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The measurement of energy consumption during milling different cereals using the sieve analyses

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Abstract. This paper deals with the measurement of energy consumption required for disintegration of different cereals depending on the desired fineness of obtained grist. The energy consumption necessary for milling was compared with the results of a sieve analysis before and after the disintegration process. The obtained results were compared with energy expended during the disintegration of cereals and were analysed to determine the coefficients of the ratio of fineness of milling/energy consumption. They was found to have good conformity. Special attention was paid to the RRSB distribution for determination of statistic average particle size and specific area of malt grist. Specific area of grist particles from different cereals was determined by calculation of the limited area and x axis in diagrams, this effort is necessary for optimisation of the disintegration process with impact on the quality of final food.

Key words: cereals, two roller mill, hammer mill, sieve analysis, electric energy consumption.

INTRODUCTION

Milling in food processing is the mechanical process of grain disintegration of different cereals in order to increase the surface area of cereal kernels for easier access of enzymes, water or other liquids, and biochemical processes, for example the transfer of starch into simple sugar or heat and mass transfer and so on (Chládek, 1976; Hardwick, 1995; Kunze, 2010). Milling can be either dry or wet. In the agricultural and food industry, two-, four-, five- and six-roller mills, hammer mills, and different disintegrators (dispersion milling) are frequently used for dry milling. For wet milling, only two-roller mills are suitable. The experimental activities involving those these types of equipment are meant to determine electric energy consumption during disintegration (Chládek, 2007; Basařová et al., 2010; Vaculík et al., 2013). In prehistoric times, the barley and husked wheat (*Triticum dicoccum*) used for human food were dehusked by pounding the grain in mortars. The invention of rotary grain mills, for grinding ordinary bread wheats (*T. aestivum*), is attributed to the Romans in the second century B.C. Thereafter, until the development of the rollermill in the mid-nineteenth century, wheat was ground by stone-milling. Today, even in industrial countries, some stone milling is carried out to meet special demands. A stone mill consists of two discs of hard, abrasive stone, approximately 1.20 m in diameter, arranged on a vertical axis. The types of stone used include French burr from La Ferté-sous-Jouarre, Seine-et-Marte, millstone grit from Derbyshire, German lava, Baltic flint from Denmark, and an artificial stone containing emery obtained from the island of Paxos in Greece. The opposing surfaces of the two stones, which are in close contact, are patterned with a series of grooves leading from the centre to the periphery. During operation, one stone is stationary while the other rotates. Either the upper stone ('upper stone'), or the lower stone ('under runner') may rotate, but it is usually the former. Grain fed into the centre ('eye') of the upper stone is fragmented between the two stones, and the ground products are issued at the periphery ('skirt').

The rollers used in wheat flour milling are usually 250 mm in diameter and either 800 mm, 1,000 mm or 1,500 mm long. The feed is distributed evenly over the length of the rolls by a pair of feed rollers which also control the loading. The succession of grinding stages is grouped into three systems: the *Break* system removes the endosperm from the bran in fairly large pieces, producing as little bran powder as possible. The *Scratch* system removes any small pieces of bran and embryo sticking to the endosperm. A sizing system may be used instead of the scratch system. The *Reduction* system grinds the endosperm into flour, at the same time flattening the remaining bran and embryo particles, and enabling them to be separated (Kent & Evers, 1994).

For the assessment of machines used for production of hard feed and food, quality of final product is a very important parameter. For malt milling used for brewing of traditional beer of Czech type (Pilsner beer Czech origin), it is important to measure dispersity (granulometry) of obtained malt grist. The variations in design and principle of disintegration equipment (roll, hammer and dispersion mills) variations in design and principle an impact on size particles distribution and, of course, on quality of final product. For the optimisation of the milling process (e.g. reduction of electric energy), it is the assessment of average particle size which is very important.

MATERIAL AND METHODS

For the measurement, the following cereals were used:

- barley (variety Bojos, harvest 2017, humidity 10 to 12%),
- malt (variety Sladek, harvest 2017, humidity 3 to 5%),
- wheat (variety Bohemia, harvest 2017, humidity 10 to 12%),
- rye (variety Selgo, harvest 2017, humidity 10 to 12%),
- oat (variety Korok, harvest 2017, humidity 10 to 12%),
- triticale (variety Kolor, harvest 2017, humidity 10 to 12%),
- all cereals were selected on sieve ≥ 2.5 mm.

