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Design and Performance Evaluation of a Thermostat Controlled Electric Dehydrating Machine

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Abstract- The study, design and performance evaluation of a thermostat controlled electric dehydrating machine was successfully investigated. CAD design approach for the thermostat controlled electric dehydrating machine was adopted and Autodesk Fusion 360 was used to create the solid model. The dehydrator retained a maximum dimension of 700mm$\times$ $575mm \times$ 1339mm, with four rectangular heating trays of 50cm$\times$ 30cm and 2mm thickness each which gave a heating surface area of 0.15m^2. In addition, heating coil was designed to retain the shape of swirl ring OP302 model with maximum heat output of 180kW within 60 minutes. HMI (Delta B03S212) and PLC (Delta-DVP20EX3) were used to control the thermostat set maximum temperature and time to 80℃ and $0.000011sec$ to retain the quality of Banana, Carrot and Plantain after drying. Banana was found to have the highest percentage wet moisture of 35.42% followed by Plantain 25.27% among the three chosen fruits with the least being that of the Carrot 11.72%, when dehydrated from 0 to 60 minutes. Furthermore, the highest mass loss was found in Banana, 109.1 grams followed by Plantain, 101.6 grams when each was heated for 20minutes. Also, machine efficiency and moisture removal rate of the machine were found to be 37.16% and 2.827g of moisture/sec respectively. These results suggested a considerable increase in machine output and performance. The paper evaluated the rate of product dehydration under steady state heat transfer condition with internal heat generation, electric thermostat was used to avoid overheating and under heating of products.

Indexed Terms- Thermostat, Dehydrating machine, Design, Performance, Efficiency, Product

I. INTRODUCTION

Food sustainability requires effective and efficient food preservation method. This has created a surge in the number of food dehydrators for both industrial and domestic applications. The paper aimed at designing a dehydrator or drier with controlled heating temperature to avoid product burning and to ensure uniform air circulation.

According to Mercer (2007), non-traditional methods of drying may be known as emerging drying technologies. With advancement, there are methods of water removal which are aimed at minimizing the application of heat. When drying food products that are sensitive to heat, this is especially important in order to prevent the quality of the food from being reduced. However, it should be mentioned at this point that it is extremely important to have the airflow as uniform as possible in a dryer. Sometimes, we may want the air to flow upwards through the product, or downwards through the product. But this paper adopted an upward air flow through the product heating trays to achieve double circulations.

Ibrahim and Mohammad (2022) opined that the drying process involves reducing water from the product to an acceptable level for marketing, storage, or processing. Given the absence of sufficient water, microorganisms are unable to grow and multiply. Many of the enzymes and bacteria that cause food spoilage cannot function without water.

Mohammad (2013) suggested drying temperature ranges to ensure product quality. The suitable drying temperature for fruit is 60°C - 80° C. Example Banana dries at (60°C - 70℃) until it is hard brittle. Avoid over heating to prevent darkening, vegetable are dried at (55°C - 60°C) until the legumes are brittle and crisp onion dries at (50℃ -70°C) until crisp. It is on this note that the researchers aimed to study design and performance evaluation of a thermostat controlled electric dehydrating machine.

II. MATERIALS AND METHODS

- Design Description

Dehydrating machine designed here consists of hollow box body apartment made of stainless steel with a central lagging material (glass fibre), four horizontal heating trays for placing product, centrally mounted heating coil, thermostat sensor with front gauge display, base mounted three blade circulating fan and apartment cover. In this design, heating is done uniformly and air circulation is also uniformly upward. Principles of heat transfer were utilized in the design of the dehydrator, targeting low cost and equipment suitability for small scale domestic applications. The machine was designed to dry Carrot, Plantain, Banana, etc.

- Material selection for Fabrication

When selecting engineering materials, especially for food processing equipment and in particular dehydrator, the overriding consideration for material selection is its ability to resist corrosion and contamination. Since acidity may be present, the material used for the construction of the main parts of the machine was stainless steel. This material is corrosion-resistant with sufficient strength and is easy to work on during fabrication. Though a little bit expensive, the material selected (stainless steel) satisfies both processing and mechanical requirements, allowing for maintenance, replacement, as well as offering safety with no product contamination. Materials not certified for food processing was not used.

- Material Specifications

Standard length stainless sheet for body and heating trays, 900mm × 900mm, Square pipe full length, 1¨× 1¨, thermostat display and temperature controller switch panel (0-200℃), 1500W Electric heater(swirl ring, OP302), 240V Circulating Fan, Lagging material (glass fibre), Electrode(stainless steel), paint and thinner, Fusion 360 CAD design, HMI (Delta B03S212), PLC (DELTA-DVP20EX3).

