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Investigation of selected independent variables on extrusion of rice semolina with and without propeller

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Abstract. The influence of screws with and without propeller, as well as the independent variables of material moisture content, working screw speed, feeding screw speed and die temperature on the changes of some physical and mechanical properties during singles-screw extrusion of rice semolina was studied. The response surface methodology was used with an orthogonal central composite design. Optimum modes of operation which lead to the maximization of the mass flow rate and the sectional expansion index and the minimization of the specific mechanical energy were established. The obtained results show that the use of a propeller in single-screw extrusion leads to an increase in extruder mass flow rate, a decrease in the specific mechanical energy and an increase in the sectional expansion index.

1 Introduction

The extruder screw (screw) or as scientists call it Cochlea Archimedes was made by Archimedes in Syracuse during the II Punic War. This happened around 225 BC, about 22 centuries ago. Originally, the screw invented by Archimedes was mainly used for scooping up water. In the years since, people have gradually discovered its enormous application in many fields of science.

Nowadays, the screw has a huge application, one of which is in the extrusion process. Food extrusion has been around for over 80 years. Through screw extrusion, a continuous impact on the product is achieved by means of various technological processes in flow. At the same time, the method is prospectively applicable and applied in various branches of the food, feed, biotechnological and other industries. Single-screw extrusion, initially applied in the processing of polymer raw materials, finds a wide field of action in the food industry. The advantages of single-screw extruders compared to twin-screw machines are relatively simple construction and configuration, low cost, easier and cheaper maintenance. Increasing the capabilities of single-screw extrusion by means of various additional devices is a direction that is being developed by a number of researchers.

A single-screw laboratory extruder "Brabender 20 DN", manufactured by Brabender Gmbh, Duisburg, Germany, was used in the present study. A screw with a diameter of 19.05 mm and a ratio of L/D = 20, compression 1:1, and the possibility of installing a propeller in its front part (Fig. 1), is designed for it.

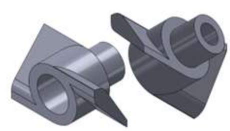

Fig. 1. 3D sketch of propeller.

Various screw configurations exist in the available literature for extruding food products. Such a multi-module screw for a single-screw extruder was designed and patented by [1]. Each module has the possibility of mounting a screw sector with different characteristics such as pitch, profile of the screw helices, angle of the screw line and others. This allows the easy extrusion of highly preconditioned, low-viscosity materials. In this way, different mechanical effects are achieved during operation.

The German company "Schaaf Technologies GmbH" has patented a device for intensifying the process of extrusion of food products, installed between the screw and the forming die [2]. It applies to single-screw extruders with a short screw in the ratio L/D = 3 (Fig.2). This unit is mainly used for the production of cereal snacks and RTE snacks. The essence of the proposed device is a fixed propeller with a certain profile at the end of the screw. When the extruder is working, the screw pushes the material through the first grid, the propeller further homogenizes it and feeds it by pressing it to the grid and the die. The propeller also acts as a spatula that pushes the material forward.

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A propeller made as the last section of a screw for processing blown polymers is patented by [3]. Through it, in single-screw extrusion, the mixing, homogenization of the material and the mechanical and thermal distribution of heat are increased Fig. 3.

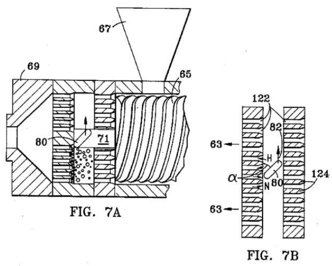


Fig. 2. Intensifying device by "Schaaf Technologies GmbH"

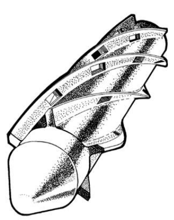


Fig. 3. Propeller for blown polymers

Available literature also describes types of mixing elements positioned in the final zone of screws for the polymer industry, such as Saxton, Maddock, Pine, Pineapple, Mailefer, Rheotoc, Bar and others Fig. 4 [4, 5, 6, 7]. All of them aim to improve the mixing of the different layers of plasticized polymer materials used in the plastics industry.

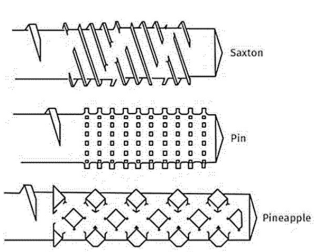


Fig. 4. Mixing elements of screw

The aim of the current study is to determine the influence of using a propeller installed at the end of a screw with a ratio L/D=20 on some selected parameters in single-screw extrusion.

