar-powered cooling is presented in Figure 1. The result shows that saturation efficiency increases as the pad thickness is increased from 20 to 40 mm and increased more significantly when the pad thickness is increased to 60 mm for all levels of water flow rate. The saturation efficiency reduces as the pad thickness is increased to 80 mm and reduced further when the pad thickness is increased to 100 mm. The reduction in the saturation efficiency is more pronounced for the pad thickness of 20 mm follow by pad thickness of 100 mm. The result at pad thickness of 40 and 80 mm also show an initial significant increase with increase in the water flow rate from 0.5 to 1.5 l/min. There is a general reduction in saturation efficiency when the water flow rate is increased above level 2(1.5 l/min) for all levels of pad thickness.

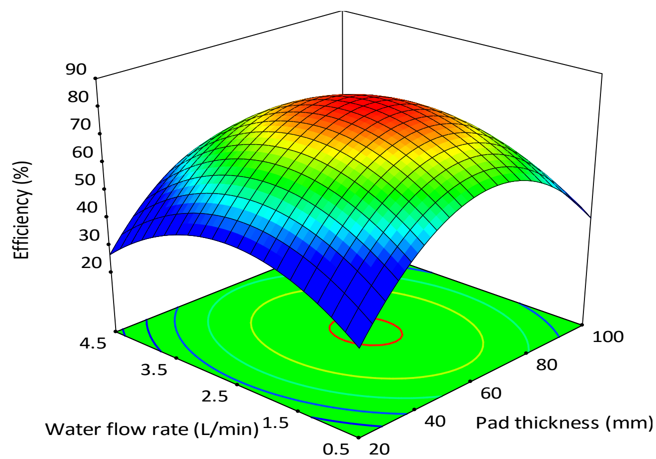

Figure 1: Effect of pad thickness and water flow rate on performance efficiency

The low performance efficiency of the cooler obtained at the low water flow rate (0.5 l/min) could be attributed to the fact that, at low level of water flow rate, the water could only partially wet the pad. This left some dry spots on the pad surface and within the pad which reduces the surface area for air-water contact and the amount of water evaporated from the pad and hence the efficiency of the cooling system. When the water flow rate is increased to 1.5 l/min, the pad becomes sufficiently wet and this increases the wet surface area for air-water contact, and more water is evaporated from the pad and result in higher efficiency of the cooling system. However, at very high-water flow rate of 4.5 l/min and especially at low pad thickness of 20 mm, the efficiency declines. This is due to the fact that, at this flow rate, the pad is excessively wet with excess water that block the pore spaces within the jute pad obstructing the free flow of air through the pad to effect enough evaporation. This could explain the high reduction in the performance efficiency at the pad thickness of 20 mm than those at 40 mm, 60 mm, 80 mm and 100 mm. Although the water flow rate is high, the pad thickness of 40 mm, 60 mm, 80 mm and 100 mm are thick enough to absorb the excess water. This result is in agreement with reports by Khater (2014) and Prajapati (2016) on optimization of cooling pads for evaporative cooling system and approach to analysis and optimization of evaporative cooling system.

3.2 Interactive effect of pad thickness and air velocity on performance efficiency

From the result of the interactive effect of pad thickness and water flow rate is presented in Table 2, there is a significant effect of the interaction between Pad thickness (PT) and Air velocity (AV) on efficiency considered as an independent variable. In this case they are all significant $p = 0.00$ ($p < 0.05$), so we can conclude that pad thickness and water flow rate did have a significant effect on the independent parameter. Since p-value = 0.00< 0.05 we reject the null hypothesis. Therefore, at the 0.05 significance level, there is enough evidence to conclude that level of pad thickness and water flow rate have a significant interaction effect on mean value of the efficiency.
The effect of the interaction between pad thickness and air velocity on the saturation efficiency of the cooler is presented in Figure 2. The result shows that at air velocity of 0.7, 1.2, and 1.7 m/s, the saturation efficiency increases positively with increase in the pad thickness from 20 mm to 60mm. It declines when pad thickness is further increased to 100 mm and the decline is more marginal at air velocity of 2.2 and 2.7 m/s.
However, at pad thickness 20 mm and 100mm there is a slight decline at air velocity 1.7 m/s. The interactive effect of pad thickness and air velocity on the mean temperature and relative humidity is presented in Figure 25 and 26 respectively. The results follow the same pattern, the combination of pad thickness level 3 and air velocity level 3 gives lowest mean temperature and highest mean relative humidity, respectively.
The low saturation of the cooling system at pad thickness 20 mm and air velocity 2.7 m/s could be due to the pad thickness is small, and this reduces the residence time within the pad to effect good evaporation couple with the high velocity that tend to pull water droplets out of the pad. As PT is to 60 mm, the distance the air has to travel through the pad and also the surface area for the evaporation of water would increase, and as a result the saturation efficiency of the system increase. Also low air velocity cannot effect good evaporation from the pad because of its low turbulence. However, the highest efficiency recorded at 60 mm and 1.7 m/s could be due to the combined effect of increase in residence time for air-water contact to effect good evaporation and the turbulence created by the high velocity. This is in tandem with earlier reports by Khater (2014) and Prajapati (2016) on optimization of cooling pads for evaporative cooling system and approach to analysis and optimization of evaporative cooling system.

