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The effect of parameters on the performance efficacy of a single screw feed extruder using a design experiments and response surface methodology

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Abstract

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Feed extrusion is one of the most energy consuming processes in the feed industry. Single screw extruders due to their numerous advantages are of great importance in agriculture all over the world. In order to increase in the efficacy of the feed extrusion process, it is developed the extruder screw by designing its flight edge with the grooved surface. This type of designing provides a condition for restraining the extruded material, which helps to reduce the feed leakage through the clearance between the screw flight edge and the extruder barrel wall. Hence, the aim of this research is to increase in the performance efficacy of the extruder by optimizing the operation parameters based on the study of the feed – screw element interaction. In this article are presented the results of the experimental researches being carried out in laboratory conditions using an extruder PE-20 filled with grain material to study the effect of operation parameters on the performance efficacy of the extruder. Determination of the effect of factors, namely the type of screw with different height of grooves on the flight edge, moisture content of the grain material and feed throat opening on the performance efficacy of the extruder, was done using a factorial design experiments and response surface methodology. It is revealed the optimal operation parameters, under which the maximum performance efficacy of the extruder is provided. In doing so, the performance efficacy of the extruder increases by 22-25% in comparison with the standard screw with the plain surface of the flight edge. The research results will be used in the development of a new single screw extruder.

Keywords: extruder; single screw; flight edge; performance efficacy; response surface

Introduction

Extruders equipped with the screw are of great importance in agriculture all over the world. Single screw extruders are the most widely used for the extrusion of feed and mixtures. They are manufactured with different screw diameters, screw flight pitches and configuration. The screw has a plain surface of flight edge. However, they have a serious disadvantage. In particular, there is a leakage of feed through the clearance between the surface of the screw flight edge and the inner wall of the extruder barrel due to the material slippage. This leads to a decrease in productivity and performance efficacy of the extruder.

The issues of increasing the productivity and performance efficacy of the extruder as well as the extrudate quality depend on the operation parameters of the extruder, in particular, on the screw design.

Development of the screw by designing its flight edge with the grooved surface provides the reduction in the feed leakage through the clearance between the surface of the screw flight edge and the extruder barrel wall due to creating the conditions for restraining the extruded material.

The extruder screw with the plain surface of the flight edge has been developed and studied by many researchers (Chen, 1993; Riaz, 2000; Zubkova, 2006; Kurmanov, 2009; Kolobov, 2010; Michelangelli & Muthuktmarappan, 2011; Deng et al., 2014; Kushnir et al., 2016; Roland et al., 2019). In doing so, the optimization of the parameters of the extruder using the factorial design experiment and response surface methodology has been done by numerous researchers (Shihani et al., 2006; Altan et al., 2008; Kurmanov, 2009; Kolobov, 2010; Karunanithy et al., 2011; Anuonye et al., 2012; Liang et al., 2012; Natabirwa et al., 2018). However, variety of studies was not focused on the single screw with the grooved surface of the flight edge.

Hence, this research is aimed to increase in the performance efficacy of the extruder by optimizing the operation parameters based on the study of the feed – screw element interaction.

Materials and Methods

In order to increase in the efficacy of the feed and mixtures extrusion process, it is developed the extruder screw by designing its flight edge with the grooved surface. This leads to an increase in the friction coefficient during operation of the extruder since the grooved surface is filled with material and occurs the internal friction between the particles of the material. It, consequently, results to the restraining the material to be extruded between the surface of the screw flight edge and the extruder barrel wall. Thus, this type of designing makes an improved the feed – extruder screw interaction in terms of the reducing the feed leakage, in doing so, the increasing in the performance efficacy of the extruder.

To confirm the hypothesis, the experimental researches in the laboratory conditions using the serial extruder PE-20 have been conducted to study the effect of operation parameters on the performance efficacy of the extruder.

