Performance evaluation of a hammer mill during grinding of maize grains

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Abstract: The performance of a hammer mill fabricated in Uganda was evaluated and the optimal performance conditions were determined. The evaluation was done with screen hole diameters (S) of 1.5, 2.0, and 3.0 mm, hammer tip speeds (H) of 68.12, 81.81, 102.17 m s^{-1} and hammer thicknesses (T) of 4.0, 5.0, and 6.0 mm for determination of energy consumption and geometric mean diameter (GMD) using a modified central composite design (CCD) split-plot experimental design. Screen hole diameter and hammer thickness had significant effects on energy consumption ($p<0.05$). S and H had a significant effect on GMD but T did not have a significant effect on GMD. S and H had significant effects on both GMD and energy consumption. Quadratic effect of T, interaction effects of TH and HS also had significant effects on energy consumption. The hammer mill was most efficient with a hammer thickness of 5 mm, hammer tip speed of 83.57 m s^{-1} and screen hole diameter of 2.16 mm, both for energy consumption and flour GMD. The achieved impact energy calculated per unit mass, were 2.93 MJ t^{-1}, 4.23 MJ t^{-1} and 6.60 MJ t^{-1} for tip speed settings of 68.12, 81.81, and 102.17 m s^{-1} respectively. Impact energy supplied did not have an effect on GMD. Hammer mill settings obtained should be tested on other grains.

Keywords: hammer mill, impact energy, particle size, split-plot design

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1 Introduction

The type of hammer mill introduced to Uganda 60 years ago is still prevalent in the milling of maize and sorghum (Independent Consulting Group, 2003). These hammer mills are highly inefficient (USAID, 2010). Hammer mills are very important in Uganda and neighboring countries as a time- and cost-effective means of milling grains. Most are manufactured by in-country artisanal fabricators. However, there are a number of concerns with locally fabricated hammer mills including: longer time required to reduce the material to the required particle size, contamination of flour due to poor quality of the steel alloy (usually scrap mild steel), especially the hammers resulting in presence of iron filings in the final flour as result of excessive wear and tear, and low efficiency (i.e., high energy consumption per mass of ground material) (Ebunilo et al., 2010).

Particle size reduction of food solids is widely used in various food industry operations when creating smaller particles from larger particles of the same material (Brennan, 2005; Reid et al., 2008). Size reduction is one of the basic steps in processing cereal grain (Dziki, 2008). For example, animal feeds undergo size reduction for a number of reasons, i.e., to expedite feed consumption, improve nutrient absorption, and reduce material handling and labor costs by facilitating easier transport of products (Berk, 2013; Wennerstrum et al., 2002). A number of methods can be used for size reduction and have been discussed by Lowrison (1974) and Saravacos and Kostaropoulos (2002). Hammer mills are widely used in processing industries because of their ability to finely grind a large variety of materials in comparison to other

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milling machines (Basiouny and El-Yamani, 2016; Bitra et al., 2009; Henderson and Perry, 1976; Scholten and McEllhiney, 1985). Hammer mills use a combination of impact, shear, and compression forces during size reduction, with the largest proportion due to the impact (Austin, 2002; Probst et al., 2013; Saravacos and Kostaropoulos, 2002).

Hammer mill performance of hammer mill is usually measured by the energy consumption and the final particle size distribution of the ground product (Ghorbani et al., 2013; Henderson and Perry, 1976; Naik and Chaudhuri, 2015). Performance can be affected by machine variables such as screen design (size of openings, position of screen, and effective screen area), hammer tip speed, hammer pattern, number of hammers, hammer position (swinging or stationary), uniformity of input materials, and air assistance (Rudnitski et al., 1990; Naik and Chaudhuri, 2015). In addition, input material variables such as initial moisture content, initial particle size, and feed rate also affect hammer mill performance (Dey et al., 2013; Mani et al., 2004a; Yu et al., 2003). The particle size distribution and the degree of fineness are very important from the technological point of view when evaluating performance of hammer mills.

