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Optimization Analysis of Thermal Efficiency of an Automated Garri Frying Machine

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[*1]Ozigbo Emmanuel S., [2]Bamgboye A. I., [3]Oduntan O. B

[1,2]Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan, Nigeria

[3]Department of Aquaculture and Fisheries Management, University of Ibadan, Ibadan, Nigeria

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ABSTRACT

The effect of the preprocessing conductions such as mash quantity (10, 20, 30, 40, and 50 kg), frying time (15, 30, 45, 60, and 75 minutes), initial moisture content (30, 35, 40, 45 and 50% wb), and temperature (140, 160, 180, 200 and 220 ºC) on thermal efficiency of an automated garri frying machine was investigated. 750 kg of the cassava mash sample was used for the frying operation which was produced from a 3 tons cassava variety, TME 419. The processing operations such as peeling, grating, fermentation, dewatering, pulverizing, and sieving were carried out using garri processing machines in the IITA factory while the frying was done using the automated garri fryer in the University of Ibadan, Nigeria. The thermal Efficiency (η_t) of the automated fryer was determined using standard equations. Response surface method was adopted to optimize the operating variables. The experimental thermal efficiency of the machine was in the range of 8.49 to 99.12 J, with the maximum fraction to minimum of 11.69. Mash quantity, frying time and temperature significantly influenced the thermal efficiency at $P < 0.05$. Regression models were established with coefficient of determination, R2 greater than 0.86. The optimum performance conditions for the thermal efficiency were 20.48 minutes frying time, 45.0 kg mash quantity, 180 ºC constant temperature and 40% wb initial moisture content at the desirability of 1.00. The effect of the preprocessing conditions (mash quantity, time, and temperature) was significant ($p < 0.05$) on thermal efficiency of the automated fryer.

1. INTRODUCTION

The economic importance of cassava in Nigeria can never be overemphasized. Cassava (*Manihot esculaenta* Crantz) is a plant that was originated from South America which was used in addition to maize, potato and rice by Amazonian Indians (Shin et al., 2021). During the 16th and 17th centuries, Portuguese explorers brought cassava to Africa through trade with the African coasts and neighboring islands (Iwuagwu, 2012). Cassava was then introduced later to Africans, and established practically in every section of tropical Africa (Friday et al., 2020). Brazil (6%), Ghana (7%), Thailand (10%), Congo (13%) and Nigeria (19%) are the leading cassava producers (Tridge, 2021). Cassava roots have a high starch content 80 – 90% (Peprah et al., 2020; Jose-Luis et al., 2020) and are high 25 mg/100 g in vitamin, 50 mg/100 g in calcium, and 40 mg/100 g in phosphorus (Montagnac *et al.,* 2009; Burns *et al.,* 2012; Safwan and Mohammed, 2016; Islamiyat et al., 2016). Other nutrients such as fat, iron, and protein are found in the cassava roots (Salvador et al., 2014). Cassava root has a lot of health benefit to the body. It has fibers that are not soluble in water, making it good for the digestive system (Temesgen et al., 2019). It is rich in chemicals like bakarotennya and Vitamin A that serve to boost the health of your eyes and avoid loss or bad vision in the future (Bandigin, 2019).

The major challenge with fresh cassava roots is that they have a short postharvest shelf life (Awoyale *et al.,* 2020), thus, it is expected to be consumed or converted into long-lasting products as fast as possible after harvest. The frying, which happens due to simultaneously heating and dehydrating the moisture content contained in the cassava by applying heat, is the most crucial unit of operation while turning cassava into garri (Akinnuli *et al.,* 2015). Garri is traditionally fried in shallow earthenware cast-iron pans (agbada) over a wood fire by women. While frying, the operator sits sideways by the fireplace, causing a variety of health problems and discomfort owing to the heat and the sitting posture. As a result, there was a need for new ideas and change to help these women deal with their difficulties. Then Odigbo and Ahmed model was developed to faithfully improve the village manual frying operations (Odigbo and Ahmed, 1985). However, the effect of heat was not significantly reduced which lead to its improvement by J.C Igbeka who made a garri fryer of a fireplace oven with a chimney and a flying pan as reported by Gbasouzor and Maduabum (2012).

