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Grinding characteristics of Asian originated peanuts (*Arachishypogaea* L.) and specific energy consumption during ultra-high speed grinding for natural peanut butter production

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ABSTRACT

Roasted peanuts of China and India origin were ground in a commercial ultra-high speed grinder operated at 20,000 rpm for 2.0–5.0 min for natural peanut butter production. Grinding characteristics of both peanuts were evaluated in terms of specific energy consumption, E_{sc} with respect to its grinding time and mean particle size. The E_{sc} increased with grinding time with China peanuts having higher E_{sc} than India peanuts. The specific energy consumption modeled to the size reduction ratio of China and India peanuts was predicted more accurately using a linear and exponential model respectively compared to the classical models by Bond, Rittinger and Kick. From the comparison of Bond's working index, W_i, the ultra-high speed grinder is said to be more energy efficient than other comminutors in terms of its capability to produce finer particle size in shorter time than the rest.

1. Introduction

Peanut is a highly nutritious food that contains about 25% protein, 48% lipid, 21% carbohydrate and other micro nutrients and is consumed worldwide for various purposes. One of the major utilization of peanuts is in the production of peanut butter. Peanut butter is usually staple with bread and crackers. It is used as flavor variety in confectionary and dessert in the food industry.

Commercially, peanut butter is produced by a two steps size reduction process; grinding and homogenizing. Initially, roasted peanuts are coarsely ground using typical grinding machines such as colloid mills, attrition mills, disintegrators and hammer mills. However, to obtain finer grinding output, the paste would then be grinded several times which could heat up the peanut butter to excessively high temperatures. Undesirable damage such as food texture damage happens due to high temperature during grinding (Saravacos and Kostaropoulos, 2002). This damage resulted in sensory changes and loss of valuable ingredients in food thus the grinding process requires extensive cooling methods. The homogenizer is implemented to overcome this problem and is capable to improve the percentage of fine texture of peanut butter. The peanut butter product that undergoes the homogenization step is called homogenized peanut butter. As the same physical processes of mixing, droplet disruption and droplet coalescence occur during both the primary (grinding) and secondary (homogenization) phase. It is useful if these two steps procedure can be done using a single apparatus by applying ultra-high speed grinding. While reducing the number of equipment used, it also reduces processing time, cost and product handling from one machine to another thus ensure hygiene.

In peanut butter production, the dry grinding process is involved. It is solely a size reduction operation and is an intensive energy process where it consumes majority of the total power during the flour and feed production (Dziki, 2008). The mechanical energy during grinding is required for materials breakdown and also to overcome friction between the moving parts of the machine (Ghorbani et al., 2010), *i.e.* between the blade and the materials. Previous studies reported that the energy consumption during grinding depends on the ratio of initial and final particle size distribution of materials before and after milling (Ghorbani et al., 2010), moisture content (Dijkink and Langelaan, 2002; Dziki, 2008; Jha and Sharma, 2010), hardness (Dziki, 2008), the feed rate of material (Garg et al., 2010; Jha and Sharma, 2010), pre-treatment before grinding (Djantou et al., 2007; Dziki, 2008; Ngamnikom and Songsermpong, 2011; Velu et al., 2006), and machine variables, *i.e.* type of machine, speed and screen size (Garg et al., 2010; Ghorbani et al., 2010; Ngamnikom and Songsermpong, 2011). The energy consumption for grinding various types of food and

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agricultural materials increases with screen opening size changed from coarser to finer, increase of material hardness and moisture contents but decreased when feed rate increased. Pre-treatment such as drying (*i.e.* microwave and freeze-drying) and crushing assist in altering the physical properties of the materials have helped to decrease the moisture content, hardness, and particle size of the material thus reduce the energy requirement during grinding. With crushing introduced, the total energy consumption for grinding decreased by 19–23% and 21–17% for the hard and soft wheat kernel respectively (Dziki, 2008).

The performance of a grinder or miller which varies with equipment and material is measured by energy consumption and particle size distribution of ground product. Hammer mill is the most widely and preferably used because of its capability to produce wide range of particle size, cost effective and easy to handle. Common grinders and miller used are operated between 360 and 4000 rpm to produce flour as shown in Table 1 where studies on grinding characteristics and energy requirement of various food and agricultural materials including the alfalfa chops (Ghorbani et al., 2010), rice (Ngamnikom and Songsermpong, 2011), peas (Dijkink and Langelaan, 2002), dried mangoes (Djantou et al., 2007), dried maize grain (Velu et al., 2006), popped gorgon nut (Jha and Sharma, 2010) and wheat (Dziki, 2008) are available. The objective of this research was to study the grinding characteristics and specific energy consumption for peanut grinding to produce peanut butter, a paste form product using an ultra-high speed grinder at 20,000 rpm. The three well-known classical models for predicting energy requirement during grinding *i.e.* Kick, Rittinger and Bond were used to study this particle size reduction process. The difference in the three models is in its suitability for different product size where the Kick's model is for coarse grinding (crushing and coarse crushing), Rittinger's for small particle size (fine grinding) and the Bond formula for intermediate grinding (Rhodes, 1997).