Studies by Arthur et al. (1982) showed that energy consumption increased with finer screen size when milling wheat straw, corn stover, and rice straw. Energy consumption is relatively high when milling to obtain small particle size because screen opening size affects particle size (Al-Rabadi, 2013; Miao et al., 2011). Fang et al. (1997) studied the effects of the main operational parameters of both hammer and roller mills, with energy efficiency as the performance indicator and found screen size had a significant effect on mill performance.

Another important property affecting hammer mill performance is the moisture content of the feed material. An increase in raw material moisture content increases energy consumption during size reduction (Miao et al., 2011). Mani et al. (2004b) showed that energy consumption increased as moisture increased when milling corn stover and switch grass. Yancey et al. (2011) compared grinding energy and particle size with varying moisture contents of corn stover, switchgrass, and wheat straw. Hardness and friability of a food material determines the amount of energy needed to grind the food. Harder food materials require more energy to grind than softer foods due to the greater amount of vitreous endosperm to floury endosperm (Dziki and Laskowski, 2005). These hard materials are able to resist the propagation of cracks. Therefore, it is important to know mechanical properties of the materials so as to have proper design and optimization of size reduction equipment. According to Brennan and Grandison (2011), only 2.0% to 0.1% of energy supplied is used to create new surfaces. The study was designed to evaluate screen hole diameter, hammer tip speed and hammer thickness effects on performance of a locally fabricated hammer mill for energy consumption and geometric mean diameter of flour particles.

2 Materials and methods

The milling experimentation was carried out using a new locally fabricated hammer mill at the Makerere University, School of Food Technology, Nutrition and Bioengineering pilot plant, in Kampala, Uganda. Maize grain of the quality protein variety Longe 5 (Nalongo) was used throughout. About 1,000 kg of grain with 13%-15% dry basis (db) moisture content was purchased from a farmer in Kayunga district, thoroughly mixed and stored 26.2^{o}C in hermetic grain storage bags on wooden pallets for two weeks. Moisture content of maize grains was determined according to the ASABE Standard S352.2 (2012) by drying 15 g samples at 103^{o}C for 72 h in a hot-air oven. Grain sample mass was measured using a platform scale (B15 Axis).

The minimum purity of the grain used for the experiment was ~ 99.9% by visual observation. Stones, broken grains and metal were removed from maize batch by screening through a 6.3 mm wire mesh and passage over ferrous magnets (Corn Refiners Association, Inc., 2006). Larger impurities like plastic strips and small nails were removed by hand. The amounts of maize grains used during the test were at least 80% of the specified milling capacity (500 kg h^{-1}) of the hammer mill as rated by the fabricator. A representative sample of whole grain maize weighing at least 1 kg was retained, sealed in a whirl-pak sampling bag (Nasco International Inc.) and stored in a refrigerator at –4^{o}C.

2.1 Experimental design and procedures

The evaluation was done comparing screen hole diameters (S) of 1.5, 2.0, and 3.0 mm; hammer tip speeds (H) of 68.12, 81.81, 102.17 m s^{-1}; and hammer thicknesses (T) of 4.0, 5.0, and 6.0 mm for determination of energy consumption (kWh t^{-1}) and final flour particle geometric mean diameter. The experiment was carried out under measured constant ambient conditions of ~25°C and ~70% average humidity (Humiport 05).

The gap between the hammer tip and the inner surface of the screen was kept constant at 0.635 cm during the tests since all hammers had the same lengths, as measured along the axis of symmetry from the hammer mounting hole to the hammer end/tip. A digital caliper (measuring range: 0 to 150 mm) was used to measure the hammer thickness, gap between hammer tip and inner surface of the screen, and the screen hole diameter. Smooth screens were used. The hammer tip speeds were selected based on preliminary study. The tip speed was measured using a portable tachometer.

Table 1 Specifications of the locally fabricated hammer mill

Specification	Value
Maximum rotational speed of rotor (RPM)	2200
Hammers:	
Number of hammers	24
Length (mm)	153.81
Width (mm)	40.14
Clearance between hammer tip and screen (mm)	6.35
Size of screen holes (mm)	1.5, 2.0, 3.0
Screen width (mm)	207.76
Diameter of rotor with hammers (mm)	254
Power source	20 HP Diesel engine, rated power – 14 kW/2400 RPM

Diesel fuel consumption and final geometric mean diameter (GMD) of flour were the performance indicators. The hammer mill used in the study was fabricated by a local Metal Fabricator and Joinery company in the capital city Kampala with specifications in Table 1 above.

