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STUDIES ON CONTINUOUS GRINDING PROCESS FOR DRIED WATER CHESTNUT KERNEL

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Abstract

Grinding is a unit operation to break big solid material into smaller pieces. As far as process of grinding is concerned, power consumption, specific energy consumption and particle size distribution and mill capacity are main considerations from engineering point of view. The experiments were conducted to study the effect of speed of mill, sieve size, feed rate and time of grinding on power consumption and average particle diameter of water chestnut in continuous grinding process. Power consumption was measured for a constant feed rate of 1 and 2 kg/h at different speed of the mill varied from 800 to 1200 rpm for the sieve openings of 0.5 mm, 1.0 mm and 2.0 mm. For all the sieve sizes and feed rates, it was observed that as the speed of the mill increases, there is an increase in power consumption and found significantly low for higher sieve size and lower feed rate. The size distribution of the water chestnut kernel for different speeds and sieve sizes at constant feed rate were obtained by sieve analysis. The milling speed has no significant effect on particle size distribution of ground product and mass fraction was minimum at lower feed rate and higher sieve size. Harris model was found best suitable to describe the size distribution in continuous grinding process. Fineness modulus decreases with increase of milling speed for experimental sieve size and feed rate.

Keywords: Water chestnut, Grinding, Particle size distribution, Hammer mill, Sieve analysis.

1. Introduction

Water chestnut (*Trapa bisinosa Roxburg*) commonly known as Singhara, is an annual aquatic warm season crop. Water chestnut belongs to 'trapaceae' family. In India the two popular species *Trapa bispinosa* and *Trapa quadrispinosa* of water

Nomenclatures

a, b, c	Coefficients in Eq. (4)
a_1, b_1, c_1	Coefficients in Eq. (2)
D	Sieve size, mm
D_P	Average particle diameter, mm
F	Feed rate, kg/h
N	Milling speed, rpm
P_c	Power consumption, W
R	Correlation coefficient
t	Time of grinding, s

Greek Symbols

ϕ	Cumulative mass (%) greater than size *D*

Abbreviations

ANOVA	Analyses of variance
BIS	Bureau of Indian Standard
ISO	International organization of standardization
SE	Standard error

chestnut are widely cultivated. In general, the cultivation of water chestnut is distributed through out the country especially in Punjab, Bihar, Uttar Pradesh Madhya Pradesh, Tamilnadu, Maharastra and in some parts of Uttarakhand. Water chestnuts can be used in a variety of recipes because they have a starchy taste that is fairly neutral. Some people claim that their flavour is similar to a bland nut. Water chestnuts also have a firm and crispy texture, which adds to their appeal as an ingredient in stir-fries, salads, or any meals where the vegetables to be used must have a crunchy consistency.

Grinding is one of the oldest unit operations and is extensively used in food industry. Though there are few published works available on the grinding of food material, however, workable equipment continues to be designed and used for grinding many types of solid food materials. As far as process of grinding is concerned, power consumption, specific energy consumption and particle size distribution and mill capacity are main considerations, from engineering point of view. The study conducted on modern milling techniques and obtained refined bran free white flour from ragi. The investigation reported 60-70% yield of flour from wet milling process, however the retention of protein, calcium and phosphorous was reported to be low in such flours as compared to those obtained from dry milling process [1]. An abrasive milling process was developed in which 16-18% of the initial weight of the grain was removed by using an abrasive rice mill [2]. The study on kinetics of' breakage of maize in a small laboratory hammer mill was conducted and it was found that breakage was first order function and that the primary breakage distributions were insensitive to mill conditions or moisture content of material. The specific rate of breakage was found dependent on particle size (approximately to the third power) and increased as moisture content of the grain was reduced showing that the dried material was more brittle and a minimum rotation speed was necessary to get significant breakage [3]. The study was conducted on grinding experiment of commercial grade coriander in batch, semi-continuous and continuous grinding in a hammer mill. In batch experiment Mitra [3] studied the effect of mass size, mill speed and time of grinding on power requirement, energy consumption and particle size distribution and the case power consumption can be expressed by $P = at^b$ [4].

The final ground product should meet the quality standard suggested by the agencies like BIS and ISO for export trade. Since much of the grinding work was reported on the non-food material there is a need to carry out experimental studies to study the various operations of machine parameters such as mill speed and screen openings on the performance of ground material. Present study was conducted mainly to see grinding behaviour of dry water chestnut in hammer mill.

