MODELING RICE GRAIN CLEANING PROCESS IN A STATIONARY DESTONER

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ABSTRACT
The quality of local rice is a major concern for the future of the Nigerian rice sector. The major problem being the appearance and cleanliness of the rice delivered to the market. They are characterized by high percentage of impurities like husk and stones as well as under size/broken grains which reduces it economic value and makes it difficult to compete favourably with imported ones. Therefore, one of the important quality addition is reduction of contaminants especially stones to the barest minimum. In this research work, a mathematical model prediction equation for destoning of rice was developed based on the physical and aerodynamic properties of rice and machine characteristics. The dimensions and physical characteristics of three rice varieties; Kano, Zaria, and Mario were determined in the laboratory. Dimensional analysis using the Buckingham Pi (π) theorem was used to obtain a functional relationship between the cleaning efficiency and independent variables which include; feed rate, acceleration due to gravity, frequency of oscillation, speed of machine, terminal velocity, bulk density, true density and moisture content. The cleaning efficiency model was validated with data obtained from a developed rice destoning machine in the Department of Agricultural and Environmental Engineering, Modibbo Adama University of Technology Yola. The destoning efficiency showed a good agreement between the predicted and experimental data at 5% level of significance.

Keywords: Mathematical Modeling, Destoning, Dimensional analysis, Efficiency, Validation

1. INTRODUCTION
Nigeria has ecologies suitable for the production of different rice varieties which can be harnessed to meet domestic and export requirements. The country has a potential land area of between 4.6 - 4.9 million hectares for food production with only about 35 % cropped to rice (Singh *et al.*, 1997). Okunola and Bamgboye (2011) reported that locally produced rice is highly nutritious, however, the quality of its milled rice are usually poor. They are characterized by high percentage of impurities like husk and stones as well as under size/broken grains which reduces it economic value and makes it difficult to compete favourably with imported ones.

Separation of materials other than grain is essential to upgrade the quality of food material. Some of the methods employed for separating materials other than grains include winnowing (traditional method), aspiration, sieving and use of vertical air stream (Ademosun, 1993; Ogunlowo and Adesuyi, 1999).

Frederick *et al*. (2003) reported that in a survey carried out on rice milling industries in Nigeria only few millers were destoning their paddy before milling. The low utilization of destoners in rice milling operations could be the cause of high presence of stones in locally milled rice, which is the major reason consumers, refrain from purchasing local rice.

Ogunlawo and Adesuyi (1999) accomplished separation of stones and other contaminants using a combination of oscillating sieves and variable directional air stream at 160 rpm. Okunola and Igbeka (2009) improved on an appropriate technology cereal cleaner by Igbeka (1984) and obtained a higher cleaning efficiency of 71% for paddy.

Suleiman (2008) constructed a kitchen model wet-grain destoner for rice with destoning efficiency of 93% but recommended further investigation on the destoning efficiency. An observed drawback of the wet grain destoner is that the time required for separation of rice from stones was not specified.

This paper considered modeling the rice grain cleaning process in a stationary rice destoner to develop a mathematical model combining physical, aerodynamic properties of rice, with machine constructional and functional parameters. The objective of this paper is to model the rice grain cleaning process in a stationary destoner and to validate the model equation using a developed machine.

2.0 METHODOLOGY

A mathematical model was developed to deal with the processes of separating rice from impurities and stones. Two important physical phenomena were identified. The passage of air stream over rice to separate it from materials other than grain using their terminal velocity and passage of rice through oscillating sieve to ensure that only rice sized materials are treated. An analytical description of these phenomena was made in terms of crop feed rate, speed of machine, diameter of sieve opening, amplitude, frequency of oscillation and power requirement. These are then related to separation efficiency. The separation process was divided into two separate events (1) the flow of milled rice from hopper to aerodynamic medium and (2) the passage of rice from aerodynamic medium to the oscillating sieve.

The physical parameters affecting the separation are:

a. Crop factors: crop variety, maturity stage, grain moisture content (θ_g), bulk density of grain ρ_g (kg/m^3) and particle density ρ_p (kg/m^3).
b. Machine factors: feed flow rate q (kg/s), frequency of sieve oscillations α (1/s), velocity of air (V_a), static coefficient of friction μ, acceleration due to gravity g (m/s^2) and terminal velocity of particles (both rice and other materials) V_t (m/s).

Dimensional analysis of the Buckingham π method was used to obtain the mathematical model of the separation process. The Buckingham Pi theorem states that "the number of dimensionless and independent quantities required to express a relationship among variables in any phenomenon is equal to the number of quantities involved minus the number of dimensions in which those quantities may be measured (Simonyan *et al*, 2006).