2 Materials and methods

2.1 Materials

Rice semolina produced by Mill Sliven AD under TD 141-2017 was used. The initial moisture content of the semolina was 13% and the average particle diameter was d = 0.302 mm. The moisture content of the extrudates is determined using an analytical balance and a dryer. They are grounded and dried at 105°C and weighed to a constant mass.

2.2 Extrusion

The experiments were carried out on a single-screw extruder "Brabender 20 DN", manufactured by Brabender Gmbh, Duisburg, Germany. The following modes were used during operation: nozzle with a diameter of 4 mm, screw with compression 1:1, temperatures of 1 and 2 zones are fixed at 80°C and 100°C, respectively.

2.3 Mass flow rate

Mass flow rate was measured using a stopwatch and an electronic Kern balance with an accuracy of 0.01 g per ten samples for each point of the experimental design and was calculated using the formula:

$$Ge = \frac{m.3600}{t.1000},\ kg/h \qquad (1)$$

where: m - mass of the extrudate, g; t – time, s.

2.4 Sectional expansion index

The sectional expansion index (SEI) of the extrudates was measured using a micrometer with an accuracy of 0.02 mm on 10 samples for each point of the experimental plan and was calculated according to the formula:

$$SEI = \frac{De^2}{d^2} \qquad (2)$$

where:
De - diameter of the extrudate, mm;
d - nozzle diameter, mm.

2.5 Specific mechanical energy

The specific mechanical energy (SME) is determined indirectly by using the formula:

$$SME = \frac{M.\varpi}{G.3600},\ W.h/kg \qquad (3)$$

where:
M - torque,
Nm - it is measured by an electro-mechanical system, built into the drive of the extruder equipped with a digital display;
ϖ - angular speed, s^{-1}.

2.6 Planning the experiment

The response surface method was used to analyze the experimental data. It can be applied successfully and with practical value in the study of processes, depending on a large number of independent variables and quantities, the mechanism of which is not well known. The method models the behavior of the studied variable Y when the independent variables X_i, X_j, ..., X_n change in the studied n-dimensional factor space. The equation by which the response could be calculated can be written as follows:

$$Y = b_{o+} \sum_{i=1}^{k} b_1 . x_i + \sum_{1<i<j<k} b_{ij} . x_i . x_j + \sum_{i=1}^{n} b_{ii} . x_i^2 \quad (4)$$

Two identical orthogonal composition plans of a type 2^4+2.4 +star was carried out. The first series of experiments was carried out without a propeller and the second with a propeller. Table 1 shows the selected independent variables in natural form, their levels and star arms. The levels of variation of each of the independent variables were chosen as a result of previously conducted experiments. Statistical software Statgraphics XVI Trial Version was used for analysing the data results.

Table 1. Independent variables

Independent variables	Upper level	Low leve	Center	-star	+star
Feeding screw speed N_f, min^{-1}	24	36	30	21	39
Working screw speed, N_w, min^{-1}	200	240	220	190	249
Moisture content,W, %	20	24	22	19	25
Die temperature, T_m,°C	110	130	120	105	135

3 Results and discussion

Table 2 show the results of the statistical analysis of variance (ANOVA-test) for mass flow rate without and with the propeller at a confidence interval of 95% and a significance level $P \leq 0.05$.

Table 2. ANOVA-test for mass flow rate without and with propeller

Without propeller			With propeller		
Source	*F*	*P*	Source	*F*	*P*
A:Nf	372	0.00[#]	A:Nf	250.9	0.00[#]
B:Nw	0.00	0.98	B:Nw	0.07	0.79
C:W	56.4	0.00[#]	C:W	41.55	0.00[#]
D:Tm	3.26	0.09	D:Tm	0.00	0.99
AA	0.39	0.54	AA	0.00	0.98
AB	0.30	0.59	AB	7.01	0.02[#]
AC	9.39	0.01[#]	AC	7.56	0.01[#]
AD	2.25	0.16	AD	1.48	0.24
BB	1.40	0.26	BB	0.08	0.78
BC	0.13	0.72	BC	7.01	0.02[#]
BD	2.93	0.11	BD	0.84	0.37
CC	8.91	0.01[#]	CC	0.09	0.77
CD	2.75	0.12	CD	1.64	0.22
DD	0.16	0.70	DD	2.52	0.14