Preparation of grist

Cereal samples (weight 1 kg) were crushed using following equipment:

- two roller mill VKM 130/150 (Czech Republic) with gap adjustments of this mill in the range 0.3, 0.4, 0.5 mm. The capacity of the mill is 200 kg h^{-1} (Figs 1 and 2),
- the hammer mill type Taurus (Fig. 3), supplied by the company TAURUS LTD Chrudim (Czech Republic) was utilized for the milling of cereals.

Material was milled by means of eight hammers as well as by friction between a sieve (size 3.0, 4.0 and 5.0 mm) and milled materials. The capacity of the mill is 200 kg h^{-1} (Fig. 3). Every experiment was repeated 10 times. The average value and standard deviation was calculated and the results are listed in Tables 1 and 2.

Figure 1. Two roller mill VKM 130/150.

Figure 2. Two rollers (view from below).

Figure 3. Hammer mill Taurus.

Sieve analysis of grist

For the determination of crushed malt dispersity, a test sieve shaker (sieve analyzer) HAVER EML 200 digital plus T (Germany) (Fig. 4). The experiment used a test sieve shaker 2.50, 2.00, 1.60, 1.40, 1.25, 1.00, 0.80, 0.63, 0.50, 0.40, 0.315, 0.25, 0.20, 0.16, 0.125, 0.09 and 0.063 mm (17 pcs) including the bottom. For the measurement of oat grist, 19 sieves were used (because of extremely big oat particles sieves of 3.15 mm and 4.0 mm were added). For the weighing of malt and other cereals samples (1,000 g) and fractions from test sieves, a digital laboratory scale KERN PEJ 2200 – 2M (Germany) (Fig. 5), weighing range 0 to 2,200 g, weighing accuracy +/- 0.01 g was used.

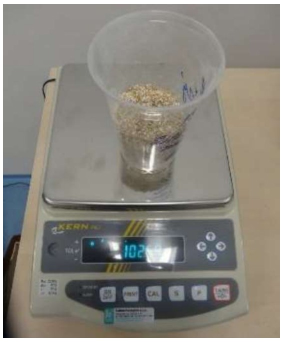

Figure 4. The test sieve shaker (sieve analyzation).

Figure 5. Digital laboratory scale KERN PEJ HAVER EML 200 digital plus T 2 200 – 2M.

The method of evaluation of the test sieving data

This method is described by Maloun (2001). The data obtained from the sieve analysis is relatively difficult to evaluate in a reproducible way. Therefore, a graphical interpretation of the data is often used as it helps in more easily imagining the analytical form of the function (which describes the granulometric composition of the sample).

From the analytical form of the function, it is possible to obtain the essential characteristics of the bulk materials. There are important characteristics such as, 'the co-efficient of polydispersity' and the mean statistical size of the particle $\overline{x}$ which determines the precision of milling.

This non-symmetry does not allow for the standard distribution. RRSB distribution – an exponential relation by Rosin, Rammler and Sperling – was invented for the fine grained materials. According to Bennett modification of this relation, it is possible to express the proportional evaluation of the relative residue on the sieve as (Maloun, 2001):

$$R = 100\exp\left[-\left(\frac{x}{\bar{x}}\right)^{n}\right][\%] \tag{1}$$

where R – the relative residue on the sieve (%); x – the dimension of separate particle (mm); $\bar{x}$ – is the main statistical size of the particle (mm); n – the material constant.