III. METHODS

The authors adopted CAD design approach for the thermostat controlled electric dehydrating machine. Fusion 360 was used to create the solid model. The dehydrator retained a maximum dimension of 700mm$\times$ $575mm \times$ 1339mm. Four rectangular heating trays of 50cm× 30cm, 2mm thick was created and held to the side inner walls of the dehydrator with rails to achieve four horizontal levels, according to Fig 2.0 to Fig 4.0. The thermostat was designed as shown in the Fig 1.0. Heating coil was designed to retain the shape of swirl ring OP302 model.

IV. EQUATIONS

Considering the steady state condition, mass balance for the system is given as below.

$Mass\ entering\ the\ machine\ Drier =$
$Mass\ coming\ out\ from\ Drier +$
$Mass\ lost\ on\ Drier$

$M, kg = M_f + M_l$ …… (1)

The wet and dry moisture for the three products can be evaluated as below

$\%\ wet\ Moisture = \frac{Mass\ of\ moisture}{Total\ mass\ of\ material} \times 100$ ……(2)

$\%\ dry\ Moisture = \frac{Mass\ of\ moisture}{Total\ mass\ of\ material} \times 100$ ……(3)

The efficiency of the machine is given below.

$$ME = \frac{Average\ mass\ of\ product\ dried}{Average\ mass\ of\ product\ entering\ drier} \times 100$$ …..(4)

Also, the machine drying capacity can be given as below.

$$Machine\ Capacity = \frac{Average\ mass\ of\ product\ dried}{TOtal\ time\ taken} = \text{g of moisture/sec}$$

Considering the steady state condition, with internal heat generation, q_{gen} for the system, the heat transfer balance is given below

$$Rate\ of\ internal\ heat\ generation = Conduction\ rate = Convection\ rate$$

$$q_{gen} \times A \times L = -KA\frac{dT}{dx} = hA(T_2 - T_s)$$ ….. (5)

$T_s = surface\ temperature\ of\ heating\ coil\ of\ dehydrator$

$T_2 = temperature\ of\ product\ heating\ trays$

Temperature distribution at any radius on the round heating coil surface is given below

$$T_r = \frac{q}{4k}(R^2 - r^2) + T_1$$ …….(6)

Temperature distribution at any distance on the inner plane wall of dehydrator is given below

$$T_x = \frac{qx^2}{2k} + T_1 + \frac{qL^2}{2k}$$ …….(7)

$T_1 = initial\ temperature$

The time required to attain any given temperature can be evaluated using lumped capacitance method as below.

$$\frac{T - T_\infty}{T_i - T_\infty} = \exp\left[\frac{-hA_s}{\rho V\, C_p}\right]t$$ ….. (8)

Provided

Biot number, $B_i = \frac{hs}{k} = \frac{hl}{k} = < 0.1$

Time constant, $\tau_t = \frac{\rho V\, C_p}{hA_s}$ …… (9)

Overall heat generated by the heater is given by Joules' equation as below

$H = I^2 R \times t$ **….. (10)**

$\mathrm{I = current, R = resistance\ at\ time, t}$

Surface area of heating tray, $A = L \times W = m^2$

Voltage, V = 240V

$$P = I \times V = 1500W$$

Also,

$R = \frac{V}{I} =$ Ohms

Overall heat generated by the heater within 1 hour

$$H = 6.25^2 \times 38.4 \times 120 = 180kW$$

Maximum surface temperature of heating coil was 260℃. Heat transfer from the coil surface to the heating trays is by convection due to forced circulating air. The maximum convective heat transfer coefficient of forced air is 500kW/m^2.

$H = hA(T_1 - T_s)$ …(11)

T_s = Heating tray surface temperature

Since the maximum drying temperature for the Banana, Carrot and Plantain is 80℃, thermostat set temperature and time should be evaluated as below.

