

The effect of processing parameters on energy consumption of ball mill refiner for chocolate

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Abstract

A laboratory ball mill consisting of a vertical cylinder, equipped with a rotating shaft with arms, and filled with steel balls as a grinding medium has been used in the experiments. The aim of the study was to examine the effect of agitator shaft speed and amount of grinding media (steel balls) on power requirements and energy consumption of a ball mill. With constant mass of the steel balls (20, 30 and 40 kg), the agitator shaft speed was increased from 10 to 100% of the maximum speed, which corresponds to a speed of 50 rpm. The power consumption (W) was recorded upon which milling energy consumption (J/kg) has been calculated. The results were statistically analyzed using ANOVA. The increase of the agitator shaft speed, in steps of 10% to the maximum speed of 50 rpm, led to a statistically significant increase in milling energy consumption. At low agitator shaft speed (10%), increase in the mass of the steel balls had no influence on the power requirements. Power requirements for the grinding runs using 30 and 40 kg are similar and higher compared to power requirement in trial with 20 kg, as agitator shaft speed increases from 20 to 70%. At high agitator shaft speeds ($\geq 80\%$), increase in steel balls mass led to a significant increase in power requirements of the ball mill.

Keywords: ball mill refiner, processing parameters, power requirements, energy consumption.

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Size reduction of cocoa solids is an important unit operation in the production of chocolate. During this operation, called refining, cocoa solids and sugar crystals are reduced to a size that makes them small enough that they cannot be detected on the tongue [1]. It is followed by the phase of conching in which chocolate aroma is fully developed, and the newly created surface during the size reduction of cocoa solids is covered with fat, improving the flow properties [2]. During any comminution operation, both material properties and milling methods affect particle breakage [3]. The factors affecting particle size reduction can be classified into those arising from the physicochemical properties of the material and those related to the design and operation of the milling equipment [4]. Comminution equipment can be classified according to the process or the maximum size of product [5], while comminution as an industrial process is evaluated upon investment and energy costs and the characteristics that they provide to the product. In traditional chocolate production line, grinding is carried out using a five roll mill (four vertically aligned grinding rolls and the feed roll), with feed roll gap and roll speed as adjust-

able parameters [6]. However, the equipment used in traditional production lines is relatively expensive with regards to investment and energy consumption and the process is time consuming (up to 48 h) [3,7]. Over the years, possibilities and solutions have been sought out in order to find the alternative to traditional process and make it more efficient especially for the medium-small size companies. The most common ones are based on using a ball mill [2], in which both grinding (refining) and conching is carried out simultaneously. Surprisingly, over the years only a few papers have been published dealing with the issue of using the ball for these purposes [1,7–9,11].

Ball mills are vertical or horizontal cylinders (stationary tank), equipped with a rotating shaft with arms, filled to as much as 70% of the available volume with grinding media (usually steel balls) [8]. The mass and the balls are agitated by a shaft with arms, rotating at a variable speed [1]. Generally, size reduction in any practical machine is achieved by mechanical forces (compression, impact or shear) that cause rupture while one of the forces is usually predominant [10]. In the ball mill refiner the feed material is comminuted between the grinding media, the stirrer and the cylinder wall by compression and shear [7,8]. The factors affecting the grinding action of the ball mill are the mill speed and quantity, type and size of grinding media.

The aim of this study was to examine the effect of agitator shaft speed and amount of grinding media (steel balls) on energy consumption of a laboratory ball mill.

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MATERIALS AND METHODS

Experiments were conducted using a laboratory ball mill constituted of a double-jacket cylinder, 0.25 m in diameter and 0.31 m in height (0.0152 m³ in volume), containing 9.1 mm diameter water resistant steel balls and a stirring group. The vertical shaft with horizontal arms, while rotating, puts the steel balls in movement. A little of vegetable fat was added to minimize undesirable friction between the steel balls. The ball mill is equipped with a temperature control system made up of a water jacket equipped with temperature sensor and thermo-regulators controlled by electric board. The experiments were carried out at 35 °C. The agitator shaft speed was increased from 10 to 100% (in steps of 10%) of the maximum speed, which corresponds to a speed of 50 rpm. The experiments were carried out without the material flow.