Because the shape of the curve is not suitable for graphical expression, the distribution function can be linearized:

$$\frac{100}{R} = \exp\left[\left(\frac{x}{\bar{x}}\right)^{n}\right][\%] \tag{2}$$

and yields the relation:

$$\log\left[\log\frac{100}{R}\right] = n \cdot \log x + C \tag{3}$$

where $C = \log(\log e) - n \cdot \log \bar{x}$

which in turn givesY and X values:

$$Y = \log\left[\log\frac{100}{R}\right];\ X = \log x \tag{4}$$

The $\bar{x}$ value is defined by the inflexion point of the distribution function curve, which is given by the particular value of the cumulative relative residue. This is possible to obtain from the equation:

$$f''(R) = 0$$

that means from:

$$\left\{y = \log\left[\log\frac{100}{R}\right]\right\}'' = 0 \tag{5}$$

If the calculated second derivative is set equal to zero, the value of the relative residue corresponding to the point of inflexion is obtained:

$$R = \frac{100}{e} = 36.79\ [\%] \tag{6}$$

For the calculated value there is given $x = \bar{x}$. It is possible to locate the $\bar{x}$ value from the diagram (Maloun, 2001; Chládek et al., 2013; Smejtková et al., 2016).

On the base of results obtained from different cereals, diagrams were constructed in which the axis x represents the sizes of sieve holes and the axis y is the mass of the fractions curves on the sieves (log log (100/R)).

The resulting area between the measured points and the x axis was measured and compared to the electricity input (log x); the obtained results are listed in tables 1 and 2 and discussed in the 'Results and discussion' section.

Determination of electric energy consumption during milling of different cereals

For exact determination of electric energy consumption during milling of different cereals, the three-phase power quality analyzer C.A 8332 device (Fig. 6), supplied by the French company Chauvin, was used. This compact device, shock resistant, with graphic representation, enables an instant image of network´s principal characteristics to be obtained and of their variation over a period of time to be monitored.

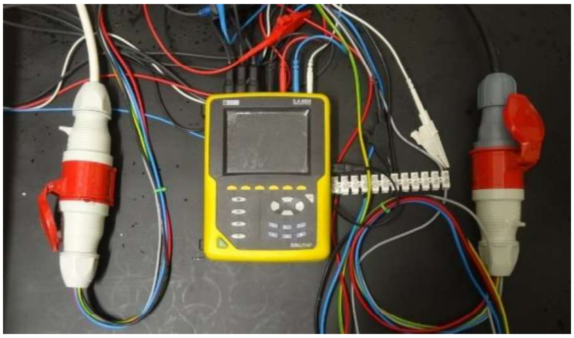

Figure 6. Three-phase power quality analyzer C.A 8332 for electric energy consumption measurement.

The multi-task measurement system simultaneously handles all the measurement functions of various magnitudes, detection, and continuous recording without any constraints. The device is designed for the following activities: measurements of AC rms voltages up to 480 V (phase to neutral) or 830 V (phase to phase); measurements of AC up to 3,000 A. Measurements of the frequency 50 and 60 Hz and other parameters.

Using the above mentioned RRSB theory, the middle particle size and area between the curve and axle x both parameters were compared, and good agreement was observed.

RESULTS AND DISCUSSION

Results of sieve analysis of different cereal grist were evaluated and expressed in following ways:

- as a size of surface area limited by the distribution curve and axle x (Fig. 7),
- as a statistical average size of the particle and standard deviation.

Those figures, depending on gap /sieve) size, type of cereals and measured electricity inputs are listed in Tables 1 and 2.

The size of this area corresponds to the average size of particle. For evaluation, this parameter was divided by initial size of particle 2.5 mm. At the start of measurement, the electricity consumption of roller and hammer mills during idling was determined and the measured value was calculated.

For cereals (the weight of every sample was 1.0 kg, size ≥ 2.5 mm, measured 10 times), durations of crushing of every sample were in the range 16 to 18 seconds.

Durations of sieve analysis of every sample were in the range 120 to 200 minutes. The calculated average size of grist particle and standard deviation were obtained from these results. All experimental data are shown in Tables 1 and 2.