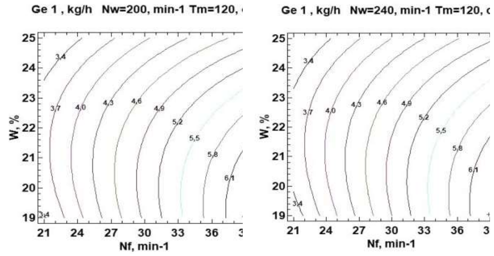
[#] - statistically significant ($P \leq 0.05$)

In the experiments without propeller, four of the effects were statistically significant as their P-value was less than or equal to the chosen significance level (P_{crit} = 0.05 at α = 5%). After eliminating the non-significant effects, the following adequate equation was obtained for the change in mass flow rate without a propeller.

$$Ge_1 = -17,470 + 0,555.Nf + 1,632.W - 0,012.Nf.W - 0,045.W^2 \quad (5)$$

In the experiments with propeller, five of the effects were statistically significant. After eliminating the non-significant effects, the following adequate equation was obtained:

$$Ge_2 = 25,045 + 0,002.Nf + 0,933.W + 0,001.Nf.Nw - 0,014.Nf.W - 0,004.Nw. \quad (6)$$



6a **6b**

Fig. 6 Change in mass flow rate Ge_1, kg/h depending on the moisture content of the material and the feeding screw speed without a propeller at the die temperature of T_m = 120°C and working screw speed: **Fig. 6a**. N_w = 200 min^{-1}; **Fig.6b.** N_w = 240 min^{-1}

Figs. 6a and 6b show the mass flow rate contours of estimated response surface for extrusion without a propeller, depending on the two statistically significant independent variables - N_f, min^{-1} and W, %. The temperature of the die is fixed at 120°C and the working screw speed changes from N_w = 200 min^{-1} to N_w = 240 min^{-1}. Mass flow rate increases when increasing the feeding screw speed and lowering the moisture content of the raw material (Ge_1 = 6.4 kg/h) and decreases almost twice at the lowest speed of the feeding screw and low moisture content. Similar results during single-screw extrusion of rice flour enriched with carrot were reported by [8] and during extrusion of pea starch by [9] The same influence was observed in the experiments with propeller (Figs. 7a and 7b).

An interesting phenomenon is observed at low values of the feeding screw speed, where there is a peak value of mass flow rate at about 21.5 - 22% moisture content of the material. As the moisture content increases or decreases from this value, mass flow rate decreases. The increase in moisture content in the material rises the friction coefficient between the material particles and the feeding screw speed and leads to a decrease in the mass flow rate. At the same time, lower moisture content leads to a lower bulk density of the material and together with the lower speed of the feeding screw, mass flow rate decreases at moisture contents below 21%.

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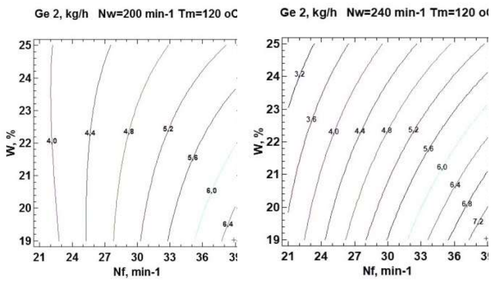


7a 7b

Fig. 7. Change in productivity Ge_2, kg/h depending on the moisture content of the material and the feeding screw speed with a propeller at the die temperature of $T_m = 120°C$ and working screw speed: **Fig. 7a.** $N_w = 200$ min^{-1}; **Fig. 7b.** $N_w = 240$ min^{-1}

Under the same conditions, the mass flow rate in the experiments with the propeller was about 10% higher than that without the propeller. In the experiments with a propeller, the increase in the working screw speed increases the mass flow rate by more than 10%. Mass flow rate depends on the co-operation of the feeding and working screw, cylinder and die. The maximum pressure is reached at the end point of the working screw. With the propeller, the maximum pressure in the extruder is shifted to the entrance of the die. Hence, it reduces the filling of the inter-turn space of the working screw, which reflects positively on the flow of the material from the feeding screw.

Table 3 show the results of the statistical analysis of variance (ANOVA-test) for sectional expansion index without and with the propeller at a confidence interval of 95% and a significance level α=5%.