3.3 Effect of water flow rate and air velocity on performance efficiency

From the result of the interactive effect of pad thickness and water flow rate is presented in Table 2, there is a significant effect of the interaction between Water flow rate (WR) and air velocity (AR) on efficiency considered as an independent variable. In this case they are all significant $p = 0.037$ ($p < 0.05$), so we can conclude that pad thickness and water flow rate did have a significant effect on the independent parameter. Since p-value = 0.037 < 0.05 we reject the null hypothesis. Therefore, at the 0.05 significance level, there is enough evidence to conclude that level of pad thickness and water flow rate have a significant interaction effect on mean value of the efficiency.
The effect of the interaction between water flow rate and air velocity on the performance efficiency of the cooler is presented in Figure 3. The result shows that at water flow rate of 0.5, 1.5, 2.5, 3.5 and 4.5 l/min and air velocity of 0.7, 1.2, 1.7, 2.2 and 2.7 m/s, the increase in performance efficiency of the evaporative cooler is high initially and then remains either constant or declines with increase in air velocity.

The result at water flow rate of 0.5 and 3.5 l/min also shows high initial increase with increase in the air velocity from 0.7 to 1.2 m/s. It then remains constant as the velocity is increased to 1.7 m/s and then declines with further increase in the air velocity to 2.7 m/s.

The initial high rate of increase in the performance efficiency of the evaporative cooler with increase in the air velocity could be due to the turbulence flow developed at high air velocity. Air moving at low velocity is not turbulent and could only evaporate the water on its path; this reduces the amount of water evaporated. The flow becomes turbulent as the air velocity is increased, this increases the area of air-water contact and hence, the amount of water that could be evaporated. The low performance efficiency of the cooler obtained at the low water flow rate (0.5 l/min) could be attributed to the fact that, at low level of water flow rate, the water could only partially wet the pad. This left some dry spots on the pad surface and within the pad which reduces the surface area for air-water contact and the amount of water evaporated from the pad and hence the efficiency of the cooling system. When the water flow rate is increased to 1.5 l/min, the pad becomes sufficiently wet and this increases the wet surface area for air-water contact, and more water is evaporated from the pad and result in higher efficiency of the cooling system. However, at very high water flow rate (4.5 l/min) and especially at low air velocity (0.7 m/s), the efficiency declines. This is due to the fact that, at this flow rate, the pad is excessively wet with excess water that block the pore spaces within the jute pad obstructing the free flow of air through the pad to effect enough evaporation. This could explain the high reduction in the performance efficiency at the air velocity of 0.7 m/s than those at 1.2 m/s, 1.7 m/s, 2.2 m/s and 2.7 m/s. At water flow rate of 0.5 and 3.5 l/min and air velocity of 1.2 and 1.7 m/s, the efficiency remain constant, this could be as a result of the combined effects of water flow rate and air velocity.

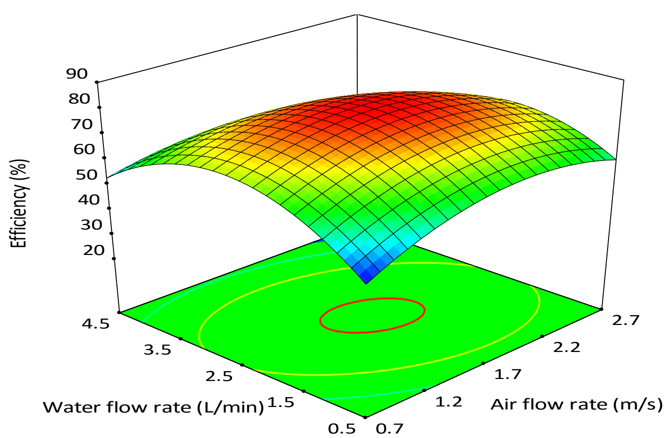

Figure 3: Effect of air flow rate and water flow rate on performance efficiency

3.4 Optimization of the Performance Efficiency and Validation of the Models

The optimization of the operating condition for the cooling performance of the solar-powered evaporative cooling system was successfully conducted in duplicate at laboratory experiments. Table 2 presents the experimental design of full factorial model of central composite rotatable design (CCRD) with the correspondent response (performance or cooling efficiency). Based on the results from the multiple regression analysis of the experimental data, a second order polynomial equation was obtained as outlined in equation (3) as follows:

$$Y = -70.13 + 29.79W_{fr} + 2.541P_t + 45.40A_{fr} - 0.031W_{fr}P_t - 2.90W_{fr}A_{fr} - 0.043P_tA_{fr} - 4.95{W_{fr}}^2 - 0.019{P_t}^2 - 10.60{A_{fr}}^2 \quad (11)$$