The mathematical expression for rice destoning efficiency (η) between the significant dependent and independent variables is then given thus: considering parameter that may affect cleaning and separation of rice in the destoner.

$$\eta = (\rho_g, q, \alpha, g, V_m, V_t, \mu, \theta_g, \rho_p) \qquad (1)$$

Where, η = destoning efficiency (%), ρ_g = bulk density of grain (kg/m^3), q = feed flow rate (kg/s),

α = frequency of sieve oscillation (1/s), g = acceleration due to gravity (m/s^2), V_m = machine's operating speed (m/s), V_t = terminal velocity of rice grains (m/s), μ = coefficient of friction, θ_g = moisture content of rice grain (%)
ρ_p = bulk density of particles (kg/m^3)

Mathematically, $f(\eta, \rho_g, q, \alpha, g, V_m, V_t, \mu, \theta_g, \rho_p) = 0$ (2)

The dimensional matrix of variables is given as:

	η	ρ_g	α	q	g	V_m	V_t	μ	θ_g	ρ_p
M	0	1	0	1	0	0	0	0	0	1
L	0	-3	0	0	1	1	1	0	0	-3
T	0	0	-1	-1	-2	-1	-1	0	0	0

μ, θ_g are dimensionless and are therefore excluded from the dimensionless terms determination.

$f(\rho_g, q, \alpha, g, V_m, V_t, \rho_p) = 0$ (3)

While the dimensional equation for the above equation is
$(ML^{-3})(MT^{-1})(T^{-1})(LT^{-2})(LT^{-1})(LT^{-1})(ML^{-3}) = 0$ (4)

Total number of variables n = 7 and there are m = 3 fundamental dimensions. Therefore the number of π-terms expected would be n – m = 7 – 3 = 4. The number of variables in each group will be m + 1 or 3 + 1= 4. Equation (4) becomes: $f_1(\pi_1, \pi_2, \pi_3, \pi_4) = 0$ (5)

and the recurring variables selected are $\alpha V_m \rho_g$

$$\pi_1 = \alpha^{a_1} V_m^{b_1} \rho_g^{c_1} q \quad (6)$$

$$\pi_2 = \alpha^{a_2} V_m^{b_2} \rho_g^{c_2} g \quad (7)$$

$$\pi_3 = \alpha^{a_3} V_m^{b_3} \rho_g^{c_3} V_t \quad (8)$$

$$\pi_4 = \alpha^{a_4} V_m^{b_4} \rho_g^{c_4} \rho_p \quad (9)$$

When the six equations above are solved the dimensionless Pi-terms obtained are:

$$\pi_1 = \frac{\alpha^2 q}{V^3{}_m \rho_g} \quad (10)$$

$$\pi_2 = \frac{g}{\alpha V_m} \quad (11)$$

$$\pi_3 = \frac{V_t}{V_m} \quad (12)$$

$$\pi_4 = \frac{\rho_p}{\rho_g} \quad (13)$$

Substituting them in Equation (5) becomes;

$$f_1\left(\frac{\alpha^2 q}{V^3{}_m \rho_g}, \frac{g}{\alpha V_m}, \frac{V_t}{V_m}, \frac{\rho_p}{\rho_g}\right) = 0 \quad (14)$$

$$\eta = f_1\left(\frac{\alpha^2 q}{V^3{}_m \rho_g}, \frac{g}{\alpha V_m}, \frac{V_t}{V_m}, \frac{\rho_p}{\rho_g}, \mu, \theta_g\right) = 0 \quad (15)$$

Combining the dimensionless terms to reduce it to a manageable level according to (Simonyan *et al.*, 2006) by multiplication and division:

$$\pi_1 \times \pi_2^{-1} = \frac{\alpha^2 q}{V^3{}_m \rho_g} \times \frac{\alpha V_m}{g} = \frac{\alpha^3 q}{V_m^2 \rho_g g} \quad \text{Becomes } \pi_{12} \quad (16)$$

$$\pi_3 \times \pi_4^{-1} = \frac{V_t}{V_m} \times \frac{\rho_g}{\rho_p} = \frac{V_t \rho_g}{V_m \rho_p} \quad \text{Becomes } \pi_{34} \quad (17)$$

Multiplying equation 3.16 by the inverse of $\frac{\mu}{\theta_g}$ that is $(\pi_7)^{-1}$ or ($\pi_{12} \times \pi_7^{-1}$)

$$\frac{\alpha^3 q}{V_m^2 \rho_g g} \times \left(\frac{\mu}{\theta_g}\right)^{-1} = \frac{\alpha^3 q}{V_m^2 \rho_g g} \times \frac{\theta_g}{\mu} = \frac{\alpha^3 q \theta_g}{V_m^2 \rho_g g \mu} \quad \text{Becomes } (\pi_{72}) \quad (18)$$

$$\eta = f(\pi_{34}, \pi_{72}) \quad (19)$$

$$\eta = f\left\{\frac{V_t \rho_g}{V_m \rho_p}, \frac{\alpha^3 q \theta_g}{V_m^2 \rho_g g \mu}\right\} \quad (20)$$

3. RESULTS AND DISCUSSION

The prediction equation is established by allowing one π term to vary at a time while keeping the other constant and observing the resulting changes in the function (Shefii *et al.*, 1996). This is achieved by plotting the values of (η) against (π_{34}) neglecting (π_{72}) (Figure 1) and η against π_{72}neglecting π_{34}(Figure 2) at the four moisture levels.