Frying or drying is one of the many food processing and preservation activities involving heat transfer. Food properties such as specific heat capacity, thermal conductivity, and thermal diffusivity influence the thermal efficiency of food frying or drying machine (Sanni et al., 2016). A good knowledge of the thermal properties and behaviour of foods during frying operation is thus, very important for optimum design and application of dryer/fryers (Serpil and Servet, 2006). Thermal conductivity (*k*) is the ability of a material to conduct heat. In porous food materials thermal conductivity depends mostly on proximate composition but other factors such as void ratio, shape and size, and moisture content can also affect the property. Thermal conductivity of food materials vary. Models have been developed to predict the thermal conductivity of food materials but product specific factors must be considered in their application (Choi, Y. and Okos, 1986; Murakami and Okos, 1989; Rahman, 1995). Specific heat (*Cp*) is the amount of heat required to increase the temperature of a unit mass of material by one degree (J/kg°C) and therefore, depends largely on the process of heating (either by constant pressure or constant volume) (Sanni et al., 2016).

Therefore, the study is aimed at investigating the thermal property and drying behavior of cassava garri in an automated garri frying machine and also optimizes the operating variables in view to obtain the optimum thermal efficiency of the fryer.

2. RESEARCH METHODOLOGY

2.1 Study Area

The research was carried out at a cassava processing factory in International Institute of Tropical Agriculture (IITA) and University of Ibadan, Ibadan, Nigeria. IITA Headquarters is located at Idi-Ose, Moniya, Ibadan, Oyo State, Nigeria. IITA is the research leading organization in West Africa. It is located in the forest-savannah agro-ecology, at a height of 248 meters above sea level, with 7° 30 8 N latitude, and 3° 54 37 E longitude. IITA is rich in Alfisol clay loam, with a pH range of 5.0 to 6.5.

2.2 Sample Preparation

750 kg of garri sample was obtained from the processing procedures involving peeling, washing, grating, fermenting, dewatering, sieving and frying of 3,000 kg of cassava fresh roots. The roots

were obtained from a cassava breeding centre of the International Institute of Tropical Agriculture (IITA). The mash quantity, initial moisture content, frying time, and temperature of the mash sample were adjusted. The operating speed of the machine was adjusted to 84 rpm. The energy consumption and thermal efficiency was determined using the equation 1 – 3 below as stated by Choi and Okos (1986).

$$Q_U = W_C C_C (T_f - T_i) + W_d h_{fg} (M_i - M_f) \quad (1)$$

$$Q_a = (1.30 + 0.292t) \times 10^3 \text{ for experiments using } 0.03 \text{ m}^3/\text{s} \quad (2)$$

$$\eta_t = \frac{Q_U}{Q_a} \quad (3)$$

Where, W_c – mass of wet cassava mash added to the fryer, C_c – the specific heat capacity of wet cassava mash calculated using Choi and Okos' model (1986), T_f – the cassava meal's final frying temperature, T_i – the temperature of the cassava mash when it was first made which was 25°C, W_d – the mass of dry matter content of cassava garri, h_{fg} – the heat of vaporization of water at the frying temperature, M_i – the initial moisture content of the cassava mash, M_f – the cassava mash's final moisture contents, Q_a – the true heat dissipated by the heating components (kJ), η_t (%) is the thermal efficiency and t is the frying time (minutes) required to achieve the specified final moisture content for the cassava.

2.3 Experimental Design

The relationships between the operating parameters (mash quantity, frying time, initial moisture content and frying temperature) were studied on the thermal efficiency while frying garri using an automated garri frying machine made electrical elements as heat sources. 4-factors, 5-level D-optimal design using Design Expert software (Version 11.0 Ease-Stat Inc., Minneapolis, USA) was used for the experiment. The independent variables mash quantity, frying time, initial moisture content and frying temperature were varied over 10, 20, 30, 40, 50 kg; 15, 30, 45, 60, 75 mins; 30, 35, 40, 45, 50% wb; and 140, 160, 180, 200, 220 °C, respectively. The levels, codes and intervals of the independent variables used are shown in Table 1.