2. Materials and Methods

Commercial grade water chestnut procured from local market was used as the basic raw material for the present study. The kernels were cleaned and stored in poly bags at room temperature. For the grinding operations a hammer mill with fixed blades was used in the study. An R_o-tap sieve shaker was used to obtain size distribution of ground material. The base sieve used in continuous grinding experiments was having average whole size of 0.5 mm, 1.00 mm and 2 mm. After the grinding operation particle size distribution was determined by sieve analysis by taking a 100 g representative sample.

To study the effect of different operational conditions of a hammer mill on the power requirement and particle size distribution of the ground material, the experiment were planned to observe the grinding behaviour of water chestnut kernels. Mill speeds, sieve sizes and feed rates were considered as independent variable for continuous grinding. Power consumption and particle size distribution were taken as dependent variables for continuous grinding.

The full factorial design has been used for continuous grinding. For continuous grinding, an experimental plan comprising of three independent variables namely speed of mill (800, 1000 and 1200 rpm) and sieve size having three levels (0.5, 1.0 and 2.0 mm) and feed rate having two levels (1 and 2 kg/h) was chosen. Power consumption in grinding was recorded with help of a wattmeter at an interval of 120 seconds. The ground product coming out of the grinding chamber and was collected in a polythene bag, fastened directly under the mill to reduce loss of fine particles. After the grinding operation particle size distribution was determined by sieve analysis by taking a 100 g representative sample.

3. Results and Discussion

3.1. Power consumption

The power consumption in grinding of water chestnut kernel was calculated on the basis of mill speed, *N*, feed rate, *F*, and sieve size, *D*. Full second order models were fitted for the variation of power consumption with the independent parameters

$$P_c = 7.768 + 5.096F + 2.27D - 2.71N - 1.47F^2 - 0.01D^2 + 0.9N^2$$
$$-0.157FD - 1.02DN - 0107FN \quad (1)$$

The results of analyses of variance (ANOVA) for second order model were applied. The calculated *F* value for fitted model was more than *F* tabular value

(Table 1) and the coefficient of determination, R^2 has a value of 99.56%. Thus the model is acceptable.

Table 1. The Results of Analyses of Variance (ANOVA).

	Df	SS	MS	*F*
Regression	9	170.8685	18.98539	257.6565
Residual	9	0.74606	0.082896	
Total	18	171.6146		

Power consumption was measured for a feed rate (1 kg/h and 2 kg/h) at different speeds of the mill and sieve sizes. Figures 1 to 6 exhibit the characteristic feature of grinding. Figures 1, 2 and 3 show the effect of speed on power consumption in continuous grinding process for 0.5, 1 and 2 mm sieve sizes for 1 kg/h feed rate whereas Figs. 4, 5 and 6 show the effect of speed on power consumption in continuous grinding process for 0.5, 1 and 2 mm sieve sizes for 2 kg/h feed rate. From Figs. 1 to 6 for various sieve sizes and feed rates, it appears that in continuous grinding process after 20 minutes of grinding the power consumption was found almost constant, similar finding has been reported [5] It also indicated by Figs. 1 to 6 for feed rate 1 and 2 kg/h at early stage of grinding the power consumption increases linearly, similar finding has been reported [6]. The trends show that at constant feed rate, power consumption decreases with increase in sieve size at different experimental milling speeds. Similarly at constant sieve size, as feed rate increases, power also increases for each milling speed. These graphs show that for bigger sieve size and lower feed rate, the power requirement is significantly low. In all the cases initially power consumption was in lower range and gradually as time continues the power requirement increases to some extent. It may be due to the reason that initially to break the whole grain or its broken fractions large power is required since the grain offer more resistance to breakage. After initial breakage the liner particles offer less resistance to breakage resulting lesser power consumption. The graphs show that the relation between power consumption and time of grinding is nonlinear. The variation of power consumption for feed rate and speed of operation could be represented by the following equation

$$P_c = a_1/(1 + b_1 e^{-c_1 t}) \qquad (2)$$

The values of a_1, b_1 and c_1, the standard error (SE) and correlation coefficient (R^2) values are given in Table 2. The values of R^2 ranged from 0.9316 and 0.9823 along with the values of SE from the range 0.2320 to 0.3258. The coefficient values of a_1, b_1, and c_1 are found to be from range of 6.35 to 10.2656, 4.2327 to 6.49 and 0.1547 to 0.3778 respectively.