Time constant, $\tau_t = \frac{\rho V\, C_p}{hA_s} < 0.1$

Hence, time to reach a set temperature of 80℃;

$I_o = I_i + (I_{in} - I_i)e^{-t/\tau}$….. (12)

V. RESULTS

Table 1:0 Mass Losses of three Products Carrot, Plantain, and Banana in the Dehydrator with Time

S/N	PRODUCT	INITIAL MASS (g)	TIME (MINUTES)	FINAL MASS (g)	MASS LOSS (g)
1	Banana	308	0-20	198.9	109.1
2	Carrot	203	20-40	179.2	23.8
3	Plantain	402	40-60	300.4	101.6

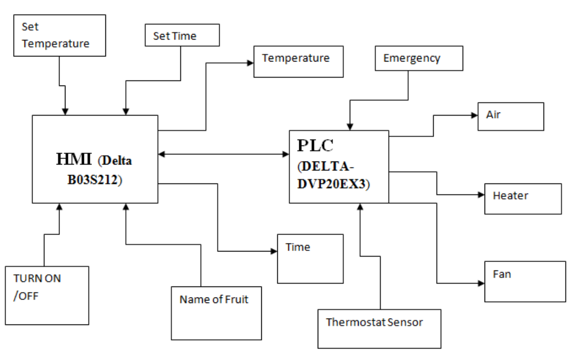

Fig 1.0: Controller Block Diagram of Thermostat for Dehydrating Machine

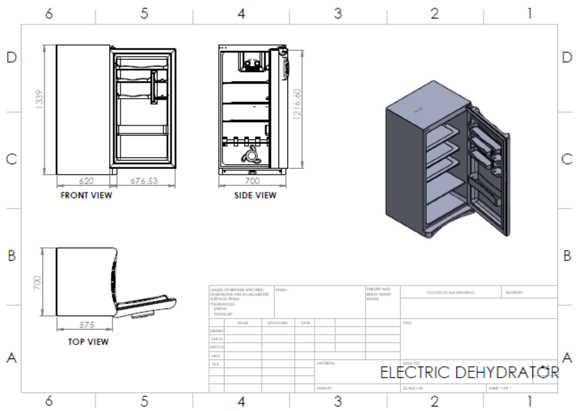

Fig 2.0: Orthographic View of (Open) Dehydrating Machine

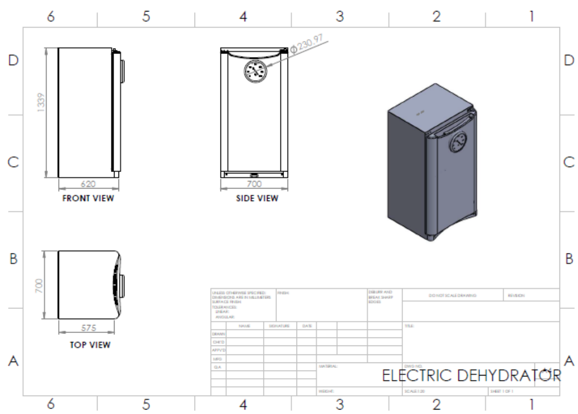

Fig 3.0: Orthographic View of (Closed) Dehydrating Machine

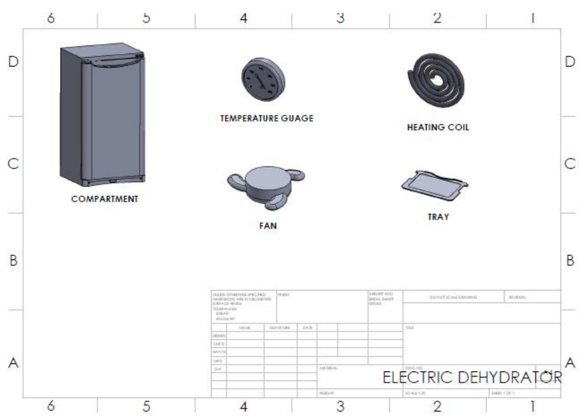

Fig 4.0: Component View of Dehydrating Machine

The wet and dry moisture for the three products can be evaluated as below

$$\% \, wet \, Moisture \, for \, Banana = \frac{109.1}{308} \times 100 = 35.42\%$$

$$\% \, wet \, Moisture \, for \, Carrot = \frac{23.8}{203} \times 100 = 11.72\%$$

$$\% \, wet \, Moisture \, for \, Plantain = \frac{101.6}{402} \times 100 = 25.27\%$$

$$\% \, dry \, Moisture \, for \, Banana = \frac{109.1}{198.9} \times 100 = 54.85\%$$

$$\% \, dry \, Moisture \, for \, Carrot = \frac{23.8}{179.2} \times 100 = 13.28\%$$

$$\% \, dry \, Moisture \, for \, Plantain = \frac{101.6}{300.4} \times 100 = 33.82\%$$

Table 2:0 Moisture Content of three Products Banana, Carrot and Plantain after Dehydration

S/N	PRODUCT	%WET MOISTURE	%DRY MOISTURE
1	Banana	35.42	54.85
2	Carrot	11.72	13.28
3	Plantain	25.27	33.82

The efficiency of the machine is given below.