2. Materials and methods

2.1. Materials

Two types of peanuts which were originated from China (Virginia variety) and India (Spanish TMV-2 variety) were used for the natural peanut butter production in this study. A 1 kg batch size for each selected peanuts type was used for roasting where peanuts were divided and filled into two aluminum trays of dimension $14 \times 10\ \text{cm}^2$ placed in a convection oven (Memmert UNB 500, Germany). The roasting conditions were 152 °C-60 min and 158 °C-45 min for China and India peanuts, respectively based on optimized roasting temperature and times (Mohd Rozalli et al., 2014). A digital calliper was used to measure the size of roasted peanuts randomly by taking 50 samples per batch of roasting.

2.2. Measurement of physical properties of roasted peanuts

Moisture content of roasted peanuts was determined following the A.O.A.C official method (A.O.A.C, 1996) and was reported as loss in weight after drying, following Eq. (1):

$$\text{Moisture content } (\%\text{ dry basis}) = \frac{M_{H_2O}}{M_{\text{solids}}} \times 100 \quad (1)$$

where M_{H2O} is the loss in weight of the sample after drying (g) and M_{solids} is the initial weight of the sample before drying (g).

Texture analysis of peanuts was evaluated in terms of hardness and fracturability using the Kraft knife adapter probe attached to a texture analyzer (TA.XT$_{\text{Plus}}$, Stable Micro Systems, Godalming, Surrey, U.K.) calibrated with a 5 kg load cell. The test speed was set to 1.00 mm/s while the post-test speed was 10 mm/s. The penetration distance was taken as half of the diameter of the peanuts which is 2.00 mm and 1.50 mm for the China and India peanuts, respectively. The sample was placed centrally on the cutting block with the blade perpendicular to the nut length and the test commenced around the mid region of the sample. It then withdraws from the sample and returns to its starting position. Textural properties were derived from the force–time curves. The first peak of first compression in the force–time curves represents the fracturability (mm) and the maximum peak of the first compression (N) indicates the hardness value. Fracturability is the force applied on food sample to break or fracture which can be defined as brittleness or crispness. The test was performed in ten replications per sample.

2.3. Grinding equipment and operation

Fig. 1 shows the experimental setup to measure power during grinding operation. The roasted peanuts used in this experiment were ground using an ultra-high speed commercial electric mixer grinder at 20,000 rpm (M-PLAN multi-function processor, M-PLAN Sdn. Bhd., Malaysia) fitted with a single-phase motor and three rotational blades. Grinding operation was conducted intermittently (ON: 1 s; OFF 1 s) to avoid excessive heating of samples. The electrical current was measured with a clamp meter (Fluke 345, Fluke Corp., USA) and the readings were used to calculate the electrical energy consumption. The temperature of the peanuts before and after grinding and the surrounding was measured using logging thermometer (HI 98804, K-J-T Thermometer, Hanna Instruments Inc., USA). The peanut butter was stored in air-tight glass jar prior to analysis.

The peanut butter was made by grinding 250 g of roasted peanut for different grinding duration of 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 or 5.0 min. The grinding times were recorded with a digital stop watch. Each grinding time was repeated twice. From the data obtained by the clamp meter, the electrical power for single phase was calculated using Eq. (2):

Table 1
Value of work index for different agricultural materials from literature.

Material	Comminutor	Speed (rpm)	Work index (kJ/kg)	References
Gum karaya	Dry grinder	n/a	1310–1861	Walde et al. (1997)
Wheat	Dry grinder	n/a	8358–12,245	Walde et al. (2002)
Dried maize grain	Hammer mill	3600	292–1017	Velu et al. (2006)
Dried mangoes	Knife grinder	450	1246–4270	Djantou et al. (2007)
Popped *makhana*	Hammer mill	3900	2124–8424	Jha and Sharma (2010)
Coriander seeds	Hammer mill	1440	1650–15,461	Shashidhar et al. (2013)
	Pin mill	n/a	11,521	
Alfalfa chops	Hammer mill	360	n/a	Ghorbani et al. (2010)
Rice	Hammer mill	n/a	n/a	Ngamnikom and Songsermpong (2011)
Peas	Hit mill	10,000, 18,000	n/a	Dijkink and Langelaan (2002)

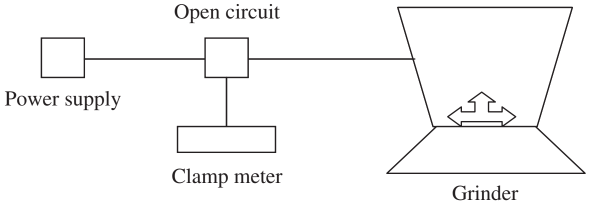

Fig. 1. Schematic diagram for power measurement of ultra-high speed grinder during grinding operation.

$$P = (A \times V \times pf)/1000 \tag{2}$$

where P is the power (kW), A is the current (ampere), V is the voltage and pf is the dimensionless power factor between -1 and 1 generated respectively with grinding time read from the clamp meter. The power factor of an electrical power system is defined as the ratio of the real power flowing to the load with the apparent power in the circuit (IEEE, 2000).

