Process and Energy Parameters of Horizontal Centrifugal Mill for Grinding Soybeans

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Abstract. The paper represents the results of experimental studying the process and energy parameters of a new design of a horizontal centrifugal mill for grinding cereals. The most difficult grain to make flour is soybeans since this product is very viscous and moist and contains a high percentage of oil. The characteristics of a new horizontal centrifugal mill are given. The most essential soy flour and semolina property determining their industrial use is functionality, i.e. the ability to form stable water-in-oil emulsions. The high emulsifying properties of soy flour allow not only improving the organoleptic properties and increasing the nutritional value and bioavailability but also reducing the product loss during thermal treatment. Along with functionality, the neutral taste and smell of soy flour make it comparable in application effect (competitiveness) with functional soy concentrates and isolates.

1. Introduction
Currently, almost all developed countries widely use products obtained by processing soybeans. The use of proteins obtained by processing soybeans in commercial food production provides the below main effects:

- the final product’s nutritional value and bioavailability increase, and the soy protein properties ensure better assimilating all proteins contained in the product,
- the exceptional functionality of soy proteins improves the appearance and organoleptic properties of food products,
- significant economic effects such as reducing cost and production losses, improving quality, and standard batches are achieved.

2. Relevance
In the food industry, cereals are usually ground in mills operating on the principle of millstones. The efficiency of such mills is low, and it is difficult to ensure their tightness that leads to high workshop dustiness. At low rotation speeds, they have low performance due to their design. A fundamentally new mill design has been developed, which has a significantly higher rotation speed of the crushing member, and, consequently, a higher performance.

3. Theoretical
The performance of existing centrifugal mills operating on the principle of millstones and used to grind cereals depends on many factors and is determined experimentally. So far, the affecting factors have not been combined with a theoretically grounded formula.

The analysis of the performance equations available for existing centrifugal mills and the results of preliminary experiments allowed ranking these factors. The factors affecting the centrifugal mill
operation are ranked as follows: 1. the area of the gap between the peripheral parts of the fixed and rotating discs; 2. the rotation speed of the disk; 3. the bulk density of the crushed material.

The centrifugal mill throughput can be determined by the formula:

\[ Q = S_z \rho v_r, \text{kg/s}, \]  

(1)

where \( S_z \) is the area of the gap between the peripheral parts of the fixed and rotating discs, \( \text{m}^2 \); \( \rho \) is the bulk density of the crushed material, \( \text{kg/m}^3 \); \( v_r \) is the radial velocity of a particle at the edge of a rotating disk, \( \text{m/s} \).

The area of the gap between the rotating and fixed discs can be determined by the formula:

\[ S_z = \pi D h, \]  

(2)

where \( D \) is the outer diameter of the rotating disk; \( h \) is the width of the gap between the rotating and fixed discs, \( \text{m} \).

The \( v_r \) value is determined by the formula:

\[ v_r = n D/2 \sin \alpha, \]  

(3)

where \( n \) is the disk rotation speed, \( \text{s}^{-1} \); \( D/2 \) is the radius of the crushing member, \( \text{m} \); \( \alpha \) is the disk end face notch inclination angle, deg.

Substituting equations (2) and (3) into (1), we obtain:

\[ Q = \pi D^2/2 h n \rho \sin \alpha, \text{kg/s} \]  

(4)

Considering that the initial grinding occurs between the ribs and the accelerating baffles of the fixed and rotating disks, particles with the size significantly different from the linear size of the soybean may hit the peripheral gap between them, therefore, it seems necessary to introduce a correction factor \( K_\rho \) for the change in the material bulk density in the gap – \( K_\rho \).

The final equation form (4) is as follows:

\[ Q = \pi D^2/2 h n \rho K_\rho \sin \alpha, \text{kg/s} \]  

(5)

The specific performance of the mill is determined by the formula:

\[ q = Q/V, \text{kg m}^{-3}/\text{s} \]  

(6)

where \( V \) is the grinding zone volume, \( \text{m}^3 \) (for the mill considered, 0.003 \( \text{m}^3 \)).

The mill performance by the design grade of 0.074 mm is determined by the formula:

\[ q_{074} = Q \gamma_{074}/100, \text{kg m}^{-3}/\text{s} \]  

(7)

where \( \gamma_{074} \) is the yield by 0.074 mm grade (200 mesh).

