Optimization of the sunflower seeds extrusion process in obtaining sunflower cake

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Abstract. One of the promising directions is the use of the design of the extruder working bodies, where the implemented method of compaction, movement with the timely withdrawal of sunflower cake in a bulk form, is applied. Based on the results of experimental studies using the planning method, a mathematical model of the extrusion process was obtained, which describes the specific energy consumption of the extruder in obtaining sunflower cake. The centerpoints of the experiment are located in the study area, which makes it possible to establish the optimal parameters of the factors for their various combinations. The analysis of two-dimensional sections in interaction with each other makes it possible to determine the optimal values of all the factors under study: the material temperature at the exit - $t = 133.67$ °C; the extrusion auger winding pitch - $h = 7.58$ mm; the matrix die hole area - $S = 323.89$ mm². With these values of the factors, the minimum specific energy consumption of the improved extruder $E = 69.06$ kW-h/t compared to serial ones is ensured due to the implementation of the intake and the extrusion augers connected in sequence in the form of a catenoid. This includes the joints of the sections in the form of a parabola according to the normal distribution law, the tops of the conical head in the form of a parabola, which shows that the material is not damaged when leaving the conical head, and affects its mass and density.

1. Introduction
Extrusion is one of the most promising methods for preparing food for feeding. In the process of extrusion [1], the process material is simultaneously influenced by pressure and temperature, as a result of which the structure of the feed fiber changes, starch is dextrinized to glucose, the feed is sterilized, the inhibitors of the digestive tract are inactivated, and the palatability is improved [2, 3].

The current trend in the development of extrusion technologies is to ensure the maximum reduction in the extrusion process energy consumption with improving the quality of the extrudate [4].

In the production of extruded feed products, the quality indicators of the product, as well as the energy consumption of the extrusion process, depend both on the properties of the process material and on the design and operating parameters of the extruder [5-8]. One of the promising directions is the use of the design of the extruder working bodies, where the implemented method of compaction, movement with the timely withdrawal of sunflower cake in a bulk form, is applied.

2. Materials
Experimental studies were conducted using an improved extruder according to the Patent of the Russian Federation (RU 2693072) (Figure 1).
3. Results

Based on the results of experimental studies, using the planning method, a mathematical model of the extrusion process was obtained, which describes the specific energy consumption of the extruder in obtaining sunflower cake:

\[ y_s = 70,641 - 1,2x_1 - 2,192x_2 - 4,8x_3 - 1,75x_1x_2 - 0,25x_1x_3 - 0,75x_2x_3 + 4,375x_1^2 + 13,376x_2^2 + 4,375x_3^2. \] (1)

To study the factors’ impact on the optimization parameter, Table 1 was built.

Table 1. Factors impacting on the quality of sunflower cake production by an improved extruder, their symbols and levels of variation

| Factors                                  | Symbols | Variation step | Variation level |
|------------------------------------------|---------|----------------|-----------------|
| Temperature of the material at the exit from the extrusion auger of the die [9], °C | \( x_1 \) | 25             | –1 0 1          |
| Extrusion auger winding pitch, mm        | \( x_2 \) | 2              | 6 8 10          |
| Matrix die hole area [10], mm²           | \( x_3 \) | 100            | 200 300 400     |

The analysis of the mathematical model (1) was conducted by the method of finding the extremum in space, that is, by the method of processing response surfaces in two-dimensional space [11].

After calculating the regression coefficients, the hypothesis of the second order model adequacy was tested. For this, the corresponding sums of squares, variances and F-test were calculated. For the mathematical model (1), the tabular value of the F-criterion is \( F_{0.05} = 4.74 \), and the calculated value will be:

\[ F_{calc} = \frac{10,8805}{5,582} = 1.95. \]

Since the tabular values of the Fisher criterion are greater than the calculated value, then model (1) is adequate as a second-order polynomial.

The coordinates of the maximum point are obtained by differentiating the model (1) and solving the systems of the equations [11].

The maximum point coordinates (coded values) of the surfaces will be:

\[ x_1 = 0.1751; x_2 = 0.1092; x_3 = 0.5629. \]
Substituting the obtained values of the results of the coded values into the equation (1), we determine the minimum specific energy consumption \( E = 69.07 \text{ kW-h/t} \).