The electrical energy consumption during grinding was calculated using Eq. (3):

$$E = P \times t \tag{3}$$

where E is the energy (kW s with conversion of 1 kW h = 3600 kJ) and t is grinding time (s).

The specific energy consumption during grinding operation was calculated using Eq. (4):

$$E_{sc} = \frac{\text{Input electrical energy, } E \text{ (kJ)}}{\text{Weight of roasted peanuts (kg)}} \tag{4}$$

where E_{sc} is the specific energy input (kJ/kg).

2.4. Models for energy requirement prediction during a grinding process

Size reduction is quantified by comparing the new particle size generated to the energy consumed for generating the size reduction. Mathematically, these three classical proposals can be considered as being the integrals of the same differential equation,

$$\frac{\delta E}{\delta d} = K(d)^n \tag{5}$$

where δE is the differential energy required producing a change, δd is a particle's typical size length, d, and K and n are constants.

The energy required to reduce the initial particle size, d_1 to d_2 is obtained from the integration of Eq. (5):

$$E_{sc} = K \int_1^2 \frac{\Delta d}{d^n} \tag{6}$$

The expressions from integration of Eq. (6) assuming n value as -1, -2 and -1.5 respectively gave the Kick, Rittinger and Bond constants as illustrated in Eqs. (7)–(9) (Rhodes, 1997).

$$E_{sc} = K_K \ln \frac{d_1}{d_2} \tag{7}$$

$$E_{sc} = K_R \left(\frac{1}{d_2} - \frac{1}{d_1} \right) \tag{8}$$

$$E_{sc} = W_i \left(\frac{1}{\sqrt{d_2}} - \frac{1}{\sqrt{d_1}} \right) \tag{9}$$

$$K_B = 0.3162 W_i \tag{10}$$

In the above equations, E_{sc} is specific energy consumption, d_1 is initial roasted peanuts diameter (mm), d_2 is final diameter after grinding (mm), by taking $d_{0.5}$ as average particle size. K_K, K_R and K_B were experimentally determined constants for Kick, Rittinger and Bond model respectively. W_i is the Bond's working index, defined as the energy required to reduce the size of unit mass of material from infinity to 100 μm or less of final product size (Rhodes, 1997).

2.5. Particle size analysis

Particle size analysis of peanut butter was performed using Mastersizer 2000 equipped with Hydro 2000 MU (A) cell input unit (Malvern Instruments Ltd., Worcesterchire, UK). The samples were prepared by adding 15 ml acetone to 0.01 g of each sample in 25 ml test tubes. The sample was dispersed in acetone by using a vortex mixer at 2000 rpm. A transfer pipette was then used to add the diluted solution dropwise to the distilled water filled cell of the analyzer. The sample was added until the obscuration was 0.1–0.2. The obscuration refers to the amount of light which is obscured by the sample because of diffraction and absorption. The sample was continuously stirred and pumped to the analyzer. Each sample was swept 250 times by the laser for each reading with no waiting interval between each reading. Each sample was analyzed five times and averaged. The initial diameter, d_1 is the initial diameter of roasted peanuts and the final diameter, d_2 is the measured particle size after grinding. The $d_{0.5}$ is the particle size at which 50% of the particle size distribution (PSD) falls below. The commercial peanut butter used for comparison of $d_{0.5}$ was Lady's Choice™ smooth and spreadable peanut butter from Unilever (Malaysia) Holdings Sdn. Bhd.

2.6. Statistical analysis

All results presented are the average of the number of repetitions of the respective experimental runs with its standard deviation. Significant mean differences were determined by the student t-test using Microsoft Data Analysis Tool Pack where differences were considered significant at $p < 0.05$ and marked with different superscripts. Eqs. (7)–(9) were fitted to the experimental data at each grinding time by using the Solver function of Microsoft Excel 2007 to obtain the constants. The criteria for selecting the best fitted model were the highest coefficient of determination (R^2) and the lowest mean squared error (MSE).

3. Results and discussion

3.1. Physical properties of roasted peanuts

Table 2 shows the physical and textural properties of both types of roasted peanuts. The peanuts differed physically in sizes and textural properties, *i.e.* hardness and fracturability as indicated by significant mean difference ($p < 0.05$). The larger size of China peanuts resulted higher hardness and fracturability which is less preferable in terms of peanut grinding. The India peanuts which are smaller in size allowed better and more even heat distribution during roasting process resulting more brittle and crispier peanuts which assisted the grinding process with the lower hardness and

Table 2
Physical properties of roasted peanut of China and India.