The extrusion process occurs as follows. The electric motor installed in the frame 5 through a belt drive rotates a high-speed screw located in the working part 8 in a cylindrical barrel, Figure 1. The portion of the material prepared for extrusion is manually fed into the hopper 1, the mixture feed mechanism 3 is driven through the eccentric. The material is fed through the receiving funnel 7 connected directly with the screw barrel mounted on the frame 5. The mass is picked up by the screw and moves along the axis of the extruder to the forming head which is fixed on the working part 8. The created pressure in the extruder barrel squeezes the extrudate through the holes of the matrix to the outside.

The main investigated factors were: the type of screw with different heights of grooves on the flight edge, moisture content of the grain material and feed throat opening.

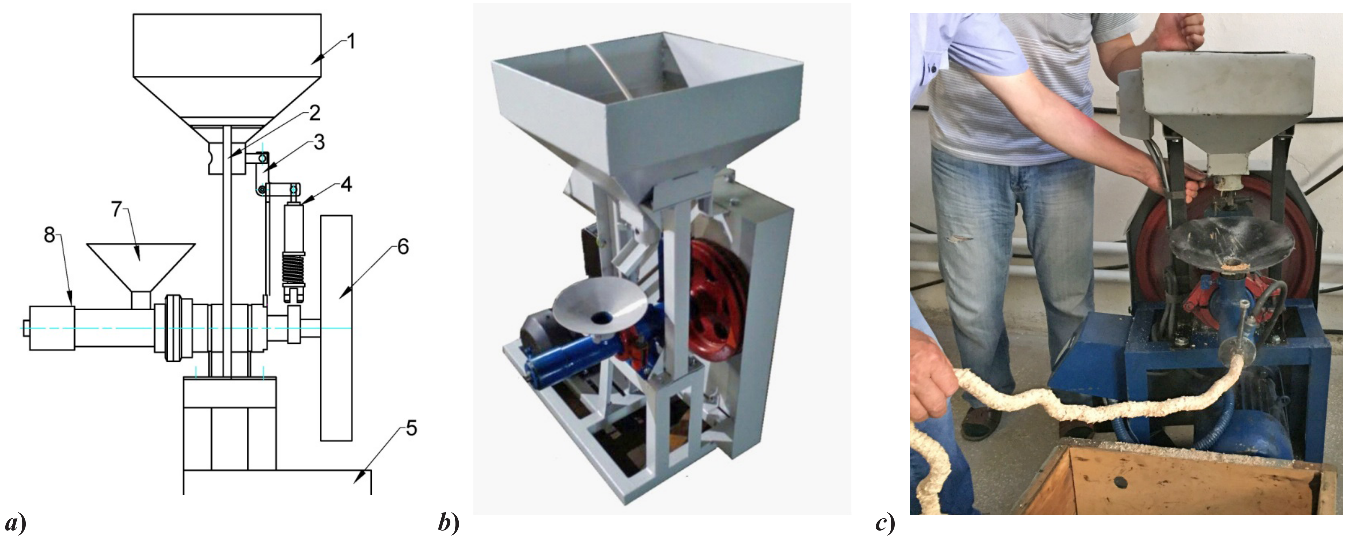
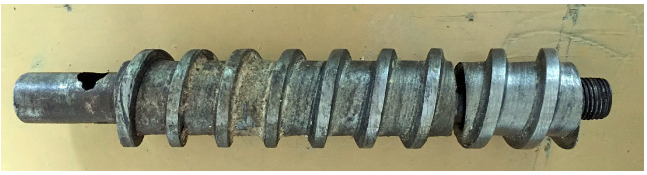
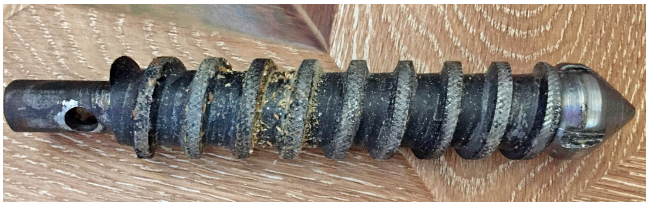