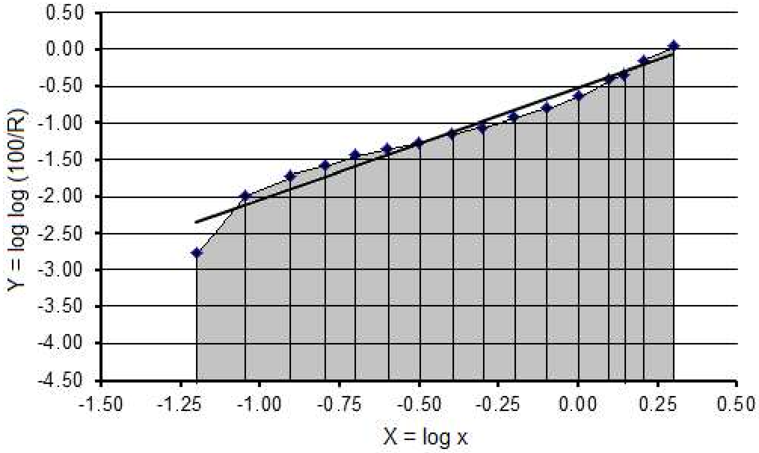

Figure 7. The determination example of the area size limited by the distribution curve and x-axis for malt grist.

Table 1. Two-roller mill - the dependence of power on the middle size of grist particles and different gap size

No	Cereals	Gap	Area beneath curve	Average size of particle	Standard deviation	Initial dimension/ standard deviation	Input	Input/ middle size
		mm	mm^2	mm	mm	mm	kW	kW mm^{-1}
Two-roller mill – gap 0.3 mm								
1.0	Idling	0.3	-	-	-	-	0.52	-
1.1	Barley grist	0.3	9,965	1.09	0.18	2.29	1.26	1.15
1.2	Malt grist	0.3	9,442	0.89	0.25	2.81	0.81	0.91
1.3	Wheat grist	0.3	8,362	1.56	0.27	1.60	1.36	0.87
1.4	Rye grist	0.3	10,220	1.47	0.14	1.70	1.72	1.17
1.5	Oat grist	0.3	6,002	1.96	0.21	1.28	0.92	0.46
1.6	Triticale grist	0.3	8,149	1.53	0.19	1.63	1.21	0.79
Two-roller mill – gap 0.4 mm								
2.0	Idling	0.4	-	-	-	-	0.52	-
2.1	Barley grist	0.4	9,572	1.29	0.15	1.94	1.20	0.93
2.2	Malt grist	0.4	9,085	1.01	0.19	2.48	0.74	0.73
2.3	Wheat grist	0.4	8,029	1.78	0.28	1.40	1.25	0.70
2.4	Rye grist	0.4	9,794	1.68	0.26	1.49	1.60	0.95
2.5	Oat grist	0.4	5,720	2.20	0.11	1.14	0.82	0.37
2.6	Triticale grist	0.4	7,947	1.62	0.21	1,54	0.97	0.59
Two-roller mill – gap 0.5 mm								
3.0	Idling	0.5	-	-	-	-	0.52	-
3.1	Barley grist	0.5	8,529	2.21	0.08	1.13	1.06	0.47
3.2	Malt grist	0.5	8,237	1.20	0.15	2.08	0.71	0.59
3.3	Wheat grist	0.5	7,005	2.12	0.11	1.18	1.16	0.54
3.4	Rye grist	0.5	8,739	2.08	0.30	1.20	1.47	0.70
3.5	Oat grist	0.5	5,198	2.15	0.19	0.86	0.71	0.26
3.6	Triticale grist	0.5	7,361	1.79	0.24	1.57	0.87	0.48

Table 2. Hammer mill - the dependence of power on the middle size of grist particles and different size of sieve