The milling energy consumption, E (J/kg), was calculated by Eq. (1):

$$E = \frac{Pt}{m} \quad (1)$$

Here, m is the mass of the steel balls (20, 30 and 40 kg) and t is the time of the grinding run (180 s) determined by the chronometer. The milling energy consumption during grinding runs was determined using a Network recorder MC750/UMC750 (Iskra MIS, Slovenia). Power readings, P (W), were recorded every 15 s, giving a total of 13 power readings during the 3 min interval of the grinding run. The results are expressed as mean ± standard deviation, as coefficient of variation, and as 95%

confidence interval for mean values given by Student's *t*-distribution. The mean values of corresponding data (P) are used to calculate the milling energy consumption according to Eq. (1). The significance of the differences between power readings obtained at different agitator shaft speeds and steel balls mass were statistically analyzed using ANOVA (analysis of variance). All statistical analyses were performed using Statistica 10 software.

RESULTS AND DISCUSSION

The mean value (MV), standard deviation (SD), coefficient of variation (CV) and 95% confidence interval for the power readings given by Student's *t*-distribution (CI), as well as energy consumption, E (J/kg), calculated according to Eq. (1), are given in Table 1.

Basic statistical parameters show that at same agitator shaft speed power readings are highly reproducible, with CV below 0.4% and CI less than ±1 W. Since the time of the grinding run ($t = 180$ s) was kept constant through the experiment, with constant mass of the steel balls, the power and energy consumption are directly correlated according to Eq. (1). Practically, the values of the basic statistic parameters determined for the power readings can be directly transferred to energy consumption. The correlation between the agitator shaft speed and power, as well as the correlation between agitator shaft speed and energy consumption, is very high ($r = 0.997$). They both exhibited similar relationship as the agitator shaft speed was altered, giving an almost linear response, as can be seen from Figures 1 and 2.

Table 1. Power readings, energy consumption and basic statistical parameters

Steel balls mass, kg	Power reading [W]	Agitator shaft speed (% of the maximum speed of 50 rpm)									
		10	20	30	40	50	60	70	80	90	100
20	Mean value	165.65	178.55	213.18	248.10	282.46	316.65	353.02	376.11	417.88	464.22
	±SD	±0.45	±0.32	±0.33	±0.37	±0.50	±1.06	±1.26	±1.15	±1.49	±1.18
	CV / %	0.273	0.181	0.153	0.149	0.177	0.334	0.356	0.305	0.357	0.254
	±CI	±0.27	±0.20	±0.20	±0.22	±0.30	±0.64	±0.76	±0.69	±0.90	±0.71
	Energy consumption E / J kg ⁻¹	1490.9	1607.0	1918.7	2232.9	2542.2	2849.9	3177.2	3385.0	3760.9	4177.9
30	Mean value	167.81	186.71	221.34	262.05	298.27	336.61	366.01	406.84	457.41	510.39
	±SD	±0.43	±0.54	±0.41	±0.45	±0.68	±0.82	±0.82	±0.97	±1.03	±1.13
	CV / %	0.254	0.288	0.185	0.172	0.229	0.245	0.223	0.239	0.225	0.221
	±CI	±0.25	±0.33	±0.25	±0.27	±0.41	±0.50	±0.49	±0.59	±0.62	±0.68
	Energy consumption E / J kg ⁻¹	1006.8	1120.2	1328.0	1572.3	1789.6	2019.7	2196.1	2441.0	2744.4	3062.3
40	Mean value	168.95	189.46	226.89	263.19	300.28	338.96	371.91	426.09	492.13	554.57
	±SD	±0.35	±0.69	±0.84	±0.55	±1.05	±1.20	±0.86	±0.91	±1.34	±2.36
	CV / %	0.207	0.366	0.370	0.207	0.350	0.354	0.231	0.215	0.272	0.426
	±CI	±0.21	±0.42	±0.51	±0.33	±0.64	±0.72	±0.52	±0.55	±0.81	±1.43
	Energy consumption E / J kg ⁻¹	760.3	852.6	1021.0	1184.4	1351.2	1525.3	1673.6	1917.4	2214.6	2495.6