2.2 Determining fuel consumption and final particle size distribution during grinding

Maize grain was sun dried on tarpaulin sheets for 24 hours and then tested for moisture content immediately before the grinding tests and moisture content analyzed the next day of the tests for verification. Experimental runs consisted of 20 kg grain samples of 13% dry basis (db) ground for 10 minutes during which 2 kg samples of flour were collected in triplicate for laboratory analysis.

The rotor shaft speed (rpm) was measured using a portable digital photo tachometer (Neiko 20713A, 99,999 RPM accuracy). Different shaft speed settings were achieved by changing the pulley sizes, pulleys of 4″, 5″, and 6″ inches in diameter were used. These were chosen from readily available pulleys around the city and sizes chosen after trials to select the independent variable speeds to use. A diesel combustion engine (Table 1) was used and the fuel consumption was recorded for each milling test run. Fuel was fed from an overhead calibrated plastic container for easy estimation of fuel consumed in milliliters (mL).

All fuel measurements were made in triplicate and the average was used. Energy consumption was calculated from the amount of fuel (diesel) using calorific value of 36 MJ l^{-1}. The time required for grinding each batch of maize grain was noted using a stop clock. All measurements were taken with and without load in the mill. The inlet temperature of the maize grains and the outlet temperature of the flour were recorded using digital test thermometer (Brannan Thermometers Cleator Moor Cumbria England) before and after milling respectively. Before running tests, the hammer mill, was adjusted as per recommendations by the fabricator.

2.3 Determination of impact energy

Method for determination of energy utilized for grinding using the hammer mill at Makerere University was described in Figure 1 by Nikolov (2004).

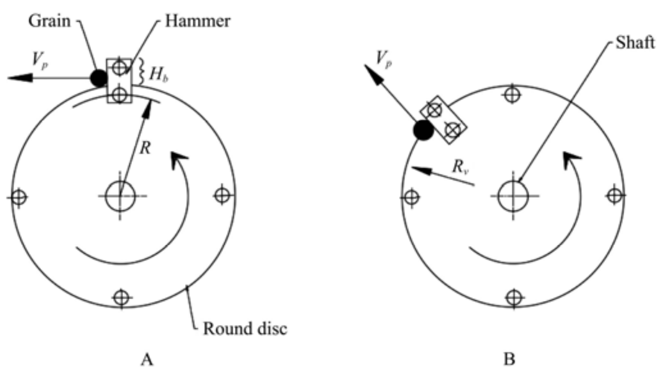


Figure 1 Left: A single particle just after impact with the hammer of a hammer crusher. Right: A single particle leaving the hammer of a vertical shaft crusher; Vp denotes the particle velocity (Nikolov, 2004)

$$E=0.5(R+0.5H_b)^2\omega^2 \quad (1)$$

where, E is energy per unit mass (MJ t^{-1}); R is the hammer length from the shaft (m); H_b is the height of the impact area of the hammers (m) and ω is the hammer angular velocity (s^{-1}).

2.4 Particle size distribution

Particle size distribution of the ground maize flour particles was determined using log-normal particle size analysis, as described in ASABE Standard S319.4 (2008). A rotary sieve shaker (Ro-Tap, W.S. Tyler, Mentor, Ohio) equipped with 14 sieves including the pan (U.S. standard sieve numbers 4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, and pan) was used, as described in ASABE Standard S319.4 (2008). The set of sieves was vibrated for 10 min, after which the ground material retained on each sieve was weighed and reported in percentage (g per 100 g). The GMD and geometric standard deviation were calculated using the procedure specified in ASABE Standard S319.4 (2008).

