Experimental determination of useful resistance value during pasta dough kneading

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Abstract. There is a large quantity of materials produced in the form of dry powder or low humidity granulated masses in the modern market, and there is a need to develop new manufacturing machinery and to renew the existing facilities involved in the production of various loose mixtures. One of the machinery upgrading tasks is enhancing its performance. In view of the fact that experimental research is not feasible in full-scale samples, an experimental installation was to be constructed. The article contains its kinematic scheme and the 3D model. The angle of the kneading blade location, the volume of the loose mixture, rotating frequency and the number of the work member double passes were chosen as variables to carry out the experiment. The technique of the experiment, which includes two stages for the rotary and reciprocating movement of the work member, was proposed. The results of the experimental data processing yield the correlations between the load characteristics of the mixer work member and the angle of the blade, the volume of the mixture and the work member rotating frequency, allowing for the recalculation of loads for this type machines.

1. Introduction

A large number of equipment for the preparation of diverse mixtures is used in various industries, construction and agriculture. The paddle blade mixing machines enjoy the widest representation in comparison with drum, screw, frame, vibration or others type mixers, since they are quite universal and can be controlled throughout the mixing process, rapidly and easily adjusted to work with different materials. Such mixing machines are most often used in the manufacture of loose mixtures.

Due to the fact that there is a large quantity of materials produced in the form of dry powder or low humidity granulated masses in the modern market, there is a need to develop new manufacturing machinery and to renew the existing facilities involved in the production of various loose mixtures. One of the machinery upgrading tasks is enhancing its performance [1].

The performance of paddle blade mixers may be improved by increasing the geometric parameters of the working chamber (length, width), by increasing the speed of the mixer actuator movement, as well as by reducing the downtime of the equipment due to technological or technical reasons. However, during the downtime of the mixing equipment, the mixtures change their properties which results in significantly increased work member load over time. To reduce the starting moments before restarting the mixer, it is necessary to release the working chamber from the mixture, which leads to additional loss of time and raw materials.
In addition, the work members of some mixers perform not only rotary but also reciprocating movement which is necessary to eliminate the "dead" zones in the kneading of loose mixtures.

The purpose of this research is to identify functional load dependencies of the mixer work member on the kinematic, geometric and technological parameters. Thus, it was necessary to construct an experimental installation, select the testing equipment and develop a technique for conducting the experiment.

2. Theory, materials and methods

The selection of parameters influencing the load characteristics (circumferential $P_c$ and radial $P_r$ powers) of the mixer work member was carried out in accordance with the calculation formulae proposed in the referential sources [2]:

$$P_c = F \left[ g \cdot R \cdot \rho \cdot \tan \left( \frac{\pi}{4} + \frac{\gamma}{2} \right) + 2 \cdot c \cdot \tan \left( \frac{\pi}{4} + \frac{\gamma}{2} \right) \right] \cdot (\cos \alpha + \mu \cdot \sin \alpha); \quad (1)$$

$$P_r = F \left[ g \cdot R \cdot \rho \cdot \tan \left( \frac{\pi}{4} + \frac{\gamma}{2} \right) + 2 \cdot c \cdot \tan \left( \frac{\pi}{4} + \frac{\gamma}{2} \right) \right] \cdot (\sin \alpha - \mu \cdot \cos \alpha), \quad (2)$$

with $F$ being the area of the blade working surface immersed into the mixture; $g$ - free fall acceleration; $R$ - rotation radius of the blade plane center; $\rho$ - the apparent density of the mixture in the working chamber; $\gamma$ - the angle of the mixture internal friction; $R_m$ - unit resistance of the mixture to kneading; $\alpha$ - angle of the blade location relative to the radius; $\mu$ - the friction coefficient of the mixture against the blade.

Some of the parameters ($\rho$, $\gamma$, $R_m$, $\mu$) are defined by the properties of the kneaded components and for each mixture are permanent, while the design parameters of the mixing actuator ($\alpha$, $F$, $R$) may be modified according to the requirements of the process. The analysis of the expressions (1) and (2) showed that they did not take into account the impact of the work member rotating frequency change on its load characteristics. Based on this analysis, the following parameters were selected for the experimental studies: the angle of the kneading blade location relative to the shaft rotation axis, the volume of the loose mixture per one blade, the rotating frequency and the frequency of the work shaft reciprocating movement.