Where:

Y = Cooling Efficiency, %

W_{fr} = Water flow rate, L/min

P_t = Pad thickness, mm

A_{fr} = Air flow rate, m/s

The regression coefficients and corresponding p-values for the model are presented in Table 3, indicating that the model was highly significant because of its very low p-value ($p = 0.0010$). The confidence level of A ($p = 0089$), B ($p = 0.0028$), AC ($p = 0.0200$), BC ($p = 0.0103$), A^2 ($p = 0.0005$), B^2 ($p < 0.0001$) and C^2 ($p = 0.0214$) were above 95% ($p < 0.05$), suggesting that the model terms A, B, C, AC, BC, A^2, B^2, and C^2 had significant effects on the response Y (cooling efficiency)(Table 3). Specifically, linear terms of A, B, and C interactive terms AC, BC, and quadratic terms of A^2, B^2, and C^2 had a significant effect on the cooling or performance efficiency, whereas the effects of the term AB was not significant. The fit of the model was checked by the coefficient of determination (R^2) and the adjusted coefficient of determination (Adj-R^2).

In this study, it was found that the value of the coefficient of determination, R2 was 88.86%, indicating that 88.86% of the cooling variation of the evaporative cooling system is attributed to the factors (water flow rate, pad thickness and air flow rate) and only 11.14% could occur due to chance. The Adj-R2 value is a modification of R2 based on the number of variables used in the model, which was 78.83%, indicating that the regression equation fitted the data very well. The p-value of 'lack-of-fit' was 0.1841 (>0.05), implying that the 'lack-of-fit' was not significantly relative to the pure error and the model was fairly stable. All these findings indicated that the models were useful in predicting the cooling performance efficiency.

Table 3: ANOVA for response surface quadratic model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1896.08	9	210.68	8.86	0.0010
A	49.70	1	49.70	2.09	0.0089
B	20.70	1	20.70	0.8706	0.0028
C	0.7225	1	0.7225	0.0304	0.0451
AB	3.12	1	3.12	0.1314	0.7245
AC	16.82	1	16.82	0.7073	0.0200
BC	1.44	1	1.44	0.0608	0.0103
A^2	615.78	1	615.78	25.89	0.0005
B^2	1514.57	1	1514.57	63.69	< 0.0001
C^2	176.41	1	176.41	7.42	0.0214
Residual	237.81	10	23.78		
Lack of Fit	237.73	5	47.55	3241.84	0.1841
Pure Error	0.0733	5	0.0147		
Cor Total	2133.89	19			

Note: Statistically significant at 95% of confidence level ($p < 0.05$) (*); A = Water flow rate; B = Pad thickness; C = Air flow rate

The optimization of the evaporative cooling system functional parameters; water flow rate, pad thickness and air flow rate was carried out using numerical technique in RSM (response surface methodology) with the goal of maximizing the cooling performance efficiency. The ramp of the optimization process is shown in Figure 4, with optimum values of 2.33 L/min of water flow rate, pad thickness of 61.24 mm and air flow rate of 1.78 m/s. On the other hand the cooling performance efficiency and desirability of 81.05% and 0.983 respectively were also obtained.