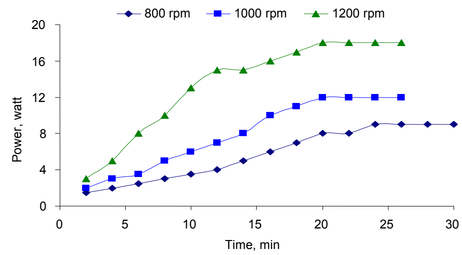

Fig. 1. Effect of Speed on Power Consumption in Continuous Grinding Process for 0.5 mm Sieve and 1 kg/h Feed Rate.

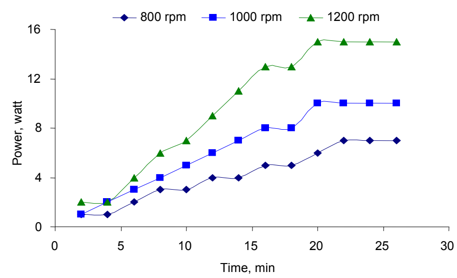

Fig. 2. Effect of Speed on Power Consumption in Continuous Grinding Process for 1 mm Sieve and 1 kg/h Feed Rate.

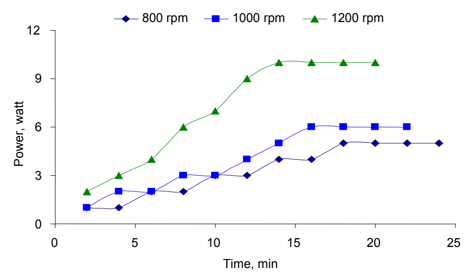

Fig. 3. Effect of Speed on Power Consumption in Continuous Grinding Process for 2 mm Sieve and 1 kg/h Feed Rate.

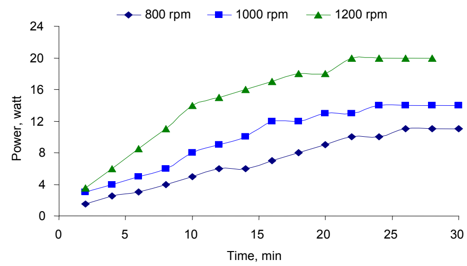

Fig. 4. Effect of Speed on Power Consumption in Continuous Grinding Process for 0.5 mm Sieve and 2 kg/h Feed Rate.

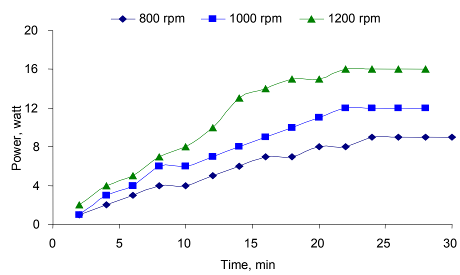

Fig. 5. Effect of Speed on Power Consumption in Continuous Grinding Process for 1 mm Sieve and 2 kg/h Feed Rate.

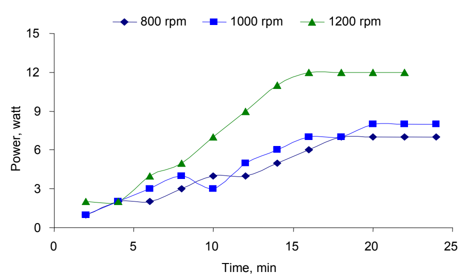

Fig. 6. Effect of Speed on Power Consumption in Continuous Grinding Process for 2 mm Sieve and 2 kg/h Feed Rate.

Table 2. Values of Standard Error, Coefficient of Correlation and Coefficients of Equation for Calculating Power Consumption in Continuous Grinding Process.