Parameter	China	India
$^{\alpha}$Average length (mm)	13.91 ± 1.05^a	9.22 ± 0.64^b
$^{\alpha}$Average diameter (mm)	3.89 ± 0.81^a	2.85 ± 0.51^b
$^{\beta}$Moisture content (% dry basis)	1.61 ± 0.16^a	1.64 ± 0.14^a
$^{\chi}$Hardness (N)	5.43 ± 0.31^a	3.89 ± 0.43^b
$^{\chi}$Fracturability (mm)	0.81 ± 0.08^a	0.70 ± 0.07^b

Different letters in the column indicate significant differences ($p < 0.05$).
Values are given as means ± standard deviation with sample size $n = 50^{\alpha}$, 3^{β} and 30^{χ}.

fracturability values. Both peanuts were roasted to achieve similar level of moisture content of 1.6% which approximate to the moisture content of commercial peanut butter measured priory (Mohd Rozalli et al., 2014).

3.2. Particle size distribution

The range of particle size distribution (PSD) of peanut particles in peanut butter with respect to grinding time is presented in Table 3. Fig. 2a and b illustrates the PSD for 2.0, 3.0, 4.0 and 5.0 min of grinding for the China and India peanuts respectively. Both peanut butter samples show multimodal particle size distribution with a central main peak. The PSD also had a larger range for a shorter grinding time, *e.g.* 0.42–1445.44 μm for 2.0 min and 0.12–316.23 μm for 5.0 min grinding time. The volume of the main peak reduced with grinding time decrease. The PSD of the smaller particle size of 0–2 μm was undistinguishable in terms of different grinding times for both types of peanut butter. At bigger particle size 100–600 μm, peaks appeared inversely with grinding time. This indicates that for a shorter grinding time of 2.0 min, there were more of the larger particle sizes. The PSD at this point reflects that a longer grinding time has efficiently distributed the particle size to almost normal distribution.

Deniz et al. (2008) suggested that the presence of different and resolvable food components caused multimodal histogram in the particle size distribution in food material. Similar multimodal histograms were reported for peanut flour (Lima et al., 2000), sesame paste (Deniz et al., 2008) and chocolate (Servais et al. 2002). Multimodal particle size distribution was found useful to increase the maximum value of volume fraction and considerably reduce the viscosity of suspensions which leads to optimum suspension transport and fluid performance during high solid content processing (Servais et al., 2002).

Fig. 3 shows that $d_{0.5}$ decreased with grinding time for both peanut types. The difference between the two types of peanuts is that the India peanuts decreased more rapidly for the first 3 min while the China peanuts' decrement was more gradual overall suggesting a slower rate of particle size reduction in the China peanuts compared to the India peanuts. The difference in the rate of size reduction in this study was affected by the hardness, fracturability and size of the roasted peanuts (Table 2) although some studies found that hardness, initial size and shape did not entirely influence the size reduction rate (Indira and Bhattacharya, 2006; Vishwanathan and Subramanian, 2014). Vishwanathan and Subramanian (2014) explained that the hardness measured in terms of crushing strength may not be a reliable indicator because the grinding force involved in crushing is different from those in the grinding apparatus. For this study and also Vishwanathan and Subramanian (2014)'s, the mixer grinder used involved cutting and shearing forces while the hammer mill used by Indira and Bhattacharya (2006) was more of impact and compression forces. In this study fracturability was a better indicator than hardness for comparing grinding characteristics because the hardness measurement applied cutting strength and resembles the cutting force in the grinder while the fracturability test used force to create initial crack to break a material and is initiated by any mechanical forces involved in a grinding mechanism. Hardness value may also be dependent upon crushing, compression and cutting forces which is applicable in certain type of grinder and miller (Saravacos and Kostaropoulos, 2002).

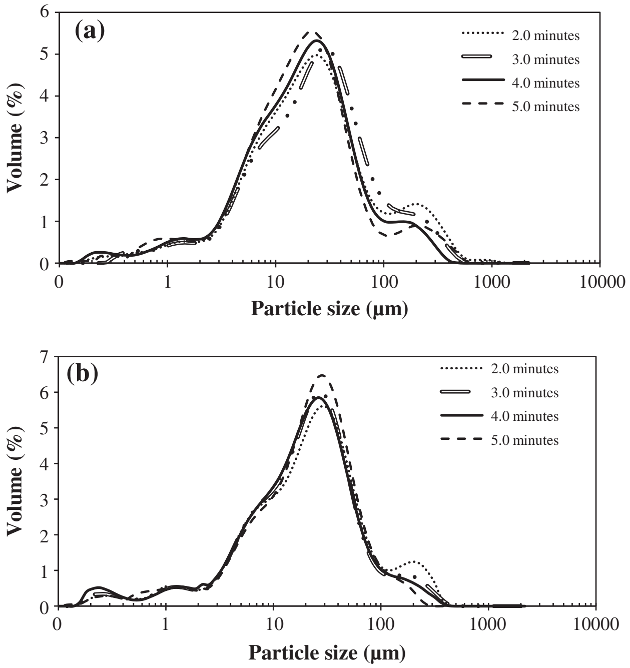

Fig. 2. Particle size distribution of peanut particles in peanuts butter produced from (a) China peanuts and (b) India peanuts.

