Conceptual Modeling for Multiscale Design Simulation of Grain Slurry Food Starch Processing Machine

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Abstract
Conceptual models for mechanistic profiling of an integrated grain slurry food starch processing machine were derived in this study to foster its multiscale analysis, design improvement and mass production as per each end user's holding capacity. The novel machine constitutes the only existing design for continuous process of milling, sieving, dewatering and water recycling operations in grain slurry food starch extraction. Thus, the quantification of the theoretical frameworks relating the operational profiles and interactions of components of this machine using mechanistic modeling technique to enable its multiscale replication and wide application. The developed models revealed specific energy consumption and capacity of this machine as function of is shafts, grinding discs, auger conveyors, barrel, dewatering drum parameters and mass of the grain processed and these account for in its empirical function. Therefore, conceptual models developed should pioneer further advancement of this integrated machine's design, application and replication.

Keywords: *Design Improvement, Grain Slurry Food Starch, Machine, Mechanistic Models, Multiscale Simulation*

I. INTRODUCTION

Cereal grain based slurry food diets/beverages constitute an essential and integral part of consumer sector in sub-saharan Africa because of their high nutritive values and fast preparation process from the grain slurry food starch granule/paste (Ukwuru *et al.,* 2018). Extraction of the grain food starch from soaked grains involves strenuous sequential process of wet milling, sieving and dewatering (Oloyede *et al.*, 2016). Thus, full mechanization/automation of these operations remained keen interest of stakeholders in this sector to match ever increasing daily demand for grain slurry diets and beverages in this region (Simolowo, 2021; Tugbiyele, 2009; Oloyede *et al.*, 2016). This prompted the development of an integrated milling-sieving-dewatering machine by Nwankwojike *et al.*, 2022) which fostered continuous process of milling, sieving, dewatering and water recycling operations in grain slurry food starch extraction. The works of Egwuagu *et al.* (2021a) showed that this integrated machine is technically and economically viable for general adoption and advancement of food processing sector because it reduced drudgery, process water consumption and food loss to sieved chaff and improves hygiene/food security and profits. However this innovation is not yet widely sought for as expected despite these merits because of inadequate tool for its desired mass production and advancement for optimal operation.

Egwuagu *et al.* (2021b) developed empirical simulations relating the functional parameters of the integrated grain slurry food processing machine and used for its multi response performance optimization but the results cannot be applied for its multiscale investigation because they were derived from design specific operation data. This record indicated 87Kg/h, 98.75%, 25.35% and 183kJ/Kg as optimal throughput, extraction efficiency, cake moisture content and specific energy consumption of this machine at its basic operational water feed rate, sieving shaft speed, dewatering drum speed and pump pressure settings of 70L/h, 10rpm, 0.59rpm and 90kPa respectively. Application of these optimization results improved the operation of the existing design and scale of this machine but not applicable to its replication in line with different processing capacities of end users. This because the empirical models applied in this study did not account for all component profile of this machine. Therefore, replication with the empirical simulation is prone to traits of sub-optimal design generation and this prompted the need for a mechanistic based simulation of this novel grain slurry food starch processing machine to enable its effective mass production in accord with end users' holding capacities. This is because mechanistic models are not subject to idiosyncrasies in data since data are not required for its development (Ming, 2000; Mihir, 2008). In addition, mechanistic simulation provides more realistic predictions and opportunity to test the sensitivities of the process to meaningful entities that are capable of pointing fundamental improvements in process operability (Ming, 2000; Agunwamba, 2007; Mihir, 2008). Hence, this work aim to develop conceptual mechanistic models relating the operation of this machine with its component profiles and process parameters as precursor to its multiscale analysis, design improvement and development.

II. MATERIAL AND METHODS

The conceptual models relating the elements and process parameters' profiles of the integrated grain slurry food starch processing machine were developed in this study with mechanistic modeling procedure as postulated by Ming (2000) and Mihir (2008). This involve description of the machine and its operation, designation of its element and process parameters' symbols and sign conventions. Others include application of basic scientific laws and other ancillary parameters' interactions with some assumptions to formulate and solving/simplifying the equations governing the machine's operation as well as verification of dimensional homogeneity of the derived model parameters.