Analysis of variance provides a statistical test of whether or not the means of several groups are all equal. The basic hypothesis that had been set was that there was no statistically significant difference between the power requirements at different agitator shaft speed. The hypothesis has been rejected and results showed that, with constant mass of the steel balls, every increase of 10% of the agitator shaft speed led to a statistically significant ($p < 0.05$) increase in power requirements and milling energy consumption. The dynamic of the increase in grinding runs with different mass of the steel balls had a similar trend (Figures 1 and 2). Beside energy consumption, the agitator speed

also influences the magnitude of the stress and the relative contributions of compressive and shearing forces. The magnitude and the nature of the forces acting on particles will determine the degree of particle size reduction and energy required for grinding. In practice, the agitator should be run at the lowest possible speed to meet the requirements of the process. However, in some cases, with slow agitator the particle size of the product and demands for increased capacity could not be met.

Comparing the power requirements, recorded at the same agitator speed but with different steel ball mass, a certain pattern can be noticed (Figure 1). At

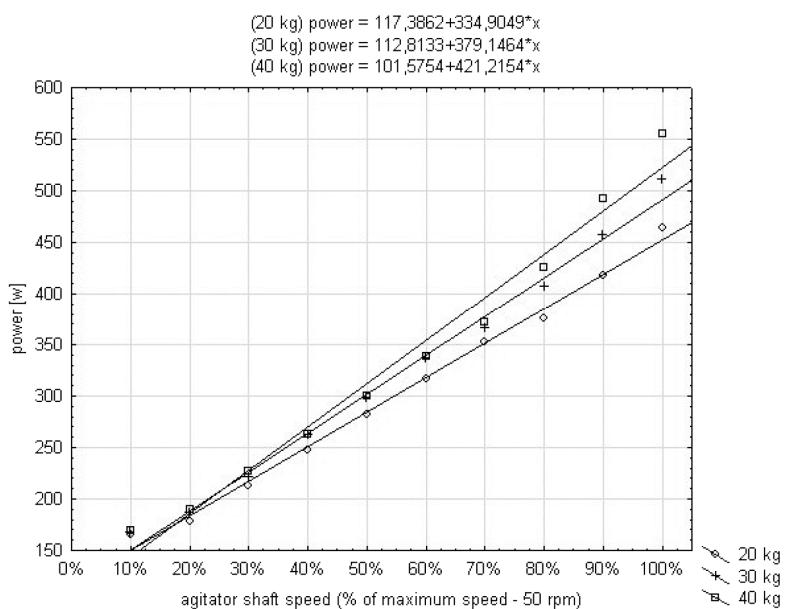


Figure 1. Effect of agitator shaft speed and steel balls mass on power requirements.

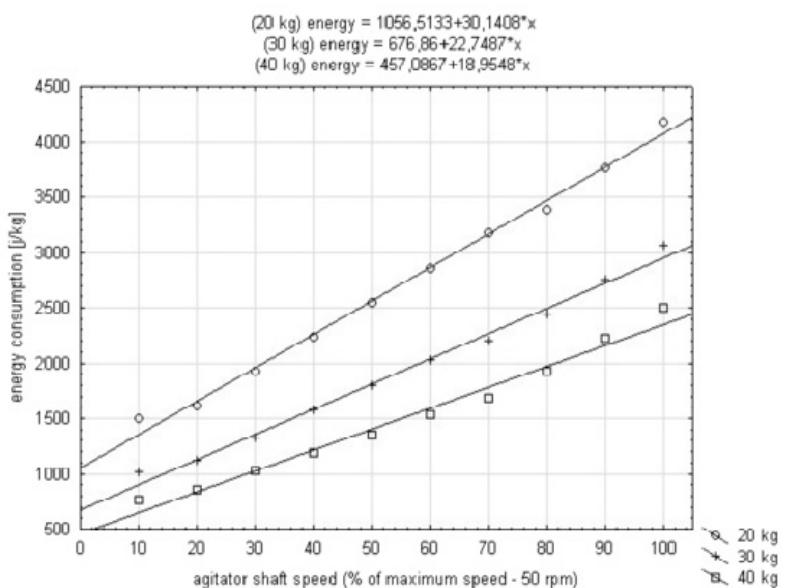


Figure 2. Effect of agitator shaft speed and steel balls mass on milling energy consumption.