Fig. 1. Extruder PE-20: *a* – schematic view; *b* – general view; *c* – extrusion process; *1* – hopper; *2* – hopper carrier; *3* – mixture feed mechanism; *4* – pusher; *5* – frame; *6* – driven wheel; *7* – receiving funnel; *8* – working part

During the experiments 3 types of single screw with different heights of grooves on the flight edge, the value of which was 0, 0.5 and 1 mm, were used (Figure 2). The experimental studies were conducted with a grain material (wheat), the moisture content of which was changed by adding water and controlled with a digital electro-moisture meter "Wile 55". The value of the moisture content was 18, 22 and 26%. The supply of grain material was carried out by opening the feed throat at 15, 25 and 35 mm, corresponding to the minimum, average and maximum levels, respectively. The coding values of these factors are given in Table 1.



***a*)**



***b*)**

***c*)**

Fig. 2. Investigated types of the extruder screw: *a* – screw with the plain surface of the flight edge with groove height of *H* = 0 mm; *b* – screw with the grooved surface of the flight edge with the height of *H* = 0.5 mm; *c* – screw with the grooved surface of the flight edge with the height of *H* = 1 mm

As an optimization criterion, the performance indicator of the extruder efficacy *Q/N* (kg/kW·h) was considered. This indicator allows the performance efficacy of the extruder to be determined and relation between performance and power consumption for the extrusion process to be objectively evaluated. Determination of the effect of the investigated factors on the performance efficacy of the extruder was done using the factorial design experiments and response surface methodology. For doing so, a full three-factorial design experiments at three levels of variation in triplicate was done, design matrix of which is presented in Table 2. Experimental design and mathematical processing was carried out by using the "MathCad" program.

Results

After conducting the experimental studies, the confidence intervals were assessed by Student's criterion, the adequacy of the model by Fisher's criterion. Based on the research results, a regression equation describing the effect of the height of the grooves on the screw flight edge, moisture content of grain and feed throat opening on the performance efficacy of the extruder in the grain material extruding process was obtained. The equation has the following form:

$$\mathrm{Y} = 24.55 + 1.065X_1 + 0.979X_2 - 0671X_3 + 1.865X_1X_2 - 1.698X_2X_3 - 1.376X_1^2 - 2.459X_2^2 - 8.899X_3^2 \quad (1)$$

The most significant influence on the performance efficacy of the extruder has the quadratic factors, in particular, X_3 (feed throat opening *S*) and X_2 (height of grooves on the screw flight edge *H*). Next in importance are the pairwise interactions X_1X_2 and X_2X_3, whereas the least significant has the linear factors X_3 and X_2. Increasing the values of the linear factors X_1, X_2 and reducing the value of factor X_3 leads to an increase in the performance efficacy of the extruder. The magnitude and negative sign of the X_3 and X_3^2 coefficients indicate that with an increase in the feed throat opening, the performance efficacy decreases. Interpretation of various signs for the pairwise interactions $X_1X_1^2$ and $X_2X_2^2$ is leads to the fact that the magnitude of these factors can have both positive and negative effects on the performance efficacy of the extruder.

Table 1. Coding of factor levels

Level of factor	Factor		
	X_1	X_2	X_3
	Moisture content of grain *W*, %	Height of grooves *H*, mm	Feed throat opening *S*, mm
A (+1) (high)	18	0	15
B (0)	22	0.5	25
C (–1) (low)	26	1	35
Variability interval	4	0,5	10