According to Nwankwojike *et al.* (2022), the grain slurry food milling-sieving-dewatering machine (Figure 1) comprises a water dispenser, burr mill, screw press-sieve, rotary drum, 0.5hp 65kPa vacuum pump and 4.5Hp electric motor as major components that were sequentially assembled to enable flow of material by gravity. It processes soaked grain to slurry starch cake and chaff as the dispenser feeds its hopper containing the grains with water at a regular rate. The grain-water matrix flows by gravity into the mill which effects the wet crushing while the resulting grain paste flows into the sieve. The sieve separates the paste into slurry food filtrate and chaff as its auger press compressively moves the paste from the left end of its barrel to the right under the opposing pressure of its conical stopper. This compression effects the oozing of the food filtrate out of the paste into its chute/collection through the sieve's aluminum net/chiffon nested barrel perforations while the chaff intermittently discharges through the barrel's right end aperture regulated by the backward and return motions of the stopper in tune with the barrel pressure. The water content of this filtrate drains out while its grain slurry crystallizes at the surface of the drum as the drum spins with 30% partially submergence in and out of the trough. The caking/dehydration progresses continuously by vacuuming at this filter's drying and discharging screen zones while the drained supernatant water recycles back to the water dispenser with the aid of the pump's suction. The caked slurry starch discharges into its collector as this unit's scrapper timely grazes its discharging zone.

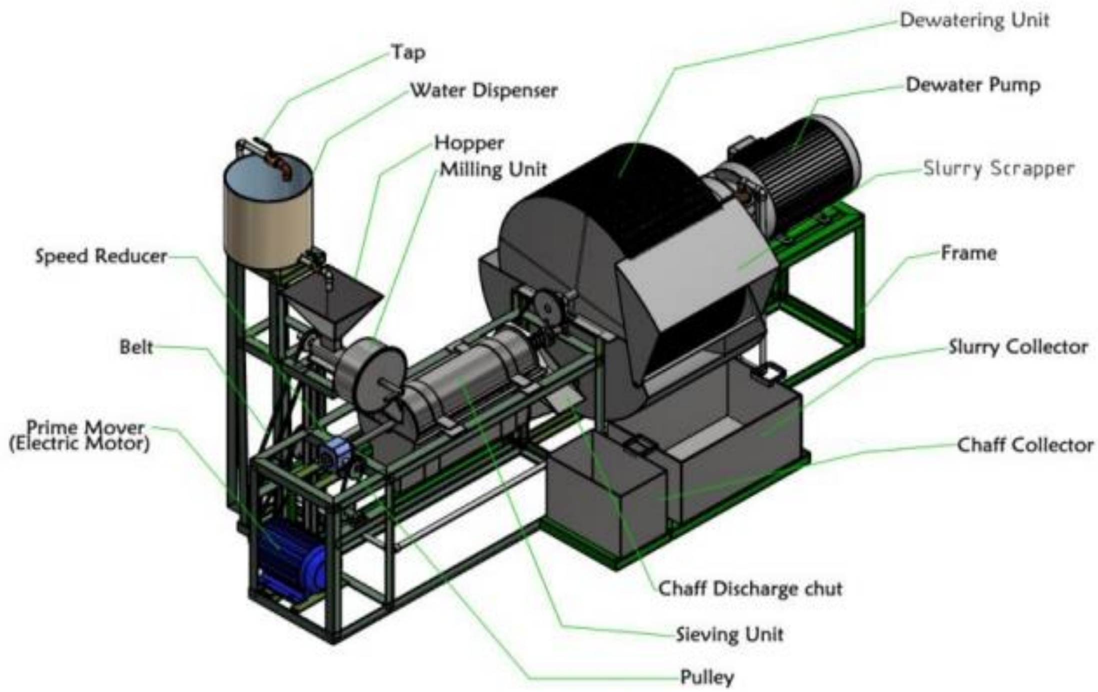

Figure 1: Integrated slurry food milling-sieving-dewatering machine.

III. RESULTS AND DISCUSSION

III.1 Model Formulation

The throughput, TP (kg/s) of the grain slurry food milling-sieving-dewatering machine is expressed mathematically as follows.

$$T_P = \rho_m Q_m \quad (1)$$

Where Q_m and ρ_m (kg/m3), the respective volumetric discharge rate and bulk density of the slurry food material processed are determined as;

$$:Q_m = A_{ds} V_{ds} = \frac{\pi}{60} D_1 N_1 L_{ds} B_{ds} \quad (2)$$

$$\rho_m = \frac{M_m}{V_d} \quad (3)$$

$$V_d = 2\pi r_d h_d [\emptyset_e - \emptyset_1] \quad (4)$$

Where r_d and h_d is the radius and weight of the rotary drum. $\emptyset_e$ is the fractional effective submergence and drying zone, and $\emptyset_1$ is the fractional ineffective discharge zone of the systems dewatering drum. Hence the bulk density of the slurry food material processed becomes;

$$\rho_m = \frac{M_m}{2\pi r_d h_d [\emptyset_e - \emptyset_1]} \quad (5)$$

Substituting equation (4) in equation (3) gives the throughput as;

$$T_p = \frac{M_m L_{ds} B_{ds} D_1 N_1}{120 r_d h_d [\emptyset_e - \emptyset_1]} \quad (6)$$