Table 1: Levels, codes, and independent variables intervals

Independent variables	Codes	- α	- 1	0	+1	+ α
Mash quantity (kg)	x_1	10	20	30	40	50
Frying time (mins)	x_2	15	30	45	60	75
Initial moisture content (% wb)	x_3	30	35	40	45	50
Frying temperature (°C)	x_4	140	160	180	200	220

2.4 Optimization and Statistical Analysis

The testing of the effects between and within the parameters was carried out using D-optimal experiment in response surface methodology (RSM) in Design Expert software (Version 11.0 Stat-Ease, Inc., Minneapolis, USA). In further analysis and correlation of the results, the mathematical models predicting the relationship between the independent variables (mash quantity, time, initial MC and temperature) and the dependent variable (thermal efficiency) were developed. In the optimization process, the independent variables were set range values while dependent variable (thermal energy) was set at a maximum value. Multiple linear regression technique was used for testing the model at 95% level of confidence. The validity of the model was obtained by using R^2 and probability of prediction F ratio test. The appropriate model was chosen based on selection of the highest order polynomial where the additional terms were significant, insignificant lack of fit, maximization of the Adjusted R^2 and the predicted R^2. The equation 4 below shows the expression of regression model determination (Ogunlade and Aremu, 2020; Chakraborty et al., 2017).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i<} \sum_{j=3}^{k} \beta_{ij} X_i X_j X_k + \sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j X_k + \varepsilon \qquad (4)$$

Where Y is the response (dependent variable), β_0 is the model intercept, $\sum_{i=1}^{k} \beta_i X_i$ characterizes the main linear effects of individual process variables, $\sum_{i<} \sum_{j=2}^{k} \beta_{ij} X_i X_j$ incorporates the interaction effects between variables and $\sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j$ represents the main quadratic effects of the variables, ε is the random error of the experimentation, X_{ijk} denotes the matrix of the uncoded process variables. The regression analysis was used to determine the unknown coefficients of $\beta_0, \beta_i, \beta_{ij}$ and δ_{ij}. The models were compared validated by comparing the experimental results with calculated results. The analysis of variance (ANOVA) was used to determine the significance of differences among the values of mash quantity, frying time, initial moisture content, and frying temperature at $P < 0.05$.

3. RESULTS AND DISCUSSION

3.1 The Effect of Mash Quantity, Frying Time, Initial MC, Temperature on the Thermal Efficiency of the Machine

The thermal efficiency of the automated garri frying machine is based on the mash quantity, frying time, initial moisture content, and temperature. As shown in Table 4.17, the thermal efficiency of the machine was in the range of 8.49 to 99.12 J, with the maximum fraction to minimum of 11.69. A fraction greater than 10 usually means that a change is needed and a fraction smaller than 3 indicates a small effect. Table 2 below presents the experimental data and results of the thermal efficiency of the automated garri fryer used. The main impact of the interaction determined for each factor on the thermal efficiency is given in Table 3. The analysis of variance for response linear model predicting the Thermal efficiency of the automated garri frying machine was shown in Table 3. The linear model F-value of 51.10 implies that the model is significant. It was observed from Table 3 that F-values for mash quantity (x_1), frying time (x_2), and frying temperature (x_4): 144.49, 59.47 and 9.13, respectively and p-values of less than 0.05; 0.0001, 0.0001 and 0.0067, respectively are significant, indicating that there was direct relationship between these independent variable with the thermal efficiency of the machine. The statistical properties of these independent variables are shown in the Table 4 below.

Table 2: Experimental Data and Results

	Factor 1	Factor 2	Factor 3	Factor 4	Response
Run	A:Mash Quantity	B:Frying Time	C:Initial MC	D: Frying Temperature	Thermal Efficiency
	kg	mins	%	Deg.Celcius	%
1	10	15	50	220	61.23
2	40	15	30	140	92.5
3	30	30	40	160	58.61
4	50	75	30	220	72.2
5	10	75	40	220	14.66
6	50	15	40	220	99.12
7	50	45	40	160	73.9
8	50	75	50	220	81
9	20	30	50	140	38.77
10	30	30	40	160	69.97
11	10	15	40	140	31.59
12	30	15	50	180	98.52
13	50	30	50	140	96.9
14	10	60	35	180	11.85
15	20	30	30	180	48.22
16	10	15	30	220	57.26
17	10	75	30	140	8.49
18	10	60	35	180	14.37
19	50	75	40	140	49.15
20	10	75	50	140	9.57
21	30	45	40	220	71.8
22	50	75	40	140	76.32
23	50	45	30	180	94.3
24	30	15	50	180	98.21
25	30	45	40	220	73.92

Table 3: Model Analysis Data for the Thermal Efficiency Response Variable for the Automated Garri Fryer.