2.5 Experimental design and statistical analysis

A split-plot experimental design was used with two whole plot treatment factors being ‘hammer thickness’ (4.0, 5.0, and 6.0 mm) and ‘screen hole diameter’ (1.5, 2.0, and 3.0 mm); and one split-plot treatment factor, the ‘tip speed’ (68.12, 81.81 and 102.17 m s^{-1}). The hammer thickness and screen hole diameter were machine factors whereas tip speed was applied to a batch of product fed into the hammer mill. The whole plot experimental unit for the machine factors was the entire product processed through the mill at a particular hammer thickness/screen size set-up. The batch of product to which a tip speed is applied was the split plot experimental unit. Since there were two sizes of experimental units a split-plot experiment was implemented. The whole plot factors, hammer thickness and screen hole diameter were arranged in a first-order response surface design with one center point (see Table 2). The entire experiment was conducted twice giving two replicates. This experimental design was also applied by Mugabi et al. (2017).

The effect of three independent variables X_1 (H - hammer thickness), X_2 (S - screen hole diameter), and X_3 (T - tip speed) at three levels on fuel consumption and final particle size distribution (dependent variables) were investigated using the polynomial model in equation (2), where X_i were coded factor variables (X_i=(level–center)/range) (Lawson, 2014; Myers et al., 2009).

$$Y = b_0 + \sum_{n=1}^{3} b_n X_n + \sum_{n=1}^{3} b_{nn} X_n^2 + \sum_{n<m}^{3} b_{nm} X_n X_m \qquad (2)$$

where, Y is the response of interest (fuel consumption or final particle size), b_0 is the value for the fixed response at the central point of the experiment; X_n and X_m (n = 1, 2, 3 and m = n+1) the input predictors of controlling variables (factors); and b_n, b_m and b_{nm} are the linear, quadratic and cross-product coefficients, respectively.

A modified central composite design (CCD) split-plot was used andwith whole-plot factor levels obtained by omitting the axial points from a two-factor CCD with five replicates at the central points (Table 2). This design fits the second-order polynomial models and can also be used to obtain an experimental error for this study. Modifications were made by eliminating the axial points of the split-plot (sub-plot) factor. The experiment was performed in a random order within each replicate (two replicates were performed giving 38 runs in total).

Table 2 First replicate of split-plot experiment

Run no.	Whole plot unit	H (X_1)	S (X_2)	T (X_3)
1		6	3	102.17
2	1	6	3	68.12
3		6	3	81.81
4		6	1.5	102.17
5	2	6	1.5	68.12
6		6	1.5	81.81
7		5	2	102.17
8		5	2	68.12
9		5	2	81.81
10	3	5	2	81.81
11		5	2	81.81
12		5	2	81.81
13		5	2	81.81
14		4	3	102.17
15	4	4	3	68.12
16		4	3	81.81
17		4	1.5	102.17
18	5	4	1.5	68.12
19		4	1.5	81.81

The experimental data in Table 2 were analyzed in R version 3.2.5 using the RSM package (R Core Team, 2016). Significance level used was p<0.05. A second-order polynomial was fitted to the data to obtain regression equations. Statistical significance of the terms in the regression equations was also examined.

3 Results and discussion

The whole plot design is first-order hence no clear statements can be made about quadratic effects of the whole plot factors. Therefore, fit of final model should be same if fit H^2 (and its interactions) or S^2 (and its interactions). This problem resulted when we eliminated the star points in the design. The final models were obtained using split-plot analysis of variance (ANOVA) to identify significant effects. There were only four degrees of freedom (df) for treatment, so after fitting the model H, H^2, S, H × S, which left no df to test for lack of fit (LoF). So H^2 was used for the LoF test to test any deviation from the first-order and hence any quadratic effects of H or S not explained.

3.1 Tip speed, screen hole diameter, and hammer thickness influence on energy consumption

Screen hole diameter (S), hammer thickness (H), and tip speed (T) treatments had significant effects on energy consumption (Table 3 (p<0.05)). Table 5 shows the different independent variables, their levels, and experimental design and observed responses of energy consumption (F) and final particle size (P) or GMD. Duplicate experiments were carried out at all design points in Table 3. The maximum energy consumption (236.52 MJ t^{-1}) was obtained at 68.12 m s^{-1} tip speed, 1.5 mm screen hole diameter and 6.0 mm hammer thickness. Quadratic effect of tip speed, interaction effects of T×H and H×S also had significant effects on energy consumption.