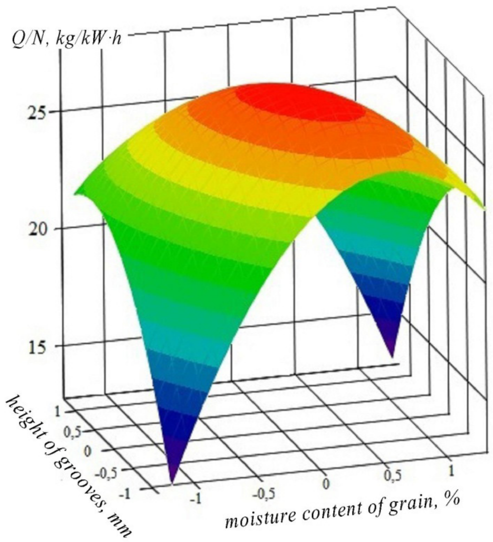
Table 2. Design matrix for a 33 factorial design

Run	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	X_1^2	X_2^2	X_3^2	*Q/N* kg/kW·h
1	+	0	+	+	0	0	+	0	+	+	12.46
2	+	0	-	+	0	0	-	0	+	+	11.52
3	+	0	+	-	0	0	-	0	+	+	18.26
4	+	0	-	-	0	0	+	0	+	+	10.53
5	+	+	0	+	0	+	0	+	0	+	16.34
6	+	-	0	+	0	-	0	+	0	+	11.93
7	+	+	0	-	0	-	0	+	0	+	16.35
8	+	-	0	-	0	+	0	+	0	+	12.48
9	+	+	+	0	+	0	0	+	+	0	22.43
10	+	-	+	0	-	0	0	+	+	0	18.58
11	+	+	-	0	-	0	0	+	+	0	19.12
12	+	-	-	0	+	0	0	+	+	0	22.73
13	+	0	0	0	0	0	0	0	0	0	24.55

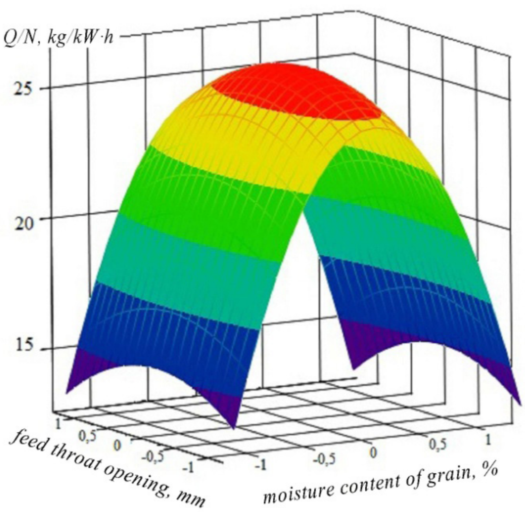
The response surface plots of the effect of the investigated factors on the performance efficacy of the extruder are shown in Figures 3-5.

Analysis of the response surface plot of the effect of the investigated factors X_1 (moisture content of grain) and X_2 (height of grooves of the screw flight edge) on the performance efficacy of the extruder shows that the maximum value of the criterion Q/N = 25.15 kg/kW·h is provided when the factor X_1 is 0.702, which corresponds to moisture content of grain of 19.2% (Figure 3). For the factor X_2, the maximum value of the criterion is reached at the point 0.465, corresponding to the height of grooves of the screw flight edge of H = 0.23 mm when decoding the variation.

Analysis of the response surface plot of the effect of the factors X_1 (moisture content of grain) and X_3 (feed throat opening) on the performance efficacy of the extruder illustrates that the maximum value of the performance efficacy of the extruder Q/N = 24.77 kg/kW·h is reached at the point 0.387 for the factor X_1 equaled to the moisture content of grain of 19.5% when decoding (Figure 4). For the factor X_3