Feed rate, kg/h	Sieve size, mm	Speed, rpm	SE	R^2	a_1	b_1	c_1
1	0.50	800	0.2363	0.9813	8.4136	5.1269	0.1562
		1000	0.2865	0.9771	10.2356	5.2694	0.1549
		1200	0.32566	0.9316	11.9856	6.2544	0.1635
	1.00	800	0.2463	0.9823	7.6952	4.6953	0.1986
		1000	0.2635	0.9803	7.9586	5.2143	0.1486
		1200	0.3156	0.9709	8.2354	6.3592	0.1329
	2.00	800	0.3124	0.9716	6.3512	3.9984	0.2135
		1000	0.2965	0.9693	6.8956	4.235	0.3653
		1200	0.3246	0.9526	7.5682	4.8652	0.3755
2	0.500	800	0.2136	0.9826	8.9136	5.2691	0.1662
		1000	0.2866	0.9609	10.9356	5.1694	0.1569
		1200	0.3566	0.9425	12.9856	6.5044	0.1935
	1.00	800	0.3463	0.9742	7.9952	4.9533	0.2196
		1000	0.3635	0.9744	7.9586	5.2343	0.2146
		1200	0.3526	0.9525	8.9354	6.93592	0.2329
	2.00	800	0.3424	0.9761	6.9612	3.9084	0.2735
		1000	0.2165	0.9582	6.8256	4.9235	0.3353
		1200	0.3646	0.9596	7.9682	4.1562	0.3855

3.2. Particle size distribution

The size distribution of the water chestnut kernel for different speed and time of grinding and different feed rate was obtained by sieve analysis. Full second order models were fitted for the variation of average particle diameter with the independent parameters. The relationship obtained is as follows

$$D_p = 31.17 - 0.0056F + 0.02476D + 0.011N - 0.00043F^2 + 0.0017D^2 + 0.0024N^2 - 0.002FD + 0.0045DN - 0.0005FN \quad (3)$$

The coefficient of determination (R^2) of Eq. (3) has a value of 89.74 %. Thus the model is acceptable. Particle size distribution of the ground product for different levels of speed of the mill is shown in Figs. 7 to 12. From these figures, it can be stated that for speed range 800 to 1200 rpm, particle size distribution of ground product shows that speed has little effect on mass fraction. This may be because at this level of speed the critical stress for rupturing the particles into fines is arrived at a level of 1200 rpm. At constant sieve size, mass fraction increases with increase in feed rate, while at constant feed rate, mass fraction decreases with increase in sieve size at different experimental milling speed similar finding have been reported [3].

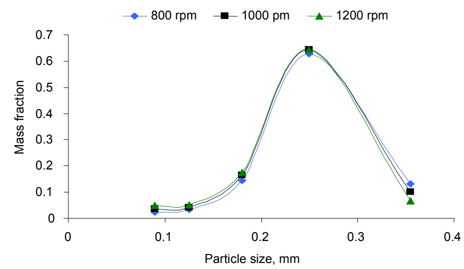

Fig. 7. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 0.5 mm Sieve and 1 kg/h Feed Rate.

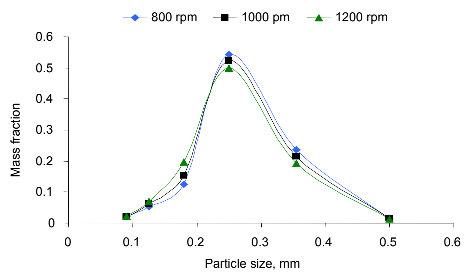

Fig. 8. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 1 mm Sieve and 1 kg/h Feed Rate.

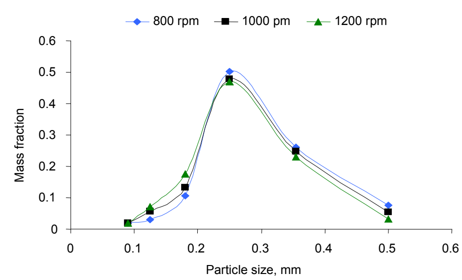

Fig. 9. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 2 mm Sieve and 1 kg/h Feed Rate.

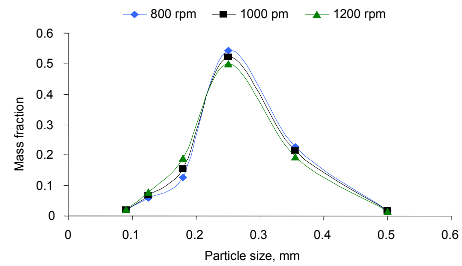

Fig. 10. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 1 mm Sieve and 2 kg/h Feed Rate.

