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Research Paper

Angular oscillation model to predict the performance of a vibratory ball mill for the fine grinding of grain

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The development of a mathematical model of a vibratory mill made it possible to determine the regularities for the complex movement of its operating mechanisms and obtain a graphic interpretation for the kinematic, power and energy characteristics of the vibratory system. On the basis of theoretical pre-requisites, a series of experimental studies were conducted that provided an opportunity to obtain the amplitude-frequency, velocity and energy characteristics of the machine under investigation and to determine their impact upon the kinetics of the fine grinding process of the grain. As a result, rational operating parameters of the examined machine were established with minimal energy input.

1. Introduction

Grain refinement is the oldest technology used by humans to produce foodstuffs. The main technological task of grinding grain is to obtain a homogeneous mixture with a desired degree of grinding of the ingredients (Butkovsky, 1990; Linch, 2005). The refining process at the mill allows components such as the parts of the wheat grain to be separated: the endosperm containing mostly starch and proteins, the germ composed mostly of lipids and proteins and the bran containing mainly dietary fibre (Liu et al., 2015; Marquart, Jacobs, McIntosh, Reicks, & Poutanen, 2007). At present, a wide variety of mills and crushers are used for the production of flour for food and animal fodder (Cho, Kwon, Kim, & Mun, 2013; Savinyh, Nechaev, Nechaeva, & Ivanovs, 2016; Sysuev, Savinyh, Aleshkin, & Ivanovs, 2016). As example,

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the production of whole grain flour is mainly affected by the milling process and the predominant techniques for grinding whole grain flours are stone mills, roller mills, ultra-fine mills and hammer mills (Kent & Evers, 1994; Kihlberg, Johansson, Kohler, & Risvik, 2004). Research in the intensification of grain refinement is reflected in many works (Bulgakov, Holovach, Bandura, & Ivanovs, 2017; Rajamani, Mishra, Venugopal, & Datta, 2000; Rosenkranz, Breitung-Faes, & Kwade, 2011; Sysuev, Ivanovs, Savinyh, & Kazakov, 2015); however, the operation of a vibratory mill for fine grinding grain lacks sufficient research. As a result of using vibration, there is a significant decrease in the coefficient of internal friction and an increase in the specific surface area of the material processed when interacting with the technical filler essentially creating gradients in the rates of internal deformations in the micro- and macro-volumes of the product.

When fine grinding, vibration makes it possible to substantially increase the shock-erasing effect due to the possible variations in its strength and frictional components and to increase the rate destruction of the grain under the impact of cyclic loads as a result of dynamic interaction between particles (Doumanidis et al., 2016; Gonzalez, 1995; Janovich, Polevoda, & Nurmetov, 2016; Mori, Mio, Kano, & Saito, 2004). The main shortcomings of the traditional machines for producing fine and highly disperse material relates to the specific energy input required for processing the raw materials, the low performance characteristics of the operating mechanisms due to the active abrasion of their operating surfaces, and reduction in technical efficiency as a result of adhesion of products with increased humidity (Manetto, Cerruto, Pascuzzi, & Santoro, 2017; Kaletnik, 2006; Nasir, 2005; Yaroshevich, 2011).

In order to eliminate the above-mentioned shortcomings and increase the operational and technical performance of grinding machines, it is proposed to investigate using complex vibrational impacts.

The scientific purpose of this study was to develop a mathematical model of a vibratory mill and to carry out experiments to substantiate the technical parameters of its operation under the conditions required for intensified grain refinement, and to improve the operational and technical indicators on the basis of using complex vibro-mechanical impacts.

2. Materials and methods

An experimental vibratory mill using angular oscillations was used for this study (Franchuk, 1970, pp. 193–197; Janovich, 2015) but theoretical investigations to understand the process were carried out here. The energy consumption of the developed machine, its amplitude-frequency, kinetic and its operational parameters were estimated on the basis of experimental measurements, but analysis of the kinematic characteristics of the vibrator (vibration acceleration, vibration velocity and vibration displacement) was conducted using software developed for analysing grinding.

2.1. *The measure chain*

In order to determine the amplitude-frequency characteristics, an accelerometer analyser was developed, based on the 3-axis accelerometer LIS3DH (STMicroelectronics, USA), whose main features were: dynamically user-selectable full scales of ±2 g/±4 g/±8 g/±16 g, capability of measuring accelerations with output data rates from 1 Hz to 5.3 kHz.

The principle of operation of this device is the following: after connecting the sensor to the surface of the grinding chamber of the mill, the drive mechanism of the machine is switched on, due to which the resulting vibrations of the grinding chamber initiate inclusion of the integrated accelerometer that starts registration of the amplitude-frequency characteristics of the machine under study. To record the rotation speed of the drive shaft, the UNI-T UT372 (Uni-Trend Technology Limited, China), wireless tachometer was used, whose main technical features were measurements from 10 to 99,999 RPM with an accuracy 0.04% +/− 2dgt. The control and selection of the rotational speed of the motor shaft was carried out with the help of the autotransformer AOSN-20-220-75 (Zapadpribor, Lviv, Ukraine), which is intended for operation with alternating current. To determine the energy characteristics of the machine studied, an electronic wattmeter EMF-1 (Tequipment.net, Long Branch, NJ, USA) was used.

The dispersion ability of the material was determined using sieve analysis using a laboratory sieve analyser A-20 (LabTime, Moscow, Russia), whose main technical features were: diameter of screen 200 mm, number of screen 4–10, amplitude of oscillations − 2 to 4, frequency of oscillation 1500 rad s^{-1}, granularity 0.008–5 mm. It was used as standard screen machine grading all kinds powder material particle. In order to determine the relative humidity of the material, a Wile 55 moisture meter (Farmcomp Oy, Tuusula, Finland) was used to measure the moisture content of various types of grain and seeds, the data being stored in the memory of the instrument. The Wile 55 m can measure a wide range of moisture, grain 8–35% and oil seeds 5–25%. Wile 55 is the basic tool for precise quick measurement of grain moisture. It has automatic temperature compensation that utilises the internal temperature sensors for both grain and the temperature of the device itself. To determine the specific surface area of the treated material during the vibratory grinding process with the particle size being in the range 25–1000 μm, a PSH-9 (Company Hranat, Moscow, Russia) that had the following main features: range of specific surface area of the material 0.03–5 $m^2\ g^{-1}$, time of one analysis 3.5 min, accuracy 0.5%. This instrument measures the permeability of a layer of material through which air is leaking under pressure close to the atmospheric one.

To analyse the quality of the crushed raw material, a laboratory sampler was applied for sampling by the point selection method. To control the supply of material, a mobile vibratory dispenser PG-2 (Company Vybrotekhnyk, Russia) was used, whose main technical features were: size of the source material 0.05–5 mm, productivity 400 kg h^{-1}, amplitude of oscillation of the tray 2 mm, bunker volume 9 dm^3.