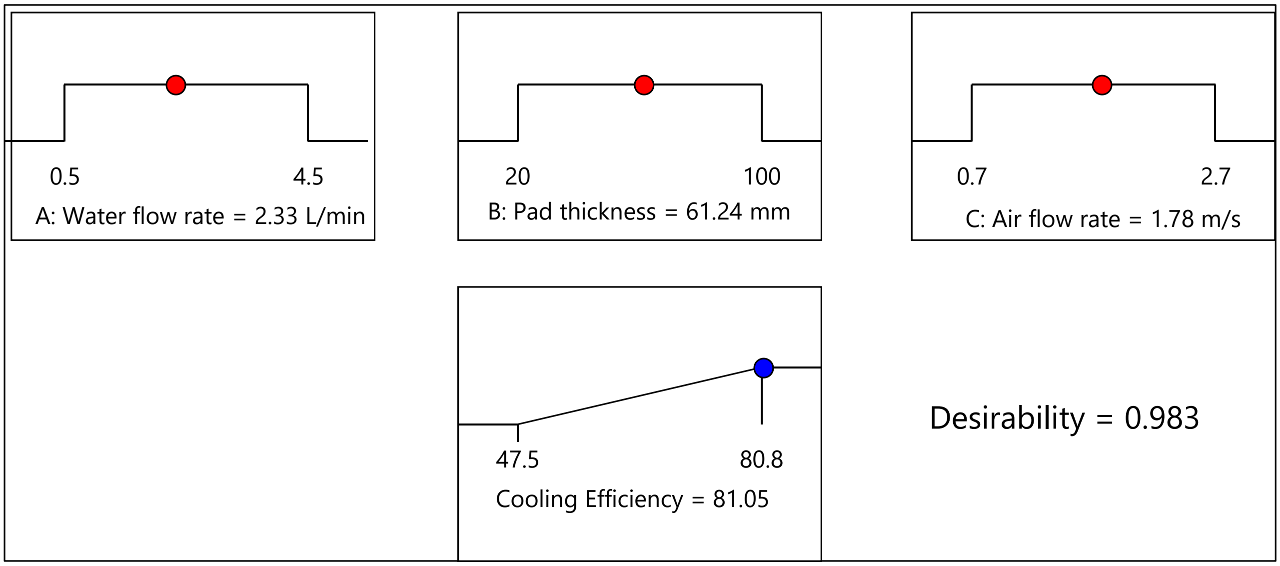

Figure 4: Ramp for optimization of cooling performance parameters

From the optimal cooling parameters of the evaporative cooler (Figure 4), giving the optimum cooling efficiency of 81.05%. This result could be explained by the fact that at pad thickness of 61.24 mm and water flow rate of 2.33 L/min, the pad was sufficiently moist, but without an excessive flow of water to block the pore spaces within the pad, for the air movement. In addition, at air velocity of 1.78 m/s, the flow is turbulent enough and mixes well as it travels in all directions through the pad. This increases the area of air water contact and hence, the amount of water that could be evaporated, thus an increase in the cooling efficiency. The 81.05% cooling performance efficiency obtained in the evaporative cooler, in Ibadan with an average ambient condition of 33°C and 44% temperature and relative humidity respectively is considered efficient.

3.5 Validation of model

The cooling performance was optimized with the design expert to obtain optimal cooling conditions. The agreement between the experimental and predicted values for the cooling efficiency from the solar-powered evaporative cooler was obtained from the parity plot between the predicted and the experimental values as shown in Figure 5. For validation purposes, a test run under the obtained optimal cooling conditions was carried out in order to evaluate the precision of the quadratic model; Comparing the experimental and predicted results for cooling performance of the solar-powered evaporative cooling system, it was established that the error between the experimental and predicted is less than 0.5%, therefore it can be concluded that the generated model has sufficient accuracy to predict the cooling performance of the solar-powered evaporative cooling system.

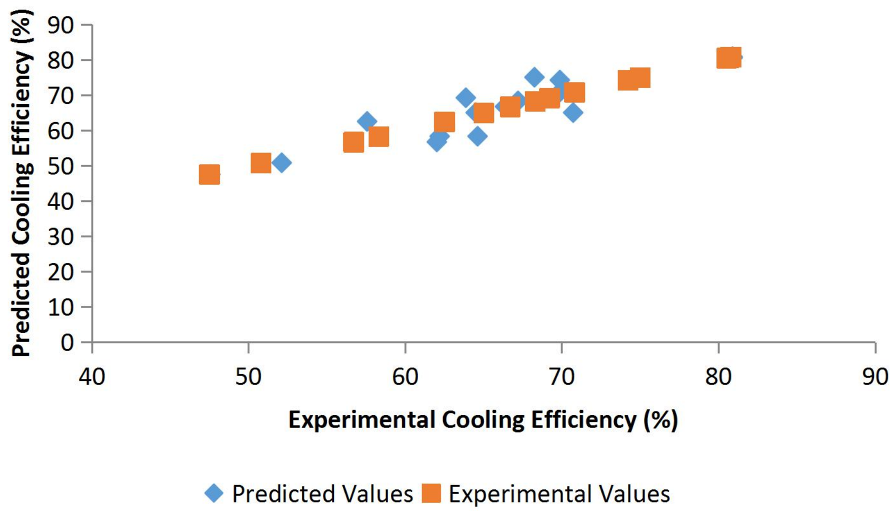

Figure 5: Predicted and actual values for cooling performance efficiency of the solar-powered evaporative cooling system

4.0 Conclusions

In this study, a-3 factor experiment was performed to optimize the cooling performance of the solar-powered evaporative cooling system. The individual and interactive roles of the three factors (water flow rate, pad thickness and air flow rate) were investigated by RSM. The maximal predicted value of the cooling efficiency was 81.05% and a mean value of 68.61% was achieved in the experiment under optimal cooling conditions, which was in a close agreement with the model prediction. This study provided useful information on how to improve the cooling performance efficiency by optimizing the cooling conditions by using statistical methods.

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