As a result of the calculation, the following coefficients were obtained for finding the specific energy consumption of the extruder:

\[
B_1 = 4.375; \quad B_2 = 13.329; \quad B_3 = 4.422.
\]

The obtained coefficients for the family of regression equations in canonical form for the specific energy consumption of the extruder will have the following form:

– the sunflower cake temperature at the exit from the extrusion auger of the die and the extrusion auger winding pitch (Figure 2 a):

\[
y - 69.065 = 4.375X_1^2 + 13.329X_2^2,
\]

(2)

or

\[
\frac{(X_1)^2}{4.375} + \frac{(X_2)^2}{13.329} = 1;
\]

– the sunflower cake temperature at the exit from the extrusion auger of the die and the matrix die hole area (Figure 2 b):

\[
y - 69.065 = 4.375X_1^2 + 4.422X_3^2,
\]

(3)

or

\[
\frac{(X_1)^2}{4.375} + \frac{(X_3)^2}{4.422} = 1;
\]

– the extrusion auger winding pitch and the matrix die hole area (Figure 2 c):

\[
y - 69.065 = 13.329X_2^2 + 4.422X_3^2,
\]

(4)

or

\[
\frac{(X_2)^2}{13.329} + \frac{(X_3)^2}{4.422} = 1.
\]

Substituting different values of the responses in (2) – (4), we obtain the equations of the corresponding contour curves of the response surfaces: for (2) this is the family of ellipses, and for (3) and (4) – the curved surfaces of the minimax type. The graphical calculation results are shown in Figure 2.

The analysis of the given two-dimensional sections \( X_1 - X_2 \) (Figure 2 a) shows that with a decrease in the factors \( X_2 \) (the extrusion auger winding pitch) and \( X_1 \) (the material temperature at the exit), the specific energy consumption indicator decreases and has a minimum value of \( E = 70 \text{ kW-h/t} \).
Figure 2. Two-dimensional sections to study the $X_1$, $X_2$ and $X_3$ factors impact on the specific energy consumption of the extruder: 

a – the material temperature ($x_1$) at the exit and the extrusion auger winding pitch ($x_2$); 
b – the material temperature ($x_1$) at the exit and the matrix die hole area ($x_3$); 
c – the extrusion auger winding pitch ($x_2$) and the matrix die hole area ($x_3$)
The analysis of the two-dimensional sections $X_1 - X_3$ (Figure 2 b) and $X_2 - X_3$ (Figure 2 c) shows that the factor $X_1$ (the material temperature at the exit) and $X_3$ (the matrix die hole area) fixed at the zero level determine the optimal values:

- for the $X_1$ factor (the material temperature at the exit) $t = 133.67 \, ^\circ C$;
- for the $X_2$ factor (the extrusion auger winding pitch) $h = 7.58 \, \text{mm};$
- for the $X_3$ factor (the matrix die hole area) $S = 323.89 \, \text{mm}^2$ at the minimum specific energy consumption of the extruder $E = 69.06 \, \text{kW-h/t}$.

The $X_2$ factor (the extrusion auger winding pitch) has the same impact on the optimization parameter as the $X_3$ factor (the matrix die hole area), since the contour curves are circular, which shows the uniform impact of each factor on the optimization parameter.

4. Conclusion

The centerpoints of the experiment are located in the study area, which makes it possible to establish the optimal parameters of the factors for their various combinations.

The analysis of two-dimensional sections in interaction with each other makes it possible to determine the optimal values of all the factors under study:

- $X_1$ – the material temperature at the exit $t = 133.67 \, ^\circ C$;
- $X_2$ – the extrusion auger winding pitch $h = 7.58 \, \text{mm};$
- $X_3$ – the matrix die hole area $S = 323.89 \, \text{mm}^2$.

With these values of the factors, the minimum specific energy consumption of the improved extruder $E = 69.06 \, \text{kW-h/t}$ compared to serial ones is ensured due to the implementation of the intake and the extrusion augers connected in sequence in the form of a catenoid, and the joints of the sections in the form of a parabola according to the normal distribution law, as well as the tops of the conical head in the form of a parabola, which affects that the material is not damaged when leaving the conical head, and affects its mass and density.

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