The mill performance by the design grade of 0.200 mm is determined by the formula:

\[ q_{200} = Q \gamma_{200}/100, \text{kg m}^{-3}/\text{s} \]  

(8)

where \( \gamma_{200} \) is the yield by 0.200 mm grade.
4. Practical
The horizontal centrifugal mill has been developed for fine grinding of cereals, particularly, soybeans. The mill consists of a body 1 with a cover 2, a disc 5 mounted on a shaft 3 and rotating on bearings 4, made in the form of a truncated hollow cone 6 with a peripheral annular part, the inner cavity of which is divided by accelerating and cutting baffles 7 into sections. Equidistantly to the disc 7, a disc 8 is mounted, made in the form of a hollow truncated cone with a peripheral annular part, throughout the inner surface of which the cutting ribs 9 are evenly distributed.

The mill also contains loading 10 and unloading 11 pipes and a drive. The fixed disc is attached to the body by springs 12.

The material to be ground is first crushed by cutting baffles 7 and 9 and then in the gap between the working faces of the peripheral annular parts of the cup-shaped discs 5 and 8.

When an uncrushable object hits the annular gap between the discs, the fixed disc 8 is deflected in the axial direction and returned to the operating position by springs 12.

The operating principle of the mill developed is as follows: the material is pre-crushed in the gap between the rotating 5 and fixed 8 discs under the cutting loads by cutting ribs and baffles. Then, the particles are additionally crushed between the peripheral parts of the cup-shaped disks 5 and 8 due to catching between them in the radial rectangular grooves, while the angle between the cone generatrix and the cup-shaped conical disk’s peripheral part base is acute, and the radial rectangular grooves are opposed. When an uncrushable object hits the gap between the discs, the fixed disc 8 is deflected in the axial direction and returned to the operating position by springs 12.

Grinding occurs under the action of friction forces arising from the difference in the rotation speeds of the crushed material parts in the fixed 8 and rotating 5 discs and due to the cutting loads between the cutting ribs and baffles; the particles are additionally crushed between the peripheral parts of the bowl-shaped discs 5 and 8 due to catching between them in the radial rectangular grooves, while the angle between the cone generatrix and the cup-shaped conical disk’s peripheral part base is acute.

Patent No. 2295389 was received on April 21, 2005, for the invention of the mill.

The centrifugal mill is schematically shown in Fig. 1.
2. The width of the gap between the rotating and fixed disks, s, mm.
3. The moisture content of grains, w, %.

To obtain a mathematical dependence, a full factorial experiment $2^3$ was used. The factor levels were chosen based on the mill’s crushing member dimensions, the required granulometric composition of the product ground, and the consumer’s requirements, and the variation intervals were chosen based on the actual factor variation intervals.

Variables coded (9):

\[
\begin{align*}
X_1 &= \frac{n - 8,4}{4,2} ; \\
X_2 &= \frac{s - 1,0}{0,5} ; \\
X_3 &= \frac{w - 6,0}{4,0}
\end{align*}
\]  

As a result of data processing in the Mathcad environment, the regression equation coefficients have been obtained, and their significance checked.

The equations obtained to determine the mill performance (10) and power consumption (11) are given below.

\[
\begin{align*}
Y_Q &= 72,9 + 43,7 X_1 + 43,3 X_2 - 17,3 X_3 + 26,0 X_1 X_2 - \\
&- 10,4 X_1 X_3 - 10,5 X_2 X_3 \\
Y_N &= 147,9 + 29,6 X_1 - 6,2 X_2 + 20,0 X_3 - 1,3 X_1 X_2 + \\
&+ 4,0 X_1 X_3 - 14,3 X_2 X_3
\end{align*}
\]  

The relevant plots are shown in Figs. 2 & 3 (at a minimum grain moisture content $w = 2.0\%$).

![Figure 2](image1)

![Figure 3](image2)
5. Conclusion
The most efficient soy flour production is provided by mills operating on the principle of millstones; the use of a high-speed horizontal centrifugal mill will increase the grinding efficiency at minimum unit dimensions. The developed technique and software for determining the mill throughput and performance by the yield of -0.200- and -0.074-mm grades allow easy control over grinding.

6. References
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