	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	20702.55	4	5175.64	51.10	< 0.0001	Significant
x_1	*14653.16*	*1*	*14653.16*	*144.69*	*< 0.0001*	
x_2	*6022.61*	*1*	*6022.61*	*59.47*	*< 0.0001*	
x_3	*186.94*	*1*	*186.94*	*1.85*	*0.1894*	
x_4	*925.12*	*1*	*925.12*	*9.13*	*0.0067*	
Residual	2025.51	20	101.28			
Lack of Fit	*1586.41*	*15*	*105.76*	*1.20*	*0.4522*	*not significant*
Pure Error	*439.10*	*5*	*87.82*			
Cor Total	22728.07	24				

Table 4: Statistical Properties of the Independent Variables

	Coefficient		Standard	95% CI	95% CI	
Factor	Estimate	df	Error	Low	High	VIF
Intercept	59.95	1	2.02	55.72	64.17	
A-Mash Quantity	29.75	1	2.47	24.59	34.91	1.01
B-Frying Time	-19.91	1	2.58	-25.30	-14.52	1.03
C-Initial MC	3.77	1	2.78	-2.02	9.56	1.03
D-Temperature	7.48	1	2.47	2.32	12.64	1.01

The F-value for initial moisture content (x_3) of 1.85 and p-value of 0.1894 greater than 0.05, indicated that there was no direct significance effect of the variable on the thermal efficiency of the machine. The Lack of fit F-value of 1.2 implies that the Lack of Fit is not significant at 99% confidence level. There is only a 45.22% chance that a Lack of Fit F-value this large could occur due to noise which is good. The value of R^2 (86.24%) and Adj-R^2 (89.31%) are close to 1.0 which is very high indicating that there was a high correlation between the observed values and predicted values. The model analysis of the result obtained is presented in Table 5. Adequate Precision measures the signal to noise ratio. A ratio greater than 4 is desirable as reported by Montgomery (2001). Therefore, adequate precision ratio of 26.23 indicates an adequate signal.

Table 5: Model Analysis for Thermal Efficiency of the Garri Fryer

	Std.		Adjusted	Predicted		
Source	Dev.	R-Squared	R-Squared	R-Squared	PRESS	
Linear	10.06	0.9109	0.8931	0.8624	3126.93	Suggested
2FI	11.57	0.9175	0.8586	0.4369	12797.81	
Quadratic	9.98	0.9562	0.8949	0.4116	13373.67	
Cubic	9.37	0.9807	0.9073		+	Aliased

The modified linear model was shown in Eq. (5) where y_{TE} represented thermal efficiency in response surface experiment (RSM).

$$Y_{TE} = 59.95 + 29.75x_1 - 19.91x_2 + 3.77x_3 + 7.48x_4 \quad \ldots\ldots\ldots\ldots\ldots (5)$$

It was observed from the model equation (5) above that the coefficients of x_1, x_3, and x_4 are positive while x_2 is negative which means that a change in a unit mass increase of mash quantity, initial moisture content and frying temperature will directly result in increase in the thermal efficiency of the automated garri frying machine by 29.75%, 3.77% and 7.48%, respectively. This is in confirmation with the report of Sanni et al (2016) that effective thermal diffusivity and efficiency increase with temperature. A similar report was recorded by Flores et al (2012). However, a unit increase in the frying time will inversely lead to a decrease in the thermal efficiency of the machine by 19.91%. The 3-D surface plot in 1below shows the effect of frying time and mash quantity. The curve explains that there was a sharp increase in the thermal efficiency as the mash quantity increases while a resultant decrease as the frying time increases. The optimum performance of thermal efficiency of 42.7% was observed as at the frying time of 20.48 minutes and mash quantity of 45.0 kg, constant temperature of 180 ^oC and initial moisture content of 40% wb. According to the Sanni et al (2014), a thermal efficiency range value of 25 – 70% for cassava meal rotary dryers is recommended. In Sanni et al (2015), pulverized cassava meal moisture content of 40 – 50% (wet basis) and drum temperature range from 140 – 200 ^oC is used for garri production.

The contour graph in Figure 2 below shows the points where all processing parameters met. Figure 3 shows the graph of the predicted values versus actual values and the closeness of the data along the curve line is the indication that the result better fit the model. While the Figure 4 shows the perturbation plot of the thermal efficiency and the independent variables used indicating the line view of the response surface. The plots provides how response change as each factor moves from a chosen reference point with all other factors held constant at the reference point.

