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Improvement of the milling energy indices by speed control of the asynchronous motor of the grinder in a small-scale production of corn flour

Amélioration des indices d'énergie de broyage par contrôle de la vitesse du moteur asynchrone du broyeur pour la production à petite échelle de farine de maïs

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ABSTRACT:

Usually in practice, the grain mill operates at a constant frequency without a motor control unit, (i.e.: 3000 rpm (50 Hz)). In those conditions, the granularity of the corn flour is not standard and the specific grinding energy is high. In this paper, the influence of the motor speed control on the grinding energy of a hammer grinder used for a small-scale production of corn flour is studied. An adjustable speed drive is used to apply a scalar control and a vector control to the motor of the grinder for the motor rotation frequency from 40 Hz to 60 Hz with a step of 5 Hz. The milling energy indices are assessed for these motor rotation frequencies and types of control. From these parameters, it is shown that, above 45 Hz, the motor control improves the granularity of corn flour. The vector control of voltage allows to have the lowest grinding energy consumption. Compare to grinding without motor control, it is possible with the grinding under control of the motor to save useful specific grinding energy of the order of 51 to 72 %, of 46 to 60 % and of 14 to 60 % respectively with the vector controls of tension and of current, and with the scalar control. The grinding energy indexes of Bond and Pujol used have similar behaviour to that of the grinding energy. The specific grinding energy as well as the grinding energy indices are then strongly influenced by the grinding process.

Keywords: Milling energy indices; Induction motor; Drive motor control; Hammer grinder; Corn flour.

RÉSUMÉ :

Habituellement en pratique, le broyeur de céréales fonctionne à fréquence constante sans unité de commande du moteur (soit : 3000 tr / min (50 Hz)). Dans ces conditions, la granularité de la farine de maïs n'est pas standard et l'énergie spécifique de broyage est élevée. Dans cet article, l'influence de la commande de la vitesse du moteur du broyeur sur l'énergie de broyage d'un broyeur à marteaux utilisé pour une production à petite échelle de farine de maïs est étudiée. Un variateur de vitesse est utilisé pour appliquer une commande scalaire et une commande vectorielle au moteur du broyeur pour les fréquences de rotation du moteur de 40 Hz à 60 Hz par pas de 5 Hz. Les indices d'énergie de broyage sont évalués pour ces fréquences de rotation du moteur et ces types de commande. A partir de ces paramètres, on montre qu'au-dessus de 45 Hz, la commande du moteur permet d'améliorer la granularité des poudres de maïs. La commande vectorielle en tension du moteur permet d'avoir la plus faible consommation d'énergie de broyage. Comparé au broyage sans commande moteur, il est possible avec le broyage avec commande du moteur d'économiser une énergie spécifique de broyage de l'ordre de 51 à 72 %, de 46 à 60 % et de 14 à 60 % respectivement avec les commandes vectorielles de tension et de courant, et scalaire. Les indices d'énergie de broyage de Bond et Pujol utilisés ont un comportement similaire à celui de l'énergie spécifique de broyage. L'énergie spécifique de broyage ainsi que les indices d'énergie de broyage sont alors fortement influencés par le procédé de broyage.

Mots clés : Indices d'énergie de broyage ; Moteur à induction ; Commande du moteur ; Broyeur à marteaux ; Farine de maïs.

1. INTRODUCTION

Cereal flours (from maize, millet, rice, sorghum, etc.) are used in many dietary habits in most Third World countries and developing countries. Production of these flours is still done today either manually using a mortar or a stone, or using a grinder driven by an internal combustion machine, or by small grinders trained by electric motors of medium power (less than 10 HP).

In the food and mining industry, it is shown that only about 1 % of the total energy consumed by the grinding system is actually used to generate new surfaces (Hoduoin et al., 1994). The rest is usually dissipated as heat. The energy efficiency of the grinding operation can therefore be linked to the new surfaces formed during the size reduction process. (Barbosa-Canovas et al., 2006). In general, the energy consumption during the grinding process depends on the geometric and kinematic characteristics of the grinder and on the physical properties of the particles to be grinded (Dziki and Laskowski, 2004).