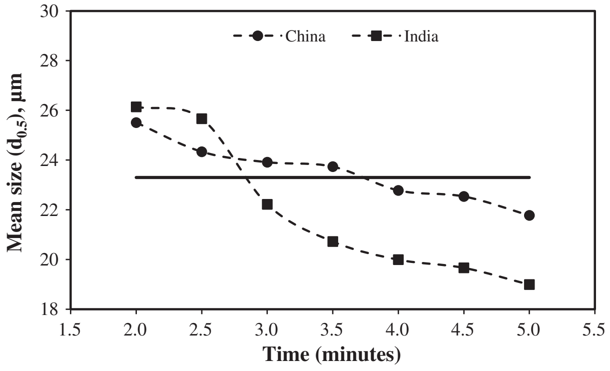

Fig. 3. Effect of grinding time on mean particle size ($d_{0.5}$). The horizontal grey line represents the $d_{0.5}$ of commercial peanut butter at 23.30 ± 0.32 μm.

Table 3
The effect of grinding duration on the range of particle size distribution of peanut butter produced from China and India peanuts.

	Grinding time (min)	$d_{0.1}$[a] (μm)		$d_{0.5}$[a] (μm)		$d_{0.9}$[a] (μm)		Range of peanut particle size (μm)	
		China	India	China	India	China	India	China	India
S2.0	2.0	4.82 ± 0.09^a	4.72 ± 0.04^a	25.51 ± 0.60^a	26.14 ± 0.34^a	109.94 ± 3.51^a	155.06 ± 5.57^a	0.42–1445.44	0.21–549.54
S2.5	2.5	4.81 ± 0.04^a	4.70 ± 0.02^a	24.33 ± 0.12^b	25.66 ± 0.93^a	101.84 ± 1.87^b	133.97 ± 7.52^b	0.32–630.96	0.36–478.63
S3.0	3.0	4.44 ± 0.02^b	4.39 ± 0.08^b	23.91 ± 0.21^c	22.22 ± 0.42^b	88.20 ± 4.08^c	132.53 ± 7.09^b	0.18–549.54	0.18–416.87
S3.5	3.5	4.38 ± 0.04^c	4.21 ± 0.08^c	23.73 ± 0.20^c	20.72 ± 0.60^c	77.85 ± 1.41^d	126.96 ± 8.49^b	0.16–478.63	0.16–363.08
S4.0	4.0	4.33 ± 0.02^d	4.19 ± 0.04^c	22.78 ± 0.13^d	19.99 ± 0.22^d	72.40 ± 3.24^e	85.24 ± 2.82^c	0.16–478.63	0.16–316.43
S4.5	4.5	4.26 ± 0.05^e	3.89 ± 0.03^d	22.53 ± 0.35^e	19.66 ± 0.16^e	66.70 ± 0.97^f	81.26 ± 3.24^d	0.16–416.87	0.16–275.42
S5.0	5.0	3.79 ± 0.09^f	3.83 ± 0.04^e	21.77 ± 0.25^f	18.99 ± 0.10^f	64.69 ± 1.86^g	79.06 ± 2.48^d	0.12–316.23	0.12–275.42

Different letters in the column indicate significant differences ($p < 0.05$).

[a] Values are given as means ± standard deviation ($n = 10$).

Studies which compared grinding characteristics of soy and red gram (Vishwanathan and Subramanian, 2014) and different legumes (Indira and Bhattacharya, 2006) obtained identical trend with India peanuts where the size reduction rate rapidly decreased in the initial stage and thereafter reduced drastically at the same grinding parameter. Ouattara and Frances (2014) also obtained similar trend with India peanuts in the evolution of median particle size of fixed calcite suspensions concentration during grinding in a stirred media mill for all stirrer speeds. This similar pattern of size reduction rate is therefore common and possible for different samples, grinding apparatus or grinding parameter.

3.3. Energy requirement for grinding

Fig. 4 shows that E_{sc} during peanut butter production from the grinding of roasted peanuts increased with grinding time as expected in Eq. (3) where electrical energy consumption is linearly related with grinding time. The E_{sc} of China peanuts is higher than India peanuts due to harder China peanuts than the India peanuts, thus more energy was required to break the whole peanuts which had more resistance to breakage. Similarly, during the grinding of hard wheat, higher values of E_{sc} were obtained by Dziki (2008) than the soft wheat regardless of moisture content levels. The experimental data of E_{sc} versus grinding of the China and India peanuts fitted well with a linear and an exponential function with R^2 value 0.99 and 0.93, respectively. The exponential function obtained by India peanuts could be contributed by the greater number of peanuts, 312 ± 10 peanuts versus 256 ± 13 for the China, used for a same weight loading during grinding. The more constant E_{sc} for the initial grinding process up to 3.0 min for the India peanut was probably due to the energy required for breaking down a greater number of peanuts. The higher number of peanuts available during grinding also induced more friction between the peanuts themselves creating more heat release and exhibited a higher temperature (Fig. 5). Even though peanut butter was formed after 3.0 min of grinding, temperature during grinding continued to increase for both peanuts. The mean particle sizes, $d_{0.5}$ of the China and India peanuts at 3.0 min were 23.91 μm and 22.22 μm respectively (Fig. 3) and were very close to the commercial peanut butter at 23.30 ± 0.32 μm (represented by a straight, grey line). Heat generated at that point of peanut disintegration continued to accumulate with time because as the number of particles increased with time, more friction was induced either between the particles themselves or with the blades and surface of the grinder. Considerable energy can be dissipated when unbroken particles and broken particles rub against each other under impulse loading or under sustained high pressures as in the ball mill and high-pressure roll mill respectively (Kapur et al., 1993). Ghorbani et al. (2010) concluded that most of the total energy consumption during grinding stage is wasted as heat, and only about 0.06–1% are consumed for material disintegration. The energy consumed for material disintegration is based on the energy required to create new fracture surface area relative to the mechanical energy input (Tromans, 2008).