An experimental installation was constructed in order to determine the impact of the selected parameters, which could be varied within the required limits, on the work member load characteristics. The 3D model of the installation kinematic scheme is presented in Figure 1.

**Figure 1.** Kinematic scheme of experimental mixing machine
The installation is a continuous mixer consisting of several elements (Figure 1). The installation working chamber (1) has a semicylinder shape. The chamber has charging (2) and discharging (3) holes with lids, as well as an inspection window of transparent plastic in the top cover for the mixing process visual monitoring. The mixer work member is a shaft (4) with a kneading blade (5). The installation has two separate drives. The first one imparts the rotary movement of the work shaft and consists of an electric motor (EM1) and a V-belt transmission (6), a driven pulley (7) of which acts as a sensor with resistance strain gage (rsg1). A special mechanism has been installed for the reciprocal movement of the work member consisting of an electric motor (EM2), worm gear (8), toothed gear (9), and eccentric mechanism (10), the driven link (11) of which acts as a sensor with resistance strain gage (rsg2). All these elements as well as the control system are mounted on a welded frame (12). In addition, the installation is equipped with a device to regulate the blade angle as well as frequency converter with a range of changes in the work member rotating frequency within 40 to 160 min\(^{-1}\).

The National Instruments strain gage module NI USB-9237 was used as testing equipment. The module was connected to the personal computer with LabVIEW Signal Express software installed. The resistance strain gages were connected with a half-bridge circuit.

Experimental technique includes the following stages:

Stage 1. Conducting load measurements of the blade with different combinations of the work member rotary movement. The variable parameters: the angle of the blade location relative to the work shaft axis (0 °, 22.5 °, 45 °, 67.5 °, 90 °); the volume of the loose mixture per one blade (0.0040 m\(^3\); 0.0045 m\(^3\); 0.0050 m\(^3\); 0.0055 m\(^3\); 0.0060 m\(^3\)); and the work member rotating frequency (40 min\(^{-1}\), 80 min\(^{-1}\), 120 min\(^{-1}\), 160 min\(^{-1}\)). 100 experiments were carried out, each experiment requiring 7-10 measurements.

Stage 2. Measuring the load on the blade at its reciprocal movement (without rotation). The variable parameters: the angle of the blade location (0 °, 22.5 °, 45 °, 67.5 °, 90 °), the volume of the mixture (0.0040 m\(^3\); 0.0045 m\(^3\); 0.0050 m\(^3\); 0.0055 m\(^3\); 0.0060 m\(^3\)). The number of double passes was constant (4 double passes/min) since it was discovered at the initial phase of the experiment that the work member load does not vary significantly when this option is changed. Twenty-five experiments were carried out (5-7 measurements during each experiment).

3. Results and discussion

Experimental data were obtained through the LabVIEW Signal Express software product as graphic images (Figure 2) and processed in the Table Curve (Figure 3).

![Figure 2](image.png)

Figure 2. A standard graphical image of sensor deformations due to work member load: a - rotary movement; b - reciprocal movement

The experimental studies have shown that the blade load is complex and can be represented by a 10-order polynomial. A mathematical dependency is as follows:
\[ M(\tau) = 8.26754 + 0.00027\tau - 0.01099\tau^2 + 0.35105\tau^3 - 3.34634\tau^4 + 15.37148\tau^5 - 39.90131\tau^6 + \ldots + 61.57415\tau^7 - 55.69268\tau^8 + 26.95052\tau^9 - 5.26655\tau^{10}. \]

**Figure 3.** A standard graph resulting from the processing of experimental data with the *Table Curve*

This indicates significant and non-linear resistance of the medium into which the blade was placed. The results of the experimental data were processed by the maximum load values on the work member. The results of the data processing are presented in graphs (Figures 4-8).

Figure 4 shows the graphs resulting from the measurement at the frequency of 120 min\(^{-1}\). The X axis shows the volume values of the mixture per the kneading blade, the Y axis shows the load on the blade. The graphs correspond to the measurements at the blade angles of 0°, 22.5°, 45°, 67.5°, 90° (top-down).