Smallest screen hole diameter (1.5 mm) when fitted in the hammer mill consumed the most energy (161.94 MJ t^{-1}) of all the screen sizes. The hammer with largest thickness (6 mm) and tip speed of 68. 12 m s^{-1} also consumed the highest energy of 148.41 and 160.31 MJ t^{-1} respectively. Interaction combinations T (68.12 m s^{-1}) × S (1.5 mm), T (68.12 m s^{-1}) × H (6 mm), and S (1.5 mm) × H (6 mm) had high energy consumptions of 188.82, 187.83, and 178.62 MJ t^{-1} respectively. It was also noted that the smallest screen hole diameter (1.5 mm), largest hammer thickness (6 mm) and smallest tip speed (68.12 m s^{-1}) were responsible for higher energy consumptions. Screen hole diameter of 2 mm did not show any significant difference in energy consumption at all the three levels of tip speed that was used.

Mani et al. (2002) also stated that specific energy consumption for grinding wheat straw (8.3% w.b.) using a hammer mill with screen sizes of 0.794, 1.588 and 3.175 mm were 185.58, 142.52 and 38.77 MJ t^{-1} respectively. Comparison of specific energy and grinding rate using two different hammer thicknesses (3.2 and 6.4 mm) was studied by Vigneault et al. (1992) and found that average specific energy for thin and thick hammers was 36.72 and 44.64 MJ t^{-1}. Hence, thin hammers exhibited 13.6% specific energy conservation and also a 11.1% increase in grinding rate. This concurred with the experiment where 6 mm hammer had highest energy consumption (148.43 MJ t^{-1}) than the 4 mm thick hammer (131.33 MJ t^{-1}).

Table 3 Analysis of variance of grinding energy consumption and GMD of particles data

Effect	df	MSE	F value	Pr > F	MSE	F value	Pr > F
		GMD (mm)			Energy consumption, F (MJ t^{-1})		
Replication	1	0.01710			0.796		
H	1	0.01373	6.12	0.02360*	135.4	93.140	<0.0001*
S	1	0.12778	56.96	<0.0001*	643.4	442.63	<0.0001*
H×S	1	0.00564	2.520	0.13010	122.4	84.21	<0.0001*
LoF	1	0.00174	0.503	0.51722	683.925	470.53	<0.0001*
Error (a)	4	0.00345			2.258		
T	1	0.000876	0.355	0.5582	590.1	405.98	<0.0001*
T^2	1	0.000060	0.024	0.8772	154.2	106.08	<0.0001*
T×H	1	0.003139	1.400	0.2522	72.7	50.04	<0.0001*
H×T^2	1	0.003265	1.460	0.2433	4.965	3.42	0.0811
S×T	1	0.001903	0.850	0.3691	7.195	4.95	0.0391*
S×T^2	1	0.002618	1.17	0.2942	38.295	26.35	<0.0001*
Error (b)	20	0.002243			1.4535		

Note: *indicates significant effect at p<0.05. GMD is geometric mean diameter and MSE is mean square error. Error (a) is whole-plot error and Error (b) is split-plot error.

Regression coefficients, obtained by using a least squares technique to predict a quadratic polynomial model for response (energy consumption, F) are shown in Table 4. To account for lack of fit (LoF), H^2 was fit as a surrogate for either H or S quadratic effects. The model showed a significant LoF at p<0.05 (with F value = 103.58 and Pr> F≤0.0001).

$$F=3281-1389\cdot H+143.3\cdot H^2+85.66\cdot S-64.5\cdot T+0.3248\cdot T^2-3.011\cdot H\cdot S+27.75\cdot H\cdot T-2.847\cdot T\cdot H^2 \quad (3)$$

The model determination coefficient R^2 (0.9032) from the final model in equation (3), suggested that the fitted model could explain 90.32% of the total variation. This implies a satisfactory representation of the milling process by the model. It was also observed from Figure 1 that values of the predicted energy consumption were in agreement with the observed values in the range of operating variables of the experiment. Most of the observed energy consumption values are located between 108.0 and 180.0 MJ t^{-1}, with some outliers above 216.0 MJ t^{-1}. Probably this arose from the selected experiment design points.