Cereal mills are systems in which the load varies during operation. Their motors do not then work under the nominal conditions; this leads to additional energy losses (Saidur et al., 2012). To minimize such losses, the speed of the motor should change regularly to accommodate the new load (Saidur and Mahlia, 2010). Adjustable speed drives are used in industry to adapt the speed of the motor to its load (Blaabjerg et al., 2017) and to maintain the speed of the motor at a constant level when the load is variable (Blaabjerg et al., 2017), (Saidur et al., 2009) or when the motor is operating under partial load conditions (ie, far from its rated load) as in the case with cereals mills. The use of adjustable speed drives thus offers the possibility of reducing the energy consumed by the motor by 30 to 60 % and increasing the lifetime of the motor by allowing a smooth start and stop. This can contribute to a global energy saving of 15 to 40 % (Saidur et al., 2010). The use of an adjustable speed drive to control an electric motor also allows operation at speeds above his rated speed and eliminates the mechanisms of acceleration and friction losses (Blaabjerg et al., 2015), (Saidur et al., 2012). However, the use of an adjustable speed drive in an electric power system damage the quality of the power system (Tchoffo et al., 2019a ; Tchoffo et al., 2019b; Singh et al., 2014). Applications with adjustable speed drive can be classified into constant torque applications and variable torque. The grindstone mills can be classified in the family of constant torque applications. In this category, the speed of the motor does not significantly change. The active power of the motor is proportional to the torque and the speed of the motor. Thus, reducing speed while keeping the torque constant contributes directly to saving energy (Blaabjerg et al., 2017). Most hammer mills locally made and use by local population in Cameroon, do not have a constant flow feed device of the grinding chamber. They are therefore classified in the family of variable torque applications for which the active power of the motor is proportional to the cube of the rotation speed of the motor. Thus, the energy saving potential in these systems using adjustable speed drives is high compared to the conventional connection of the motor to the grid where it is supposed to operate in its nominal conditions (Blaabjerg et al., 2017).

In this work, the results of corn milling operations carried out with a hammer mill controlled through an adjustable speed drive (Altivar 71) and powered by the conventional power grid, are presented in the view to improve the milling energy indices. The objective is to study the influence of the milling conditions on the energy consumed during corn milling operations by varying the rotation speed of the grinder motor. The total and useful specific grinding energies, and the grinding energy indices obtained for different motor rotation frequencies and different types of motor control are assessed and analyzed.

2. MATERIALS AND METHODS

2.1. Materials and experimental setup

The experimental setup is composed of a hammer mill; brand: THURM, Germany; Type: DDR/GDR KMERA 112M2 3/1. It is driven through a belt by a three-phase asynchronous motor with the following features: cosφ : 0.87; rate frequency: 50 Hz; rate speed: 2880 rpm; rate power: 4 kW. The corn flour comes out of the grinder through a cylindrical sieve with circular meshes of diameter 1mm. An adjustable speed drive was used to set the motor rotation frequency and the type of motor control. Its features are: brand: ALTIVAR made by Schneider Electric; type: ATV71HU75N4. The system is powered by a 400 V, 50 Hz three-phase electrical grid. These equipment's and the power analyser are configured and connected as shown in figure 1. For milling on the motor controlled trough the adjustable speed drive, the switch-disconnector K_1 was closed and $K_2$was opened. For tests on the motor without control, the switch-disconnector K_1 was opened and K_2 was closed.