No	Cereals	Sieve	Area beneath curve	Average size of particle	Standard deviation	Initial dimension/ standard deviation	Input	Input/ middle size
		mm	mm^2	mm	mm	mm	kW	kW mm^{-1}
Hammer mill – sieve 3.0 mm								
4.0	Idling	3.0	-	-	-	-	0.76	-
4.1	Barley grist	3.0	9,178	0.93	0.16	2.69	2.90	3.12
4.2	Malt grist	3.0	11,421	0.59	0.11	4.24	1.80	3.05
4.3	Wheat grist	3.0	10,514	0.84	0.14	2.98	3.20	3.80
4.4	Rye grist	3.0	9,261	1.04	0.19	2.40	4.30	4.13
4.5	Oat grist	3.0	9,612	0.89	0.22	2.81	4.90	5.50
4.6	Triticale grist	3.0	9,815	0.88	0.25	2.85	3.70	4.20
Hammer mill – sieve 4.0 mm								
5.0	Idling	4.0	-	-	-	-	0.76	-
5.1	Barley grist	4.0	8,437	0.96	0.14	2.60	2.69	2.80
5.2	Malt grist	4.0	10,426	0.63	0.19	3.97	1.71	2.71
5.3	Wheat grist	4.0	9,763	0.93	0.24	2.69	2.98	3.20
5.4	Rye grist	4.0	8,259	1.07	0.24	2.34	4.06	3.74
5.5	Oat grist	4.0	8,487	1.05	0.28	2.38	4.58	4.36
5.6	Triticale grist	4.0	9,294	0.89	0.19	2.81	3.49	3.92
Hammer mill – sieve 5.0 mm								
6.0	Idling	5.0	-	-	-	-	0.76	-
6.1	Barley grist	5.0	8,155	1.02	0.11	2.45	2.55	2.50
6.2	Malt grist	5.0	10,095	0.68	0.21	3.68	1.68	2.47
6.3	Wheat grist	5.0	9,258	1.07	0.27	2.34	2.45	2.29
6.4	Rye grist	5.0	8,014	1.11	0.15	2.25	3.98	3.59
6.5	Oat grist	5.0	8,298	1.13	0.29	2.21	4.49	3.97
6.6	Triticale grist	5.0	8,928	0.91	0.16	2.75	3.38	3.71

The following figures (Figs 8, 9 and 10) illustrate the area, limited by curve and x-axis, average size of particle and electricity input depending on cereals, type of milling equipment, and gap and sieve size.

Figure 8. The results - the area limited by the distribution curve and x-axis.

From the analysis of achieved results, it is obvious that the optimal equipment with the lowest electric energy consumption was shown by the two-roller mill using a 0.3 mm gap by milling malt (0.81 kW) and the highest consumption by malt milling using hammer mill was 1.8 kW (sieve 3.0 mm). The highest electric energy consumption was determined to be in the case of oat milling using a hammer mill. (On the other hand should be considered the price of roll mill (appr. 3x higher as the hammer mill) were measured.

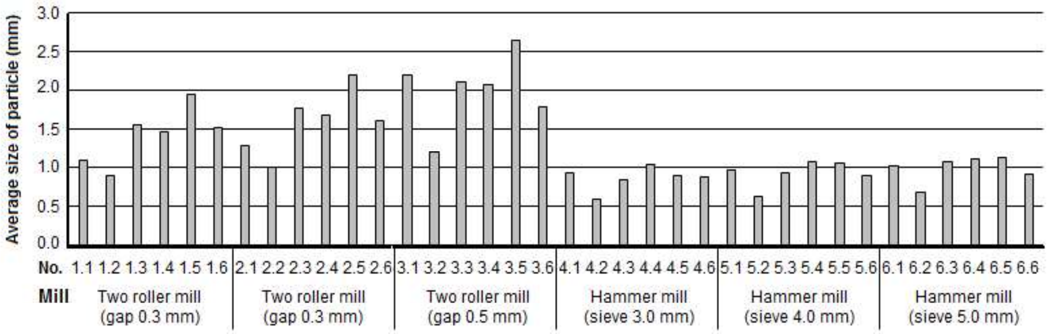

Figure 9. The results – the average size of particle for different cereals and gap (sieve) size.

Malt milling consumed the least energy, due to the very low water content (only 3 to 5% water) in malt kernels and the grain's very fragile structure. The manufacturers of malt mills supply their equipment with unnecessarily energy-consuming electric motors, when smaller motors could do the job well and more economically. The hammer mill has very low efficiency, roughly 3% to 5%, with high electricity consumption, causing financial losses.

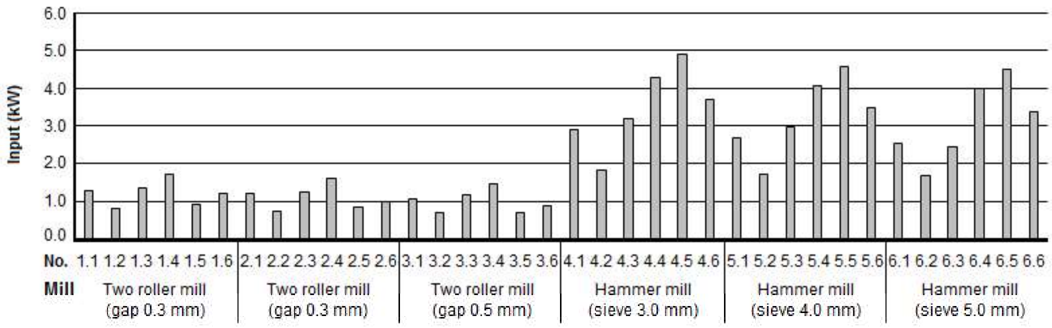

Figure 10. The results – the electrical input for different cereals and gap (sieve) size.