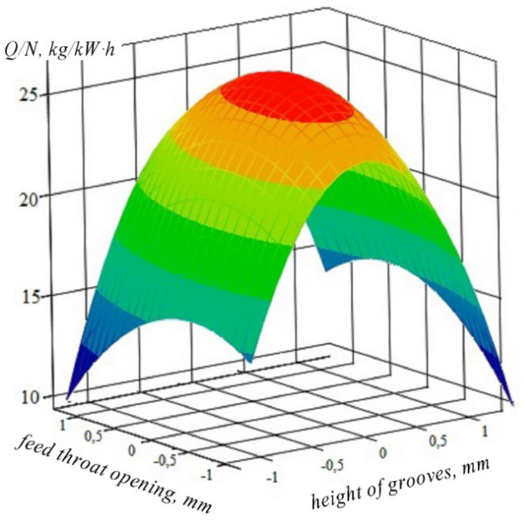
X_3 = 0 (*S* = 25 mm)
Fig. 3. Response surface plot of the effect of the moisture content of grain X_1 and height of grooves of the screw flight edge X_2 on the performance efficacy of the extruder



X_2 = 0 (*H* = 0.5 mm)
Fig. 4. Response surface plot of the effect of the moisture content of grain X_1 and feed throat opening X_3 on the performance efficacy of the extruder

the maximum value of the performance efficacy of the extruder is provided at the point -0.038, corresponding to the feed throat opening of S = 25.38 mm.

Analysis of the response surface plot of the effect of the factors X_2 (height of grooves of the screw flight edge) and X_3 (feed throat opening) on the performance efficacy of the extruder demonstrates that the maximum value of the performance efficacy of the extruder Q/N = 24.68 kg/kW·h is reached at the point 0.219 for the factor X_2, which corresponds to the height of grooves of the screw flight edge of H = 0.11 mm when decoding the variation (Figure 5). The maximum value of the criterion for the factor X_3 is at the point -0,059, corresponding to the feed throat opening of S = 25.59 mm.



$X_1 = 0$ ($W = 22\%$)

Fig. 5. Response surface plot of the effect of the height of grooves of the screw flight edge X_2 and feed throat opening X_3 on the performance efficacy of the extruder

Thus, the optimal values of the operation parameters were revealed: moisture content of grain W = 19.2...19.5%, height of grooves of the screw flight edge H = 0.11... 0.23 mm and feed throat opening S = 25.38...25.59 mm. With the indicated values of the parameters, the maximum value of the performance efficacy of the extruder 24.68...25.15 kg/kW·h is provided.

Discussion

The obtained results of the comparative studies revealed that with the selected operation parameters, in particular, the height of grooves of the screw flight edge of H = 0.11...0.23 mm and feed throat opening S = 25.38...25.59 mm and optimum moisture content of grain W = 19.2...19.5%, the performance efficacy of the extruder increases by 22-25% in comparison with the standard screw with the plain surface of the flight edge.

The research results will be used in the development of a new single screw extruder.

Conclusions

Extruder screw with the plain surface of flight edge have low performance efficacy due to the feed leakage through the clearance between the surface of the screw flight edge and the inner wall of the extruder barrel because of the material slippage.

Development of the screw by designing its flight edge with the grooved surface provides the reduction in the feed leakage due to the restraining the material between the surface of the screw flight edge and the extruder barrel wall, in doing so, the increasing in the performance efficacy of the extruder.

The experimental studies revealed the effect of the selected factors, in particular, the type of screw with different heights of grooves on the flight edge, moisture content of grain and feed throat opening on the performance efficacy of the extruder. As an optimization criterion, the performance indicator was considered, which allows the performance efficacy of the extruder to be determined and relation between performance and power consumption for the extrusion process to be evaluated.

The optimal operation parameters were revealed: moisture content of grain 19.2...19.5%, height of grooves of the screw flight edge 0.11...0.23 mm and feed throat opening 25.38...25.59 mm, which provide the maximum performance efficacy of the extruder.

Comparative studies revealed that with the selected operation parameters, the performance efficacy of the extruder increases by 22-25% in comparison with the standard screw with the plain surface of the flight edge.

The research results will be used in the development of a new single screw extruder.

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