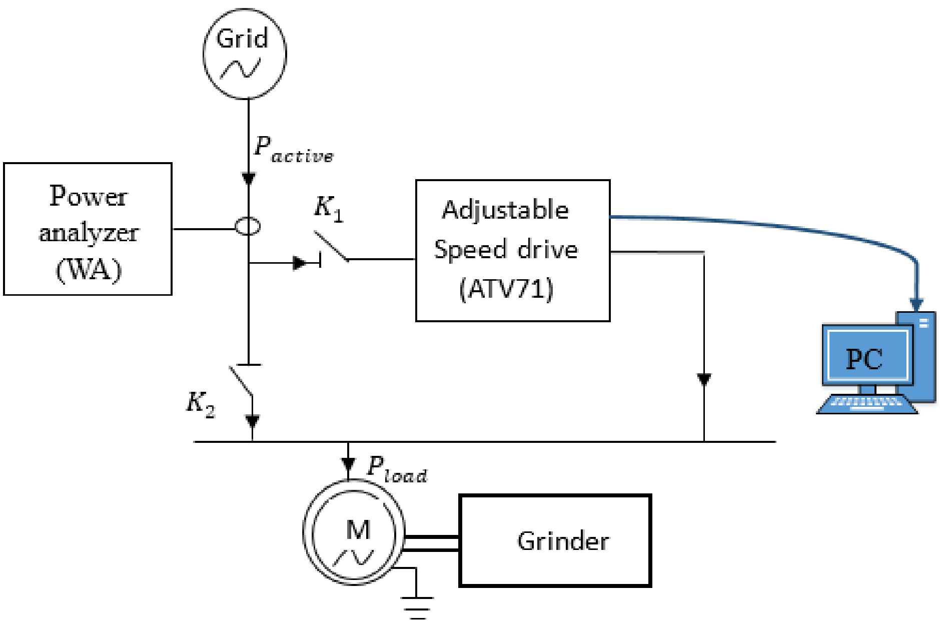

Figure 1. Diagram of system configuration

2.2. Methods

The corn used for grinding tests is of the Shaba variety which is white in color. The samples used were grown in the Mbere Division in the Adamaoua Region of Cameroon. They were harvested in September 2016. The corn kernels to be milled were calibrated using two circular mesh sieves of diameters 8mm and

11 mm. Thus, the samples used during grinding tests consist of those passing through the sieve of diameter 11 mm and those retained by the sieve of diameter 8 mm. These samples were dried during 4 hours in an oven at 80 °C, in order to set the water content to a maximum value of 15.5 % recommended by the "Codex Alimentarius" for whole corn intended for the production of corn flour by milling for human consumption (FAO, 1985).

Batch grinding operations were conducted by filling the grinding chamber at 30 % of its total volume which were evaluated as equal to 4.4 L. The used adjustable speed drive allowed to apply three types of commands on the motor for the frequencies of rotation of 40 Hz to 60 Hz in steps of 5 Hz. These commands are standard scalar control (SC), open loop vector control of voltage (VCU), and open loop vector control of current (VCI). Each grinding test was repeated three times.

Dimensions of the corn kernels were meseared in other to assess their physical properties. These measurements were done using a digital caliper, OTMT brand, France, with a precision of ± 0.01mm. The main physical properties of the grains assessed are:

- The mean length (L), width (W) and thickness (T).
- The equivalent diameter of grains which corresponds to its geometric diameter (D). It is deduced from the dimensions of the grains using relation (1) (Mohsenin, 1980), (Davies, 2009).

$$D_g = (L.W.T)^{1/3} \tag{1}$$

- The sphericity of grains (ϕ_s) which is an index of its roundness. Due to the non-spherical form of the corn grains, it is assessed using relation (2) (Mohsenin, 1980), (Davies, 2009).

$$\phi_s = \frac{(L.W.T)^{1/3}}{L} \tag{2}$$

The corn flours obtained were classified using a horizontal and vertical vibrating electric sieving machine, HENSGRAND (China) brand and of STSJ-4 Digital High Frequency Sieve Shaker type, comprising a sieve battery consisting of seven square mesh sieves with diameters: 0.04, 0.125, 0.2, 0.25, 0.315, 0.5 and 0.8 mm respectively. The equivalent diameter of the corn flour particles retained on each sieve is the geometric mean of the diameters of the two adjacent sieves. The sieving time was set at 20 minutes to meet ASTMD452 standards, which states that sieving should continue until less than 0.5 % of the mass of the initial material passes through the sieve every 2 minutes for a dry product (Allen, 2003). The masses of the corn flour fractions retained on each sieve were measured using a WANT brand electronic scale, type: WT50001 and precision ± 0.1 g. The average equivalent diameter of the powder particles is calculated using reletaion (3) (Laskowski et al. 2005):

$$d_s = \frac{\sum_{i=1}^{n} d_i \cdot g_i}{100} \tag{3}$$

Where d_i is the geometric mean diameter of particles retained on the sieve $N° \, i$. This diameter is taken as the geometric mean between the sieve mesh sizes $N° \, i$ and $N° \, (i-1)$. g_i is the mass fraction of particles retained on the sieve $N° \, i$.