$ME = \frac{339.25}{913} \times 100 = 0.3716$ = 37.16%

Also, the machine drying capacity can be given as below.

$Machine \, Capacity = \frac{339.25}{120} = 2.827$g of moisture/sec = 0.002827kg/sec

Overall heat generated by the heater is given by Joules' equation as below

$H = I^2 R \times t$ **….. (10)**

$\text{I = current, R = resistance at time, t}$

Surface area of heating tray, $A = 0.5 \times 0.3 = 0.15m^2$

Voltage, V = 240V

$$P = I \times V = 1500W$$

$$I = \frac{1500}{240} = 6.25A$$

Also,

$R = \frac{V}{I} = \frac{240}{6.25} = 38.4$ Ohms

Overall heat generated by the heater within 1 hour

$$H = 6.25^2 \times 38.4 \times 120 = 180kW$$

Maximum surface temperature of heating coil was 260°C. Heat transfer from the coil surface to the heating trays is by convection due to forced circulating air. The maximum convective heat transfer coefficient of forced air is 500kW/m^2.

$H = hA(T_1 - T_s)$ …(11)

$$180000 = 500000 \times 0.15 \times (260 - T_s)$$

$T_2 = 260 - \frac{180000}{500000 \times 0.15} = 257.6$℃ heating tray surface temperature

Since the maximum drying temperature for the Banana, Carrot and Plantain is 80℃, thermostat set temperature and time should be evaluated as below.

Time constant, $\tau_t = \frac{\rho V C_p}{h A_s} < 0.1$

Hence, time to reach a set temperature of 80℃;

$I_o = I_i + (I_{in} - I_i)e^{-t/\tau}$….. (12)

Time constant, $\tau_t = 4.824 \times 10^{-5}$/s

$$80 = 260 + (35 - 260)e^{-t/4.824\times10^{-5}}$$

$$80 - 260 = (35 - 260)e^{-t/4.824\times10^{-5}}$$

$$-180 = -225e^{-t/4.824\times10^{-5}}$$

$$-180 = -225e^{-t/4.824\times10^{-5}}$$

$$0.8 = e^{-t/4.824\times10^{-5}}$$

$$0.8 = e^{-t/4.824\times10^{-5}}$$

$$-0.223 = -t/4.824 \times 10^{-5}$$

$$t = 0.223 \times 4.824 \times 10^{-5} = 0.000011sec$$

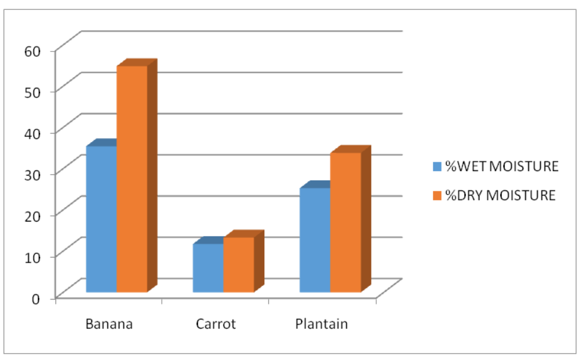

Fig 5.0: Bar Graph of Dry and Wet Moisture Content of Banana, Carrot and Plantain after Dehydration

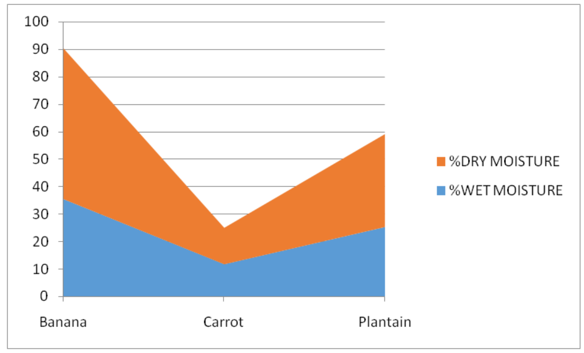

Fig 6.0: Area Graph of Dry and Wet Moisture Content of Banana, Carrot and Plantain after Dehydration

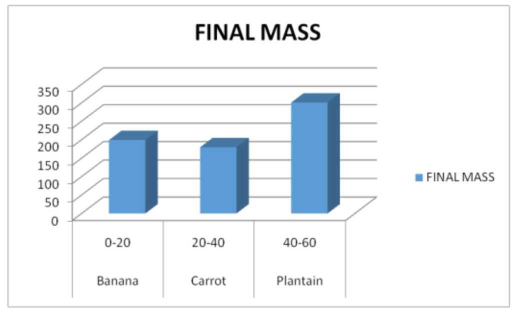

Fig 6.0: Bar Graph of Dry or Final mass of Banana, Carrot and Plantain after Dehydration