**Figure 4.** The dependency of kneading blade load on the volume of the granulated mass and the blade angle (rotating frequency of the work shaft being 120 min\(^{-1}\))

Figure 5 shows the graphs based on the measurements made at the volume equivalent to 4.5 liters of the mixture per one kneading blade. The X axis reflects the work member rotating frequency, the Y axis shows the load on the blade, the graphs correspond to the measurements at the blade angles of 0°, 22.5°, 45°, 67.5°, 90° (top-down).

**Figure 5.** The kneading blade load dependency on the working shaft rotating frequency and the blade angle (the volume of granulated mass per one blade being 0.0045 m\(^3\))
Figure 6 shows the graphs obtained at the blade angles of 90° and 70°.

Figure 6. The dependency of kneading blade load on the volume of the granulated mass and the rotating frequency of the work shaft: solid line - blade angle being 90°; dash-and-dot line - blade angle being 70°.

The results of the experimental data processing of the rotary movement sensors maximum deformation values while changing the volume of the mixture and the blade angles indicate the linear character of the load change and may be represented by the mathematical dependency:

\[ M(V) = kV + b, \]

where the \( k \) and \( b \) values were determined by empirical evidence individually for each case [3, 4], which allows predicting the dynamics of load growth when changing such parameters as the volume of the mixture and the blade angles.

Similar results have been obtained by changing the speed of the experimental installation shaft rotation. The nature of the load characteristics changes is also explicitly rectilinear.

The analysis of the experimental data demonstrates that load characteristics are increasing with the increase in rotating frequency. In addition to that, it is possible to calculate their values when the work member rotating frequency increases. The interpolation formula can be used for determining the forces acting on the work shaft in case of blade angles change.

Similar experimental studies have been carried out for the reciprocating movement of the work shaft. In this case, the load dependence on the blade angle and the volume of the mixture is described by a second order polynomials:

\[ M(V) = aV^2 + bV + c, \]

where \( a \), \( b \) and \( c \) depend on the specific conditions of the experiment.

The graphs of the blade load at reciprocating movement are shown in Figure 7. The Y axis specifies the blade load and the X axis specifies the volume of the mixture per kneading blade.

Figure 7. The load at the reciprocating movement, depending on the amount of granulated mass per one kneading blade and the blade angle.

The experiment also yielded the dependencies of the work member load on the mixture volume and the experimental installation downtime at the rotating frequency of 120 \( \text{min}^{-1} \), the blade angle location at 45° and the volume of the mixture per one blade within 0.004 to 0.006 \( \text{m}^3 \) (Figure 8). The Y axis
reflects the load values on the mixer work member; the X axis reflects the downtime of the apparatus. Mathematical dependency is presented as follows:

\[ M(\tau) = a \cdot \ln\left(\frac{\tau}{5} + 1\right) + b \]

where \( a \) and \( b \) are defined individually for each case in accordance with experimental data.

![Figure 8](image.png)

**Figure 8.** The load dependency on the volume of the mixture and the downtime (blade angle being 45°; shaft rotating frequency being 120 min\(^{-1}\))

In case it is necessary to obtain intermediate values for the defined parameters, the interpolation or approximation method can be used.

4. Conclusion

The following parameters were selected for the experiment: the angle of the kneading blade location; the volume of the loose mixture; the rotating frequency and the number of double passes of the work member.

An experimental installation has been developed to vary these parameters within the following ranges: the angle of blade location from 0° to 90°; the volume of the mixture from 0.004 to 0.006 m\(^3\); the work member rotating frequency from 40 to 160 min\(^{-1}\); the number of double passes, from 1 to 4 per minute. We propose the technique of the experiment, which includes two stages for the rotary and reciprocating movement of the work member. The results of the experimental data processing yield the correlations between the load characteristics of the mixer work member and the angle of the blade, the volume of the mixture and the work member rotating frequency, allowing for the recalculation of loads for this type machines.

Experimental studies have shown that after a 40 minutes mixer downtime the load is increased by 30% to 50%.

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