During grinding tests, the electrical power parameters of the motor were automatically recorded using Schneider Electric's "SoMove lite" software, which allows communication between the adjustable speed drive and a computer. When the motor is directly connected to the grid, its active power has been measured using a power analyzer. The model used is the C.A 8220 power analyzer made by Chauvin Arnoux (France).

From the curves of the variation as a function of time of the active power absorbed by the motor during the grinding test, the total consumed energy (E_a) is assessed as the area of the surface between the power curve and the time axis. The trapezoidal rule is used to evaluate this surface area. The energy losses recorded during each grinding test correspond to the area of the surface between the curve of the active power at no load (which is constant) and the time axis. The useful grinding energy (E_u) is then the difference between the total energy consumed and the recorded energy losses. The total specific energy (E_{as}) and the useful specific energy (E_{us}) of grinding are then assessed using relations (4) and (5) in which *m* is the mass of the grinded corn sample (Laskowski et al., 2005).

$$E_{as} = \frac{E_a}{m} \tag{4}$$

$$E_{us} = \frac{E_u}{m} \tag{5}$$

Several particle size reduction theories exist to assess the grinding energy index. The most known derive from the energetic laws of Rittinger, Kick and Bond. However, Bond's law is a good compromise between the two others. It is well adapted to a variety of materials, ranging from coarse to fine through medium (Barbosa-Canovas et al., 2006). It is therefore the Bond index (K_b) given by the relation (6) that has been evaluated in this work (McCabe et al., 1993), (Lee et al., 2013).

$$K_b = E_{us} \left(\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}} \right)^{-1} \tag{6}$$

The Bond energy index or work index (W_i) is deduced from Bond index (K_b) using relation (7).

$$W_i = \frac{K_b}{0.3162} \tag{7}$$

Assuming that the surface area created during grinding is mainly due to the production of fine particles, the Grinding energy index can be defined by a correlation between the useful specific energy (E_{us}) of grinding and the quantity of flour (Q_{fa}) produced. Flour is considered as corn powder particles with smaller than 200 µm (Pujol et al., 2000). Thus, a new grinding energy index K' is defined as in relation (8) and assessed in this work.

$$K' = \frac{E_{us}}{Q_{fa}} \tag{8}$$

3. RESULTS AND DISCUSSION

3.1. Physical properties of corn grains

A sample of 1000 corn kernels extracted from the sample to be milled was used to assess the physical properties of corn kernels. Table 1 gives the average values of these parameters. These parameters for studies done on the varieties of corn grown in Nigeria (Aremu et al., 2014) and in India (Ashwin Kumar et al., 2017) are also given in this table. It can be seen that, the corn variety studied in this work weighs relatively more than the Indian varieties (Ashwin Kumar et al., 2017). This can affect the true density of these varieties. The mean sphericity index of corn variety treated in this work is 0.72 ± 0.01 (72 %). It is relatively higher than that of Indian varieties. In general, the differences observed between the values of the parameters in Table 1 are mainly due to the corn varieties treated by authors as well as the crops conditions which are not the same.

Table 1. Mean values of some physical and morphological properties of corn grain

Parameters	This study	(Aremu et al.. 2014)	(Ashwin Kumar et al.. 2017)
Moisture content of the grains (%)	9.28 ± 0.45	5.14	12 - 20
Mass of 1000 grains (g)	401.00 ± 0.10	/	232.86 - 270.42
Mean length of grain, L (mm)	11.47 ± 0.14	/	11.00 -11.29
Mean width of grain, W (mm)	9.43 ± 0.05	/	7.91 - 8.35
Mean thickness of grain, T (mm)	5.15 ± 0.07	/	3.83 - 4.50
Geometric mean diameter of grain, D_g (mm)	8.23 ± 0.04	/	6.93 à 7.51
Mean sphericity index of grain (ϕ_s)	0.72 ± 0.01	/	0.63 - 0.67

3.2. Average equivalent diameter of corn powders

The average equivalent diameter of the corn powder particles is shown in Figure 2 as a function of the motor frequency and the type of control. It is between 0.37 ± 0.06 mm and 0.41 ± 0.07 mm for corn powders obtained with motor control and 0.40 ± 0.07 mm for that obtained without motor control. For milling with motor control, the average equivalent diameter gradually decreases in the frequency range used (40 Hz to 60 Hz). Beyond 45 Hz, the average equivalent diameter for milling with control becomes progressively smaller than that without control. In this frequency range, the motor control makes it possible to improve the granularity of the corn powders. The type of control applied to the grinder motor seems to have no effect on the average equivalent diameter of the powders for motor frequencies above 50 Hz.