low agitator shaft speed (10%), there was practically no difference in power readings between the grinding runs with different amount of grinding media. At agitator speed in the range of 20–70%, the power readings recorded with $m = 30$ kg and $m = 40$ kg were similar and relatively higher compared to the grinding run with $m = 20$ kg. At high agitator shaft speeds ($\geq 80\%$), the difference in power requirements became noticeable between the grindings run with 30 and 40 kg as well. However, it is interesting to point out the hypothesis that there is no statistically significant difference between the power requirements in the grindings runs with different steel balls mass has been rejected even at 10% agitator speed, there the difference between the grinding runs is only 1–2 W. The fact that the power readings within the individual grinding runs were highly reproducible (extremely small SD, CV and CI) causes statistically significant difference even in the cases of small difference between power readings of individual grinding runs, such as 1–2 W, which from the practical side of view can be considered negligible.

Increasing the mass of the steel balls at same agitator speed led to a significant decrease in energy consumption (Figure 2). It needs to be pointed out that the power readings were recorded without material flow and the energy consumption calculated using Eq. (1) is relative to the mass of steel balls. Usually, the energy required for grinding is given as energy consumption per unit mass of grounded material. Therefore, a more realistic view on influence of the mass of the balls on energy consumption can be obtained only with the grinding runs with material flow, because this processing parameter also influences the magnitude of the forces acting on particles and the degree of particle size reduction.

CONCLUSION

The consumption of energy in the process, especially in the process where the large part of it is energy required for grinding, should be kept at the lowest possible level. The agitator shaft speed significantly influences the energy consumption of the ball mill. Therefore, the agitator should be run at lowest possible speed to meet the degree of particle size reduction

that is needed (or any other product quality parameter), and handle the capacity of the process.

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IZVOD

UTICAJ PROCESNIH PARAMETARA NA POTROŠNJU ENERGIJE U KUGLIČNOM MLINU ZA PROIZVODNJU ČOKOLADE

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(Naučni rad)

U ovom radu primenjen je i ispitani laboratorijski kuglični mlin koji se sastoji od vertikalnog cilindra, opremljenog rotirajućim vratilom sa mešaćima i napunjenoj čeličnim kuglicama kao medijumom za mlevenje. U kugličnom mlinu proces mlevenja se ostvaruje usitnjavanjem materijala između čeličnih kuglica, mešača i zida cilindra silama kompresije i smicanja. Faktori koji utiču na proces mlevenja su brzina mešanja, kao i količina, vrsta i veličina medijuma za usitnjavanje. Primenom kugličnog mlina u proizvodnji čokolade objedinjuju se dve procesne faze istovremeno, faza mlevenja i faza končiranja. Cilj istraživanja je bio da se ispita uticaj brzine mešača i udela medijuma za usitnjavanje (čeličnih kuglica) na iznos potrebne snage i potrošnju energije u kugličnom mlinu. Pri konstantnoj masi čeličnih kuglica (20, 30 i 40 kg), brzina obrtanja vratila sa mešaćima je povećavana od 10 do 100% od maksimalne brzine (koja odgovara brzini od 50 o/min). Potrebna snaga (W) je registrovana, a energetska potrošnja (J/kg) je izračunata. Dobijeni rezultati su statistički obrađeni pomoću statističke metode analize varijanse (ANOVA). Povećanje brzine vratila sa mešaćima, u iznosima od po 10% do maksimalne brzine obrtanja od 50 o/min, dovelo je do statistički značajnog povećanja potrošnje energije za mlevenje. Pri malim brzinama vratila (10%), povećanje mase čeličnih kuglica nije imalo nikakav uticaj na potrebnu snagu, odnosno potrošnju energije. Prilikom porasta brzine obrtanja vratila od 20 do 70%, energetski zahtevi pri količini medijuma za usitnjavanje, čeličnih kuglica od 30 i 40 kg, su slični i veći u odnosu na energetske zahteve pri primeni 20 kg čeličnih kuglica. Pri velikim brzinama obrtanja vratila sa mešaćima ($\geq 80\%$), povećanje mase čeličnih kuglica doveđe do značajnog povećanja potrošnje energije u kugličnom mlinu.

Ključne reči: Kuglični mlin • Procesni parametri • Potrebna snaga • Potrošnja energije