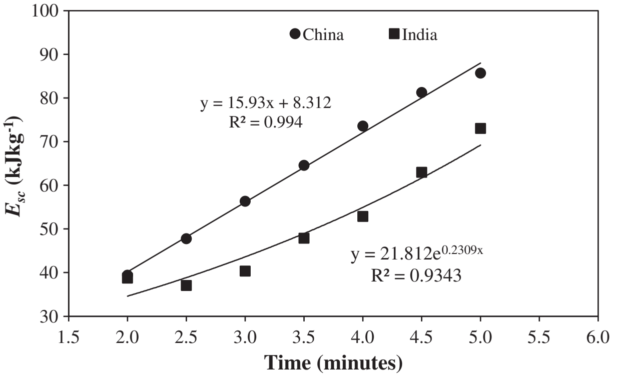

Fig. 4. Effect of grinding time on specific energy consumption during grinding process of roasted China and India peanuts. The solid line indicates the regression analysis of the data.

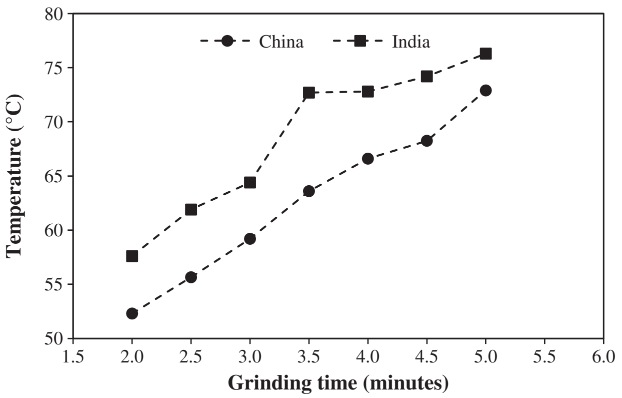

Fig. 5. Effect of grinding time on generated temperature during grinding process of roasted China and India peanuts.

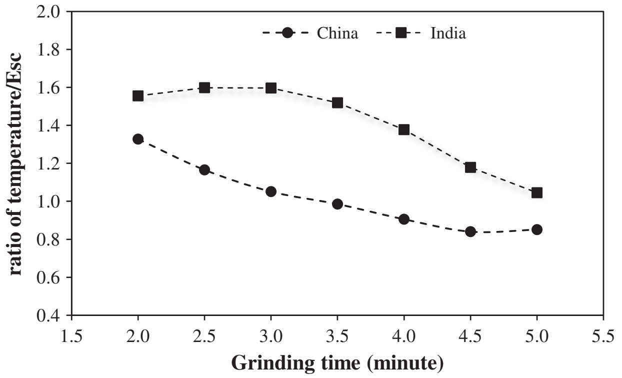

Fig. 6. Temperature-E_{sc} ratio as a function of grinding time.

In analyzing the heat dissipated versus grinding energy efficiency, Fig. 6 shows that the temperature-E_{sc} ratio reduced over the grinding time. This suggests that the grinding process gets more energy efficient such that less heat was generated towards the later stage of grinding than the earlier stage as the smaller particles size had less directional and frequency of contacts making less stress (Saravacos and Kostaropoulos, 2002). As further size reduction becomes more difficult and requires more energy to create new fracture, more energy was utilized to overcome physical difficulties of the peanuts and less energy was dissipated as heat. The generally lower temperature-E_{sc} ratio in the China peanuts than India suggested that heat generated per energy input is lower and its grinding was more efficient. When the effective E_{sc} (E_{sc}/r) is higher (Table 4), more energy is utilized per size reduction. The India peanut has slightly higher effective E_{sc} than the China peanuts indicating overutilization of energy for size reduction of India peanuts although it required less energy (Fig. 4) and as a result its temperature-E_{sc} was higher (Fig. 5).

Fig. 7 shows the relationship between E_{sc} and the ratio of initial to final particle size, r of roasted peanuts. E_{sc} increased with an increasing size reduction ratio of roasted peanuts and this was describable using a simple linear model and an exponential function for the China ($R^2 = 0.96$, $MSE = 10.16$) and India ($R^2 = 0.91$,

Table 4
Parameters of three models for grinding of roasted peanuts in ultra-high speed grinder.