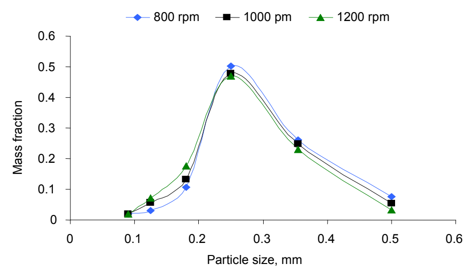

Fig. 11. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 2 mm Sieve and 1 kg/h Feed Rate.

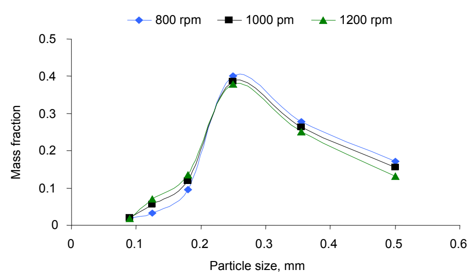

Fig. 12. Effect of Speed on Mass Fraction of Ground Product in Continuous Grinding Process for 2 mm Sieve and 2 kg/h Feed Rate.

The size distribution of ground water chestnut was obtained by sieve analyses and modelling of particle size distribution. Harris model [2] represented as Eq. (4) was found suitable to describe the size distribution in continuous grinding process

$$\phi = 1/(a + bD^c) \tag{4}$$

The values of a, b and c, the standard error and correlation coefficient values are given in Table 3. The values of the coefficient a are found to be in range from 1.0135 to 1.0985. The values of the coefficient b varied in range from 402545 to

744515. Evaluation of the data shows that as the sieve size increases, the coefficient *a* and *b* showed a tendency to increase and as the speed of the mill increases. The value of the coefficient *c* of equation increases with an increase of speed of mill and sieve size for experimental feed rate and the value of '*c*' ranged from 9.0223 to 14.966.

Table 3. Values of Standard Error, Coefficient of Correlation and Coefficients of Equation for Cumulative Mass Fraction in Continuous Grinding Process.

Feed rate, kg/h	Sieve size, mm	Speed, rpm	SE	R^2	*a*	*b*	*c*
1	0.50	800	0.0533	0.9763	1.0236	413261	9.0223
		1000	0.0526	0.9854	1.0369	402545	9.0564
		1200	0.0502	0.9862	1.0136	435653	9.0765
	1.0	800	0.0562	0.9685	1.0135	498955	10.469
		1000	0.0612	0.9765	1.0236	466452	10.636
		1200	0.0696	0.9654	1.0359	478523	10.459
	2.0	800	0.0676	0.9954	1.0426	479363	10.886
		1000	0.0681	0.9721	1.0563	593695	11.525
		1200	0.0654	0.9821	1.0569	578566	11.646
2	0.50	800	0.0669	0.9632	1.0599	499654	10.556
		1000	0.0695	0.9965	1.0612	468656	10.756
		1200	0.0603	0.9642	1.0689	435663	10.999
	1.0	800	0.0635	0.9987	1.0699	695256	12.861
		1000	0.0496	0.9799	1.0724	534955	11.765
		1200	0.0621	0.9687	1.0756	678475	12.996
	2.0	800	0.0632	0.9932	1.0896	665254	11.965
		1000	0.0794	0.9922	1.0985	635963	11.495
		1200	0.0502	0.9955	1.0956	744515	14.966

4. Summary and Conclusions

For continuous grinding, power consumption was measured for sample feed rate ranging from 1 to 2 kg/h at different speed of the mill varied from 800 to 1200 rpm for the sieve sizes of 0.5, 1.0 and 2.0 mm. The effects of mill speed, sieve size and feed rate were observed on the power consumption. Full second order model was fitted for the variation of power consumption with the independent parameters. As the speed of the mill increases, there was an increase in power consumption. In all the cases initially power consumption was in lower range and gradually as time continues the power requirement increase to some extent. The relation between power consumption and time of grinding was nonlinear. Power consumption was low for higher sieve size and lower feed rate.

The size distribution of the water chestnut kernel for different speed and sieve size for different feed rate was obtained by sieve analysis. Full second order model was fitted for the variation of average particle diameter with the independent parameters. For a particular sieve size and feed rate, there is no significant effect of mill speed on particles size. Taking sieve size constant, less fine particles were produced at lower feed rate and at constant feed rate, mass fraction decreased with increase in sieve size for different experimental mill speed. Harris Model was found to be best fitting for the particle size distribution of the ground product.

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