Table 4 Standard CCD in split-plot design, experimental data for three-level-three factor response surface analysis

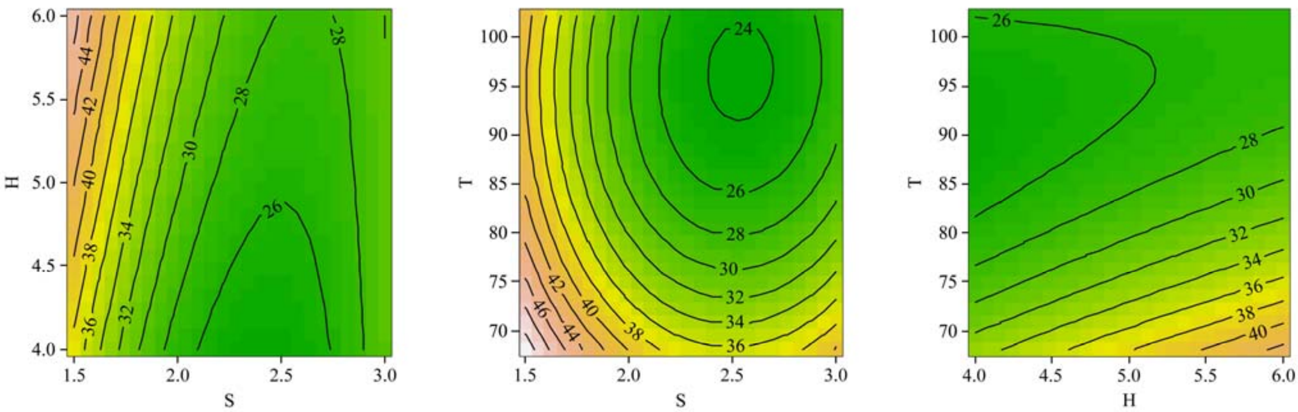
Run	H (mm)	S (mm)	T (m s^{-1})	F (MJ t^{-1})	Predicted F	Residuals	P (mm)	Predicted P	Residuals
1	6	3	102.17	100.08	25.531	2.269	0.809	0.827	–0.018
2	6	3	68.12	145.44	35.376	5.024	0.853	0.772	0.081
3	6	3	81.81	109.08	31.418	–1.118	0.766	0.794	–0.028
4	6	1.5	102.17	145.44	35.111	5.289	0.64	0.696	–0.056
5	6	1.5	68.12	236.52	54.343	11.357	0.653	0.677	–0.024
6	6	1.5	81.81	163.80	46.61	–1.11	0.608	0.684	–0.076
7	5	2	102.17	118.44	32.155	0.745	0.837	0.751	0.086
8	5	2	68.12	118.44	41.94	–9.04	0.701	0.734	–0.033
9	5	2	81.81	109.08	38.006	–7.706	0.729	0.741	–0.012
10	5	2	81.81	118.44	38.006	–5.106	0.722	0.741	–0.019
11	5	2	81.81	109.08	38.006	–7.706	0.784	0.741	0.043
12	5	2	81.81	118.44	38.006	–5.106	0.769	0.741	0.028
13	5	2	81.81	118.44	38.006	–5.106	0.758	0.741	0.017
14	4	3	102.17	100.08	23.161	4.639	0.738	0.835	–0.097
15	4	3	68.12	154.44	37.017	5.883	0.944	0.913	0.031
16	4	3	81.81	100.08	31.446	–3.646	0.986	0.882	0.104
17	4	1.5	102.17	136.44	37.009	0.891	0.675	0.725	–0.05
18	4	1.5	68.12	145.44	35.28	5.12	0.691	0.684	0.007
19	4	1.5	81.81	145.44	35.975	4.425	0.716	0.7	0.016
20	6	3	102.17	100.08	25.241	2.559	0.776	0.785	–0.009
21	6	3	68.12	145.44	35.086	5.314	0.659	0.73	–0.071
22	6	3	81.81	109.08	31.128	–0.828	0.741	0.752	–0.011
23	6	1.5	102.17	138.24	34.821	3.579	0.639	0.654	–0.015
24	6	1.5	68.12	223.92	54.053	8.147	0.653	0.634	0.019
25	6	1.5	81.81	163.80	46.321	–0.821	0.681	0.642	0.039
26	5	2	102.17	114.84	31.866	0.034	0.827	0.708	0.119
27	5	2	68.12	118.44	41.65	–8.75	0.731	0.692	0.039
28	5	2	81.81	109.08	37.716	–7.416	0.693	0.698	–0.005
29	5	2	81.81	114.84	37.716	–5.816	0.709	0.698	0.011
30	5	2	81.81	110.16	37.716	–7.116	0.719	0.698	0.021
31	5	2	81.81	118.44	37.716	–4.816	0.686	0.698	–0.012
32	5	2	81.81	112.68	37.716	–6.416	0.757	0.698	0.059
33	4	3	102.17	94.68	22.872	3.428	0.811	0.793	0.018
34	4	3	68.12	165.60	36.727	9.273	0.772	0.87	–0.098
35	4	3	81.81	89.28	31.157	–6.357	0.824	0.839	–0.015
36	4	1.5	102.17	141.84	36.719	2.681	0.66	0.682	–0.022
37	4	1.5	68.12	149.40	34.991	6.509	0.628	0.642	–0.014
38	4	1.5	81.81	153.00	35.686	6.814	0.607	0.658	–0.051