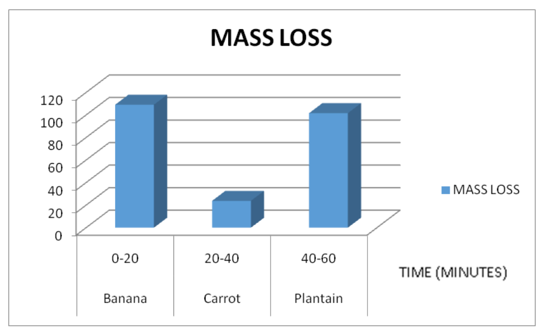

Fig 7.0: Bar Graph of Mass Loss of Banana, Carrot and Plantain after Dehydration

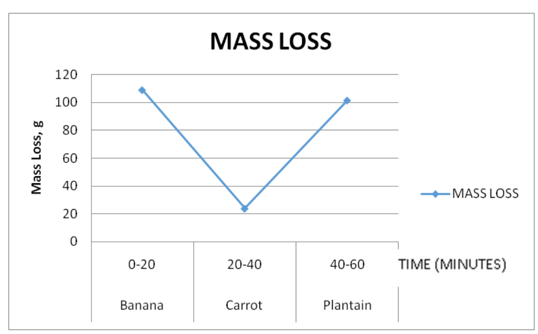

Fig 7.0: Line Graph of Mass Loss of Banana, Carrot and Plantain after Dehydration

DISCUSSION

The results of the study, design and performance evaluation of a thermostat controlled electric dehydrating machine were discussed here. CAD design approach for the thermostat controlled electric dehydrating machine was adopted and Autodesk Fusion 360 was used to create the solid model. The dehydrator retained a maximum dimension of 700mm$\times$ $575mm$ $\times$ 1339mm, with four rectangular heating trays of 50cm$\times$ 30cm and 2mm thickness each which gave a heating surface area of $0.15m^2$ according to Fig 2.0 to Fig 4.0. Heating coil was designed to retain the shape of swirl ring OP302 model with maximum heat output of 180kW within 60 minutes. HMI (Delta B03S212) and PLC (DELTA-DVP20EX3) were used to control the thermostat set maximum temperature and time to 80℃ and $0.000011sec$ to retain the quality of Banana, Carrot and Plantain after drying.

According to table 2.0 and Fig5.0 and Fig 6.0, Banana was found to have the highest percentage wet moisture of 35.42% followed by Plantain 25.27% among the three chosen fruits with the least being that of the Carrot 11.72%, when dehydrated from 0 to 60 minutes according to table1.0. It was also noted that the highest mass loss was found in Banana, 109.1 grams followed by Plantain, 101.6 grams when each was heated for 20minutes, according to Table1.0 and Fig 6.0 and Fig 7.0. The machine efficiency and machine capacity was found to be 37.16% and 2.827g of moisture/sec respectively. These results suggested a considerable increase in machine output and performance.

CONCLUSION

The design and performance evaluation of a thermostat controlled electric dehydrating machine was obviously achieved. The machine efficiency and moisture removal rate were found to be 37.16% and 2.827g of moisture/sec respectively. It was also deduced that the use of thermostat controller, would retain food quality and protect equipment against overheating.

RECOMMENDATIONS

The following recommendations are suggested based on the study:

1) To avoid overheating of foods and materials, digital thermostat controller should be deployed.
2) Engineering materials not certified for handling should not be used to avoid food poisoning or gaseous emission.
3) The use of human machine interface and programmable logic controller would improve machine performance and minimize sudden failure.
4) Moderately rotating circulation fan must be used to ensure uniform and steady heating.

REFERENCES

[1] Ibrahim, S & Mohammad, A. (2022). Design of a Prototyping Food Dehydration Machine.

[2] *Palestine Polytechnic University, College of Engineerin, Hebron.* Retrieved 27 October 2023 from: http://www.researchgate.com

[3] Mohammad, S. (2013). Design and Construction of a Vegetable Drier. *International Journal Of Engineering And Science ,(2)9, pp. 88-94.*

[4] Mercer, D. G. (2007). An Introduction to Food Dehydration and Drying. Retrieved 27 October 2023 from: http://www.researchgate.com

[5] Vincenti, W. G, & Kruger, C. H.(1965). *Introduction to Physical Gas Dynamics.* New York: Wiley.

[6] White, F. M. (1998). *Applied Thermodynaics.* 4th ed. New York: McGraw-Hill.