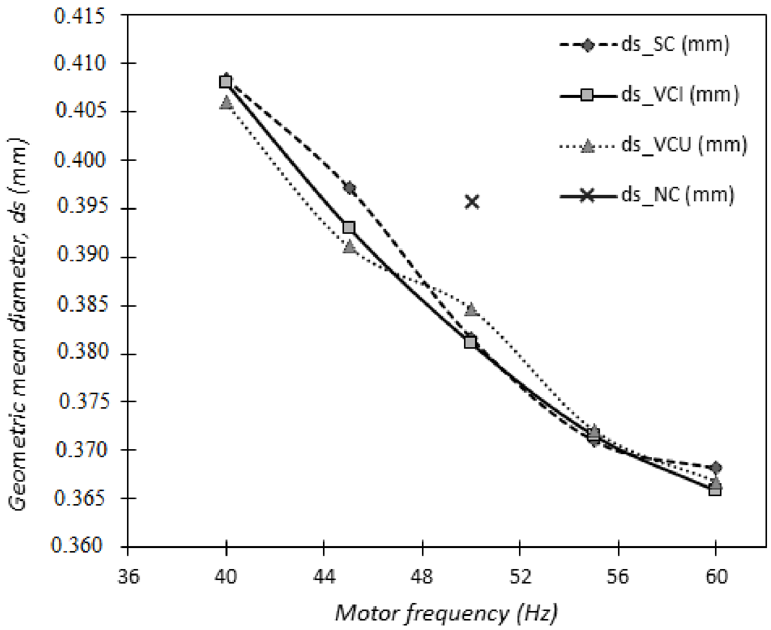

Figure 2. The geometric mean diameter of corn powder as a function of motor frequency and the type of control (NC- No Control; SC- Scalar Control; VCU and VCI – Voltage and current Vector Controls)

3.3. Specific grinding energy

The variation of the total specific energy (E_{as}) and of the useful specific useful energy (E_{us}) as function of motor rotation frequency and the type of its control are given in Figure 3.