$$\eta = 10.067\pi_{34} - 4.608 \quad (21)$$

$$\eta = -0.0023\pi_{72} + 0.7864 \quad (22)$$

Then combining the two equations the component equation becomes

$$\eta = f_1(\pi_{34}, \pi_{72}) - f_2(\pi_{34}, \pi_{72}) + k \quad (23)$$

$$= (10.067\pi_{34} - 4.608) - (-0.0023\pi_{72} + 0.7864) \quad (24)$$

$$= 10.067\pi_{34} + 0.0023\pi_{72} - 4.608 + 0.7864 \quad (25)$$

Therefore the prediction equation becomes

$$\eta = 10.067\pi_{34} + 0.0023\pi_{72} - 3.82 \quad (26)$$

Substituting the values of the dimensionless π terms gives the equation for the destoning efficiency of the machine (Figure 3). Model efficiency prediction equation becomes:

$$\eta = 10.067\left(\frac{V_t \rho_g}{V_m \rho_p}\right) + 0.0023\left(\frac{\alpha^3 q \theta_g}{V_m^2 \rho_g g \mu}\right) - 3.82 \quad (27)$$

$$\eta_{pred} = 4.0785.\eta_{\exp} - 9.3925 \quad (28)$$

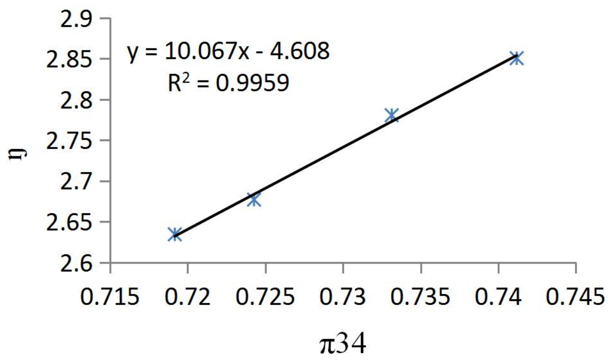

Figure 1: ŋ against Dimensionless π_{34}

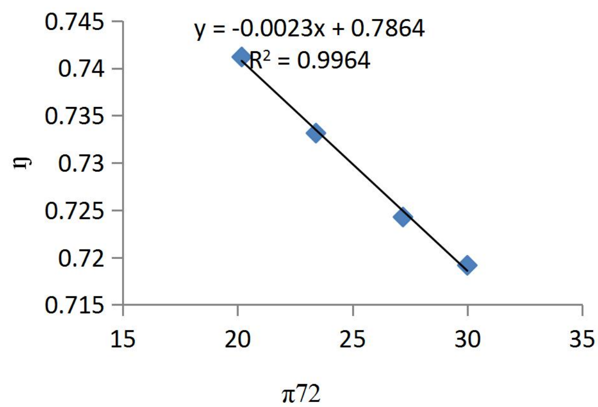

Figure 2: ŋ against Dimensionless π_{72}

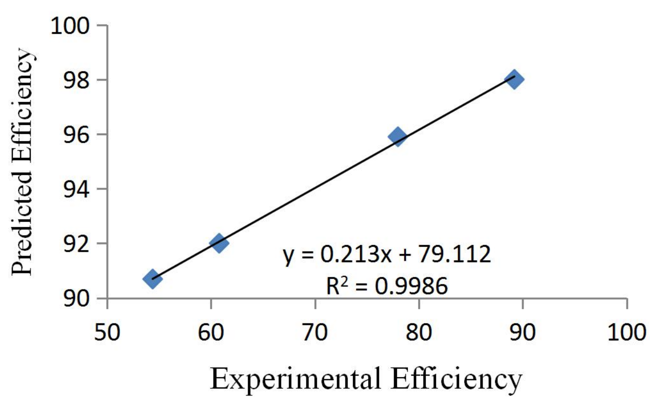

Figure 3: Predicted Efficiency against Experimental Efficiency

The destoning efficiency is affected by many factors, which act in diverse ways to prevent their effects to be evaluated separately. Simonyan *et al*. (2006) reported the effect of material rate on separation efficiency as parabolic. Regression equation was used to describe the relationship between the efficiency and other variables.

The predicted destoning efficiencies obtained were compared with the experimental values by applying the hypothesis b – β = 0. The t-test for paired two samples of means was used to test the significance β; the computed t_b value was compared with the tabular t value. The tabular t values at 5% level of significance with (n-2) = 2 degrees of freedom are 3.182 is greater than the computed t_b value of - 6.42 at 5% level of significance. β is said to be significantly different from zero if the absolute value of the computed t_b value is greater than the tabular t value at the prescribed level of significance. Since the tabular values are greater than computed values there is no significant difference between the predicted and experimental slope.

4. CONCLUSION

A mathematical model for separation of rice from stone was developed using the Buckingham Pi method of dimensional analysis, considering the crop and machine parameters. Analytical description of these phenomenon were made in terms of crop feed rate, speed of machine, diameter of sieve hole, amplitude frequency of oscillation and power requirement. Dimensional analysis using the Buckingham Pi theorem could be a veritable tool in the modeling of agricultural and food engineering studies.

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