The processing time, *t* of this machine was derived from its the volumetric discharge rate of processed slurry (Equation 9) as follows

$$Q_m = \frac{V_d}{t} \quad (7)$$

$$t = \frac{120 M_m r_d h_d [\emptyset_e - \emptyset_1]}{L_{ds} B_{ds} D_1 N_1} \quad (8)$$

Thus, the total *E* (J) consumed by the machine's power transmission elements derived from Nwankwojike *et al* (2016), Richard and Keith (2011) as follows;

$$E = \frac{2\pi t}{60}\left[N_1\sqrt{{M_{bm}}^2 + {M_{tm}}^2}\right] \quad (10)$$

Where belt tensions, the maximum twisting moments of the both drives are determined from the following relations given by Sharma and Aggarwal (2006) as follows;

$$M_t = (T_1 - T_2)\frac{D_i}{2} \quad (11)$$

$$T_1 = T_{max} - T_c \quad (12)$$

$$T_{max} = \delta A \quad (13)$$

$$T_c = Mv^2 \quad (14)$$

Therefore the drive's shaft torque (Mt_h) becomes;

$$Mt_d = \left[\delta_d A_d - M_d\left(\frac{\pi D_d N_d}{60}\right)^2\left(1 - \frac{1}{log^{-1}\left[\frac{\mu_d \theta_d cosec\beta_d}{2.3}\right]}\right)\right]\frac{D_{d1}}{2} = XD_{d1}\left(0.5\delta_d A_d - 0.0014 M_d {D_d}^2 {N_d}^2\right) \quad (15)$$

Where

$$X = 1 + \frac{1}{log^{-1}[1.37\mu_d cosec\beta_d - 0.015\mu_d cosec\beta_d sin^{-1}\left(\frac{D_{d1} - D_{d2}}{2C_d}\right)} \quad (16)$$

$$C = \frac{L}{4} - 0.393(D_{d2} - D_{d1}) + \sqrt{\left(\frac{L-157}{4}\right)^2 - \frac{(D_{d2} - D_{d1})^2}{8}} \quad (17)$$

The maximum bending moment on of the drive shaft (Figure 2) was determined from its force analysis as follows.

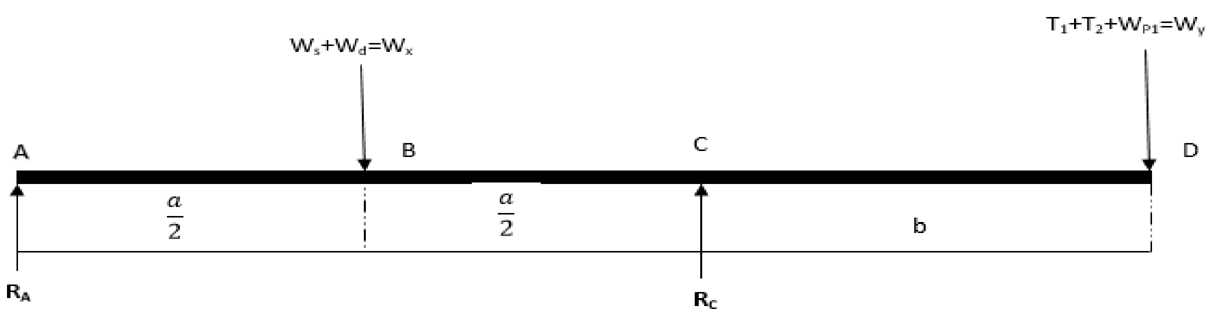

Figure 2: Force analysis of extraction drum shaft of grain slurry food milling-sieving-dewatering machine (Nwankwojike *et al*., 2022)

$$R_A a + W_y b = W_x * \frac{a}{2} \quad (18)$$

$$R_A = \frac{W_x a - 2W_y b}{2a} \quad (19)$$

$$R_C = \frac{W_x a - 2W_y a + 2W_y b}{2a} \quad (20)$$

$$B_{MA} = 0 \quad (21)$$

$$B_{MB} = \frac{R_A a}{2} = \frac{W_x a - 2W_y b}{4} \quad (22)$$

$$B_{MC} = R_A a - \frac{W_x a}{2} = W_y b \quad (23)$$

$$B_{MD} = R_A b - w_x \left(b + \frac{a}{2}\right) + R_c b = 0 \quad (24)$$

$$B_{ME} = 0 \quad (25)$$

Shear force

$$SF_A = -R_A = \frac{W_y b - 2W_x a}{2a} \quad (26)$$

$$SF_B = -R_A + W_x = -\frac{W_x a + 2W_y b}{2a} \quad (27)$$

$$SF_C = -R_A + W_x - R_C = -w_y \quad (28)$$

$$SF_A = -R_A + W_x - R_C + w_y = 0 \quad (29)$$

From the shear force analysis, there is a change in sign from positive to negative as we move from point B to C, Hence , Maximum bending moment occurs at point C.