Table 3. ANOVA-test for sectional expansion index without and with propeller

Without propeller			With propeller		
Source	***F***	***P***	***Source***	***F***	***P***
A:Nf	5.94	0.03#	A:Nf	0.48	0.50
B:Nw	7.49	0.01#	B:Nw	8.63	0.01#
C:W	13.1	0.00#	C:W	17.48	0.00#
D:Tm	2.18	0.16	D:Tm	6.16	0.03#
AA	0.82	0.38	AA	1.00	0.33
AB	0.32	0.58	AB	3.78	0.07
AC	0.93	0.35	AC	1.45	0.25
AD	0.15	0.70	AD	0.33	0.57
BB	0.83	0.38	BB	0.14	0.72
BC	3.06	0.10	BC	6.68	0.02#
BD	0.68	0.42	BD	0.20	0.66
CC	1.07	0.32	CC	0.84	0.37
CD	0.12	0.73	CD	10.07	0.00#
DD	3.59	0.08	DD	0.33	0.57

- statistically significant ($P \le 0,05$);

In the case without a propeller, three of the effects are statistically significant. After eliminating the non-significant effects, the following adequate equation was obtained for the change in sectional expansion index when extruding without a propeller:

$$SEI_1 = -42,891 + 0,371.Nf + 0,014.Nw - 0,204.W \quad (7)$$

In the case with a propeller, three of the effects are statistically significant. After eliminating the non-significant effects, the following adequate equation was obtained for the change in sectional expansion index:

$$SEI_2 = 50,038 + 0,038.Nw - 2,302.W - 0,373.Tm - 0,008.Nw.W + 0,021.W.Tm \quad (8)$$

The increase in the working screw speed in combination with low moisture content of the raw material leads to an increase in the sectional expansion index (Fig. 8). At a high speed of the feeding screw, SEI increases by an additional 7 %. Better mixing of the layers of plasticized material and the increased pressure of the material in the die at the propeller, leads to an increase of the expansion index.

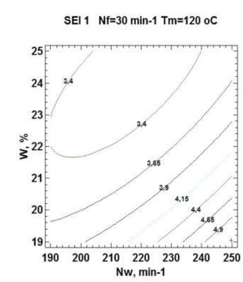


Fig. 8. Change in sectional expansion index SEI_1, depending on the moisture content of the material and the working screw speed without a propeller

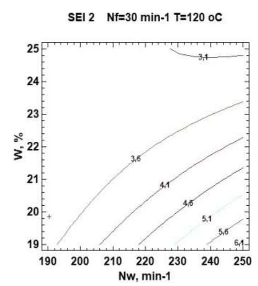


Fig. 9. Change in sectional expansion index SEI_2, depending on the moisture content of the material and the working screw speed with a propeller

Table 4. ANOVA-test for specific mechanical energy without and with propeller

Without propeller			With propeller		
Source	***F***	***P***	***Source***	***F***	***P***
A:Nf	26.2	0.00#	A:Nf	5.63	0.03#
B:Nw	0.6	0.45	B:Nw	0.03	0.86
C:W	14.3	0.00#	C:W	32.87	0.00#
D:Tm	0.32	0.58	D:Tm	12.80	0.00#
AA	0.51	0.48	AA	0.11	0.74
AB	0.13	0.72	AB	1.99	0.18
AC	0.20	0.66	AC	0.33	0.57
AD	5.05	0.04#	AD	0.94	0.35
BB	0.84	0.37	BB	1.28	0.28
BC	0.77	0.39	BC	0.03	0.86
BD	0.01	0.91	BD	0.79	0.39
CC	0.09	0.77	CC	0.01	0.94
CD	0.20	0.66	CD	1.10	0.31
DD	0.35	0.56	DD	0.64	0.43

- statistically significant ($P \le 0,05$);

The maximum sectional expansion index in both cases, as could be expected, is at high feeding screw speed and low moisture content of the material. Similar results were reported by [10]. The influence of moisture content on SEI was stronger in the propeller experiments. In Tables 8 and 9 the maximum values of the expansion and the parameters at which it was achieved can be distinguished. In the experiments with propeller, the increase in expansion was about 19.7%, with comparable parameters of the independent variables.

Table 4 show the results of the statistical analysis of variance (ANOVA-test) for specific mechanical energy without and with the propeller at a confidence interval of 95% and a significance level α=5%.