Agriculture Canada (1971) and Vigneault et al. (1992) studied the effect of hammer thickness on grinding rate and specific energy consumption and revealed that with change in hammer tip speed, different grinding rates and specific energy consumptions were attained depending on hammer thickness. They also concluded that increase in energy consumption was intensified by increase in tip speed and hammer thickness. In this experiment, it was observed that increase in hammer thickness led to increase in energy consumption but not tip speed.

The entire relationships between hammer mill factors and energy consumption can be better understood by examining the response surface plots generated by the predicted model. however, these may not be easily interpreted due to the confusion on whether the quadratic effects (H^2 or S^2) are responsible for the deviation from linearity.

The critical values for the three variables were within the experimental region with; screen hole diameter, hammer thickness, and tip speed at 2.16 mm, 5.0 mm and 83.57 m s^{-1} respectively as optimal performance settings for the hammer mill.

The fitted response surface for the energy consumption by the model was generated using R program and given in Figures 2a, 2b and 2c. The entire relationships between hammer mill factors and energy consumption can be better understood by examining the contour and response surface plots generated by the predicted model. Screen hole diameter (S) and tip speed (T) were observed to decrease the energy consumption as both increased. The convex nature of the response surfaces suggests that there are well-defined optimal variables.



(a) H and S (b) T and S (c) T and H

Figure 2 Contour plots showing the effect of variables on the energy consumption

The critical values for the three variables were within the experimental region. Figure 2(a) showed that screen hole diameter between 2.0 and 2.5 mm and with hammer thickness between 4.5 and 5.0 mm led to low energy consumption (93.6 MJ t^{-1}). In Figure 2(b), it can be seen that screen hole diameters between 1.5 and 2.0 mm give higher energy consumptions above 144.0 kWh t^{-1}. Study by Bochat et al. (2015) and Muntean et al. (2013) concluded that rotor design, the hammer angle, the hammer end peripheral speed, the diameter of holes in the screen, and the hammer gap all had significant effects on specific energy consumption.

3.2 Tip speed, screen hole diameter, and hammer thickness influence on geometric mean diameter

Summary of ANOVA for the selected model for the effect of screen hole diameter, hammer thickness and tip speed is listed in Table 3. The ANOVA of the linear regression model demonstrated that the model was highly significant (p<0.05). Lack-of-Fit (pvalue = 0.51722) which is the variation due to the model inadequacy, was not significant for the model (p>0.05). Therefore, there was no evidence to indicate that the order model did not adequately explain the variation in the responses since we used the quadratic effect (H^2) to test for lack of fit. Hammer thickness and screen hole diameter were observed to have significant effect on GMD at p<0.05. Tip speed did not have a significant effect on GMD.