$$B_{MC} = w_y b \quad (30)$$

Where;

$$W_y = T_1 + T_2 + W_{p1} = X\left(\delta_d A_d - 0.0028 M_d D_{d1}{}^2 N_{d1}{}^2\right) + W_{p1} \quad (31)$$

Hence; substituting equation (31) into the maximum bending moment relation of equation (30) gives;

$$M_{bd} = B_{MC} = Xb\left(\delta_d A_d - 0.0028 M_d D_{d1}{}^2 N_{d1}{}^2\right) + W_{p1} b \quad (32)$$

Accounting for a 10% possible energy loss due to drive friction and substitution of equations 1 to 9 and 32 into 10 gives the total energy consumed by the machine for processing a unit mass of grain slurry food starch was derived as;

$$E = \frac{11.31 r_d h_d [\emptyset_e - \emptyset_1]}{L_{ds} B_{ds} D_1 N_1} [N_d \sqrt{[Xb\left(\delta_d A_d - 0.0028 M_d D_{d1}{}^2 N_{d1}{}^2\right) + W_{p1} b\,]^2 + [X D_{h1}\left(0.5\delta_d A_d - 0.0014 M_d D_d{}^2 N_d{}^2\right)]^2} \quad (33)$$

Therefore, the energy consumed by the machine for processing a unit mass of grain slurry food starch was derived from the specific energy (*SE*) equation (34) of Nwankwojike *et al* (2016) as;

$$SE = \frac{Pt}{M_m} \quad (34)$$

$$SE = \frac{11.31 M_m r_d h_d [\emptyset_e - \emptyset_1]}{L_{ds} B_{ds} D_1 N_1} [N_d \sqrt{[Xb(\delta_d A_d - 0.0028 M_d D_{d1}{}^2 N_{d1}{}^2) + W_{p1} b\,]^2 + [X D_{h1}(0.5\delta_d A_d - 0.0014 M_d D_d{}^2 N_d{}^2)]^2} \quad (35)$$

IIII.2 Dimensional Homogeneity Validation of the Derived Models

The dimensional homogeneity of the derived conceptual throughput and specific energy models of grain slurry food milling-sieving-dewatering machine was analyzed and confirmed as follows;

$$\boldsymbol{T_p} = \frac{\boldsymbol{M_m L_{ds} B_{ds} D_1 N_1}}{\boldsymbol{120 r_d h_d}[\emptyset_e - \emptyset_1]}$$

$$MT^{-1} = L^3 T^{-1}(M^{-1}(ML^{-3}M) \quad (36)$$

$$MT^{-1} = MT^{-1} \quad (37)$$

$$\boldsymbol{SE} = \frac{\boldsymbol{11.31 M_m r_d h_d}[\emptyset_e - \emptyset_1]}{\boldsymbol{L_{ds} B_{ds} D_1 N_1}} [\boldsymbol{N_d} \sqrt{[\boldsymbol{Xb}(\boldsymbol{\delta_d A_d} - \boldsymbol{0.0028 M_d D_{d1}}{}^2 \boldsymbol{N_{d1}}{}^2) + \boldsymbol{W_{p1} b}\,]^2 + [\boldsymbol{X D_{h1}}(\boldsymbol{0.5\delta_d A_d} - \boldsymbol{0.0014 M_d D_d}{}^2 \boldsymbol{N_d}{}^2)]^2}$$

$$ML^2T^{-2} = T\{T^{-1}[[(MLT^{-2})L - L(MLT^{-2})]^2 + [L(MLT^{-2})]^2]^{\frac{1}{2}} \quad (38)$$

$$ML^2T^{-2} = ML^2T^{-2} \quad (39)$$

Thus, these conceptual models is dimensionally adequate and apt for mechanistic profiling of this machine It revealed specific energy consumption and capacity of this machine as function of is shafts, grinding discs, auger conveyors, barrel, dewatering drum parameters and mass of the grain processed. Since empirical functions of this system of Egwuagu *et al.* (2021b) did not account for these parameters, the use of conceptual models developed in this study is recommended for advancement of this integrated machine's design, application and replication.

IV. CONCLUSION

Conceptual models for mechanistic profiling of an integrated grain slurry food starch processing machine were developed in this study to foster its multiscale analysis, design improvement and mass production as per each end user's holding capacity. The developed models revealed specific energy consumption and capacity of this machine as function of is shafts, grinding discs, auger conveyors, barrel, dewatering drum parameters and mass of the grain processed. Hence, application of conceptual models of this machine is recommended for advancement of its design, wide application and replication.

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