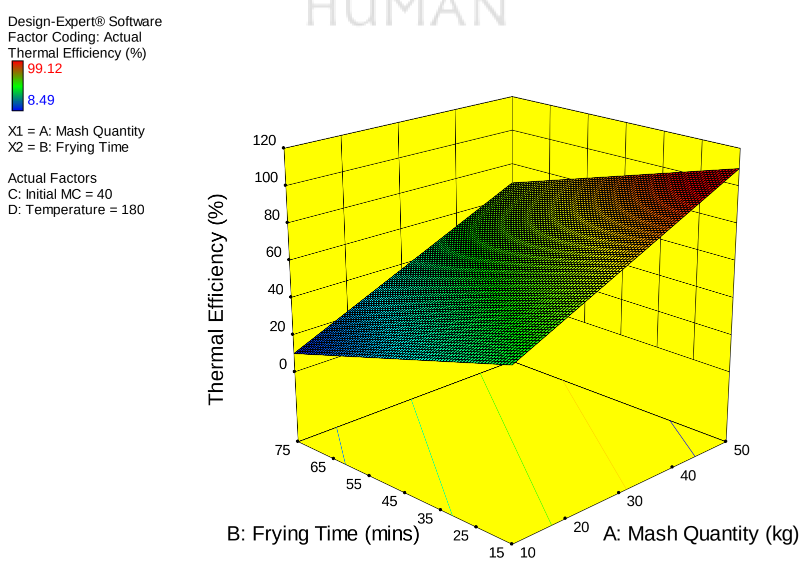

Fig. 1: The 3-Dimensional Surface Curve for Variation in the Thermal Efficiency at the Initial Moisture Content of 40% and Frying Temperature 180^{o}C

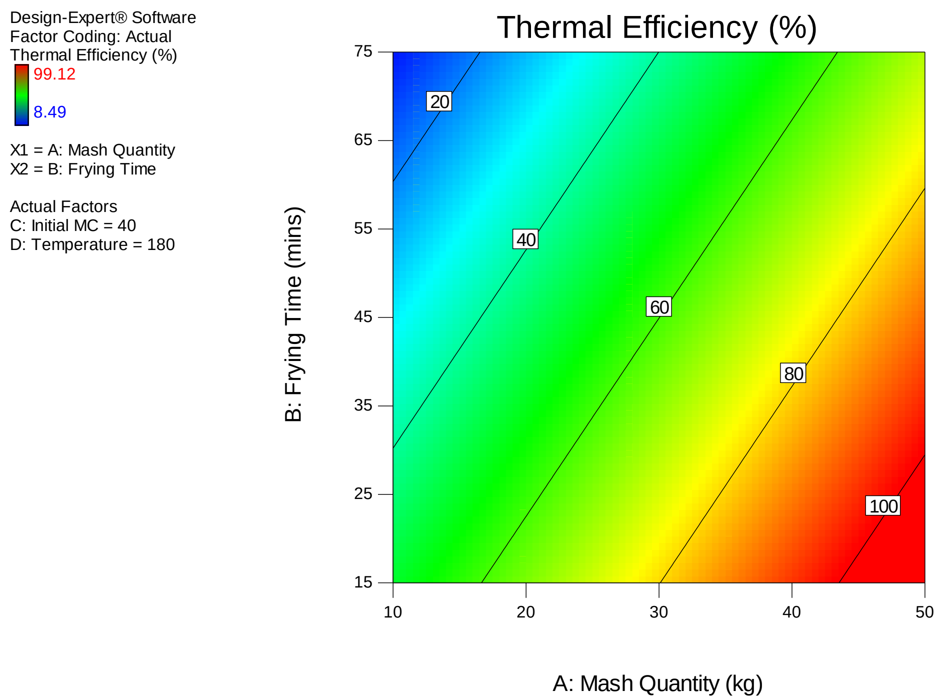

Fig. 2: The Contour Graph for the Variation in the Thermal Efficiency at the Initial Moisture Content of 40 % and Frying Temperature 180 ºC