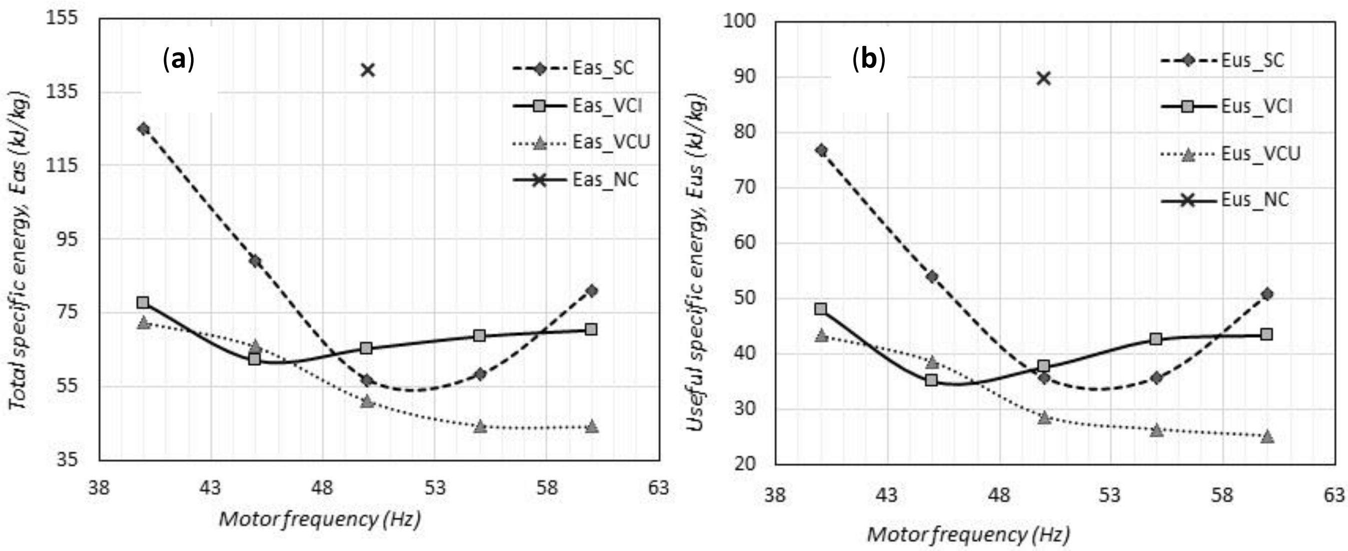

Figure 3. Total and useful specific grinding energy (E_{as} (a) and E_{us} (b)) as function of motor frequency and the type of control

The two figures have the same tendencies. Only the magnitudes change. The total specific energy being more important than the useful one. This figure shows that by using motor control, these specific energies vary with the rotation frequency of the motor as follows: with the scalar control, the specific grinding energy decreases and reaches a minimum between 50 Hz and 55 Hz then goes back up; with the vector control of current, it decreases and then rises with a minimum of 45 Hz and a maximum of 55-60 Hz; with the vector control of voltage, it continuously decreases but tends to a constant value from 55 Hz to 60 Hz. On the other hand, the values of E_{us} and E_{as} for milling with control of motor are lower than those without control at all the rotation frequencies. Thus, the use of the motor control reduces the values of the specific energies of grinding (E_{us} and E_{as}). This is in accordance to the assertion that the using of the motor control can reduce the energy consumption of the hammer mill to grind corn as suggested above with the curves of variation of the grinding duration and the literature on the use of adjustable speed drives to control the speed of rotation of asynchronous motors (Saidur et al., 2010).

The values of these specific energies of grinding under control compared to their values without control lead to conclude that the use of a control on the motor allows it to apply a greater mechanical action on the corn kernels at the beginning of the grinding, allowing a rapid fragmentation and therefore a rapid particle sizes reduction. Thus, the grinding duration is lower and the total energy consumed too compared to grinding without control.

The milling with motor control shows that it is possible to save useful specific grinding energy of the order of 51 to 72 %, of 46 to 60 % and of 14 to 60 % respectively with the vector controls of tension and of current, and with the scalar control. On the other hand, the vector control of voltage allows to minimize the grinding energy consumption in the motor rotation frequency range of 50 – 60 Hz.

3.4. Grinding energies indices

The influence of the rotation frequency of the motor and the type of control on the grinding energy indices of Bond (K_b) and Pujol (K') is shown in Figure 4. The two indices have similar behaviour for the considered controls and their profiles are identical to those of specific energies. Conclusions that can be drawn from the variation of these indices are therefore identical to those on the specific grinding energy. The values of K' are in the range of 390 and 1048 kJ/kg with the scalar control, of 335 and 585 kJ/kg and of 285 and 525 kJ/kg with vectors controls of current and of voltage respectively. On the other hand, the values of K_b are between 27.16 and 63.23 kJ.kg^{-1}.mm$^{1/2}$ with the scalar control, between 28.17 and 39.42 kJ.kg^{-1}.mm$^{1/2}$ and between 19.37 and 35.61 kJ.kg^{-1}.mm$^{1/2}$ with vectors controls of current and of voltage respectively. For the tests without control of the motor, they are about 1074.30 kJ.kg^{-1} for K' and 72.33 kJ.kg^{-1}.mm$^{1/2}$ for K_b. It appears directly that the index K' is more discriminatory than the index K_b.

For tests without control of the motor, the Bond work index (W_i) is about 228.76 kJ.kg^{-1}.mm$^{1/2}$. Its value is between 87.44 and 199.97 kJ.kg^{-1}.mm$^{1/2}$ with scalar control, between 89.09 and 124.68 kJ.kg^{-1}.mm$^{1/2}$ and between 61.25 and 112.63 kJ.kg^{-1}.mm$^{1/2}$ with vectors controls of current and of voltage respectively. These Bond work indices (W_i) obtained in this work and given in Table 2 are thus far less to that reported by Velu et al., (2006). When the water content of the corn varies from 17.2 to 4.9 %, the Bond work index varies from 698.76 to 291.96 kJ.kg^{-1}.mm$^{1/2}$. Specifically, at the water content of 9.6 %, he obtains a Bond work index of 421.92 kJ.kg^{-1}.mm$^{1/2}$. From above observations, it can be conclude that the grinding energy indices are strongly influenced by the grinding process.