Table 4 shows the regression coefficients for the model (equation (4)) after analysis. Screen hole diameter (S) had a highly significant effect (p<0.05) whereas the hammer thickness and tip speed (T) did not have a significant effect on GMD.

$$P = -0.2075+0.106 \cdot S+0.3742 \cdot H - 0.001506 \cdot T - 0.04598 \cdot H \cdot T+7.33310^{-5} \cdot H^2 \quad (4)$$

Comparisons between the experimental data and the predicted values obtained using prediction models for energy consumption and final particle size have been summarized in Table 5. It was also observed from Table 4 that values of the predicted final particle size were in agreement with the observed values in the range of operating variables of the experiment. As observed, most of the predicted GMD values are located between 0.6 and 0.85 mm, with some outliers above 0.9 mm.

Lowest GMD (0.64 mm) was obtained with combination of tip speed, screen hole diameter and hammer thickness of 102.17 m s^{-1}, 1.5 mm and 6 mm respectively. It was also noted that an increase in S at all tip speeds (T) led to an increase in final particle size of the ground maize. Decrease in H with increase in T led to an increase in GMD.

It was observed that with an increase in screen hole diameter and decrease hammer thickness, there is considerable increase in final particle size to GMD of >0.8 mm. Increase in particle size was not affected by tip speed while increasing screen hole diameter. It was also observed that when decreasing H while increasing T>85 m s^{-1} the GMD would increase to higher than 0.76 mm. Thin hammers (3.2 mm) were observed to give smaller final product size with GMD of 491 μm compared to 507 μm when thick hammers (6.4 mm) were used (Vigneault et al., 1992). A study by Basiouny and El-Yamani (2016) and Hajratwala (1982) found that as mill speed increased (~2100 rpm and ~5000 rpm respectively), the particle size distribution of ground flour decreased.

3.3 Impact energy achieved

Conservation of linear momentum before and after impact of the hammer and particle is assumed when finding impact energy per unit mass. Equation (1) was used to calculate the impact energy of the hammer mill used during the experiment.

The achieved impact energy calculated per unit mass, considering the conservation of linear moment before and after impact energy mass was 2.93 MJ t^{-1}, 4.23 MJ t^{-1} and 6.60 MJ t^{-1} for 68.12, 81.81, and 102.17 m s^{-1} respectively for the hammer mill used. On average, these impact energies 2.93 MJ t^{-1} and 6.60 MJ t^{-1} gave 0.7285 and 0.7412 mm respectively, this confirmed the results from ANOVA that only screen size had a significant effect on GMD. A study by Healy et al. (1994) reported that when a roller mill was used, 19.08 and 33.12 MJ t-1 energy was required to achieve 0.9 and 0.7 mm final particle size of ground maize respectively, whereas, 79.99 MJ t-1 energy was required to achieve 0.3 mm of ground maize when using a hammer mill. This could have been due to the different maize varieties used, type of hammer mill used and type of power transmission system used on the mill. The hammer mill reduces size of materials by impact and energy dissipated upon contact between the maize grain and the hammer varies with the square of the peripheral speed varies with the rotor radius of the mill. The energy of impact at the tip of the hammer is much greater and has been said to be over four times as great as at the mid-point of the hammer (Ahmed and Rahman, 2012). This shows the need for variable speed inclusion on hammer mills which can determine how coarse the product will be since the engine had a constant rpm output to the mill.

4 Conclusion

During performance evaluation of locally fabricated hammer mill in Uganda, several levels of T, H, and S were evaluated for their effects on energy consumption and particle size using a CCD in split-plot experimental design. Additionally, performance settings with best energy efficiency and most uniform particle size and impact energy calculations in the mill were conducted. S, H and T had significant effect on energy consumption (p<0.05). Screen hole diameter and hammer thickness had significant effects on both GMD and energy consumption. Only Screen hole diameter had significant effect on particle size since impact energy did not show any significant difference in particle size of flour. Obtained hammer mill settings (S – 2.16 mm, H – 5.0 mm & T – 83.57 m s^{-1}) gave best energy efficiency and most uniform particle size.

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