Peanut's origin	Grinding time (min)	*Size reduction ratio, r (d_1/d_2)	$^\delta$Specific energy, E_{sc} (kJ kg^{-1})	Effective, E_{sc} (E_{sc}/r)	$^\delta$Work index, W_i (kJ kg^{-1})	$^\delta$Bond's constant, K_B (kJ kg^{-1})	$^\delta$Kick's constant, K_K (kJ kg^{-1})	$^\delta$Rittinger's constant, K_R (kJ kg^{-1} m^{-1})
China	2.0	545.36 ± 1.57	39.40 ± 0.69	0.07	6.50 ± 0.11^{a}	2.05 ± 0.04^{a}	6.27 ± 0.15^{a}	986.67 ± 14.56^{a}
	2.5	571.66 ± 0.03	47.76 ± 2.82	0.08	7.78 ± 0.46^{b}	2.46 ± 0.15^{b}	7.56 ± 0.39^{b}	1164.71 ± 68.78^{b}
	3.0	581.74 ± 1.87	56.33 ± 1.27	0.10	9.14 ± 0.20^{c}	2.89 ± 0.06^{c}	8.95 ± 0.14^{c}	1359.17 ± 34.85^{c}
	3.5	586.07 ± 0.94	64.56 ± 2.94	0.11	10.37 ± 0.47^{d}	3.28 ± 0.15^{d}	10.18 ± 0.39^{d}	1533.20 ± 67.47^{d}
	4.0	610.73 ± 0.19	73.56 ± 2.16	0.12	11.59 ± 0.34^{e}	3.66 ± 0.11^{e}	11.53 ± 0.25^{e}	1683.04 ± 49.39^{e}
	4.5	617.29 ± 12.32	81.24 ± 0.87	0.13	12.60 ± 0.13^{f}	3.98 ± 0.04^{f}	12.71 ± 0.19^{f}	1829.25 ± 16.92^{f}
	5.0	638.88 ± 10.00	85.68 ± 3.02	0.13	13.17 ± 0.46^{f}	4.17 ± 0.15^{f}	13.31 ± 0.34^{f}	1850.55 ± 36.41^{f}
India	2.0	352.72 ± 4.34	38.73 ± 1.57	0.11	5.99 ± 0.24^{a}	1.89 ± 0.08^{a}	6.30 ± 0.26^{a}	961.68 ± 36.22^{a}
	2.5	359.27 ± 12.43	37.04 ± 1.75	0.10	6.16 ± 0.26^{a}	1.95 ± 0.08^{a}	6.56 ± 0.29^{a}	972.57 ± 36.88^{a}
	3.0	414.99 ± 0.12	40.34 ± 2.19	0.10	5.94 ± 0.32^{a}	1.88 ± 0.10^{a}	6.66 ± 0.36^{a}	869.09 ± 47.12^{a}
	3.5	444.96 ± 4.05	47.87 ± 0.16	0.11	6.97 ± 0.07^{b}	2.20 ± 0.10^{b}	7.98 ± 0.01^{b}	986.42 ± 4.57^{b}
	4.0	461.18 ± 4.89	52.86 ± 0.74	0.12	7.51 ± 0.10^{c}	2.37 ± 0.03^{c}	8.62 ± 0.12^{c}	1059.03 ± 14.34^{c}
	4.5	468.90 ± 0.99	62.96 ± 0.55	0.13	8.86 ± 0.10^{d}	2.80 ± 0.03^{d}	10.23 ± 0.01^{d}	1236.84 ± 16.12^{d}
	5.0	485.52 ± 1.54	73.01 ± 1.60	0.15	10.11 ± 0.21^{e}	3.20 ± 0.07^{e}	11.81 ± 0.25^{e}	1390.70 ± 27.26^{e}

Different letters in the column indicate significant differences ($p < 0.05$).
Values are given as means ± standard deviation with sample size $n = 10^*$ and 2^δ.

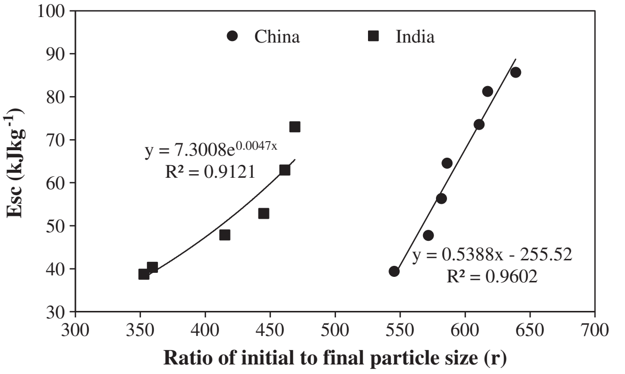

Fig. 7. Specific energy consumption as a function of size reduction ratio. The solid line indicates the regression analysis of the data.