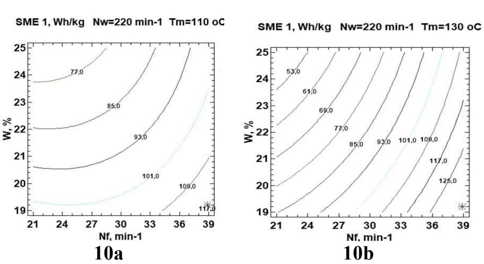
In both cases, three of the effects are statistically significant. The following adequate equations were obtained for the changes in specific mechanical energy with and without a propeller.

$$SME_1 = 270{,}561 - 19{,}757.N_f + 1{,}725.W + 0{,}109.N_f.T_m \quad (9)$$

$$SME_2 = 18{,}084 + 0{,}154.\ N_f + 2{,}19234.N_w - 14{,}576.W + 1{,}374.T_m \quad (10)$$

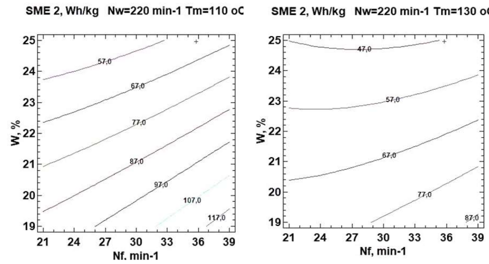
Figs. 10 and 11 show the specific mechanical energy contours of estimated response surface for extrusion without and with a propeller, depending on two statistically significant independent variables - N_f, min^{-1} and W, %. The temperature of the die changes from 110 to 130°C and the working screw speed is fixed to N_w = 220 min^{-1}. In both cases, the increase in moisture content at low speed of the feeding screw leads to a decrease in the specific mechanical energy. The obtained dependencies correspond to those reported by [11] in single-screw extrusion of rice flour enriched with dried pumpkin.

When using a propeller, the mechanical energy required to extrude 1 kg of material is between 14 and 30% less than when extruding without a propeller. In the experiments carried out in the center of the plan, the use of a propeller at the end of the screw leads to a reduction of energy consumption by more than 20%. This may be due to better homogenization of the material and lower pressure in the screw. This, in turn, reduces the friction of the fluidized material on its surface. Also, the angle of attack of the propeller blades is about 30% greater compared to the helix of the working screw. This improves and eases its work.



10a 10b

Fig. 10. Change in specific mechanical energy depending on the feeding screw speed and the moisture content without a propeller
Fig. 10a. T_m =110°C; **Fig. 10b.** T_m=130°C



11a 11b

Fig. 11. Change in specific mechanical energy depending on the feeding screw speed and the moisture content with a propeller.
Fig. 11a. T_m =110°C; **Fig. 11b.** T_m=130°C

Optimization of the process has been done to establish modes in which maximum mass flow rate Ge and sectional expansion index SEI is achieved, at a minimum level of specific mechanical energy SME. The optimum operating modes of the extruder and the optimum values of the three dependent variables are presented in Table 5. When operating without a propeller, the pressure in the extruder has a maximum value at the end of the working screw. In the case with a propeller, this peak is moved immediately after the propeller. The presence of a propeller at the end of the screw leads to an increase in the pressure in front of the die, which has a favorable effect on the mass flow rate and the sectional expansion index. This also results in less resistance at the end of the feeding screw. At the same time, the specific mechanical energy decreases when reducing the screw load. The displacement of the maximum pressure in the extruder towards the nozzle leads to an increase in the final pressure immediately before the exit of the material. This in turn leads to an increase in the expansion index.

Table 4. Optimal modes of operation and optimal values of dependent variables

Variable	*Without propeller*	*With propeller*
N_f, min^{-1}	35.3	34.5
N_w, min^{-1}	249.7	249.7
W, %	22.5	19.03
T_m,°C	113.7	134.3
Ge, kg/h	5.36	7.5
SME, Wh/kg	91.5	77.6
SEI	4.73	5.28

The data presented in table 10 shows very clearly that the presence of a propeller at the end of the screw in single-screw extrusion leads to an increase in mass flow rate by up to 30% and the sectional expansion index by up to 10%, as well as a decrease in the consumed specific mechanical energy by up to 17%.

4 Conclusion

By using the response surface method, adequate mathematical models were obtained, describing the influence of feeding screw speed, working screw speed, the moisture content of the material and the temperature of the die on the dependent variables mass flow rate, sectional expansion index and specific mechanical energy. Optimum modes of operation were established, which lead to an increase in mass flow rate and sectional expansion index and a decrease in specific mechanical energy. The use of a propeller in single-screw extrusion leads to an increase in extruder mass flow rate by up to 30%, a reduction in the specific mechanical energy consumed by up to 17% and an increase in the expansion index by up to 10%.

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