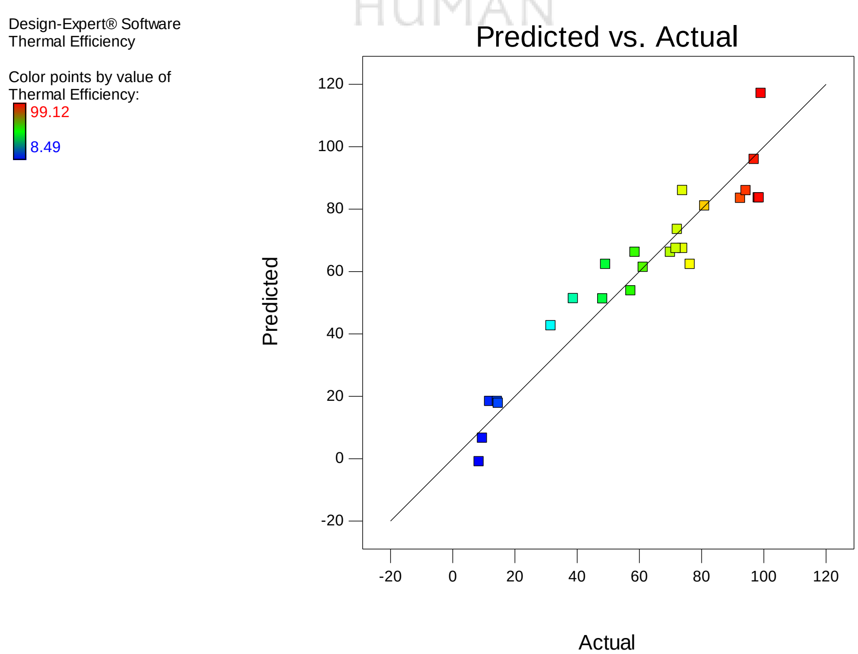

Fig. 3: The Perturbation Plot for Thermal Efficiency

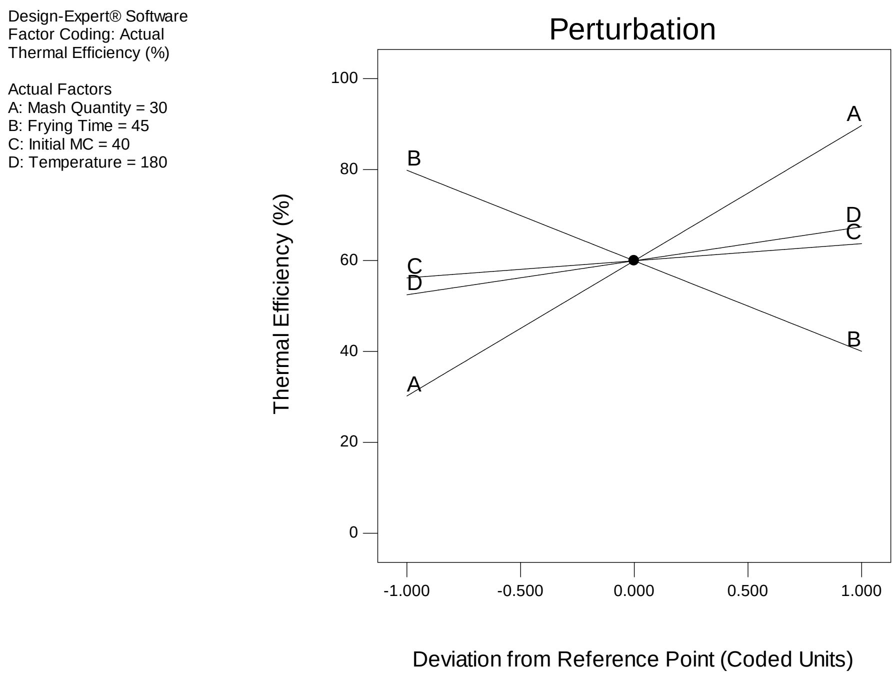

Fig. 4: The Perturbation Plot for Thermal Efficiency

CONCLUSION

The study to investigate the optimal thermal efficiency an automated garri frying machine was carried out. Data analysis showed that a unit mass increase of mash quantity, initial moisture content and frying temperature would directly result in increase in the thermal efficiency of the automated garri frying machine, while a unit increase in the frying time would inversely lead to a decrease in the thermal efficiency of the machine. The performance evaluation showed that the optimum thermal efficiency of 42.7% was observed at the processing conditions: frying time of 20.48 minutes and mash quantity of 45.0 kg, constant temperature of 180 ^{o}C and initial moisture content of 40% wb at desirability of 1.00.

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AUTHOR CONTRIBUTION

Ozigbo Emmanuel S.: Original drafting writing of the study, methodology, project administration and validation. Oduntan O. B.: formal analysis, methodology, result and discussion. Bamgboye A. I.: project supervision, proof reading, review and editing.

CONFLICT OF INTEREST

Ozigbo Emmanuel S., Bamgboye A. I., and Oduntan O. B declare that there are no conflicts of interest on the financial and commercial publication of the article.

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