$MSE = 9.37$) peanuts respectively. The increase of E_{sc} was more than proportionately to the size reduction ratio increase, with 10 units for the China and 3 units for the India peanuts per unit of size reduction. A simple linear relationship between the E_{sc} and the size reduction ratio was obtained in grinding studies using hammer mill for alfalfa chops (Ghorbani et al., 2010) and coriander seeds (Shashidhar et al., 2013) with R^2 0.95 and 0.93 respectively. Those results reported that when size reduction ratio increased four times, the energy consumption increased about 7 and 14 times, respectively. For minerals, the size reduction ratio also increased linearly with energy when quartz and dolomite particles were ground in roll mills while ball mill curve showed two straight line segments for both minerals (Fuerstenau et al., 1990). This suggests that the ultra-high speed grinder used in this study required high E_{sc} for a small change in size reduction of materials due to its capability to grind peanuts to paste form in a short time. The E_{sc} versus size reduction ratio relationship suits differently with types of millers used for grinding and ground materials.

3.4. Effect of grinding time on grinding constants

Table 4 shows the constants obtained from the three energy laws, the Bond, Kick, and Rittinger models giving work index (W_i), Bond's constant, Kick's constant and Rittinger's constant. All the constants are measure of energy uptake and they increased with grinding time disregard of peanuts origin. The grinding of soy and red gram also show increment of the constants with time (Vishwanathan and Subramanian, 2014). The increase of the constants is influenced by other factors including screen size (Shashidhar et al., 2013) and initial feed size (Ghorbani et al., 2010). Bond's work index, Wi met the criteria of this study as almost 90% of the final particle size was less than 100 μm (Table 3). The W_i of China peanuts was slightly higher than India peanuts for all grinding time due to greater energy consumption to grind China peanuts. References listed in Table 1 show that W_i varied with type of material and comminutor and ranged from 292–15461 kJ/kg for hammer mill, 1246–12245 kJ/kg for grinder and 11521 kJ/kg for pin mill. The W_i of this ultra-high speed grinder had tremendous lower values at average of 10.17 ± 0.31 kJ/kg and 7.41 ± 2.27 for grinding China and India peanuts, respectively (Table 4) for peanut butter grinding when compared to the comminutors surveyed (Table 1) and indicates that the ultra-high speed grinder is very energy efficient. This analysis of constant value from the Kick, Rittinger and Bond's model at various grinding time was more appropriate given that the generalization of an overall constant over the entire grinding time gave poor R^2 values of 0.09, 0.35 and 0.21, respectively for the China peanut and 0.21, 0.61 and 0.41, respectively for India peanut. The generalization of grinding process using a single constant were used to describe energy requirement during grinding of mineral (Vishwanathan and Subramanian, 2014) and probably is not suitable for describing food and agricultural materials such as soy and red gram due to complexity of food materials. Vishwanathan and Subramanian (2014) suggested that deeper understanding of food complexity is necessary for further modification of these grinding laws which were originally proposed for minerals grinding. In particular, Kick's law is based on the theory of reduction where same energy requirement in reduction of 10 μm particle to 1 μm with reduction of 1 m boulders to 10 cm blocks (Rhodes, 1997). This assumption cannot be accepted especially in fine and ultrafine grinding (Balaz, 2008). While the Bond's and Rittinger's, they are suitable for energy prediction in intermediate and fine grinding respectively, they ignore the contributions of particle size distribution of the feed and the product, particle interactions and the energy absorbed for particle deformation (Rhodes, 1997). Among the three energy models, the Rittinger's model had a better fit with R^2 value below <0.61. The Rittinger's model also described the grinding coriander seeds (Shashidhar et al., 2013) and alfalfa chops (Ghorbani et al., 2010) relatively well with R^2 0.94 and 0.97 respectively. The bigger size reduction ratio in this peanut grinding work at 352.72–638.88 than those in coriander seeds at 1.29–5.26 and alfalfa chops at 2.5–11.5 could be the reason of the slight poorer fit.

The curve-fitted models of E_{sc}-size reduction ratio in Fig. 7 in the form of linear and exponential model can be proposed for energy prediction in food and agricultural milling instead of using the classical laws of Kick, Rittinger and Bond. Ghorbani et al. (2010) also found a linear model of E_{sc}-size reduction ratio for alfalfa chops grinding process and Vishwanathan and Subramanian (2014) found no remarkable trend in E_{sc}-size reduction ratio for soy and red gram.

4. Conclusions

The grinding operation using ultra-high speed grinder to produce peanut butter from roasted China and India peanuts reveals that even though the grinding energy was greater when the material was bigger and harder, the energy was utilized better in the sense of energy was used up promoting propagation of crack in order to fracture the roasted peanuts rather than for size reduction. Thus, fracturability value can be a reliable indicator in assessing the difference in energy requirement for roasted peanut grinding. The comparison of W_i with other comminutor suggests that the ultra-high speed grinding is more energy efficient in reducing particle size to ultrafine size in a short time despite higher energy needed. The description of grinding energy for food and agricultural material is complex and does not necessarily fit into the classical laws of grinding.

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