On figures 11 and 12 is shown the comparison of average particle size of malt grist, area beneath the RRSB (Rosin, Rammler, Sperling and Bennett, Eq. 1) distribution curve and x axis on measured input for malt and barley grist. The obtained result confirmed good coincidence with theory. Very similar results were obtained from evaluation of wheat, rye, oak and triticale measurement.

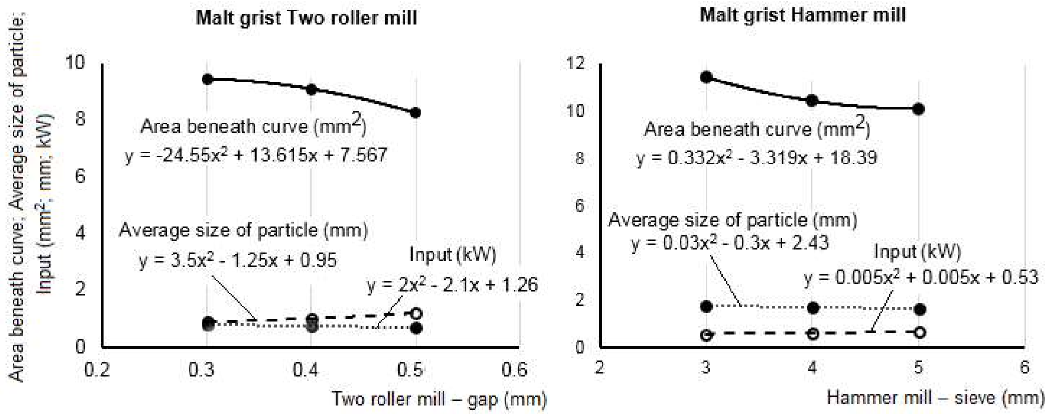

Figure 11. The comparison of impact of average size of grist and area beneath the curve on input for malt grist.

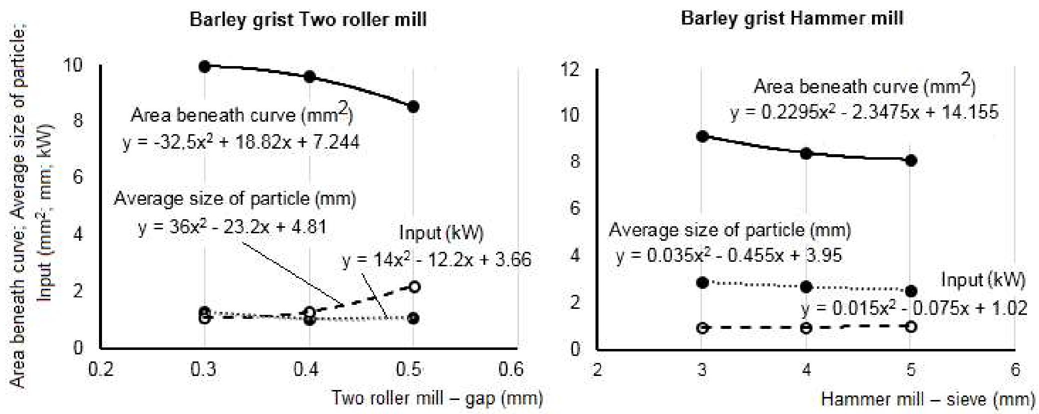

Figure 12. The comparison of impact of average size of grist and area limited by the curve and x-axis on electric input for barley grist.

CONCLUSIONS

All results obtained from sieve analysis and measurement of electricity input are in close agreement and can be used for optimization of electricity consumption during disintegration processes used for feed and food industry.

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