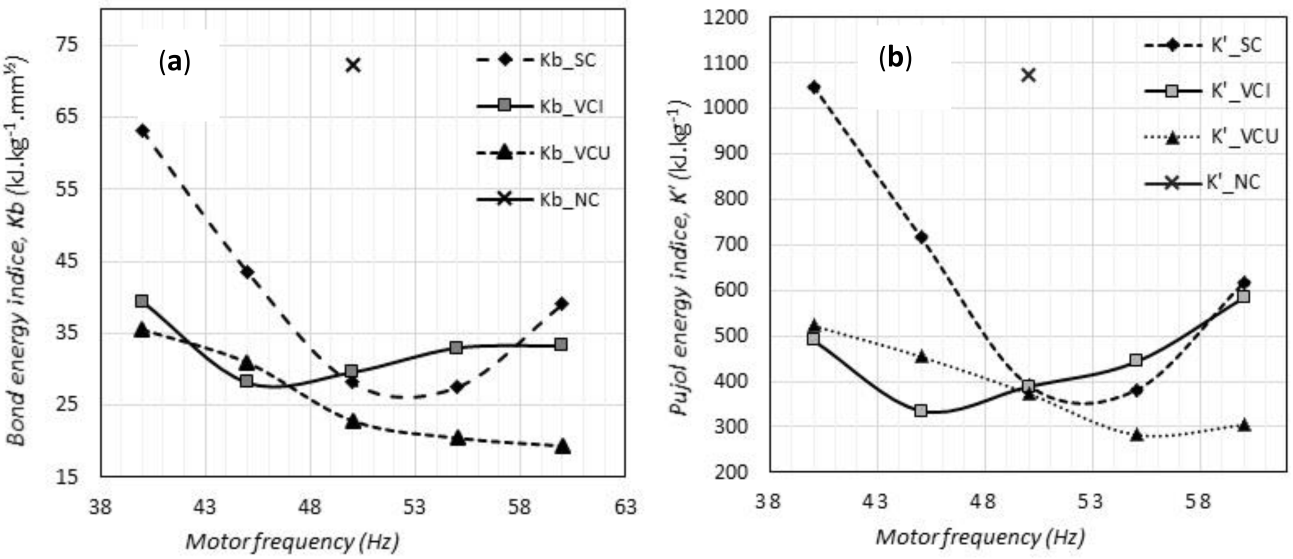

Figure 4. Bond (K_b) (a) and Pujol (K') (b) grinding energies indices as function of motor frequency and the type of control

Table 2. Bond work index (W_i)

Motor rotation Frequency (Hz)	Wi_SC ($kJ.kg^{-1}.mm^{1/2}$)	Wi_VCI ($kJ.kg^{-1}.mm^{1/2}$)	Wi_VCU ($kJ.kg^{-1}.mm^{1/2}$)	Wi_NC ($kJ.kg^{-1}.mm^{1/2}$)
40.00	199.97	124.68	112.63	
45.00	138.00	89.09	98.05	
50.00	89.05	93.66	72.39	228.76
55.00	87.44	104.31	64.75	
60.00	123.72	105.29	61.25	

4. CONCLUSION

The aim of this work was to study the influence of grinding conditions on energy consumption during grinding operations of corn carried out with a hammer mill controlled by an adjustable speed drive. The results obtained show that in general, the use of motor control during grinding improves the granularity of the corn flours. The assessment of the specific grinding energy as well as the grinding energy index shows a potential of energy saving during the grinding operation under motor control. Indeed, it shows that with motor control, the specific grinding energy is lower than that motor control. It is thus possible to achieve a relative gain of useful specific energy of the order of 14 to 60 %, of 51 to 72 % and of 46 to 60 % with scalar and vectors controls of voltage and of current respectively. In the motor rotation frequency range of 50 – 60 Hz, vector control of voltage provides the lowest power consumption during grinding.

5. DECLARATION OF CONFLICT OF INTEREST

The authors declare that there is no conflict of interest existing in relation to this publication.

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